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2.0101 The Earth Surface Mineral Dust Source Investigation: Earth Venture Spectroscopy Mission

Robert Green (Jet Propulsion Laboratory),
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The Earth Surface Mineral Dust Source Investigation EMIT is planned to measure the Earth’s mineral dust source regions from the International Space Station starting in 2021. EMIT will use visible to short wavelength infrared (VSWIR) imaging spectroscopy to measure the arid land dust source regions of the Earth. Mineral dust emitted into the atmosphere under high wind conditions is an important element of the Earth system. Mineral dust impacts direct and indirect radiative forcing, weather, atmospheric chemistry, cryosphere melt, surface hydrology, and the biogeochemistry of ocean and terrestrial ecosystems, and can be a hazard to human populations. The Earth’s mineral dust cycle consists of source, transport, and deposition phases. Surface mineral dust source composition knowledge is required for initialization of Earth System Models to accurately simulate the dust cycle to investigate and understand impacts on the Earth system. Today, detailed composition of the Earth’s mineral dust source regions is uncertain. The spectroscopically derived mineral composition from EMIT measurements will be used to improve the dust source region initialization of modern Earth System Models. These models will be used to investigate the impact of direct radiative forcing in the Earth system that depends strongly on the composition of the emitted mineral dust aerosols. These new measurements and related products will be used to address the EMIT science objectives and made available to the science community for additional investigations. We present an overview of the EMIT mission and development activities.

2.0103 Preparation and Execution of the InSight Instrument Deployment Phase

Travis Imken (Jet Propulsion Laboratory), Khaled Ali (Jet Propulsion Laboratory), Philip Bailey (NASA Jet Propulsion Lab), Pranay Mishra (NASA Jet Propulsion Lab), James Penrod (JPL), Cristina Sorice (NASA Jet Propulsion Laboratory), Marleen Sundgaard (Jet Propulsion Laboratory), Maggie Williams (NASA Jet Propulsion Lab),
Presentation: Travis Imken, Monday, March 9th, 09:45 AM, Jefferson

The NASA InSight lander arrived at Mars on November 26th, 2018 on a unique science mission to study the interior of the red planet. InSight’s instrument suite is investigating the geophysical characteristics of Mars, providing a glimpse into the formation and evolution of the planet, and by similarity, other terrestrial bodies. To complete this mission, the lander used the Instrument Deployment Arm (IDA) to execute a precision deployment of two instruments to the surface: the Seismic Experiment for Interior Structure (SEIS), a three-axis seismometer, and the Heat Flow and Physical Properties Package (HP3), a heat probe ‘mole’ designed to burrow into the Martian crust. A third deployable called the Wind and Thermal Shield (WTS) was placed over SEIS to isolate it form the Martian environment. InSight is the first mission to deploy payloads on another planet. This paper will discuss both the pre-landing and on-surface work that led the successful deployment of the three surface elements. Prior to landing, the team executed detailed operations planning, nominal and off-nominal test campaigns, rehearsals of the instrument site selection process, and personnel and process readiness tests. The deployment phase ultimately spanned the lander's first 87 sols (Martian days) on the surface, as the team worked through unique challenges to characterize the workspace, prepare the IDA, deploy the payloads, and commission the instruments. With the instruments now successfully deployed, InSight has entered the heat probe penetration and science monitoring phase for the remainder of its 1 Martian year (26 Earth month) prime mission. This work has been carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Government sponsorship acknowledged.

2.0104 Parker Solar Probe: A Mission to Touch the Sun

James Kinnison (JHU-APL), Patrick Hill (Johns Hopkins University/Applied Physics Laboratory), Nour Raouafi (Johns Hopkins University Applied Physics Laboratory), Yanping Guo (JHU-APL), Nickalaus Pinkine (JHU/APL),

Presentation: James Kinnison, Monday, March 9th, 08:55 AM, Jefferson

On August 12, 2018, Parker Solar Probe (PSP) began its seven-year exploration of the inner heliosphere and the Sun's corona. Using specially designed systems to protect from the Sun's intense environment and power the spacecraft, PSP has already provided game-changing insights into coronal heating, the source of the solar wind, and how the solar wind is propagated into the interplanetary medium to interact with Earth. More than a decade in the making, PSP was designed, built, operated and managed by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) as part of NASA's Living With a Star program. PSP launched into a solar orbit, and used a Venus gravity assist to lower the orbit perihelion to complete the planned solar encounters (where the solar distance is less than 0.25 AU), currently with perihelion as close to the Sun as 0.17 AU. PSP will use six more Venus gravity assists over the next six years to reduce its perihelion from 0.17 AU to 0.046 AU in the last three encounters. During solar encounter, measurements to characterize the in situ environment will be made by four instrument suites: FIELDS (electromagnetic fields), SWEAP (solar wind plasma), ISOIS (energetic particles) and WISPR (imaging of the coronal structure). We discuss the scientific motivation for PSP and the instrument suite used to make these ground-breaking measurements. We describe the development of PSP since inception in 2007, the extreme environments to which the observatory is exposed and how these environments drove design, technologies that enable the mission, and the final configuration of both the mission and the observatory. Finally, we give an account of post-launch commissioning and operations in early orbits, and an assessment of observatory performance over these first orbits.

2.0107 InSight MIssion: Early Surface Operations

Tom Hoffman (Jet Propulsion Laboratory),

Presentation: Tom Hoffman, Monday, March 9th, 09:20 AM, Jefferson

InSight Mission: Early Operations is a paper by Tom Hoffman, Brian Bone, Jonathan Grinblat, Myron R. Grover, Travis Imken of the Jet Propulsion Laboratory, California Institute of Technology. The InSight Mission successfully landed on Mars on November 26, 2018 and has been conducting science operations since then. The initial operations included evaluation of the lander health and surveying the area around the lander. Once these steps were complete the process of deployment of three instrument elements to the Martian Surface began. The deployment was conducted in parallel with the start of science data collection. The science delivered from InSight has started to uncover the geophysical characteristics of Mars and allows the use of comparative planetary geophysical techniques to better understand the formation and evolution of Mars and thus by extension other terrestrial planets. The mission science uses several instrument and sensors, many of which are international contributions to gather the science data.

This paper will describe InSight science objectives and the surface mission operations and results to date.

2.0108 Imaging X-Ray Polarimetry Explorer (IXPE) Mission, Concept and Development Status

William Deininger (Ball Aerospace), William (Bill) Kalinowski (Ball Aerospace), Brian Ramsey (NASA - Marshall Space Flight Center), Janice Houston ,

Presentation: William Deininger, Monday, March 9th, 10:10 AM, Jefferson

The Imaging X-Ray Polarimeter Explorer (IXPE) is designed to expand understanding of high-energy astrophysical processes and sources, in support of NASA's first science objective in Astrophysics: "Discover how the universe works." Polarization uniquely probes physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic (GR) coupling to black-hole spin—that are not otherwise measurable. Imaging enables the specific properties of extended x-ray sources to be differentiated. IXPE, an international collaboration, is a NASA Small Explorer (SMEX) designed as a 2-year mission which launches to a cirular LEO orbit at an altitude of 540 km and an inclination of 0 degrees. The payload uses a single science operational mode capturing the X-ray data from the targets. The mission design follows a simple observing paradigm: pointed viewing of known x-ray sources (with known locations in the sky) over multiple orbits (not necessarily consecutive orbits) until the observation is complete. The Observatory communicates with ground stations via S-band link. The IXPE Observatory consists of spacecraft and payload modules built up in parallel to form the Observatory during system integration and test. IXPE's payload is a set of three identical, imaging, X-ray polarimeter systems mounted on a common optical bench and co-aligned with the pointing axis of the spacecraft. Each system, operating independently, comprises a 4-m-focal length Mirror Module Assembly that focuses X-rays onto a polarization-sensitive imaging detector separated by the deployable boom. Each Detector Unit (DU) contains its own electronics, which communicate with the payload computer that in turn interfaces with the spacecraft. Each DU has a multi-function filter wheel assembly for in-flight calibration checks and source flux attenuation. The payload is accommodated on the spacecraft top deck. The spacecraft provides the necessary resources to support and operate the payload elements and enable continuous science data collection. The ground system consists of three major elements: the ground stations for data receipt and command upload to the Observatory; the Mission Operation Center (MOC); and Science Operations Center (SOC). The primary ground station, contributed to the IXPE mission as part of an international collaboration with ASI is at Malindi, Kenya. The back-up ground station is in Singapore through the NEN. TDRSS is used for launch and early operations. The MOC is located at CU/LASP using their existing multi-mission MOC. The SOC is located at MSFC and the data archive at the GSFC HEASARC. The IXPE Project completed its Phase A activities in July 2016 with the submission of the Concept Study Report to the NASA Explorers Program Office as a Small Explorer (SMEX) Mission. The IXPE Project was selected in January 2017. The IXPE Project held SRR in September 2017, had Mission PDR in June 2018 and completed Mission CDR in June 2019. Currently, all major subcontracts are in place for spacecraft and payload equipment. The flight instrument equipment is being fabricated and tested as are the flight X-ray optics. This paper summarizes the IXPE mission, provides more details on the Observatory, expected launch process, MOC and SOC along with design and development status.

2.0110 NASA-ISRO Synthetic Aperture Radar (NISAR) Mission

Kent Kellogg (Jet Propulsion Laboratory),

Presentation: Wendy Edelstein, Monday, March 9th, 10:35 AM, Jefferson

NISAR is a multi-disciplinary Earth-observing radar mission that makes global measurements of land surface changes that will greatly improve Earth system models. NISAR data will clarify spatially and temporally complex phenomena, including ecosystem disturbances, ice sheet collapse, and natural hazards including earthquakes, tsunamis, volcanoes, and landslides. It provides societally relevant data that will enable better protection of life and property. The mission, a NASA-ISRO partnership, uses two fully polarimetric SARs, one at L-band (L-SAR) and one at S-band (S-SAR), in exact repeating orbits every 12 days that allows interferometric combination of data on repeated passes. NASA provides the L SAR; a shared deployable reflector; an engineering payload that supports mission-specific data handling, navigation and communication functions; science observation planning and L SAR data processing. ISRO provides the S-SAR, spacecraft, launch vehicle, satellite operations, and S-SAR data processing. The mission will be launched from the Satish Dhawan Space Centre, Sriharikota, India. Mission development has addressed many unique challenges and incorporates many "firsts" for a jointly-developed free-flyer radar science mission. Key challenges addressed by this mission include: (1) Very high degree of integration with international partner elements requiring a close coordination between teams separated by 12 time zones and 14,000 km (8700 miles); (2) Simultaneous wide-swath, fine resolution, multi-polarization radars providing 12 day global coverage; (3) Science observation plan that optimizes measurements while balancing energy and communication constraints; (4) Stowing 12 m reflector and boom within a 4-m fairing; (5) Accommodating two powerful radars operating at high duty cycle returning 38 Tb/day average data volume; (6) On-board handling, downlinking, and timely ground processing and distribution of high daily data volume; (7) Precise pointing control for the large, flexible antenna; (8) L-SAR waveforms that meet science requirements without interfering with terrestrial navigation systems. These challenges produced several "firsts," including: (1) High rate direct-to-Earth Ka-band mission data system; (2) First digitally beamformed SAR array fed reflector; (3) First dual-frequency SAR using SweepSAR; (4) Largest known SAR antenna aperture in history; (5) First use of commercial cloud-based ground processing and distribution systems for such a mission.

2.0111 CapSat-DRAGONS

Joe Burt (NASA - Goddard Space Flight Center),
Presentation: Joe Burt, Monday, March 9th, 11:00 AM, Jefferson

-CapSat-DRAGONS is a mission to measure orbital debris in the earth science orbit called the A-Train. CapSat-DRAGONS stands for Capsulation Satellite – Debris Resistive/Acoustic Grid Orbital National Aeronautics and Space Administration (NASA)-Navy Sensor. This presentation will focus on the mission architecture and technical challenges associated with implementing this type of a low cost rideshare mission.

2.0114 Europa Clipper Mission: Onward to Implementation!

Maddalena Jackson (Jet Propulsion Laboratory), Todd Bayer (NASA Jet Propulsion Lab),
Presentation: Maddalena Jackson, Monday, March 9th, 11:25 AM, Jefferson

Europa, the fourth largest moon of Jupiter, is believed to be one of the best places in the solar system to look for extant life beyond Earth. The 2011 Planetary Decadal Survey, Vision and Voyages, states: "Because of this ocean's potential suitability for life, Europa is one of the most important targets in all of planetary science". Exploring Europa to investigate its habitability is the goal of the proposed Europa Clipper mission. This exploration is intimately tied to understanding the three "ingredients" for life: liquid water, chemistry, and energy. The Europa Clipper mission would investigate these ingredients by comprehensively exploring Europa's ice shell and liquid ocean interface, surface geology and surface composition to glean insight into the inner workings of this fascinating moon. The Europa Clipper Project envisions sending a flight system, consisting of a spacecraft equipped with a payload of NASA-selected scientific instruments, to execute numerous flybys of Europa while in Jupiter orbit. A key challenge is that the flight system must survive and operate in the intense Jovian radiation environment, which is especially harsh at Europa. The innovative design of this multiple-flyby tour is an enabling feature of this mission: by minimizing the time spent in the radiation environment the spacecraft complexity and cost has been significantly reduced compared to previous mission concepts. The spacecraft is planned for launch from Kennedy Space Center (KSC), Cape Canaveral, Florida, USA, on a NASA supplied launch vehicle. The mission is being formulated and implemented by a joint Jet Propulsion Laboratory (JPL) and Applied Physics Laboratory (APL) Project team. At the Project Preliminary Design Review (PDR) in August 2018, it was determined that the unique integrated Solar Array + Ice Penetrating Radar antennas for the science instrument REASON, required more time to mature. This was accomplished, and in June 2019 the Clipper Mission passed its Delta Preliminary Design Review, followed by formal confirmation by NASA in August 2019 for entry into Phase C. The earliest launch opportunity is now in July 2023, one year later than originally planned. The Project is now working toward its Critical Design Review in May 2020. A down-selection to one launch vehicle by NASA is anticipated sometime this year. A selection of the NASA Space Launch System (SLS) would enable launch onto a direct-to-Jupiter trajectory. This would remove the need to fly through the inner solar system on a gravity assist trajectory to Jupiter, and therefore would significantly shorten the cruise phase. This paper will describe the progress of the Europa Clipper Mission since January 2019, including maturation of the spacecraft, subsystem and instrument designs, the beginning of fabrication of engineering models and the first flight models, planning for the verification & validation phase, and planning for operations.

2.0115 Mars Sample Return Mission Status

Brian Muirhead (Jet Propulsion Laboratory),

Presentation: Brian Muirhead, Monday, March 9th, 08:30 AM, Jefferson

This paper will provide an overview of current concepts and options for the architecture and design of a Mars Sample Return Mission, including the Sample Retrieval Lander (SRL) (developed by NASA) and the Earth Return Orbiter (ERO) (developed by ESA) . Key mission objectives and the overall campaign will be described, including the mission’s concept of operations and a notional timeline from launch to entry, through surface operations, to delivery of the samples to Mars orbit and return to Earth. The overall SRL lander vehicle concept will be described, including current options being evaluated. Key lander element options that have been studied will be discussed, including the Mars Ascent Vehicle (MAV), Sample Fetch Rover (provided by ESA), Orbiting Sample container (OS), and sample tube transfer robotics systems. For the ERO the vehicle concept will be described including key interfaces with the Capture/Containment and Return System (CCRS). Specific challenges and approaches for addressing those challenges will be discussed, including key technical margins and backward planetary protection. The information provided about possible Mars sample return architectures is for planning and discussion purposes only. NASA has made no official decision to implement Mars sample return. One liner: This paper will provide information on the current concepts for the architecture and design of a Mars Sample Return campaign.

2.02 Future Space and Earth Science Missions

Session Organizer: Robert Gershman (JPL), Patricia Beauchamp (Jet Propulsion Laboratory),

2.0201 A Robotically Assembled and Serviced Science Station for Earth Observations

Spencer Backus (NASA Jet Propulsion Lab), Rudranarayan Mukherjee (Jet Propulsion Laboratory), Timothy Setterfield (Jet Propulsion Laboratory, California Institute of Technology), Alex Brinkman (Jet Propulsion Laboratory), Gregory Agnes (NASA-JPL), Eric Sunada (Jet Propulsion Laboratory), Junggon Kim , Blair Emanuel (Jet Propulsion Laboratory), Russell Smith (Jet Propulsion Laboratory), Laurie Chappell (SSL), John Lymer (SSL),

Presentation: Spencer Backus, Tuesday, March 10th, 08:30 AM, Gallatin

In this paper we present the overall architecture of a "Science Station", a robotically assembled and serviced persistent platform that can host multiple payloads for Earth observations. Recent decadal survey findings motivate the need to have spatial and temporal concurrency in measurements from multiple instruments. We have architected the science station to simultaneously host up to twelve Earth Venture class instruments at a time. These instruments can be replaced by newer instruments periodically to take advantage of evolving science needs and technology capabilities. The Science Station can also concurrently host science, commercial, defense and other national interest payloads. The Science Station may provide a cost-effective paradigm by mitigating some of the risks and costs associated with multiple free-flyers that may otherwise be needed for the various instruments. It leverages emergent and existent technologies in robotic assembly and servicing, lower cost commercial launch vehicles, secondary launch vehicles, and rendezvous and proximity operations. In this paper, we report the findings of a survey we conducted on the desired performance of the Science Station from various instrument hosting perspectives. We report the various trade studies that we conducted to developed a feasible architecture that meets the goals of the Science Station while also meeting the constraints of a space system. We also report the various considerations in the configuration, thermal system, pointing system, overall concept of operations, and the robotic system of the Science Station architecture. The paper then describes a testbed activity we are undertaking to evaluate the supervised autonomy robotics needed for the Science Station as well as to conduct a risk-reduction demonstration of the end-to-end robotics behaviors.

2.0202 Numerical Predictions for On-Orbit Ionospheric Aerodynamics Torque Experiment

Christopher Capon (UNSW Canberra),

Presentation: Christopher Capon, Tuesday, March 10th, 08:55 AM, Gallatin

Accurate modelling of the aerodynamic interaction between the space environment and Low Earth Orbit (LEO) objects improves our ability to understand, predict and control their motion. A neglected aspect of the LEO aerodynamics problem is the charged aerodynamic interaction of these objects with the ionosphere, i.e. ionospheric aerodynamics. This work describes a prospective on-orbit ionospheric aerodynamic experiment (IEX) that aims to improve our fundamental understanding of ionospheric aerodynamics and provide \textit{in-situ} data to support ground-based experiment and numerical efforts. IEX involves the charged aerodynamic control of a formation of two 6U CubeSats. Through the establishment of an optical inter-satellite link (ISL), ionospheric torques induced through the asymmetric charging of High Voltage Panels (HVP) will be measured via the integrated buildup in reaction wheel (RW) speed required to maintain ISL quality. The purpose of this work is to provide preliminary estimates of RW speed buildups to establish measurement detection threshold and ISL control loop feedback rate requirements for the experiment. Here, induced torque estimates are made using the Particle-in-Cell (PIC)/Direction Simulation Monte Carlo (DSMC) simulations using the PIC-DSMC code, pdFOAM. These torque predictions are applied to a digital twin simulation of the satellite formation featuring couple dynamics, space environment and flight software models using the astrodynamics framework, Basilisk, and in-house space environment interaction analysis tool, rayMAN. Given a 500 km altitude circular orbit

with a 42^o inclination with ion number densities ranging between O(10^{11} - 10^{12}$ m^{-3}, pdFOAM simulations predicted an induced torque of O(-0.25) uNm given a HVP surface potential of -100 V for both the high and low density cases. An unexpected result was a net thrust prediction for the low-density cases caused by indirect thrust forces that arise from plasma sheath driven ion acceleration. Uncertainties surrounding appropriate boundary conditions for wake surface are hypothesised to have contributed to this result and are a key focus for future work. Considering an induced torque of -0.25 uNm and accounting for aerodynamic, solar radiation pressure and gravity-gradient torques, Basilisk simulations predicted an integrated buildup of 25-50$RPM over a 10 minute period. Future work discussed includes: attitude determination errors resulting from uncertainties in the ISL, controller errors from discrete-time effects and magnetically induced torques in the digital twin simulation.

2.0203 Trident: The Path to Triton on a Discovery Budget

William Frazier ,

Presentation: William Frazier, Tuesday, March 10th, 09:20 AM, Gallatin

This paper describes Trident, an intrepid Discovery mission to Neptune’s moon Triton, 30 AU from the Sun. Triton formed in the Kuiper Belt but was captured by Neptune into a highly-inclined retrograde orbit, where tidal forces thawed its interior, forming an ocean that likely persists to the present day. Recent outer solar system missions like Cassini and New Horizons, have yielded completely new models for ocean worlds, active worlds, and KBOs. Triton isn’t just a key to solar system science, it’s a whole keyring: a singular captured KBO and evolved ocean world, with active plumes, an energetic ionosphere, and a young unique surface. The NASA OPAG Roadmap to Ocean Worlds identifies Triton as the highest priority candidate ocean world, ripe for investigation. We show how exploration of Triton under Discovery is made possible by radioisotope power combined with a rare, extremely efficient Jupiter gravity-assist, enabling a simple, low-mass spacecraft design on a 13-year ballistic trajectory. Trident carries a mature complement of instruments: a Magnetometer, IR Spectrometer & Narrow-Angle Camera, Wide-Angle Camera, Plasma Spectrometer, and hardware-enabling Radio Science. The flight system design integrates heritage components from Ball with JPL leadership and expertise in key specialty areas to provide a Voyager-class robust spacecraft commensurate with a Discovery cost and risk tolerance. We demonstrate a design-to-cost process that defines achievable science requirements and objectives iteratively with development of affordable design capability. This paper summarizes the Trident encounter sequence that probes for an ocean, measures the ionosphere, and views nearly the whole of Triton as it traverses a single orbit around Neptune, mapping the >60% of the surface that is as yet unseen. Passage close to Triton’s surface allows detailed in situ measurements, characterizing its intense ionosphere and organic-rich atmosphere, and probing magnetically for the existence of an ocean. Triton gravity field and atmospheric profile measurements are made using augmentations to the spacecraft telecom system. The Triton encounter concludes with full-frame imaging illuminated by “Neptune-shine” when Trident is in Neptune eclipse, for direct comparison with Voyager 2’s observations nearly 50 years prior. We combine a straightforward fault management (FM) architecture with multiple redundant observations and substantial unallocated time to tolerate failures and ensure robustness of the encounter sequence [1]. Instruments are positioned to avoid the need for slewing within 30 minutes before and after closest approach, maintaining the high gain antenna (HGA) on the Earth and simplifying the encounter sequence design. The passive thermal design, accommodates the large solar dynamic range from Venus to Neptune by using the HGA for shade when close to the sun, and MMRTG excess heat, modulated by louvers. Shielding protects standard components from Jupiter flyby radiation effects. All mission data is returned to the Earth in less than a year from encounter using an X-band telecom system.

2.0206 Lunar SOURCE: Lunar Sounding Radar Cubesat Experiment

Carlo Convenevole (Cranfield University), Nicolo Valigi , Francesco Guiglia , Angelina Bintoudi (Aristotle University of Thessaloniki),
Presentation: Carlo Convenevole, ,

This paper presents the concept study of Lunar SOURCE, a SOUnding Radar Cubesat Experiment that aims at investigating the Lunar subsurface and eventually find and evaluate the amount of water and ice that is on the Moon.

2.0208 Using Existing Spacecraft toward Long Baselines in VLBI

Reza Ashtari (Johns Hopkins University),
Presentation: Reza Ashtari, Tuesday, March 10th, 09:45 AM, Gallatin

Very-long baseline interferometry (VLBI) allows for exceptionally high-resolution imaging in radio astronomy. Ultimately the angular resolution of radio interferometers and telescopes is determined by the separation between antennas in the array. Building on this fundamental concept, potential uses of existing spacecraft radio systems for VLBI are explored. Coherent observations performed between ground radio telescopes (GRT) and spacecraft require stringent drift tolerances for timing and synchronization between the GRT and spacecraft. Observed data using the spacecraft antenna is then recorded and stored on-board before downlink. Among candidate spacecraft, a promising contender and focus of this paper is New Horizons. Currently at a distance greater than 45 AU, New Horizons offers an outstanding baseline for astronomical radio observation and provides necessary, configurable instrumentation for performing an extended baseline observation in conjunction with a GRT or other spacecraft. Communications with New Horizons are synchronized with a 30 MHz clock signal using an ultra-stable oscillator (USO), providing an exceptional Allan Deviation of 3x10^-13 per one second integration time. Of the instruments on-board New Horizons, the Radio Science Experiment (REX) is of particular interest for its potential towards VLBI application. Developed for atmospheric measurements during occultations between the 7.182 GHz uplink from the 70-meter NASA Deep Space Network (DSN) antenna and Pluto/Charon, REX also successfully performed axial radiometric measurements of the Cygnus-A and Cassiopeia-A galaxies using the New Horizons high-gain antenna (HGA). The REX instrument's infusion with the New Horizons HGA allows for any radio measurement to be recorded, stored on-board, and ultimately to be downlinked to the DSN. For VLBI, New Horizons could receive command data for timed three-dimensional alignment synchronous to a ground-based observation. The observed data would then be recorded, downlinked, correlated, and processed for synthesized imaging. Using New Horizons for VLBI would be a proof-of-concept. With a fixed observation frequency, narrow bandwidth and receiver sensitivity of -177 dBm, New Horizons is limited as an extension for long-baseline radio interferometry. Given these restrictions, a successful VLBI measurement using New Horizons would still result in the highest angular resolution for any radio observation ever, at an astonishing 1.34 nanoarcseconds. Expanding the applications of New Horizons to VLBI observations encourages collaboration within the growing infrastructure for space-based astronomy.

2.0209 Data Mules on Cycler Orbits for High-Latency, Planetary-Scale Data Transfers

Marc Sanchez Net (Jet Propulsion Laboratory), Etienne Pellegrini (NASA Jet Propulsion Laboratory), Joshua Vander Hook (NASA Jet Propulsion Lab),
Presentation: Joshua Vander Hook, Tuesday, March 10th, 10:10 AM, Gallatin

In this work we explore the concept of a secondary “data mule” consisting of a small satellite used to ferry data from a Mars mission to Earth for downlink. The concept exploits the fact that two nearby optical communicators can achieve extremely high data rates, and that a class of trajectories called “cyclers” can carry a satellite between Mars and Earth regularly. By exploiting cycler orbits, the courier needs minimal onboard propulsion. However, cycler orbits have long periodicity, as it can take years for the satellite, Mars, and Earth to repeat their relative geometry. Therefore, we propose the use of a network of such cycler “couriers” on phase-shifted trajectories to achieve a regular cadence of downlink trips. We design a series of search and optimization steps that can output a set of trajectories that at first approximation have low onboard propulsion requirements and can be used for any regular logistics network to and from Mars, then derive the link budget for proximity optical communications to show that this network can ferry large amounts of data.

2.0211 NASA's Plan for Commercial LEO Development

Douglas Comstock (NASA Headquarters), Christie Cox (NASA - Headquarters), Robyn Gatens (NASA - Headquarters),

Presentation: Douglas Comstock, Tuesday, March 10th, 10:35 AM, Gallatin

[additional co-authors who are not in the system yet include Marybeth Edeen, Mike Read, and David Korth] A robust and competitive low-Earth orbit (LEO) economy is vital to continued progress in space. The United States is committed to encouraging and facilitating the growth of the U.S. commercial space sector that supports U.S. needs, is globally competitive, and advances U.S. leadership in the next generation of new markets and innovation-driven entrepreneurship. NASA has developed a long-term vision to achieve this goal where, one day, NASA will become one of many customers in low-Earth orbit. The plan was publicly unveiled on June 7, 2019 at Nasdaq in New York. This plan builds on, uses the capabilities of, and applies the lessons learned from over a decade of work and experience with commercial companies. This plan, entitled NASA's Plan for Commercial LEO Development, addresses how NASA will partner with industry to bolster supply of commercial LEO destinations, stimulate demand for new and emerging markets in LEO, and lays out near-term steps to achieve a robust economy in LEO. In the near term, NASA developed and is implementing a five-point plan building on the work of the last two decades. 1) NASA established a commercial use and pricing policy for the International Space Station (ISS) that will enable companies to reduce uncertainty and build business plans as they seek to perform commercial activities, including marketing; 2) NASA has announced the intent to enable flight of private astronauts to the ISS with the first mission as early as 2020, including a solicitation as a mechanism to enable the assessment and approval of these missions; 3) NASA has initiated a process for developing commercial low-Earth orbit destinations, including the overall strategy, timeline, and solicitations for developing commercial destinations using the ISS Node 2 Forward Port, and free-flyer destinations; 4) NASA has laid out a plan to pursue opportunities to stimulate scalable and sustainable demand for LEO destinations including solicitations with calls for in-space manufacturing and regenerative medicine flight demonstrations, as well efforts to expand the pipeline of potential users and seeking innovative approaches to broadly stimulate demand; 5) NASA has updated a white paper quantifying the agency's long term needs in LEO. This paper provides an overview of NASA's plan and long-term vision for development of the LEO economy, and provides a summary of progress being made in each of the five areas of the plan.

2.0212 The Sun Radio Interferometer Space Experiment (SunRISE) Mission Concept

Joseph Lazio (Jet Propulsion Laboratory), Justin Kasper (University of Michigan), Andrew Romero Wolf (Jet Propulsion Laboratory),

Presentation: Joseph Lazio, Tuesday, March 10th, 11:00 AM, Gallatin

The Sun Radio Interferometer Space Experiment (SunRISE) would provide an entirely new view on particle acceleration and transport in the inner heliosphere by creating the first low radio frequency interferometer in space to localize heliospheric radio emissions. By imaging and determining the location of decametric-hectometric (DH) radio bursts from 0.1 MHz–25 MHz, SunRISE provides key information on particle acceleration mechanisms associated with coronal mass ejections (CMEs) and the magnetic field topology from active regions into interplanetary space. Six small spacecraft, of a 6U form factor, would fly in a supersynchronous geosynchronous Earth orbit (GEO) orbit within about 10 km of each other, in a passive formation, and image the Sun in a portion of the spectrum that is blocked by the ionosphere and cannot be observed from Earth. Key aspects that enable this mission concept are that only position knowledge of the spacecraft is required, not active control, and that the architecture involves a modest amount of on-board processing coupled with significant ground-based processing for navigation, position determination, and science operations. Mission-enabling advances in software-defined radios, GPS navigation and timing, and small spacecraft technologies, developed and flown over the past few years on DARPA High Frequency Research (DHFR), the Community Initiative for Continuing Earth Radio Occultation (CICERO), and the Mars Cube One (MarCO) missions, have made this concept finally affordable and low-risk. The SunRISE concept involves utilizing commercial access to space, in which the SunRISE spacecraft would be carried to their target orbit as a secondary payload in conjunction with a larger host spacecraft intended for GEO. The Phase A study on the SunRISE mission concept was completed in 2018 July, and an Extended Phase A study was completed in 2019 September. This paper presents a summary of the concept study and current status of the mission concept. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This document contains predecisional information — for planning and discussion purposes only.

2.03 System and Technologies for Landing on Planets, the Moon, Earth and Small Bodies

Session Organizer: Ian Clark (Jet Propulsion Laboratory), Clara O'farrell (Jet Propulsion Laboratory),

2.0302 Terrain Relative Navigation for Guided Descent on Titan

Larry Matthies (Jet Propulsion Laboratory), Brandon Rothrock (NASA Jet Propulsion Lab), Shreyansh Daftry (NASA Jet Propulsion Lab), Michael Malaska (Jet Propulsion Laboratory), Evgeniy Sklyanskiy (Jet Propulsion Laboratory California Institute of Technology), Aaron Schutte (NASA Jet Propulsion Lab), Robert Hewitt (Jet Propulsion Laboratory), Jeff Delaune (Jet Propulsion Laboratory),

Presentation: Larry Matthies, Monday, March 9th, 08:30 AM, Gallatin

Titan's dense atmosphere, low gravity, and high winds at high altitudes create descent times of >90 minutes with standard EDL architectures and result in large unguided landing ellipses, with 99% values of ~110x110 km and 149x72 km in recent Titan lander proposals. Enabling precision landing on Titan could increase science return for the types of missions proposed to date and make additional types of landing sites accessible. Precision landing on Titan has unique challenges, because the hazy atmosphere makes it difficult to see the surface and because it requires guided descent with divert ranges that are one to two orders of magnitude larger than needed for other target bodies. Conceivably, such divert capability could be provided economically by a parafoil or

other steerable aerodynamic decelerator deployed several 10s of km above the surface. The long descent times lead to large inertial navigation errors, hence a need for terrain relative navigation (TRN). This would require a TRN capability that can operate at such altitudes, despite challenges of seeing the surface sufficiently clearly and of depending on map products that are two orders of magnitude lower in spatial resolution than those for Mars and airless bodies. This paper addressed the TRN problem for Titan guided descent, assuming parafoil deployment at an altitude around 40 km. We define a notional sensor suite including an IMU, a radar altimeter, and two descent cameras, with spectral responses in the VNIR (~0.5 to 1 um) and SWIR (~2.0 to 2.1 um). Due to the low resolution of current Titan map products, we define two altitude regimes (above and below ~ 20 km) that need different navigation techniques. Map matching is applicable in the upper regime, but challenging or infeasible in the lower one. Feature tracking with decent imagery is desirable in the lower regime, but challenging in the upper one. We derive image contrast requirements for TRN from prior literature and create models of achievable image contrast by radiative transfer modeling; this shows that the requirements should be achievable for a SWIR descent camera in the upper regime, and that a VNIR descent camera is preferable in the lower regime. We then develop algorithms for map matching and feature tracking with descent images and test these with synthetic images created from Cassini/Huygens data sets and our radiative transfer model. We also introduce new possibilities for TRN based on the potential to discriminate some specific types of terrain onboard in descent imagery, such as lake vs adjacent ground and dune vs interdune. We use sensor measurement noise models in simulations of state estimation with an extended Kalman filter that includes coordinates of a set of tracked features in the state vector. Case studies were done for two notional landing sites, one in a site with only dry ground and one in a Titan lake district. In both cases, the filter error model shows 3 sigma position error at touchdown on the order of 2 km.

2.0304 Europa Lander Engine Plume Interactions with the Surface and Vehicle

William Hoey (NASA Jet Propulsion Laboratory), Rebekah Lam , ANTHONY WONG (Jet Propulsion Laboratory), Carlos Soares (NASA Jet Propulsion Laboratory),
Presentation: William Hoey, Monday, March 9th, 08:55 AM, Gallatin

NASA's proposed Europa Lander Project would deliver an autonomous robotic lander with a suite of scientific equipment to the icy moon’s surface in order to excavate surface samples and search for bio-signatures. This mission concept would land on the Europan surface using JPL’s iconic Sky Crane technique, by which a powered descent vehicle is propelled and maneuvered into a hovering position with eight monopropellant hydrazine engines before lowering its lander. The gas plumes of these engines would expand rapidly into Europa’s near-vacuum surface conditions and impinge upon the moon’s surface, the lander, and descent vehicle to potentially detrimental effect. Engine plumes induce torques and heating of spacecraft and can transport gas and liquid propellant byproducts to contaminate sensitive instrument surfaces, impacting science collection. Major interactions of concern include surface contamination with, and subsurface penetration of, propellant byproducts; the removal and transport of particulates from plume-induced pressure gradients; and the sublimation of surface ices. Therefore it is critical to understand and characterize the proposed Europa Lander’s engine plumes. Landings onto Europa and other airless bodies – i.e. those without collisional atmospheres, a class including Enceladus, Earth’s moon, and many asteroids – will generate engine plume flow-fields that transition through continuum, rarefied gas-dynamic, and free-molecular regimes. Such complex, non-equilibrium flow-fields require hybrid solution schemes. A one-way-coupled continuum-to-rarefied hybrid scheme has been demonstrated, validated, and deployed for the simulation of single-engine, steady-state lander plumes impinging onto both the Earth’s moon and Europa in a multi-disciplinary

effort at JPL. The present work extends that hybrid framework to model the complex interactions of the full set of four Europa Lander descent engine plumes, each canted at 30°, generated during the final Sky Crane bridled descent. We report resultant surface pressure, heating, and contaminant depositions, and we demonstrate a framework that can be applied to model realistically-rough Europa-like surface morphologies. Likewise, we report the pressures, heat fluxes, and contaminant depositions induced by transient descent engine plumes onto both the Europa Lander and descent vehicle envelopes during landing, and we propose and outline several detailed campaigns of future work to the benefit of Europa Lander's engineering and science teams. Note: The decision to implement the Europa Lander mission will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

2.0306 Stochastic Atmosphere Modeling for Risk Adverse Aerocapture Guidance

Jack Ridderhof (Georgia Institute of Technology), Panagiotis Tsiotras (Georgia Tech),
Presentation: Jack Ridderhof, Monday, March 9th, 09:20 AM, Gallatin

In this paper we consider the problem of aerocapture guidance inside an atmosphere with the density randomly perturbed according to a Gaussian process model. We formulate the problem of solving for a single bank event as a stochastic optimization problem and then, in terms of a 3-DoF Martian aerocapture example, we study the properties of the proposed approach compared to a standard deterministic approach. The stochastic approach is shown to decrease the risk that a large delta-V is required for maneuvering after atmospheric flight to reach a target apoapsis and periapsis.

2.0307 Integrated Simulation and State Estimation for Precision Landing on Titan

Aaron Schutte (NASA Jet Propulsion Lab), Jeff Delaune (Jet Propulsion Laboratory), Evgeniy Sklyanskiy (Jet Propulsion Laboratory California Institute of Technology), Robert Hewitt (Jet Propulsion Laboratory), Shreyansh Daftry (California Institute of Technology), Marco Quadrelli (Jet Propulsion Laboratory), Larry Matthies (Jet Propulsion Laboratory),
Presentation: Aaron Schutte, Monday, March 9th, 09:45 AM, Gallatin

This paper reports on a study of the application of a ram-air parafoil to Entry, Descent, and Landing (EDL) on Titan. A comprehensive simulation was constructed to enable simulation of EDL state estimation performance from 10 minutes before entry (E-10 min) to touchdown on the surface of Titan. EDL performance is characterized assuming an entry phase starting at E-10 min followed by a parafoil guided phase for descent and landing to enable precise landing on a predetermined target. Guided descent during the parafoil phase is achieved using the parafoil steering capability while state estimation is accomplished using vision-based Terrain Relative Navigation (TRN). The simulation is used in this study to conduct Monte Carlo analysis of TRN state estimation for a full entry phase sequence followed by a straight line flight path descent and landing.

2.0308 EDL Simulation Results for the Mars 2020 Landing Site Safety Assessment

David Way (NASA - Langley Research Center), Soumyo Dutta (NASA Langley Research Center), Samalis Santini De León (Texas A&M University),
Presentation: David Way, Monday, March 9th, 11:00 AM, Gallatin

The Mars 2020 rover is NASA's next flagship mission, set to explore Mars in search of scientific evidence of past microbial life. Importantly, the rover will also, for the first time, have the ability to collect and cache rock and soil samples for retrieval and return to laboratories here on Earth. Thus Mars 2020 represents the first in a triad of ambitious missions designed to return samples from the red planet, a major step in addressing key questions about the origins of the solar system. A key step in the development of the Mars 2020 mission is the selection of a suitable landing site with the largest likelihood of

meeting scientific goals. This decision is a complex and critical one that requires close interaction between the scientific and engineering communities. The chosen landing site must be both scientifically interesting – providing the project with the greatest possible chance of gathering credible and defendable scientific evidence – and also safe enough to attempt a landing in the first place. Thus, arguably one of the most important undertakings of the EDL team, is to effectively enumerate, quantify, and communicate the landing risks to all of the stakeholders. The culmination of this effort is the Landing Site Safety Assessment, which is a review commissioned by the project, presided over by the EDL Standing Review Board, and attended by management and science stakeholders, in which the EDL team communicates their assessment of the associated landing risks and the combined probability of a successful landing at each of the final candidate landing sites. This assessment relies heavily on computer simulations of the EDL sequence. Over the course of several Landing Site Workshops, approximately thirty candidate landing sites were evaluated for scientific interest and the potential to meet scientific objectives. These sites were ranked by the science community, with the highest ranked sites moving-on the next round. Through this process, three top candidates emerged: Jezero Crater, North East Syrtis, and Columbia Hills. These three sites, along with a fourth site located approximately half-way between Jezero and NE Syrtis, were evaluated in detail by the EDL team for overall EDL performance and landing safety. In this paper, we will summarize the end-to-end EDL simulation results used in support of this assessment.

2.0309 Assessment of the Robustness of the Mars 2020 Terminal Descent Sensor in the Event of Beam Failure

Samalis Santini De León (Texas A&M University), Allen Chen (Jet Propulsion Laboratory), David Way (NASA - Langley Research Center), Paul Brugarolas ,

Presentation: Samalis Santini De León, Monday, March 9th, 10:10 AM, Gallatin

—The Mars 2020 entry, descent, and landing architecture resembles closely that of MSL. Due to the inherent similarity between both missions, Mars 2020 will make use of heritage technology and spare parts of Mars Science Laboratory (MSL), including the Terminal Descent Sensor. The Terminal Descent Sensor collects instantaneous altitude and velocity measurements of the vehicle using a six narrow-beam line of sight Doppler altimeter/velocimeter. For MSL, it was shown that the system is robust enough for one beam to be temporarily obscured by the jettisoned heatshield. In this paper, we further evaluate the system's robustness and EDL performance in the event of beam failure. This assessment was done by means of Monte Carlo dispersion analysis. In each simulation, it is assumed that one of the six beams does not collect measurements. Further analysis was conducted to evaluate system performance by employing a measurement collection scheme that leads to a lower loss of measurements. The analysis demonstrated that in the event of beam failure the TDS provides degraded altitude and velocity measurements. The largest degradation in performance is seen when the nadir pointing beam does not collect altitude measurements, resulting in timeline degradation, higher altitude errors, and higher vertical velocity at touchdown. Results showed, however, that measurements provided by the TDS to the navigation filter are sufficient to still ensure a survivable touchdown if the system employs the original beam sequences or opts to use an alternate sequence in the event that a hardware failure is discovered during the interplanetary cruise to Mars

2.0311 A Terminal Descent Radar for Landing & Proximity Operations – Prototype Lab and Field Test Results

Brian Pollard (Remote Sensing Solutions),

Presentation: Brian Pollard, Monday, March 9th, 10:35 AM, Gallatin

Mars Science Laboratory's unprecedented "sky-crane" landing utilized a new "Terminal Descent Sensor" (TDS), a Ka-band pencil beam radar for high accuracy measurements of line-of-sight range and velocity. While Mars 2020 will utilize the same design from remaining parts and new builds, the availability of the TDS for future missions is unclear due to problems of obsolescence and reproducibility; in addition, the TDS is quite large, prohibitively so for smaller missions. Remote Sensing Solutions (RSS) is currently funded under a NASA Small Business Innovative Research program to revisit the TDS design, and, notably, reduce the size, weight, and power; improve the manufacturability; and maintain or improve the performance, particularly with regard to mitigating the impacts of airborne debris. In a previous paper we summarized the results from RSS's design efforts. In this paper, we discuss the results from our recent build, assembly, test, and deployment of a full Ka-band, multi-beam radar prototype system. These results include validation of the software-defined system parameters and autonomous firmware; lab test verification of the entire sensor; and test results from a set of captive-carry flights on a rotorcraft. Notably, in addition to basic performance measures, we show some promising results of the ability of the sensor to detect measurements that may be corrupted by airborne debris, a problem that has impacted descent measurement systems since the Apollo and Viking landers. Such a capability has promise toward lowering the minimum range of operation for landing radars, potentially enabling landing and proximity operations in challenging environments.

2.0312 NAV-Landmarks: Deployable 3D Infrastructures to Enable CubeSats Navigation near Asteroids

Marco Di Fraia (Cranfield Defence and Security), Lounis Chermak (Cranfield University/ Defence Academy of the UK), Joan-Pau Cuartielles (Cranfield University), Leonard Felicetti (Cranfield University), Antonio Scannapieco (Cranfield University/ Defence Academy of the UK),

Presentation: Marco Di Fraia, Monday, March 9th, 11:25 AM, Gallatin

Autonomous operations in the proximity of Near Earth Objects (NEO) are perhaps the most challenging and demanding type of mission operation currently being considered. The exceptional variability of geometric and illumination conditions, the scarcity of large scale surface features and the strong perturbations in their proximity require incredibly robust systems to be handled. Robustness is usually introduced by either increasing the number and/or the complexity of on-board sensors, or by employing algorithms capable of handling uncertainties, often computationally heavy. While for a large satellite this would be predominantly an economic issue, for small satellites these constraints might push the ability to accomplish challenging missions beyond the realm of technical possibility. The scope of this paper is to present an active approach that allows small satellites deployed by a mothership to perform robust navigation using only a monocular visible camera. In particular, the introduction of Non-cooperative Artificial Visual landmarks (NAV- Landmarks) on the surface of the target object is proposed to augment the capabilities of small satellites. These external elements can be effectively regarded as an infrastructure forming an extension of the landing system. The quantitative efficiency estimation of this approach will be performed by comparing the outputs of a visual odometry algorithm, which operates on sequences of images representing ballistic descents around a small non-rotating asteroid. These sequences of virtual images will be obtained through the integration of two simulated models, both based on the Apollo asteroid 101955 Bennu. The first is a dynamical model, describing the landing trajectory, realized by integrating over time the gravitational potential around a three-axis ellipsoid. The second model is visual, generated by introducing in Unreal Engine 4 a CAD model of the asteroid (with a resolution of 75 cm) and scattering on its surface a number N of cubes with side length L. The effect of both N and L on the navigation accuracy will be reported. While defining an optimal shape for the NAV-Landmarks is out of the scope of

this paper, prescriptions about the beacons geometry will be provided. In particular, in this work the objects will be represented as high-visibility cubes. This shape satisfies, albeit in a non-optimal way, most of the design goals.

2.04 Access to Space and Emerging Mission Capabilities

Session Organizer: Eleni Sims (Aerospace Corporation), Kyle Kemble (Air Force Research Laboratory),

2.0402 NASA's Space Launch System: Launch Capability for Lunar Exploration and Transformative Science

Stephen Creech (NASA - Marshall Space Flight Center),
Presentation: Stephen Creech, Thursday, March 12th, 05:20 PM, Jefferson

NASA's Space Launch System (SLS) is a unique exploration asset for the agency's Artemis lunar program as well as for a new generation of bold science missions. SLS is designed for an array of missions beyond Earth's orbit. The flexible system, which can be configured for Orion, cargo, or Orion with co-manifested payload missions, offers high escape velocities to send more mass to deep space destinations. When configured with an 8.4 m-diameter fairing, SLS offers unmatched payload volume for human exploration and science missions. The initial vehicle, the Block 1 crew vehicle designated for the Artemis I mission, is fully manufactured, with much of the vehicle ready for stacking and integration. The Artemis I core stage is undergoing a series of "green run" tests this year that will culminate in an eight-minute hot-fire of the four RS-25 engines. Following stage refurbishment, the core stage will ship to Kennedy Space Center and stacking of the SLS vehicle in the Vehicle Assembly will commence. With the first Block 1 vehicle fully manufactured, production of successive builds is ramping up quickly. Much of the second Block 1 vehicle, designated for the Artemis II crewed lunar flyby mission, is manufactured. In addition, significant work has been performed on elements for the third Block 1. This vehicle will launch the first woman and next man to walk on the Moon during the Artemis III flight. For Block 1B, NASA's contract with core stage and Exploration Upper Stage (EUS) prime contractor Boeing is expected to support up to 10 core stages and up to eight EUS flight articles. Currently, Boeing is procuring long-lead items to support future core stage and EUS production. Aerojet Rocketdyne has completed production of 10 RL10C-3 engines for EUS. For the Block 2 vehicle, solid rocket booster prime contractor Northrop Grumman has begun conducting subscale tests of the evolved solid rocket motor. Poised to usher in a new generation of human and robotic deep space exploration, NASA's SLS vehicle is a unique asset, enabling more mass to destination, reduced transit time and higher C3 missions. The SLS Program will present the evolutionary path for the vehicle along with information on the several of the missions currently evaluating utilizing this potential launch option Finally, an update on the status of Artemis I green run testing and manufacturing of subsequent vehicles, including the EUS and evolved boosters, will be provided.

2.0405 Autonomous Robot Teams for Lunar Mining Base Construction and Operation

Jekan Thangavelautham (University of Arizona),
Presentation: Jekan Thangavelautham, Thursday, March 12th, 09:00 PM, Jefferson

The paper presentation will provide motivation and overview of space mining. This will be followed by discussion of materials to be mined and where they are located, followed by modelling assumptions. Results will be presented comparing, Mars and Moon. Finally overall energy cost of setting up and operating a base will be discussed along with principal feasibility.

2.0407 A Feasibility Analysis of a Variable Mass Multiple Asteroid Retrieval Mission

Gustavo Gargioni (Virginia Tech), Gavin Brown (Virginia Tech), Giulia Gargioni , Kevin Schroeder (Virginia Tech), Jonathan Black (Virginia Tech),

Presentation: Gustavo Gargioni, Thursday, March 12th, 09:25 PM, Jefferson

This paper aims to analyze the feasibility of a space-mining operation, by estimating the expenses of hardware acquisition and refueling operations for a 30-year Multiple Asteroid Retrieval Mission (MARM). The study builds on previous work on possible Near-Earth Asteroids (NEA) capable of being captured using upcoming rocketry for space-based mining. It combines the re-usability of rocket architecture with refueling capabilities to reduce costs. Furthermore, it expands the mission requirements to include a variable retrieval mass whereas previous work only considered missions that allowed for the entirety of an asteroid to be retrieved. This paper developed a high-level point of view of the mining industry which proposes to constrain the operation under an estimated amount of investment and logistical cost. Asteroid Retrieval Missions (ARMs) depart from L2 Halo orbit. The time window for the space mining operation is proposed to be three decades starting in 2030. The logistics of fuel from the Earth's surface to L2 Halo is proposed to refueled each ARM. Previously developed data mining online tool that searches for Near-Earth Asteroids (NEA) close approach database from JPL and the small body database from NASA was used as a dataset for possible candidates. The final solution was the retrieval of 60,430 metric tons with the cost per kg of USD 333.44. This reflects an 87.62\% reduction in cost per kg compared to previous work.

2.0409 New Constraint-Driven Mission Construct for Small Satellites and Constrained Missions

Lee Jasper (Space Dynamics Laboratory), Barbara Braun ,

Presentation: Lee Jasper, Thursday, March 12th, 09:50 PM, Jefferson

Small satellite developers have always designed and operated in a multi-constraint environment. This Constraint-Driven model for developing satellites (including some elements of system engineering and mission assurance) is further explored. Constraint-Driven missions alter the paradigm from traditional missions in that elements such as cost or schedule take a level of precedence over mission scope; traditionally scope is seen as fixed and resources are more tradeable. There has not been a concise, fundamental outline of how small satellites, or more broadly, constrained missions get developed. This paper attempts to create that outline and framework that is an alternative path from requirements driven (e.g. Class A - D) development that all missions are binned into, but that does not always fit. Stated another way, many practices are not conducted on constrained or small satellite missions “because they are a small sat”; this paper attempts to better define how and why that philosophy works. In this discussion Constraint-Driven Missions are defined and contrasted to Requirements-Driven Missions. The construct is based on Agile software development concepts but is also derived from multiple programs and missions (big and small) that have gone through similar practices to achieve success. The presentation will also provide an interactive example of how this model can be implemented.

2.05 Robotic Mobility and Sample Acquisition Systems

Session Organizer: Paul Backes (Jet Propulsion Laboratory), Richard Volpe (Jet Propulsion Laboratory),

2.0501 Shapeshifter: A Multi-Agent, Multi-Modal Robotic Platform for Exploration of Titan

Andrea Tagliabue , Stephanie Schneider (Stanford University), Marco Pavone (Stanford University), Ali Agha ,

Presentation: Stephanie Schneider, Tuesday, March 10th, 08:55 AM, Jefferson

In this talk we present a mission architecture and a robotic platform, the Shapeshifter, that allow multi-domain and redundant mobility on Saturn's moon Titan, and potentially other bodies with atmospheres. The Shapeshifter is a collection of simple and affordable robotic units, called Cobots, comparable to personal palm-size quadcopters. By attaching and detaching with each other, multiple Cobots can shape-shift into novel structures, capable of rolling on the surface, to increase the traverse range, flying in a flight array formation, and swimming on or under liquid. A ground station complements the robotic platform, hosting science instrumentation and providing power to recharge the batteries of the Cobots. In the first part of this talk we present the robotic platform and experimentally show the flying, docking and rolling capabilities of a Shapeshifter constituted by two Cobots, presenting ad-hoc control algorithms. We additionally evaluate the energy-efficiency of the rolling-based mobility strategy by deriving an analytic model of the power consumption and by integrating it in a high-fidelity simulation environment. In the second part we tailor our mission architecture to the exploration of Titan. We show that the properties of the Shapeshifter allow the exploration of the possible cryovolcano Sotra Patera, Titan's Mare and canyons.

2.0502 Variable Topology “Tree-Like” Continuum Robots for Remote Inspection and Cleaning

Ian Walker (Clemson University),

Presentation: Ian Walker, Wednesday, March 11th, 08:55 AM, Madison

Conventional robot manipulators are heavy, poor in accessing congested spaces due to the constraints imposed by their rigid links, and their use often relies on the additional deployment of sensor heads, which can be bulky and also difficult to deploy in tight spaces. In this paper, we introduce a novel, light, continuously bending “tree-like” robot with retractable branches. We demonstrate its ability for unique and adaptive operations over multiple scales and discuss the potential for use of such robots in Space applications. A prototype variable topology continuum robot was designed and constructed at Clemson University under NASA-funded research. The robot features a seven degree of freedom continuous backbone “trunk”, with two pairs of “branches”: two “tendril” effectors and two support “roots”. Each of the pairs of branches can be fully retracted inside the trunk, allowing it to penetrate congested environments as a single slender unit, and subsequently deploy the branches to perform a variety of tasks. The “roots” then provide physical support, while the two effectors and trunk tip enable independent but coordinated functionality: sensing (vision) in one tendril, and manipulation at two scales, via the second tendril and the trunk tip. The specifics of the new design will be described and discussed in detail in the paper. We will illustrate the operation and potential applications of the new design via a series of demonstrations, in particular the cleaning of dust from a solar panel.

2.0503 Driving Curiosity: Mars Rover Mobility Trends during the First Seven Years

Arturo Rankin (Jet Propulsion Laboratory), Mark Maimone (Jet Propulsion Laboratory), Jeffrey Biesiadecki (Jet Propulsion Laboratory), Nikunj Patel (NASA Jet Propulsion Laboratory), Daniel Levine (Jet Propulsion Laboratory), Olivier Toupet (JPL),

Presentation: Nikunj Patel, Wednesday, March 11th, 05:20 PM, Gallatin

NASA’s Mars Science Laboratory (MSL) mission landed the Curiosity rover on Mars on August 6, 2012. As of August 6, 2019 (sol 2488), Curiosity has driven 21,318.5 meters over a variety of terrain types and slopes, employing multiple drive modes with varying amounts of onboard autonomy. Curiosity’s drive distances each sol have ranged from its shortest drive of 2.6 centimeters to its longest drive of 142.5 meters, with an average drive distance of 28.9 meters. Real-time human intervention during Curiosity drives on Mars is not possible due to the latency in uplinking commands and downlinking telemetry, so the operations team relies on the rover’s flight software to prevent an unsafe state during driving. Over the first seven years of the mission, Curiosity has attempted 738 drives. While 622 drives have completed successfully, 116 drives were prevented or stopped early by the rover's fault protection software. The primary risks to mobility success have been wheel wear, wheel entrapment, progressive wheel sinkage (which can lead to rover embedding), and terrain interactions or hardware or cabling failures that result in an inability to command one or more steer or drive actuators. In this presentation, we describe mobility trends over the first 21.3km of the mission, operational aspects of the mobility fault protection, and risk mitigation strategies that will support continued mobility success for the remainder of the mission.

2.0504 Rimmed Wheel Performance on the Mars Science Laboratory Scarecrow Rover

Evan Graser (Jet Propulsion Laboratory), Arturo Rankin (Jet Propulsion Laboratory), Sean Mc Gill (NASA JPL),

Presentation: Evan Graser, Wednesday, March 11th, 04:30 PM, Gallatin

The Mars Science Laboratory (MSL) Curiosity rover experienced increasing wheel damage beginning in October 2013. While the wheels were designed to operate with considerable damage, the rate at which damage was occurring was unexpected and raised concerns regarding wheel life expectancy. As of Sol 2407, there are two broken grousers on the left middle wheel, and one broken grouser on the right middle wheel. One possible scenario, albeit remote, is that enough grousers break on a wheel such that unconstrained portions of the wheel could contact the cable running from the rover motor controller assembly to the wheel's drive actuator. If the cable to a drive actuator is damaged, that wheel may no longer respond to commands. To make progress towards a navigation goal position, that wheel would need to be dragged. To mitigate the risk of damaging a cable running to a wheel's drive actuator, the unconstrained portion of a wheel could be strategically shed by performing driving maneuvers on an immovable rock. What would remain after wheel shedding is a rimmed wheel (the outer 1/3 of the wheel). We studied the feasibility of remotely commanding the rover to perform the shed maneuver on one of its front wheels. To inform whether or not to shed the wheels, we tested the performance of driving on one or more rimmed wheels in flight. This led to a two-month test campaign in the Jet Propulsion Laboratory (JPL) Mars Yard using the Scarecrow testbed rover. Driving and steering performance was characterized on a variety of terrain types and slopes in a worst-case rimmed wheeled configuration. Test results indicate that if wheel shedding could be successfully executed in flight, Curiosity could continue to drive indefinitely on rimmed wheels.

2.0505 Design and Testing of an Ultra-Light Weight Perching System for Sloped or Vertical Rough Surfaces

Spencer Backus (NASA Jet Propulsion Lab), Jacob Izraelevitz (NASA Jet Propulsion Lab), ARASH KALANTARI (NASA Jet Propulsion Lab),

Presentation: Spencer Backus, Tuesday, March 10th, 11:25 AM, Jefferson

In this paper, we present the design, characterization, and functional demonstration of a perching system that enables a flying vehicle to land on rough sloped or vertical surfaces. Steep slopes are of particular scientific interest since they are often associated with geologically interesting features including sites of active modification (e.g. landslides/avalanches, slope streaks), exposed bedrock and/or ice, and as-yet unmodified young features (e.g. walls of fresh craters or polar pits that are actively expanding). However the steep nature of these sites makes access with traditional field robots difficult: ground vehicles are unable to traverse the steep terrain and aerial vehicles are limited by their flight time and an ability to operate near terrain. We propose to address these limitation by enabling the UAV to reliably perch on steep terrain to perform in situ measurements and collect samples. Perching also enables a solar powered UAV to

traverse large terrain features such as the Valles Marineris that could not be covered in a single flight by repeatedly perching and recharging its batteries. The proposed perching system that is being developed consists of a microspine gripper, a compliant gripper to vehicle interface, and a flying vehicle equipped with an autonomy sensor suite. The system also includes perception and control algorithms that identify perching targets and execute the required perching maneuver. To date, the majority of the effort has focused on developing and characterizing the microspine gripper. The initial prototype weighs 100 g, is capable of securely grasping a range of natural surfaces, and successful grasps support loads of over 10 N. Refinement of the gripper, integrating and testing it on a UAV, measuring aerodynamic disturbances from wall effects, and developing the required perception and control algorithms is ongoing. This paper describes the overall architecture of our proposed system, the design of the gripper, and its performance during initial testing.

2.0506 A ROS-based Simulator for Testing the Enhanced Autonomous Navigation of the Mars 2020 Rover

Olivier Toupet (JPL), Tyler Del Sesto (NASA Jet Propulsion Lab), Masahiro Ono (JPL), Steven Myint (Jet Propulsion Laboratory), Michael Mc Henry (Jet Propulsion Laboratory), Joshua Vander Hook (NASA Jet Propulsion Lab),

Presentation: Olivier Toupet, Wednesday, March 11th, 04:55 PM, Gallatin

In order to achieve the ambitious objectives of the Mars 2020 (M2020) mission, in particular the ability to autonomously traverse more challenging terrains more efficiently, new surface mobility software was developed for Enhanced Navigation (ENav). That decision was made early in the project, before most of the new surface flight software (FSW) existed, which created a need for a separate framework where the new navigation algorithms could be quickly prototyped and tested, before more realistic FSW-based testbeds became available. The JPL robotics team chose the Robot Operating System (ROS) as the environment in which to test the new ENav algorithms. This made it possible to write the algorithms in the C language required by the FSW, so they could be directly ported over to the flight module later on, while leveraging all the C++ libraries and tools provided by ROS for simulation and testing. The ENav algorithms were developed as a separate C library, and stubs were used to replace any FSW-specific code, such as Event Reporting (EVRs) and data products (DPs). A ROS simulator was developed to generate a rich set of varied 3D terrains representative of the candidate Mars landing sites and simulate the physics of the rover motion, the point cloud perceived by the rover's stereo vision system, and the new thinking-while-driving (TWD) navigation logic which directs the rover to drive autonomously to user-specified waypoints. To simulate the rover motion and perception, a ROS node was developed that uses a software library called HyperDrive Sim (HDSim), which is a wrapper for the Rover Sequencing and Visualization Program (RSVP). That library provides rover-terrain settling, realistic slip modelling, and camera rendering capability based on the rover's NavCam machine vision models. To simulate the navigation logic, a ROS node was created that initializes and runs the ENav algorithms in a way that mimics the FSW execution, while also providing the capability to load and replay data products, including re-running the recorded inputs through the ENav algorithms for testing. An engineering Graphical User Interface (GUI) was also developed to visualize various elements, such as the rover pose during the drive, the simulated and perceived terrain, the selected local and global paths to the goal, the evaluated candidate paths and the reasons why they were rejected, the keep-in and keep-out zones (KIOZs), etc. Finally, an advanced Monte Carlo (MC) framework that can run many simulations in parallel on the Cloud and automatically generate reports that capture the key ENav performance metrics was developed to evaluate the

system in a statistically-meaningful way. This presentation provides an overview of the ROS-based simulator used for testing the M2020 ENav algorithms.

2.0508 Rover Localization for Tube Pickup: Dataset, Methods and Validation for Mars Sample Return Planning

Tu-Hoa Pham (Jet Propulsion Laboratory, California Institute of Technology), William Seto (Jet Propulsion Laboratory, California Institute of Technology), Shreyansh Daftry (California Institute of Technology), Alex Brinkman (Jet Propulsion Laboratory), John Mayo , Curtis Padgett (Jet Propulsion Laboratory), Eric Kulczycki (Jet Propulsion Laboratory), Renaud Detry (NASA Jet Propulsion Laboratory),

Presentation: Tu-Hoa Pham, Wednesday, March 11th, 08:30 AM, Madison

The Mars 2020 rover mission is intended to collect samples which will be stored in metal tubes and left on the Martian surface, for possible retrieval and return to Earth by a future mission. In the proposed Mars Sample Return (MSR) campaign concept, a follow-up mission would collect the sample tubes and load them into a Mars Ascent Vehicle to be launched into orbit for subsequent transfer and return to Earth. In this work, we study the problem of tube localization and tube pickup during the MSR campaign. This is a difficult problem, as over time, the sample tubes may become partially covered by dust and sand, making it difficult to recover their pose by direct camera observation. We thus propose an indirect approach, in which the MSR rover localizes itself with respect to its environment, in particular surrounding rocks likely to remain visible after several years, then performs blind grasping of the tube using a cm-scale map of the depot including tube locations derived from Mars 2020 data. To evaluate the performance of vision-based terrain-relative localization, we introduce a novel dataset comprising over 4000 images of sample tube, sand and rocks captured on a Mars Sample Transfer Testbed (MSTT), annotated with ground-truth tube and camera poses from a Vicon motion capture system. The dataset was collected to span multiple parameters representative of different capture conditions between Mars 2020 and MSR, namely, for two different rock densities: camera type, exposure, stereo baseline, viewpoint angle, distance, height, and lighting direction (north, east, west, south - or all four). We first show that this dataset can be used to train a deep neural network for automatic image segmentation, enabling the quantitative evaluation of localization techniques while accounting for mission requirements, e.g., using only rock features and blacking out tube and sand. We then estimate the camera motion between two stereo pairs captured under different conditions by four-way feature matching and reprojection error minimization between the resulting correspondences. We perform this calculation for all possible pairs of capture conditions. By comparing the transformation estimates from terrain-relative localization to ground-truth transformations from Vicon, we obtain 270,920 pose estimation errors expressed as translation and rotation errors for the tube across 6 capture dimensions. We use these estimates to identify and characterize parameter configurations enabling robust localization, which in turn can be used to make feasibility assessments and recommendations for the Mars 2020 and MSR rover missions. We further examine the vulnerability of feature matching to variations in lighting conditions and discuss alternative localization methods using synthetic relighting and rendering. Disclaimer: The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

2.0509 Mobility Mode Evaluation of a Wheel-on-Limb Rover on Glacial Ice Analogous to Europa Terrain

William Reid , Gareth Meirion Griffith (JPL), Blair Emanuel (Jet Propulsion Laboratory), Brendan Chamberlain Simon (Jet Propulsion Laboratory), Sisir Karumanchi (NASA Jet Propulsion Lab),

Presentation: William Reid, Wednesday, March 11th, 10:10 AM, Madison

Mobile, in-situ exploration of Europa's rugged, icy surface holds the potential for enabling discovery across multiple geologic units outside the exhaust-contaminated landing zone. The spatial and compositional diversity of surface salts and organics are of significance to our understanding Europa's history and biological potential. Our knowledge of Europa's surface properties, both topographic and mechanical, is extremely limited. Furthermore, additional data will not become available prior to the arrival of the Europa Clipper spacecraft. If the exploration of Europa continues to be an area of high science-value, this work postulates that solutions to the challenges of mobility on uncertain, but likely challenging, surfaces should be developed now. In this paper, we discuss the development of a multimodal locomotion system and the results of field trials performed on fractured, glacial ice. Work was performed using the RoboSimian vehicle: a 32 degree-of-freedom, actively articulated mobility system. Three modes of mobility are compared: wheel rolling, push-rolling (inchworming) and wheel walking. Each mobility mode is designed to operate with articulated suspension whereby the normal load per wheel, body orientation, and available limb workspace are actively controlled. Each mode is presented individually alongside a discussion of its performance on terrain of varied slope and topographic roughness. Further, the utility of a multi-modal approach is presented, whereby vehicle immobilization was avoided during field trials through the selection of appropriate mobility modes as a function of terrain properties. Finally, the results of trials performed using a body- mounted sampling system and its ability to collect and process samples taken 10 cm beneath the surface are discussed.

2.0510 ARIEL: Autonomous Excavation Site Selection for Europa Lander

Masahiro Ono (JPL), Gary Doran (Jet Propulsion Laboratory), David Inkyu Kim (JPL), Kiri Wagstaff (Jet Propulsion Laboratory), Tara Estlin (NASA Jet Propulsion Laboratory), Abhinandan Jain , Kristopher Kriechbaum , Glenn Reeves (Jet Propulsion Laboratory), Marissa Cameron ,

Presentation: Masahiro Ono, Wednesday, March 11th, 10:35 AM, Madison

This paper presents ARIEL (Autonomous Ranking and Interrogation of Excavation Location), an autonomy system for selecting an excavation site on-board for NASA's Europa Lander Mission Concept. Historically, excavation site selection has been performed by a lengthy ground-in-the-loop (GITL) process involving manual inspections, assessments, and decision making in past missions. However, as Europa Lander would have approximately 20 days of lifetime after the landing, many surface activities, including excavation site selection, must be autonomously performed on-board. This paper describes the overall system of ARIEL as well as its two major algorithmic components: vision-based candidate selection and smart interrogation, which estimates the physical properties of the icy surface through physical contact with the robotic arm's end-effector. Preliminary results are presented using images from Earth analogue sites. The Europa Lander mission returned to the formulation phases in early 2019 while ARIEL was at an early stage of development. Described in this paper is a snapshot of ARIEL as of the project suspension. This paper also describes the remaining challenges to be solved, should the mission resume in the future. Europa Lander is a mission concept to land on the icy surface of Europa and search for biosignatures. A paramount challenge for the mission is the harsh radiation environment, which impacts the biosignature preservation potential and the survival of the spacecraft. As organic materials near the surface are likely damaged by radiation, the Lander would excavate a ~10 cm-deep trench and obtain samples from the bottom of the trench. In addition, the radiation would also quickly damage the electronics of the spacecraft. Therefore, the baseline Europa Lander would be powered solely by primary batteries after its separation from the solar-powered carrier stage. It would have only ~20 days on the surface to fulfill the mission requirement of excavating at least one trench and acquiring three samples, which could bring us a historic discovery that would forever change our view of the universe and life. The 20-

day expiration would allow only one GITL cycle before selecting the excavation site. The ground operators would still be able to make the final decision, but the ground-based decision-making process must be significantly simplified and expedited. In an off-nominal situation where Europa Lander does not hear from the Earth, the spacecraft must execute excavation, sampling, and sample analysis fully autonomously and transmit the data to the Earth, rather than remaining idle and acquiring no samples. This scenario leaves only two options for excavation site selection: a completely scripted approach or an adaptive, intelligent one. The first approach is to blindly excavate a pre-specified location, such as the geometric center of the workspace, hoping that the site is excavatable and scientifically promising. The other is a highly intelligent solution where the Lander optimizes the excavation site based on the onboard assessment of excavatability and science value. What is described in this paper is the second approach.

2.0511 Deployed Instrument Monocular Localization on the InSight Mars Lander

Philip Bailey (NASA Jet Propulsion Lab), Cristina Sorice (NASA Jet Propulsion Laboratory), Ashitey Trebi Ollennu (Jet Propulsion Laboratory), Khaled Ali (Jet Propulsion Laboratory), Steven Myint (Jet Propulsion Laboratory), Won Kim (Jet Propulsion Laboratory),

Presentation: Philip Bailey, Wednesday, March 11th, 09:00 PM, Gallatin

The primary purpose of the InSight Instrument Deployment System (IDS) on the Mars InSight Lander, which landed in November 2018, was to deploy three payloads: a seismometer (SEIS), a heat flow probe (HP3), and a wind and thermal shield (WTS), to the Martian surface. The system consists of the Instrument Deployment Arm (IDA), Instrument Deployment Camera (IDC) on the forearm of the IDA, and the Instrument Context Camera (ICC). A core functionality of the IDS that was critical to the success of the deployments was the ability to use only the single camera on the arm and monocular localization methods to calculate the poses of each of the instruments before and after deployment. Given that the ICC has a fisheye lens and was located under the lander, relatively far from the deployment sites, only the IDC was useful for quantitative localization. Knowledge of the exact pose of each instrument was critical for any activity that involved interacting with the instruments, such as the deployment of the WTS over SEIS to protect the instrument and reduce environmental noise. Additionally, knowledge of the instrument poses was necessary to meet the mission’s science objectives, used to accept the instrument deployment sites, and to create noise models used to help scientists interpret the instrument data. While the technology was employed on this mission to allow for stereo data to be captured by moving the single camera over a known baseline, physical arm constraints, operational constraints, and a desire for independent verification necessitated robust methods of monocular localization. Three different methods of monocular localization were developed and employed for the deployment phase of the mission. Fiducial localization using round single point fiducials across the instruments, newer and more robust April Tag fiducial detection that provide 5 points and an independent orientation from each fiducial, and a grapple localization to confirm the localization by physically lining up the IDA grapple with the hook on each instrument. This paper will discuss the motivation, implementation, and execution of each monocular localization technique employed by the IDS. Additionally, it will detail the results and error sources identified throughout the mission using downlinked images and measurements from the InSight lander.

2.0512 Analysis of Soil Deformation and Wheel Traction on Loose Terrain Using PIV

Shoko Ono (Tohoku University), Shohei Namikawa (Tohoku University), Kazuya Yoshida (Tohoku University),

Presentation: Shoko Ono, Wednesday, March 11th, 11:50 AM, Madison

A planetary rover experiences mobility problem, such as excessive slippage and entrapment, on loose terrain known as regolith. To overcome such situations, understanding wheel-soil interaction mechanics is necessary. Thus, this study focuses on soil deformation beneath a grouser wheel, and the wheel traveling performance. The soil deformation is analyzed by using imaging technique known as particle image velocimetry (PIV), and the wheel traction is measured by a force-torque (FT) sensor. The experimental results present that the soil around a grouser moves to the directions on the front and rear of the wheel when the grouser enters into the soil. After that, the soil flow describes an arc-shaped flow from the front of the wheel towards the rear-end of the wheel caused by the grouser. These results indicate that the grouser wheel causes a different flow of soil than a slick wheel. Therefore, the development of a model for the grouser wheel that takes into account soil deformation is necessary. In addition, experiments were carried out in several normal load conditions. The normal load affects the thickness of soil deformation area rather than the shape of boundary line of the soil deformation. The maximum thickness of the soil deformation area and the velocity of the soil particles increase with an increase of the normal load. As for the wheel performance, an increase in the normal load causes an increase in the wheel sinkage and traveling traction. From these results, it can be deduced that an increase in the thickness of the soil deformation area leads to an increase in the traction performance of the grouser wheel. In conclusion, this work contributes further to the understanding of wheel-soil interaction and the relationship between wheel performance and soil deformation.

2.0513 Maintenance-optimized Modular Robotic Concepts for Planetary Surface ISRU Excavators

A Howe (NASA Jet Propulsion Lab), Brian Wilcox (Jet Propulsion Laboratory), Hari Nayar (NASA/JPL), Robert Mueller (NASA - Kennedy Space Center), Jason Schuler (EASI),

Presentation: A Howe, Tuesday, March 10th, 10:35 AM, Jefferson

Modular robotic concepts are identified and evaluated over the design and operations/maintenance lifecycle for autonomous Lunar, Mars, and partial gravity planetary surface excavation and in-situ earthworks equipment. In-Situ Resource Utilization (ISRU) is the exploitation of available resources at the site of a landed spacecraft on the surface of another planetary body. It is intended that this ISRU excavator concept be capable of material extraction from native regolith, and will be able to operate in a variety of planetary surface environments after initial shake-down on the moon. Using heritage from highly multi-functional, reconfigurable robotic systems like the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE), Regolith Advanced Surface Systems Operations Robot (RASSOR), and Mars exploration rovers, we propose a flexible maintenance-optimized mobility platform concept with quick-connect/disconnect features for robotically swappable excavation implements. Dust tolerant torque transmission, power & data docking, thermal fluid connectors, and modular avionics and instrumentation will allow for autonomous swapping of tools, replacement of spares, and long-term maintenance of robotic excavators. The architecture includes modular tools for conventional excavate / scoop / haul / dump / process functions of a terrestrial mining operation on Earth, but also will have the capability to operate and robotically maintain itself without human intervention. The concepts described in this study will provide a suite of technologies, configurations, and operations ready for inclusion into a final flight-ready excavator system.

2.0515 Design and Test of an Electromechanical Rover Tether for the Exploration of Vertical Lunar Pits

Patrick McGarey (NASA Jet Propulsion Lab), Issa Nesnas (Jet Propulsion Laboratory),

Presentation: Patrick McGarey, Tuesday, March 10th, 09:45 AM, Jefferson

This talk will expand on the development a supportive tether for a proposed lunar rover concept, Moon Diver. I will cover i) a trade study of structure and materials with consideration for space heritage, ii) selected design justification, and iii) results from tests on prototype tethers looking into mechanical, electrical, and environmental properties, including exposure to rock-regolith abrasion, load profiles at temperature, and degradation due to UV exposure while exposed to vacuum. I will provide insights and lessons learned from lab and field tests, which inform our continued effort to design a tether capable of surviving rugged, lunar conditions.

2.0516 Using Elastically Actuated Legged Robots in Rough Terrain: Experiments with DLR Quadruped Bert

Daniel Seidel (German Aerospace Center (DLR)), Alin Albu Schäffer (German Aerospace Center - DLR), Presentation: Daniel Seidel, Wednesday, March 11th, 09:45 AM, Madison

This paper addresses walking and balancing in rough terrain for legged locomotion in planetary exploration as an alternative to the commonly used wheeled locomotion. In contrast to the latter, where active balancing is not necessary, legged locomotion requires constant effort to keep the main body stabilized during motion. While common quadrupedal robots require to carefully plan motions through torque control and force distribution, this paper presents an approach where elastic elements in the drive train function as an intrinsic balancing component that allows to ignore inaccuracies in the locomotion pattern and passively accommodate for terrain unevenness. The approach proposes a static walking gait algorithm, which is formulated for a general quadrupedal robot, and a hardware foot design to support the locomotion pattern. The method is experimentally tested on an elastically actuated quadrupedal robot.

2.0518 Dynamics and Control of a Hopping Robot for Extreme Environment Exploration on the Moon and Mars

Himangshu Kalita (University of Arizona), Jekan Thangavelautham (University of Arizona), Presentation: Himangshu Kalita, Tuesday, March 10th, 10:10 AM, Jefferson

High-resolution orbital imagery from the LROC reveals evidence for subsurface voids and mare-pits on the lunar surface. Similar discoveries have been made with the HiRISE camera onboard the MRO observing the Martian surface. These accessible voids could be used for a future human base because they offer a natural radiation and micrometeorite shield and offer constant habitable temperatures. Exploration of these extreme and rugged environments remains out of reach from current planetary rovers and landers. A credible solution is to develop an architecture that permits taking high exploratory risks that translates into high reward science. Rapid advancement in electronics, sensors, actuators, and power have resulted in ever-shrinking devices and instruments that can be housed in small platforms. We propose to use a small, low-cost, modular spherical robot called SphereX that is designed to hop and roll short distances. Each robot is of several kilograms in mass and several liters in volume. Each SphereX will consist of space-qualified electronics like command & data handling board, power board for power management and s-band radio transceiver for communication. Power is provided using lithium-ion primary batteries or a PEM fuel cell power supply. Communication is established through multi-hop communication link to relay data from inside the caves to a lander outside on the planetary surface. Since the temperature inside underground lunar pits is expected at -25°C, thermal management for the space-grade electronics is minimal as they can operate up to -40°C, however thermal management for the battery pack and the propellants will be done through active and passive elements. Moreover, SphereX requires use of a propulsion system and Attitude Determination and Control System (ADCS) to perform controlled ballistic hops. Hopping on very-low gravity environments is more time-efficient than rolling due to the reduced traction. In this paper, we present detailed analysis of each subsystem of SphereX and also detailed dynamics and control simulations of SphereX for ballistic hopping and rolling mobility. For ballistic hopping control, the robot has two modes: soft landing mode for traversing long distances and entering the pit through its collapsed entrance, and a fuel-efficient hard landing mode for traversing short distances. We will then present experimental results for mapping unknown cave-like environments which is done using a quadcopter for simulating low-gravity (e.g. Moon, Mars) environments and testing the control algorithms. The quadcopter mimics the dynamics of SphereX and also carries a 3D LiDAR for mapping and navigation. 3D point cloud data collected by the LiDAR is used for performing SLAM and path planning in unknown and GPS-denied environments much like the pits, caves and lava tubes on the Moon and Mars.

2.0519 Catenary Model of InSight SEIS Tether for Instrument Deployment

Cristina Sorice (NASA Jet Propulsion Laboratory), Ashitey Trebi Ollennu (Jet Propulsion Laboratory), Won Kim (Jet Propulsion Laboratory), Philip Bailey (NASA Jet Propulsion Lab), Steven Myint (Jet Propulsion Laboratory),

Presentation: Philip Bailey, Wednesday, March 11th, 09:25 PM, Gallatin

NASA's InSight Mars Lander, which landed on Mars in November 2018, completed the first precision robotic instrument placement on a planetary surface as part of its instrument deployment phase. Using the Instrument Deployment Arm (IDA), InSight deployed the two key science payload elements, a seismometer (SEIS) and heat flow probe (HP3), as well as a wind and thermal shield (WTS) placed over the seismometer. SEIS and HP3 are tethered to the lander for both power and communications purposes. Placement accuracy of the instrument deployment was essential for successful realization of the mission's core science objectives. In order to meet the requirements for placement accuracy, we worked to understand and mitigate the factors contributing to placement error. Those factors include but are not limited to: the IDA position control error, the error in the computation of the digital elevation model (DEM), the targeting error in selecting the desired placement site, and each instrument's ground interaction. In particular, the SEIS placement accuracy was greatly affected by the placement of its tether on the terrain during the instrument deployment. The SEIS tether is a stack of six flex cable belts attached at one end to the lander deck. At the other end, the tether is looped and attached to the instrument with a load shunt assembly (LSA) designed to isolate signals detected by the instrument from any noise created by the tether due to thermoelastic deformation, atmospheric events, etc. Additionally, the tether contains a field joint and a pinning mass (which grounds the tether and is used to manipulate the tether with the robotic arm post-placement). In our validation and verification (V\&V) activities, we determined that the interaction of the SEIS tether on the terrain greatly affected our instrument placement accuracy. In order to understand and minimize this effect, we created a mathematical model of the SEIS tether and then used that model to develop the deployment sequences. Ultimately, our sequences deployed both the tether and the instrument on the Martian surface, taking into consideration the whole system for a successful deployment. This paper will discuss the motivation and details of the implementation of the SEIS tether model and the ways in which the SEIS tether impacted placement accuracy in certain configurations. It will also show results from testing this model on Earth and deploying SEIS to the Martian surface on sol 22 of InSight's mission.

2.0521 Autonomous Power Grid Formation for Surface Assets Using Multiple Unmanned Ground Vehicles

John Naglak (Michigan Technological University), Carl Greene (Michigan Technological University), Casey Majhor (Michigan Technological University), Nathan Spike (Michigan Technological University),

Jeremy Bos (Michigan Technological University), Wayne Weaver ,
Presentation: John Naglak, Tuesday, March 10th, 11:00 AM, Jefferson

Mobile microgrid formation using multiple Unmanned Ground Vehicles (UGV) can establish surface power sources and integrate mission infrastructure autonomously. Advancement of this technology is martialed by the expedited Artemis mission to return to the Moon by 2024, with residence there by 2028. Many of the infrastructure deployment tasks to support this mission will depend on advance assembly by robotic agents. Consider the deployment of multiple Kilopower reactors to supply power to a lunar habitation module, with UGV's to position the reactors and connect power grid elements with cables. To accomplish this complex task, a number of robotic controllers have been integrated on all-terrain UGV's. These controllers comprise waypoint navigation, visual docking, electrical connection coupling, and electrical cable deployment. Hardware which supports the mission includes the UGV platform, odometry and perception sensors, distributed communications, and electrical grid infrastructure. Robot Operating System (ROS) provides a core development architecture. Subsystem tests in an unstructured terrestrial environment have been performed, with a full system test including multiple UGV's planned. This work reports on the current operating capability of subsystems in an outdoor terrestrial environment, and suggests the system-level validation test objectives for power grid formation.

2.0524 MMX - Development of a Rover Locomotion System

Hans Juergen Sedlmayr , Ralph Bayer , Roy Lichtenheldt (German Aerospace Center - DLR), Simon Tardivel (CNES),
Presentation: Hans Juergen Sedlmayr, Tuesday, March 10th, 09:20 AM, Jefferson

MMX (Martian Moons eXploration) is a robotic sample return mission of JAXA (Japan Aerospace Exploration Agency), CNES (Centre National d' Études Spatiales), and DLR (German Aerospace Center) with the launch planed for 2024. The mission aims to answer the question of the origin of Phobos and Deimos, which will also help to understand the material transport in the earliest period of our solar system, and of how was water brought to Earth. Besides JAXA's MMX mothership, which is responsible for sampling and sample return to Earth, a small rover which is built by CNES and DLR to land on Phobos for in-situ measurements, similar to MASCOT (Mobile Asteroid Surface Scout) on Ryugu. The MMX rover is a fourwheel driven autonomous system with a size of 41 cm x 37 cm x 30 cm and a weight of approximately 25 kg. Multiple science instruments and cameras are integrated in the rover body. The rover body has the form of a rectangular box. Attached at the sides are four legs with one wheel per leg. When the rover is detached from the mothership, the legs are folded together at the side of the rover body. When the rover has landed passively (no parachute or braking rockets) on Phobos, the legs are autonomously maneuvered to bring the rover in an upright orientation. One Phobos day lasts 7.65 earth hours, which yields about 300 extreme temperature cycles for the total mission time of three earth months. These cycles and the wide span of surface temperature between day and night are the main design drivers for the rover. This paper gives a detailed view on the development of the MMX rover locomotion subsystem.

2.0526 Safe Interactions and Kinesthetic Feedback in High Performance Earth-To-Moon Teleoperation

Michael Panzirsch (German Aerospace Center - DLR), Harsimran Singh (German Aerospace Center - DLR), Thomas Krueger (European Space Agency), Christian Ott (German Aerospace Center (DLR)), Alin Albu Schäffer (German Aerospace Center - DLR),
Presentation: Michael Panzirsch, Tuesday, March 10th, 08:30 AM, Jefferson

The international space agencies plan to implement orbiting space stations around celestial bodies as moon or Mars in the near future. Autonomous robots will be assigned with exploration tasks and the building of structures as habitats. A teleoperator interface will be available in the orbiter to assure the possibility of direct control of the robots located on the celestial body as a fallback, in case an autonomous functionality fails. Communication links will be comparable to the ones between the International Space Station and earth, reaching from direct S-band communication, to communication via geostationary relay satellites in a Ku-Forward link. Since the Lunar Orbital Platform-gateway will not be manned throughout the year, further interfaces have to be established with which the robots can be controlled from earth. An available laser link to moon provides a high-bandwidth communication with 2.6s roundtrip-delay, which currently allows for supervised control, exemplary via a tablet interface. Current advances in control theory can achieve stable and high performance kinesthetic feedback in bilateral telemanipulation at delays above 1s. This paper presents the first experimental analysis of the feasibility and human operator performance of telemanipulation with an Earth-to-Moon like delay of 3s. In light of the fact that several technologies such as visual augmentation and shared control can be integrated in addition, the results are highly promising.

2.0527 The Dual-Rasp Sampling System for an Enceladus Lander Mission

Paul Backes (Jet Propulsion Laboratory), Scott Moreland (Jet Propulsion Laboratory), Mircea Badescu (Jet Propulsion Laboratory), Dario Riccobono (Politecnico di Torino), Alex Brinkman (Jet Propulsion Laboratory), Mathieu Choukroun (JPL/Caltech), Jamie Molaro (Planetary Science Institute), Samuel Ubellacker (Jet Propulsion Laboratory),

Presentation: Paul Backes, Wednesday, March 11th, 11:25 AM, Madison

The novel Dual-Rasp sampling system has been developed for the unique sampling environment of a lander mission to the surface of Saturn's moon Enceladus. Observations from the Cassini mission suggest that Enceladus has a subsurface ocean which contains ingredients to sustain life including hydrothermal vent energy sources and necessary chemical elements. Enceladus has continuously erupting ice plumes that eject material from the subsurface liquid ocean out of surface vents. Some of the material contributes to Saturn's rings while some of the material falls back to the surface. The surface material has the potential to include evidence of life in the subsurface ocean if it exists there. The benign radiation environment of the Enceladus surface would allow surface material to be preserved. A lander mission that collects and analyzes the surface material has the potential to discover evidence of life in the Enceladus subsurface ocean. It is desired that a sampling system would acquire only very shallow surface material in the top 1cm since this would be the freshest plume material that has fallen to the surface. To account for a wide range or potential surface strengths, the sampling system was developed to enable sampling from surface material between 400 kPa to 12 MPa strength and 40-95% porosity. The low 1% Earth gravity environment limits the allowable reacted load from the sampling activity to a lander. Various sampling techniques were evaluated and the Dual-Rasp concept was selected for implementation in a prototype sampling system. The Dual-Rasp sampling system has two counter-rotating rasp cutters with teeth that remove material that is thrown up between the cutters. The cuttings follow a guide into a sample collection cup. The Dual-Rasp sampling tool would be mounted at the end of a robotic arm which would deploy the sampling tool to the surface. Two versions of the tool have been developed for sample transfer. A mechanical sample transfer system has ten sample cups on a carousel attached at the end of the robotic arm. After one 5cc cup is filled, the cup is rotated on the carousel to a volume measurement station where a plunger pushes down on the sample to measure its volume. If there is enough sample, then the tool is docked at the lander deck and the plunger pushes the cup into a science instrument inlet port. Otherwise another sampling attempt could fill the cup further. A second Dual-Rasp prototype was developed that uses a pneumatic sample transfer system to transfer the sample from the sample cup to the science instrument inlet port after the tool is docked at the lander deck. A microwave mass flow sensor is being evaluated for sample measurement for this tool version.

2.0528 Analysis of the Robot Subsystem Capability for Boulder Extraction in the Asteroid Redirect Mission

William Gallagher (SAIC), Badri Shirgur , Gardell Gefke (Vehicle Systems Integration, LLC),
Presentation: William Gallagher, Wednesday, March 11th, 09:20 AM, Madison

NASA's Asteroid Redirect Mission project aimed to send a robotic vehicle to a near Earth asteroid and retrieve a 20-ton boulder sized sample from its surface for return to trans lunar orbit. The vehicle's Capture Module (CAPM) utilized three 4-DOF articulated landing legs to touch down on the asteroid surface over the target boulder and two or three 7-DOF dexterous robot arms to place purpose-designed microspine grippers and grasp the boulder surface. The legs would then push away from the asteroid surface to extract the boulder. This paper describes the method and results of the analysis used to design the robot subsystem of the CAPM. The robot arms used for boulder extraction were built upon design heritage from other missions, including Mars rovers and Restore satellite servicing, which aided in meeting cost and schedule goals. The design considered the limits on size, stiffness, and load capability inherent in space based robots. This provided a highly constrained design problem stipulating the use of light weight, low stiffness robot arms for a challenging, high load task. During extraction, the robot arms would experience high tension loads, precluding the ability to simplify models using a rigid body assumption. The use of multiple arms to grasp the boulder provided increased load a capability for the system as a whole by creating a closed kinematic chain. The robot arm model, therefore, accounted for the flexibilities in the arm links and actuators, and it represented the boulder as a rigid object. This was used to estimate the maximum loads the robot system could sustain during boulder extraction and determine the optimal grasp location and pose for each arm. The CAPM robot arm design team leveraged NASA's massively parallel computing capability to model a large number of extraction scenarios, varying gripper location, arm pose, and boulder size. The results were used to build a simplified model for use in design trade studies. To support CAPM design trade studies, this analysis evaluated potential robot arm design changes that could be implemented with minimal impact to the design's flight heritage. The evaluation then considered systems consisting of two or three robot arms, as well as designs providing assistive cabling for bearing extraction loads. It was determined that two robot arms were insufficient for boulders requiring higher extraction loads, and the analysis described in this paper guided the addition of a third robot arm and support cables.

2.0529 Analysis of Sample Acquisition Dynamics Using Discrete Element Method

Damiana Catanoso (MCT/NASA Ames Research Center), Thomas Stucky (MCT/NASA Ames Research Center), Jennifer Case (Purdue University), Arno Rogg (NASA - Ames Research Center),
Presentation: Damiana Catanoso, Wednesday, March 11th, 11:00 AM, Madison

The analysis presented in this paper is conducted in the framework of the Ocean Worlds Autonomy Testbed for Exploration Research and Simulation (OceanWATERS) project, currently under development at NASA Ames Research Center. OceanWATERS aims at designing a simulation environment which allows for testing autonomy of scientific lander missions to the icy moons of our solar system. Mainly focused on reproducing the end effector interaction with the inherent terrain, this paper introduces a novel discrete element method (DEM)-based approach to determine forces and torques acting on the lander's scoop during the sample acquisition process. An accurate force feedback from the terrain on the scoop is required by fault-detection and autonomous decision-making algorithms to identify when the requested torque on the robotic arm's joints exceeds the maximum available torque. Knowledge of the terrain force feedback significantly helps evaluating the arm's links structural properties and properly selecting actuators for the joints. Models available in literature constitute a partial representation of the dynamics of the interaction. As an example, Balovnev derived an analytical expression of the vertical and horizontal force acting on a bucket while collecting a sample as a function of its geometry and velocity, soil parameters and reached depth. Although the model represents an adequate approximation of the two force components, it ignores the direction orthogonal to the scoop motion and neglects the torque. This work relies on DEM analysis to compensate for analytical models' deficiencies and inaccuracies, i. e. provide force and torque 3D vectors, defined in the moving reference (body) frame attached to the scoop, at each instant of the sample collection process. Results from the first presented analysis relate to the specific OceanWATERS sampling strategy, which consists of collecting the sample through five consecutive passes with increasing depth, each pass following the same circular-linear-circular trajectory. Data is collected given a specific scoop design interacting with two types of bulk materials, which may characterize the surface of icy planetary bodies: snow and ice. Although specifically concerned with the OceanWATERS design, this first analysis provides the expected force trends for similar sampling strategies and allows to deduce phenomenological information about the general scooping process. In order to further instruct the community on the use of DEM tools as a solution to the sampling collection problem, two more analyses have been carried out, mainly focused on reducing the DEM computation time, which increases with a decrease in particle size. After running a set of identical simulations, where the only changing parameter is the size of the spherical particle, it is observed that the resulting force trajectories, starting from a given particle size, converge to the true trend. It is deducible that a further decrease in size yields negligible improvements in the accuracy, while it sensibly increases computation time. A final analysis aims at discussing limitations of approximating bulk material particles having a complex shape, e. g. ice fragments, with spheres, by comparing force trends resulting in the two cases for the same simulation scenario.

2.06 Future Missions & Enabling Technologies for In Situ Exploration, Sample Returns

Session Organizer: Patricia Beauchamp (Jet Propulsion Laboratory), Michael Johnson (NASA Goddard Space Flight Center),

2.0602 Surviving and Operating through the Lunar Night

Andrew Petro (NASA - Headquarters),
Presentation: Andrew Petro, Thursday, March 12th, 11:50 AM, Gallatin

Surviving and Operating Through the Lunar Night One of the key capabilities needed for performing long-duration missions on the lunar surface is survival, and ultimately operational viability, through the lunar night. The fourteen Earth days of continuous darkness and extreme cold experienced at most locations on the Moon presents one of the most demanding environmental challenge that will be faced in the exploration of the solar system. Due to the lack of a moderating atmosphere, temperatures on the lunar surface can range from -180 C to +120 C during the day/night cycle. Permanently shadowed regions, areas of great interest for science and resource prospecting, can be even colder. Electronics and spacecraft subsystems can freeze and become unrecoverable at these extreme cold temperatures. NASA and commercial ventures are planning for increasingly complex and capable science and exploration missions to the surface of the Moon.

Surviving and operating through lunar night is critical to accomplishing key science and exploration objectives and lunar night operations are essential for a sustained presence on the Moon. This presentation will review the environmental challenges of the lunar night and the implications for the range of science, exploration, and commercial activities planned for the Moon. Previous missions and their experiences with surviving the night will be described. A variety of options including technology solutions and operational strategies for night survival and operations will be outlined. These options cover missions including simple stationary payloads, rovers, distributed instrument networks, and more complex payloads and operations such as resource prospecting, extraction and processing. The particular implications for human exploration missions will also be covered.

2.0604 Design and Control of a Mechanical Hopping Mechanism Suited for Exploring Low-gravity Environments

Jekan Thangavelautham (University of Arizona), Troy Jameson (University of Arizona), Himangshu Kalita (University of Arizona),

Presentation: Himangshu Kalita, Thursday, March 12th, 08:30 AM, Gallatin

The paper presentation will be an overview of the mechanical design of the robot and early simulation tests.

2.0606 Supervised Autonomy for Communication-degraded Subterranean Exploration by a Robot Team

Kyohei Otsu , Scott Tepsuporn (Jet Propulsion Laboratory), Rohan Thakker (NASA Jet Propulsion Lab), Tiago Vaquero , Jeffrey Edlund (JPL), William Walsh , Gregory Miles , Tristan Heywood (University of Sydney), Michael Wolf (Jet Propulsion Laboratory), Ali Agha ,

Presentation: Kyohei Otsu, Thursday, March 12th, 08:55 AM, Gallatin

The importance of autonomous robots is magnified when the robots are deployed onto areas that are too dangerous for humans. Robots have been deployed to disaster areas to assist in emergency responses, and to Mars to uncover the mystery of our neighboring planet. The DARPA Subterranean (SubT) Challenge was recently announced and presented a formidable robotics problem to foster technological advancement for operations underground. Robot teams are expected to rapidly map, navigate, and search underground man-made and natural environments including tunnel systems, urban underground infrastructure, and natural cave networks. Subterranean environments pose significant challenges for manned and unmanned operations. A system must cope with limited situational awareness due to difficult terrain, unstable structures, degraded environmental conditions, intermittent communication, severe connectivity constraints, and expansive areas of operations. The lack of situational awareness causes difficulty in multi-agent planning, which results in the inefficiency of operations. This paper describes our operational strategy to explore and map a large-scale environment with a team of robots supervised only by a single human operator. Specifically, we present how we deploy multi-agent systems into a previously unknown environment, build and maintain an in-situ communication network, and interface with the human operator who must process enormous data and control multiple robots. The core of multi-robot operations is robust and resilient single-robot autonomy. Each robot owns a mission executive that interprets the mission specifications and manages the mission progression while maintaining the robot health. We describe the mission specifications using a graphical model based on the Business Process Model and Notation (BPMN) standard. We use information roadmap (IRM) for a compact and task-oriented representation of large-scale tunnel-like environments. The IRM is a graph that captures the connectivity of the space with rich information including uncertainty, risk, traversability, and communicability. A robot traverses IRM nodes to reach the exploration boundary, and extends frontiers further into the unexplored regions. Effective distributed autonomy requires reliable communication for ensuring information delivery and state synchronization. We present a solution that combines tethered and wireless technologies to build a reliable communication backbone in the degraded subterranean environment. The data collected by the robots is sent back to the operator via the communication backbone. The operator monitors the 3D volumetric map, communication graph, and location/health of all agents in the graphical user interface. Most importantly, the operator monitors the growth and shape of the IRM graph, with the ability to modify its geometry and edge attributes. The IRM is then synched back and consumed by each robot to incorporate operator's intent in its global path planning. The presented approach was successfully integrated with hardware platforms and demonstrated in various mine environments. This paper reports the results from a series of field demonstratios including the DARPA SubT Challenge Tunnel Circuit in August 2019.

2.0608 Concept for an On-orbit Capture and Orientation Module for Potential Mars Sample Return

Paulo Younse (Jet Propulsion Laboratory), Chi yeung Chiu (NASA Jet Propulsion Lab), Jessica Cameron (NASA JPL), Marco Dolci (NASA Jet Propulsion Laboratory - CalTech), Alyssa Ishigo (NASA Jet Propulsion Lab), Dima Kogan , Eloïse Marteau (NASA Jet Propulsion Lab), John Mayo , Preston Ohta (Jet Propulsion Laboratory), Jackson Strahle (NASA Jet Propulsion Lab),

Presentation: Paulo Younse, Thursday, March 12th, 09:20 AM, Gallatin

An orbiting sample Capture and Orient Module (COM) architecture for a Capture, Contain, and Return System (CCRS) payload concept for an Earth Return Orbiter (ERO) was developed to enable on-orbit capture, orientation, and transfer of a Mars sample container into a containment vessel for potential Mars Sample Return (MSR). The module is composed of a capture mechanism for containing the Orbiting Sample (OS), a capture cone to capture and contain the OS, an orientation mechanism to orient the OS, an External Transfer Mechanism (ETM) to cage the OS during capture and assemble it into the containment vessel, a capture trigger to trigger capture mechanism and ETM closure during OS capture, and a sensing system to inspect the OS and confirm capture and orientation. Statistical modeling and simulations of the OS during capture were performed to analyze the time to contact and perturbations to the spacecraft at first contact. A half-scale functional prototype of the module was developed to demonstrate end-to-end operation.

2.0609 Predicting Biological Cleanliness: An Empirical Bayes Approach for Spacecraft Bioburden Accounting

James Benardini (NASA Jet Propulsion Lab), Arman Seuylemezian (California Institute of Technology/Jet Propulsion Laboratory), Andrei Gribok (Idaho National Laboratory),

Presentation: James Benardini, Thursday, March 12th, 10:35 AM, Gallatin

To comply with the international planetary protection policy set forth by the Committee on Space Research and NASA Agency level requirements, spacecraft destined to biologically sensitive planetary bodies have to minimize terrestrial biological contamination. Analysis, testing and inspection are the standard forward verification activities that are used to demonstrate compliance with the biological contamination requirements. For testing of spacecraft surface areas, a swab or wipe sample is collected from surfaces prior to last access and subsequently processed in the lab using NASA Approved Planetary Protection Methods for Culture Based Assays. Raw data resulting from this assay is then statistically treated employing a mathematical paradigm stemming from the 1970's Viking Lander Project to generate the bioburden density and total microbial bioburden present. This standard approach arbitrarily accounts for error and provides an upper conservative bound as it reports the maximum number of spores estimated to be present on flight hardware surfaces. A bioburden density estimate factors in the following variables: the observed bioburden count, representative volume processed, sampling efficiencies. Notably, to account for error in the approach, a 0 observed count is arbitrarily changed to a count of 1 for each hardware grouping. The data generated by spacecraft bioburden verification campaigns in the past have resulted in <80% of wipes and <90% of swabs containing a bioburden count of 0. As such, having a robust and well documented statistical approach for dealing with the probability of low incident rates is necessary to be able to estimate spacecraft bioburden. Being able to statistically describe the bioburden distribution and associated confidence level is a gamechanger for the development of bioburden allocations during mission design and will allow for tighter management of risk throughout spacecraft build. Thus, Empirical Bayes statistical approach was evaluated to estimate the microbial bioburden on spacecraft to mitigate the aforementioned mathematical concerns and provide a probabilistic bioburden distribution of the flight hardware surface. For application of this approach to performing bioburden calculations, a range of non-informative prior assumptions on hardware surfaces are explored for Bayesian analyses while informative priors using posterior distributions from prior assays are utilized for Empirical Bayes analyses. Several non-informative priors are currently under investigation to assess fitness including use of these priors to serve as a foundation to build off of NASA specification values or a basis of risk to account for unknowns during the integration and testing process. Informative priors under consideration are generated using sampled bioburden values from hardware originating within like processing environments (e.g. vendor cleaning process or similar assembly process), temporal spacecraft status events as a prediction for hardware cleanliness of future samples, and heritage system bioburden actuals to predict allocation for subsequent missions. Informative priors and probabilistic bioburden distributions are then validated using data sets from the Mars Exploration Rover, Mars Science Laboratory, and InSight missions. Using Empirical Bayes approach to generate a probabilistic bioburden distribution as demonstrated through mission use cases provides a valid approach for use in the end-to-end requirements verification process.

2.0610 Expectations for Backward Planetary Protection during a Mars Sample Return Campaign

Lisa Pratt (NASA),

Presentation: Lisa Pratt, Thursday, March 12th, 11:00 AM, Gallatin

NASA’s Mars rover, M2020, could potentially be the first step in an extraordinary campaign to bring carefully collected and sealed samples of sedimentary and igneous rocks from Mars to Earth for scientific study. The conceptual mission architecture for Mars Sample Return (MSR) must demonstrate robust containment and rigorous control of all unsterilized materials as assurance of no inadvertent harm to Earth’s biosphere. NASA and the European Space Agency (ESA) are working together on the notional Mars Sample Return campaign architecture. As part of this notional architecture, NASA would launch a sample return platform early as 2026 to land near the area explored by the M2020 rover and ESA would launch separately an Earth Return Orbiter (ERO). A small ESA fetch rover would depart from the platform and drive rapidly to locations where samples tubes have been placed on the ground for retrieval. Following transfer of the samples tubes into a sample container on a Mars Ascent Vehicle (MAV), the sample container would be launched and then released into Mars orbit for rendezvous with the ERO and return to Earth. Once landed on Earth, around 2030, the entry vehicle would be transported to a state-of-the-art receiving facility for hazard testing. This is an aggressive timeline; therefore, the two space agencies must collaborate and leverage multidisciplinary expertise across various working groups and trade studies to address several factors of the overall architecture. This publication outlines the technical trades and presents initial findings for the following collaborative efforts: 1) the Sample Safety Assessment Protocol Working Group (SSAP), 2) the JPL/NASA Sterilization Working Group (SWG), and 3) JPL/JSC Mars Sample Receiving Facility Advance Planning. The notional MSR campaign presents a complex set of backward planetary protection requirements that necessitate collaboration with multidisciplinary experts across academic, regulatory, and industrial organizations to achieve novel problem solving based on leading-edge scientific information. Continued partnering and discussion between NASA, ESA, and other stakeholders will be critical to ensuring a safe and successful MSR campaign.

2.0611 Pneumatic Sampler for Martian Moons eXploration (MMX) Mission

Kris Zacny (Honeybee Robotics Spacecraft Mechanisms Corporation), Lisa Thomas (Honeybee Robotics Spacecraft Mechanisms Corporation), Gale Paulsen (Honeybee Robotics), Dylan Van Dyne (Honeybee Robotics Spacecraft Mechanisms Corporation), Hunter Williams (Honeybee Robotics), Dara Sabahi (Honeybee Robotics / Dara Sabahi), Sherman Lam (Honeybee Robotics Spacecraft Mechanisms Corporation), Philip Ng (California PolyTechnic San Luis Obispo), Hiroki Kato , Hirotaka Sawada (Japan Aerospace Exploration Agency), Tomohiro Usui (Japan Aerospace Exploration Agency), Masaki Fujimoto (JAXA), Robert Mueller (NASA - Kennedy Space Center), Thomas Statler (NASA - Headquarters), Michael Zolensky , Leonard Dudzinski (NASA Headquarters), Philip Chu (Honeybee Robotics), Justin Spring (Honeybee Robotics Spacecraft Mechanisms Corporation),

Presentation: Kris Zacny, Thursday, March 12th, 04:30 PM, Jefferson

The goal of the JAXA's Martian Moons Exploration (MMX) mission is to explore the two moons of Mars, Phobos and Deimos, and return samples from the surface of Phobos. Honeybee Robotics is designing and fabricating a NASA-provided Pneumatic Sampler, or P-Sampler, that would capture surface material from Phobos using a pneumatic sampling approach. The P-Sampler will be mounted along a leg of the MMX lander. The sampling head of the P-sampler utilizes two sets of sampling nozzles: one set of nozzles pointed directly at the surface to kick-up and loft material into the sampling head, and a second set of nozzles to direct the oncoming material into the sample return canister further up the lander leg. A robotic arm mounted underneath the lander will then remove the sample canister and place it inside the sample return capsule. Several iterations of the P-Sampler have been designed and tested inside a vacuum chamber with Phobos analog material. In all tests, the P-Sampler successfully acquired sample, even in an extreme scenario where the sampling head was mounted 10 cm above the surface covered with gravel.

2.0613 Mars Sample Return Mission: Mars Ascent Vehicle Propulsion Design

Laura Sopegno (Polytechnic of Turin), Kimon Valavanis (University of Denver), Matthew Rutherford ,

Presentation: Laura Sopegno, ,

Mars Sample Return Mission: Mars Ascent Vehicle Propulsion Design This dissertation investigates the challenges of returning to Earth a certain amount of samples collected on the surface of Mars, through the study of the Mars Sample Return Mission (MSR). The process would allow future analysis in the terrestrial facilities of the Martian rocks and dusts, giving us more information about the composition of Mars. The core of the entire mission is the subject of this research: the propulsion design of the Mars Ascent Vehicle (MAV). This two-stage rocket has the main task to carry, into the Low Mars Orbit (LMO), the Orbit Sample (OS) capsule with the samples collected on the Martian surface with a catching rover. After reaching the target orbit with the MAV first stage, the MAV second stage is used for insert the OS canister into the LMO. In this circular orbit, the matching between the orbiter, the Mars Earth Return Vehicle (MERV), and the OS occurs, and then the final round-trip of the MERV returning to Earth with its payload.

The accomplishment of the MSR mission would represents a milestone in the future context of the space exploration.

2.0614 Dynamic Modeling, Simulation, and Analysis of Sample Capture for Potential Mars Sample Return

Alyssa Ishigo (NASA Jet Propulsion Lab), Paulo Younse (Jet Propulsion Laboratory),
Presentation: Paulo Younse, Thursday, March 12th, 09:45 AM, Gallatin

The current notional architecture for the Mars Sample Return (MSR) campaign would require autonomous on-orbit rendezvous and capture of a sample container after it has been delivered to Mars orbit by a preceding MSR mission. As part of the complete orbital payload known as the Capture, Contain, and Return System (CCRS), a concept has been developed for autonomously sensing and capturing this Orbiting Sample (OS) container. The concept, comprised of a capture mechanism and multiple optical break-beam arrays, would detect and enclose the OS into CCRS, and engage a dust-tight seal to prevent the escape of the OS or other unsterilized particles. A challenging goal for the system is to close the lid prior to the OS coming into physical contact after entering CCRS in order to reduce the risk of unsterilized Mars particles on the surface of the OS from contaminating the outside of the spacecraft. The mechanical and sensor performance requirements were driven by the broader architecture of CCRS, OS rendezvous parameters, and Planetary Protection requirements regarding the interaction and handling of the OS. The mechanism and break-beam array concepts were designed accordingly, and kinematic simulations of the mechanism's behavior, combined with a Monte-Carlo simulation of OS rendezvous/collision behaviors and corresponding break-beam sensor responses verify compliance.

2.0615 Designing a Methodology to Assess Human Factors Associated with Lunar Teleoperated Assembly Tasks

Arun Kumar (University of Colorado, Boulder), Benjamin Mellinkoff (University of Colorado, Boulder), Wendy Bailey (University of Colorado Boulder), Jack Burns (University of Colorado Boulder),
Presentation: Arun Kumar, Thursday, March 12th, 11:25 AM, Gallatin

Low-latency telerobotics can enable more intricate surface tasks on extraterrestrial planetary bodies than has ever been previously attempted. In order for humanity to create a sustainable lunar presence, well-developed collaboration between humans and robots is necessary to perform complex tasks. This presentation will discuss a methodology to assess the human factors, situational awareness (SA) and cognitive load (CL), associated with teleoperated assembly tasks. Currently, telerobotic assembly on an extraterrestrial body has never been attempted, and a valid methodology to assess the associated human factors has not been developed. The Telerobotics Laboratory at the University of Colorado-Boulder created the Telerobotic Simulation System (TSS) which enables remote operation of a rover and a robotic arm. The TSS was used in a laboratory experiment designed as an analog to a lunar mission. The operator's task was to assemble a radio interferometer. Each participant completed this task under two conditions, remote teleoperation (limited SA) and local operation (optimal SA). The goal of this experiment was to establish a methodology to accurately measure the operator's SA and CL while performing teleoperated assembly tasks. A successful methodology would yield results showing greater SA and lower CL while operating locally. Performance metrics measured in this experiment showed greater SA and lower CL in the local environment, supported by a 27% increase in the mean time to completion of the assembly task when operating remotely. Subjective measurements of SA and CL did not align with the performance metrics. This brought into question the validity of the subjective assessments used in this experiment when applied to telerobotic assembly tasks. Results from this experiment will guide future work attempting to accurately quantify the

human factors associated with telerobotic assembly. Once an accurate methodology has been developed, we will be able to measure how new variables affect an operator's SA and CL in order to optimize the efficiency and effectiveness of telerobotic assembly tasks.

2.0616 Robotics System Process and Concept for On-orbit Assembly for Potential Mars Sample Return

Jackson Strahle (NASA Jet Propulsion Lab), Marco Dolci (NASA Jet Propulsion Laboratory - CalTech), Paulo Younse (Jet Propulsion Laboratory), Chi yeung Chiu (NASA Jet Propulsion Lab),

Presentation: Paulo Younse, Thursday, March 12th, 10:10 AM, Gallatin

Proposed Mars Sample Return (MSR) missions would require on-orbit assembly of containment vessels to meet backward Planetary Protection requirements and transfer of the sample container through various stations and positions. Some operations would have to be performed autonomously, and others would require ground-in-loop decision-making stages and verification processes. One concept design for an Earth Return Orbiter (ERO) Capture, Contain, and Return System (CCRS) Transfer Mechanism (TM) is a multi-Degree of Freedom (DOF) manipulator that utilizes a passive End Effector (EE) to assist in containment vessel assembly. To converge on a feasible design, a robotic system process has been instantiated. This process is composed of three main phases: robotic problem definition (operating environment, operations/functions, system goals), robotic solution selection (trade studies on the number of degrees of freedom, number of mechanisms, types of mechanisms), robotic solution design, implementation, and verification and validation (kinematic configuration, robotic and kinematic analysis and topology optimization of components). As a final product of this process, a half-scale functional prototype of the TM was developed to demonstrate the end-to-end operation capability.

2.0617 PHALANX: Expendable Projectile Sensor Networks for Planetary Exploration

Michael Dille (KBR / NASA Ames Research Center), Danny Nuch (San Jose State University), Shiven Gupta (Duke University), Steven McCabe , Nicholas Verzic (NASA - Ames Research Center), Terrence Fong (NASA Ames Research Center), Uland Wong ,

Presentation: Michael Dille, Thursday, March 12th, 04:55 PM, Jefferson

Targets of scientific interest in planetary exploration increasingly lie in inaccessible or unsafe areas such as caves, lava tubes, or ravines not easily reached by current spacecraft and robots. Further, science needs progressively demand richer information on macroscopic and dynamic phenomena requiring long-term, wide-area measurements that cannot be fulfilled by vehicles providing sequential single-point readings. Improved study of processes such as local climate behavior and gas concentration may prove key to understanding exotic geologies and distributions of trapped water or biological activity. To address this gap, we have developed miniaturized, expendable sensors which can be ballistically lobbed from a robotic rover or static lander. These projectiles can perform sensing both during flight and once emplaced. Augmenting exploration systems with these sensors can extend situational awareness, perform long-duration monitoring, and reduce reliance on primary mobility mechanisms. This work introduces the mission architecture for PHALANX, integrating a cold gas launcher, smart projectiles, planning software, network discovery, and science sensing. We demonstrate operations pairing these sensors with a rover "mothership" such as reconnaissance using ballistic cameras and building timelapse maps of surface temperature or illumination conditions. Core to this is autonomous self-discovery and localization of sensors, providing a network infrastructure for both a "local GPS" and beyond-line-of-sight communication for the rover. We discuss the development of a terrestrial prototype including design of the launching mechanism, projectile optimization, micro-electronics fabrication, and sensor selection. This work was greatly accelerated by recent advances in commercial-off-the-shelf (COTS) components popular in the Internet of Things (IoT), providing a blossoming industry of low-power sensors. Results from early testing and characterization are presented, with capabilities demonstrated through both simulation and physical testing in a planetary analogue environment. Iterated evolution of the design is described, and finally, lessons learned to date, gaps toward eventual flight mission implementation, and continuing future development plans are discussed.

2.07 In Situ Instruments for Landed Surface Exploration, Orbiters, and Flybys

Session Organizer: Ricardo Arevalo (University of Maryland), Stephanie Getty (NASA - Goddard Space Flight Center), Xiang Li (University of Maryland, Baltimore County),

2.0701 Design and Verification of the Feet Design Used on InSights "Heat Flow Property Package Instrument”

Siebo Reershemius (German Aerospace Center - DLR),
Presentation: Siebo Reershemius, Friday, March 13th, 09:20 AM, Jefferson

The HP3 instrument measures the thermal flux through the Martian crust using a penetration probe. Launched on the InSight mission in 2018, HP3 was deployed to the surface at the beginning of 2019 and started operation shortly afterwards. During initial operation, the instrument is vulnerable to slip, due to a combination of low system mass (3.3 kg on Earth), shocks delivered by the penetration probe’s action, and the possibility of an inclined attitude on the surface. An uncontrolled position change of the instrument on the surface can reduce the scientific output and even lead to a loss of the experiment if the probe’s supporting structure moves laterally. The design of the feet has major impact on the total amount of slippage. A new feet design with a high slippage resistance capability at a low level of complexity and mass was developed for this instrument’s supporting structure. The design provides sufficient slippage resistance while fulfilling the challenging set of requirements for a Mars surface mission. The design was verified by test campaigns which emulate launch environments and operational behavior on Mars. The paper summarizes the design and qualification process of the HP3 instrument with respect to the feet development. It starts with a description of the used feet quantity and position: A four and a three feet design have been studied. The four feet configuration has been selected based on the relevant requirements and analytical estimations of the possible tipping stability. As a four feet design tends to be unstable under certain conditions a verification test campaign, which emulated the behavior on the Martian surface, was conducted and the results will be presented. The paper continues with a presentation of the foot design itself. Two design options were studied experimentally. One is similar to a turned-around cup and one resembles a flat disc with a slightly higher outer ring. Both designs have their advantage and fulfill the requirements. The designs were evaluated based on a test campaign at which a breadboard model of the instrument was equipped with both types of feet. The instrument was placed on a tilted box filled with low-cohesion soil. The hammering mechanism of the instrument was activated and the resulting slippage recorded. The design with best slippage behavior was selected for the mission. The paper further describes the verification process of the feet. The verification strategy usually used for small instruments is not sufficient as the instrument is equipped with several release mechanisms, which introduce high shocks. Therefore, the standard verification program was extended by a tailored shock test campaign. The paper closes with a summary of the planed future work: As further missions might require higher track resistance, future work focuses on ideas how to increase the track generated from the contact surface. Several ideas and first results are presented within the conclusion.

2.0702 Ultraviolet Laser Development for Planetary Lander Missions

Molly Fahey (NASA Goddard Space Flight Center), Anthony Yu (NASA - Goddard Space Flight Center), Ricardo Arevalo (University of Maryland), Andrej Grubisic (NASA Goddard Space Flight Center), Xiang Li (University of Maryland, Baltimore County), Stephanie Getty (NASA - Goddard Space Flight Center), Richard Liu (University of Illinois at Urbana-Champaign), WILLIAM MAMAKOS (DESIGN INTERFACE INC),

Presentation: Molly Fahey, Friday, March 13th, 08:30 AM, Jefferson

Mass spectrometers represent progressive analytical platforms for future in situ lander missions to explore the surface chemistry of planetary bodies. Europa (as an astrobiology objective) and the Moon (an extension of the terrestrial system) are two primary targets for future NASA missions to search for extraterrestrial life and potentially habitable environments beyond Earth, further our understanding of the timing and formation of the Solar System, and identify potentially viable economic resources such as water and/or valuable metal assets. The CORALS (Characterization of Ocean Residues And Life Signatures) and CRATER (Characterization of Regolith And Trace Economic Resources) instruments are laser-based OrbitrapTM mass spectrometers currently under development for prospective lander missions to Europa and the Moon, respectively. We report on the advancement of two compact, robust, and high technology readiness level (TRL) ultraviolet (UV) solid state lasers that serve as the sampling and ionization sources of these two investigations.

2.0703 Decisions and Trade-Offs in the Design of a Mass Spectrometer for Jupiter's Icy Moons

Davide Lasi (University of Bern), Stefan Meyer (Inselspital, Bern University Hospital), Daniele Piazza (University of Bern), Matthias Lüthi (University of Bern), Andreas Nentwig (University of Bern Physics Institute), Mario Gruber (University of Bern), Stefan Bruengger (University of Bern), Michael Gerber (University of Bern), Saverio Braccini , Marek Tulej (University Bern), Martina Föhn (University of Bern), Peter Wurz (University of Bern),

Presentation: Davide Lasi, Friday, March 13th, 08:55 AM, Jefferson

This paper tells the journey of a team of engineers and scientists towards the realization of the first Time-of-Flight (TOF) Mass Spectrometer bound to Jupiter, NIM, which will launch in 2022 onboard JUICE, the first mission of the European Space Agency bound to Jupiter's icy moons. Instead of describing the nuts and bolts of the instrument's design baseline, we interpret the design in terms of a hierarchy of 'given', architectural, and design decisions made during the lifetime of the project. These include decisions about the instrument concept, sample introduction, ionization mechanism and technology, detector, radiation shielding, manufacturing technologies, and electronics. Trade-offs are described, together with technical and programmatic factors that led to the eventual convergence to the flight model's design baseline. These factors include results for prototyping and experiments, yet risk and schedule considerations that often came in the way of the pursuit of the 'ideal' or 'best' design. We conclude this journey with the first calibration spectrum acquired with the flight model, demonstrating performance in line with the requirements. By following this approach that interprets the design in terms of decisions and trade-offs, not only we aim to provide an insightful description of the instrument that can guide the design of future generations of TOF mass spectrometers for space exploration missions, but also we aim at outlining a principled approach to the retrospective description of a complex system's design that may be useful in other domains of science and engineering.

2.0704 The SuperCam Instrument for the Mars 2020 Rover

Tony Nelson (Los Alamos National Laboratory),

Presentation: Tony Nelson, Friday, March 13th, 09:45 AM, Jefferson

In mid-2019, the SuperCam instrument was installed aboard NASA's Mars 2020 rover, which is scheduled for launch in July 2020 and a landing at Jezero crater in February 2021. SuperCam is a collaboration between Los Alamos National Laboratory (LANL; the lead institution) and the Institut de Recherche en Astrophysique et Planétologie (IRAP), funded by the French Space Agency (CNES) and with contributions by universities and laboratories in France, Spain, and Denmark. SuperCam integrates a number of observation techniques into a single instrument, which builds on the design heritage of ChemCam, a laser induced breakdown spectroscopy (LIBS) instrument aboard the Curiosity rover. While retaining ChemCam's LIBS mode, SuperCam adds a Raman spectroscopy mode, an infrared spectrometer (IR), a microphone, and improves upon ChemCam's greyscale context imager with a color imager. This paper will give a broad overview of the SuperCam instrument, which is divided into three portions: the LANL-built SuperCam Body Unit (SCBU), the French-built SuperCam Mast Unit (SCMU), and the Spanish-built SuperCam Cal Target (SCCT). The instrument operational modes will be detailed, explaining how the instrument as a whole is used to collect and process its data within the context of the Mars 2020 rover. Next, we will detail LANL's design, integration, and testing of the SCBU. The SCBU is installed inside the rover's body and features an optical demultiplexer feeding a set of three spectrometers, which are digitized by three charge-coupled devices (CCDs) from e2v, controlled by a low-noise spectrometer electronics module. The longest-wavelength visible-range spectrometer employs high-throughput transmission optics and an image intensifier to amplify and gate the incoming light in Raman mode. This transmission spectrometer is powered and controlled by a high voltage power supply, designed and built at LANL. A low voltage power supply converts rover power to voltages used by the instrument. The command and data handling (C&DH) module features Leon-3-based processor and field programmable gate array for custom logic, along with a memory array. Instrument flight software architecture will be presented, with a focus on the body unit and mast unit functionality divide. The test qualification scheme will be detailed, with information on instrument optical performance testing.

2.0705 The Processing Electronics and Detector of the Mars 2020 SHERLOC Instrument

Mike Caffrey (Los Alamos National Laboratory),
Presentation: Mike Caffrey, Friday, March 13th, 10:10 AM, Jefferson

The SHERLOC instrument (Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals) is an ultraviolet (UV) Raman and fluorescence spectrometer that will be deployed on the Mars 2020 rover mission. The instrument includes a context microscopic imager with resolution of 10 µm, and the scanning laser has a spot size of 100 µm, which allows SHERLOC to generate spatially and spectrally resolved data cubes without contact with the Martian surface (typically ~5 cm of standoff from an abraded surface); it is designed to detect and characterize organics and astrobiologically relevant minerals in the search for past life. The instrument is led by Jet Propulsion Laboratory (JPL) with electronics, software, and electronic ground support equipment provided by Los Alamos National Laboratory (LANL), among others. The instrument is composed of two main physical components: the SHERLOC body assembly (SBA) and the turret assembly (STA). The SBA resides in the main body of the rover and operates in a relatively benign environment, while the STA is mounted on the rover arm turret and experiences extreme temperature fluctuations. The SBA conditions power from the rover, interfaces with the rover for command and data handling, and provides the control for the scanner and spectrometer. The SBA incorporates a LEON3 processor that runs all of the spectroscopy flight software. The STA houses the laser, laser power supply, imagers, scanning mirror, optics, and charge coupled device detector. The STA and SBA communicate via Spacewire over 12m of flex circuit routed down the

rover robotic arm. The instrument is designed to autonomously scan a sample scene of approximately 7 x 7 mm, process the resulting data, and then subsequently interrogate regions of interest with much higher spatial and spectral resolution. This paper will describe the instrument spectroscopy electronics design and operation. It will cover the sampling and acquisition of data from the CCD, the detector noise performance, as well as storage and transmission of data to the vehicle.

2.09 Mission Design for Spacecraft Formations

Session Organizer: Giovanni Palmerini (Sapienza Universita' di Roma), Leonard Felicetti (Cranfield University),

2.0901 Lunar Orbit Design of a Satellite Swarm for Radio Astronomy

Sung-Hoon Mok (Delft University of Technology), Jian Guo (Delft University of Technology), Eberhard Gill (University of Technology), Raj Thilak Rajan (Technical University Delft),
Presentation: Sung-Hoon Mok, Friday, March 13th, 08:30 AM, Madison

Employing a satellite swarm for radio astronomy has been continuously addressed in the Orbiting Low Frequency ARray (OLFAR) project. A 100 km diameter of aperture array constructed by distributed satellites will be able to provide sky maps of better than 1 arc-minute spatial resolution at 10 MHz. However, an orbit design strategy for the swarm satellites that ensures safe intersatellite distances and relative orbit stability has not yet been developed. In this paper, a new method for OLFAR orbit design is proposed. A deterministic solution is presented based on three algebraic constraints derived here, which represent three orbit design requirements: collision avoidance, maximum baseline rate, and uvw-space coverage. In addition, an idea for observation planning over the mission lifetime is presented.

2.0902 Optimal Control Trajectories for Rendezvous of a Nanosatellite with a Resident Space Object

Parv Patel (University of Southern California), Bogdan Udrea (VisSidus Technologies, Inc.),
Presentation: Parv Patel, Friday, March 13th, 08:55 AM, Madison

There has been an increasing interest in on-orbit autonomous servicing and repair of satellites as well as controlled active debris removal (ADR) in the space industry recently. One of the most challenging tasks for servicing/repair as well as for ADR is the rendezvous and docking with a non-cooperative tumbling resident space object (RSO). The work presented in this paper deals with the optimal trajectory planning for Rendezvous of a nanosatellite with a tumbling RSO. The research described here elaborates on the previous work by Boyarko [1,2] who studies the minimum-control-effort and minimum-time problem for a 3-D rendezvous to a tumbling object which considers the full six-degree-of-freedom model that consists of the general six kinematics states (position and velocity) along with the seven attitude states (quaternion and angular rates) of the chaser and target. The current work expands the scope by adding Quadratic drag and J2 to investigate their effect on the proximity operations and establish the requirements for algorithms for closed loop attitude control and relative navigation. Additionally, the paper explores the impact of these perturbations and assesses the importance of implementing them in the linear equations of relative motions. Previous work by P.Patel et al. [3] has studied the effects of only J2 perturbations on the optimal rendezvous trajectories. The current paper expands the linear equations with the addition of quadratic drag. The control problem features additional path constraints with relative motion dynamics pertinent to the proximity space operations to match the perching state vector of the nanosatellite over a feature of interest of the RSO. The path to final docking, with a terminal constraint of a small but finite positive relative speed at contact, is also discussed. The consequences of limited thrust and finite attitude maneuver time are taken

into account and their effects on the closed loop translation and attitude control of the nanosatellite are analyzed. Moreover, the research also elaborates on the homotopic nature of the optimal control trajectories for variations in different mission design parameters including inclination, maximum thrust, and altitude. REFERENCES [1] Boyarko, G. "Spacecraft Guidance Strategies for Proximity Maneuvering and Close Approach with A Tumbling Object." Vol. Ph.D., Naval Postgraduate School, 2010. [2] Boyarko, G., Yakimenko, O., and Romano, M. "Optimal Rendezvous Trajectories of a Controlled Spacecraft and a Tumbling Object," Journal of Guidance, Control, and Dynamics Vol. 34, No. 4, 2011, pp. 1239-1252. [3] Patel, P., Udrea, B., and Nayak, M. “Optimal Guidance Trajectories for a Nanosatellite Docking with a Tumbling Resident Space Object”, 2015 IEEE Aerospace Conference, IEEEAC # 2199

2.0903 Q4 – a CubeSat Mission to Demonstrate Omnidirectional Optical Communications

Jose Velazco (Jet Propulsion Laboratory), Jaime Sanchez de la Vega (NASA Jet Propulsion Lab),
Presentation: Jose Velazco, Friday, March 13th, 09:20 AM, Madison

We are proposing a technology demonstration mission for JPL’s Inter-Satellite Optical Communicator (ISOC). The ISOC has the potential to enable up to 1 Gbps data rates over a distance up to 200 km in free space. Key features of the ISOC include full sky coverage and the ability to maintain multiple links simultaneously. The Q4 mission consists of (4) 6U CubeSats furnished with ISOCs to demonstrate high data rate communications among the spacecraft. More specifically, we seek to demonstrate the omnidirectionality of the ISOC by providing simultaneous optical links between one spacecraft and the other three. Q4 will be a demonstrator for small spacecraft swarm capabilities. Following a proposed deployment from the ISS, the CubeSats will utilize their onboard thrusters to enter their desired orbit. The orbit consists of one “leader” spacecraft in a circular orbit with a 400 km LEO altitude and three “follower” spacecraft in slightly elliptical orbits rotating azimuthally about the leader. The main mission will consist of three consecutive phases: First, the spacecraft will demonstrate pointing, acquisition, and tracking using newly developed protocols. Next, link establishment and different channel access methods (CDMA and TDMA) will be tested. Finally, Delay Tolerant Network protocols will be implemented to allow fast data sharing among the spacecraft. The distance between the communicating spacecraft will be increased as the mission progresses to characterize the link quality as a function of distance. All communications over the course of the mission will be recorded and analyzed on the ground using bit error rate as a metric for success. The current design for each the four Q4 CubeSats contains an XACT advanced ADCS system for precision beam pointing. Other components currently under consideration include MiPS cold gas thrusters for orbital maneuvering and gimbaled eHaWK 84W solar arrays. In this paper we present design considerations for the Q4 CubeSats, link budget calculations, results from preliminary mission analysis, and expected results.

2.0904 Numerical Determination of Natural Spacecraft Formations near the Collinear Libration Points

Donna Jennings (Missouri University of Science & Technology), Henry Pernicka (Missouri University of Science and Technology),
Presentation: Donna Jennings, Friday, March 13th, 09:45 AM, Madison

With increased interest in formation flying and distributed spacecraft technologies a better understanding of relative motion and natural/non-natural relative trajectories are desirable. While formation flight has been studied in some detail for Earth orbiting satellites, currently proposed NASA missions (MAXIM, SI, and TPF) and ESA’s DARWIN mission indicate a growing interest in relative motion at the collinear libration points. The focus of this work is on identifying natural formations near the collinear libration points and studying the potential of such relative trajectories being utilized for science and exploration-type missions. Segerman (2003) developed a second-order analytical solution to describe the motion of a deputy satellite about a chief in the vicinity of a collinear libration point. Collange (2004) built upon Segerman's work by designing relative motion trajectories near the collinear libration point analogous to the well-known Earth-orbiting regimes. These relative trajectories, when implemented with the CR3BP model, demonstrated unstable motion that naturally diverged without control applied. Several studies have implemented stationkeeping techniques to control desired relative trajectories, but most of these works assumed the availability of continuous control. Howell and Marchand (2005) instead utilize a discrete controller to achieve the desired non-natural formations. In addition, they investigated using a Floquet controller to find naturally existing formations near the libration points. The work this paper describes is distinguished by identifying continuous natural relative trajectories numerically from the nonlinear CR3BP differential equations by utilizing a shooting method with a two-level differential corrector. The focus is on determining natural formations in the vicinity of the Earth-Moon L2 point when using the nonlinear equations of motion of the CR3BP. In order to identify these trajectories a two-level differential corrector (Howell and Pernicka, 1987) is utilized. This method takes an iterative approach to reduce the position and velocity discontinuities to zero at predefined trajectory patch points. To initialize the corrector the state vector at each of the patch points is calculated using the first-order analytical solution for relative motion (Segerman, 2003). Next, the first level of the corrector determines a continuous path by adjusting the relative velocity states at each patch point. The second level of the differential corrector adjusts the relative position states and propagation times to minimize the subsequent velocity discontinuities. This process is repeated until the velocity discontinuities at each patch point are less than a small tolerance. These are regarded as negligible velocity discontinuities and hence a converged continuous relative trajectory is found. Upon identifying these relative trajectories analysis is conducted to determine drift rates of the uncontrolled trajectories compared to the previously mentioned analytic formations near the collinear libration points. Preliminary results indicate that the converged trajectories using the nonlinear CR3BP equations of motion maintain the reference path about five times longer than the corresponding linearized ones. As a work in progress, the authors are implementing stationkeeping to determine the amount of propellant savings a mission flying a converged relative trajectory can expect compared to a linearized formation.

2.0906 Nonlinear Dynamic Modelling of Satellite Relative Motion with Differential J2 and Drag

Ria Vijayan (University of Würzburg), Mohd Bilal (Julius-Maximilians University of Würzburg), Klaus Schilling (University Wuerzburg),

Presentation: Damiana Catanoso, Friday, March 13th, 10:10 AM, Madison

A systematic approach to modeling the relative motion of artificial satellites in the presence of perturbations is presented. The relative motion is described using relative position and velocities as states. The modeling here is restricted to low Earth orbit (LEO) satellites and therefore includes the differential J_2 and drag effects. In this paper we expand on the modeling approach that makes use of the Reference Satellite Variables for the chief's orbit using simple Newtonian mechanics to systematically derive the exact nonlinear relative motion model with differential J_2 and drag. These equations are exact for eccentric reference orbits as well as equatorial. This intuitive modeling approach shall establish a framework to incorporate other kinds of differential perturbations for higher fidelity models based on the significance of application. Simulation results of the developed nonlinear relative motion model show the effect of differential J_2 and drag captured by the equations for a LEO leader-follower formation with large intersatellite distances. The propagation errors of the model are studied for varying initial conditions and reference orbits. A subsequent analysis gives further insight into how the model developed is particularly free from singularities in the special case of J_2 and drag disturbances alone.

2.0907 Automated Design Architecture for Lunar Constellations

Jekan Thangavelautham (University of Arizona), Ravi Teja Nallapu (University of Arizona),
Presentation: Ravi Teja Nallapu, Friday, March 13th, 10:35 AM, Madison

The paper will present work on constellation design for lunar applications. The presentation will utilize multimedia (particularly video animations) to show some of the advanced concepts.

2.0909 H_2-H_infinity Model Reference Adaptive Control of Tethered Satellite System

Pouria Razzaghi (Southern Methodist University),
Presentation: Pouria Razzaghi, Friday, March 13th, 11:00 AM, Madison

This study aims to investigate the control of a triangular configuration and triple mass tethered satellite system using a novel robust H_2-H_infinity Model Reference Adaptive Control (HMRAC) scheme. The system is actuated by thrusters to generate control forces. The dynamical model of the semi-ideal system, which acts as a reference model is described with a known external disturbance, called the J2 perturbation. The proposed MRAC design methodology is based on the stable semi-ideal nonlinear reference model, which is regulated by a state feedback controller using H_2-H_infinity State-Dependent Riccati Equation (SDRE) techniques. Then, the real system with the unknown disturbances is controlled by the feedback of the reference model control scheme. The main benefit of using the HMRAC is having the robustness of the reference model, which decreases the computational burden of the classical MRAC. The numerical simulation results are presented and compared with the Linear Quadratic Regulator to demonstrate the effectiveness of the proposed control method. Also, the effectiveness of the proposed controller in improving attitude maneuverability is demonstrated.

2.0910 Image-Based Visual Servoing Control for Spacecraft Formation Flying

Leonard Felicetti (Cranfield University), Jorge Pomares (University of Alicante),
Presentation: Leonard Felicetti, Friday, March 13th, 11:25 AM, Madison

An Image-Based Visual Servoing (IBVS) strategy is proposed in this paper as a viable solution to reduce the complexity of the GNC algorithms for spacecraft formation flying. The main idea is that it is possible to drive the onboard actuators directly through the comparison of actual captured frames with reference images, without the need of reconstructing the relative pose of the observed spacecraft. The projections of the visual features of the observed objects to the image plane are therefore used to close the feed-back and the GNC loops. In the paper, analytical developments demonstrate the stability of the proposed distributed visual servoing strategy, by also taking into account the orbital and attitude dynamics of the spacecraft. The presented approach is based on an optimal control framework for the minimization of the actuation efforts, which enables the generation of specific controllers addressing different tasks and issues in a variety of maneuvers, e.g. formation acquisition, formation reconfiguration or formation keeping maneuvers. The viability of the proposed control strategy, as well as the robustness against the errors in the actuation and sensing, is assessed through numerical simulations of a realistic scenario of small-sat formation flying.

2.0911 Reconstruction of the Shape of a Tumbling Target from a Chaser in Close Orbit

Giovanni Palmerini (Sapienza Universita' di Roma), Renato Volpe , Marco Sabatini (Universita` Roma La Sapienza),
Presentation: Giovanni Palmerini, Friday, March 13th, 11:50 AM, Madison

Operations involving two or more spacecraft, including approach, rendezvous and servicing, are not always based on the cooperation among them. The lack of cooperation means a limited set of information initially available to the approaching spacecraft. Still, the determination by the chaser of the relative kinematic state of the target spacecraft stands as a required step to continue the approach. Completing this first fundamental information about relative motion, also the reconstruction of the target's shape can be considered an important part of the rendezvous and a pre-requisite for safe docking. In fact, shape reconstruction enables the chaser to understand target's configuration, to assess its integrity and eventually to compare it with already known spacecraft's models. The reconstruction needs to be accurate even while starting from the limited number of images captured only from the points of view attained during relative motion, and is indeed a quite challenging task. Due to the extremely wide range of possible relative poses and light conditions, an extensive test campaign based on numerical simulations is required to validate possible algorithms to carry on this operational phase. Only after simulations are successfully passed, it would be possible to move towards experiments in a ground-based testbed and finally to in-flight qualification. The proposed paper details the experience gained with the simulation phase at the Guidance and Navigation Lab of Sapienza Università di Roma. A software suite is developed in order to simulate in orbit acquisition of the target image, managing its 3D CAD model according to the relative dynamics and lighting conditions. Several spacecraft configurations, different in terms of shapes and relative pose, are assumed for the target, and the relevant images are captured by the chaser during its relative motion around it. An effective process for the identification and match of the features, capable to manage their appearance and disappearance during the sequence of images has been implemented. Following these steps, it is possible to gain – in addition to the understanding of the relative dynamics - an educated guess of the shape of the target. Advanced filtering techniques taking into account relative orbital dynamics are applied, significantly contributing to the final result of the process. The post-facto comparison between the actual CAD model and the estimated target's shape shows appealing success rates in the recognition task for the proposed technique.

2.10 Space Radiation and its Interaction with Shielding, Electronics and Humans

Session Organizer: Maria De Soria Santacruz Pich (Jet Propulsion Laboratory), Lembit Sihver (Technische Universität Wien),

2.1001 Radio-adaptation of Astronauts Due to Adaptive Responses

Lembit Sihver (Technische Universität Wien), S. M. Javad Mortazavi (University of Wisconsin Milwaukee),
Presentation: Lembit Sihver, Thursday, March 12th, 08:30 AM, Madison

During manned space missions, humans will be accompanied by microorganisms. This prompts us to study the characteristics of bacteria grown in space. It has been shown that a pre-exposure to low levels of either ionizing or non-ionizing radiation can make microorganisms more resistant not only to high doses of ionizing radiation but to any factor that threatens their survival (e.g. antibiotics) [2,3]. This phenomenon that is called "adaptive response" (i.e. increased resistance in living organisms pre-exposed to a low level stressor such as a low dose of ionizing radiation) [4] significantly increases the risk of serious infections in deep space missions. It's worth noting that both animal and human data confirm the disruption of the immune system during spaceflight [5]. In addition, the virulence of bacteria can also be increased significantly in space [4], hence this kind of adaptive response which increases the resistance of bacteria can endanger the astronauts' lives in space. On the other hand, A NASA report notes that as astronauts' cells will be exposed to multiple protons before being traversed by HZE particles, they can show adaptive responses. Given this consideration, it would be realistic to expect co-radioadaptation of astronauts' microbiome and their body in a deep space journey to Mars and beyond. The complexity of these phenomena and current uncertainties, which highlight the need for further studies before any long-term manned mission, will be discussed in this paper.

2.1002 Modeling Radiation Influence on Spacecraft Materials Outgassing

John Anderson (Jet Propulsion Laboratory), ANTHONY WONG (Jet Propulsion Laboratory), Daniel Fugett (Jet Propulsion Laboratory), William Hoey (NASA Jet Propulsion Laboratory),

Presentation: John Anderson, Thursday, March 12th, 08:55 AM, Madison

Spacecraft orbiting Jupiter and performing flybys or landing on Jovian moons, such as Europa, experience an environment with high radiation levels. A Radiation Induced Outgassing Test (RIOT) campaign was initiated to study of radiation effects on contamination products evolving from spacecraft materials. Materials were irradiated with a flux of 2.6x1010 electrons/cm2/s at an energy of 1.5 MeV. A physics based outgassing model has been developed to explain the observed experimental results. Material outgassing rates measured during, and subsequent to radiation exposure, can be modeled using a simple diffusion model. Use of Fick's law with a source term during irradiation, and without a source term when the radiation is turned off, gives good agreement with the experimental data. This model provides a basis for extrapolating experimentally measured outgassing rates to predict contamination outgassing as a function of the radiation levels encountered during a mission at Jupiter.

2.1003 The RadMap Telescope on the International Space Station

Martin Losekamm (Technical University of Munich), Stephan Paul (Technicql University Munich), Thomas Pöschl , Hans Zachrau ,

Presentation: Martin Losekamm, Thursday, March 12th, 09:20 AM, Madison

Protecting astronauts against the space radiation environment is one of the major challenges of human space flight. Especially in future missions to the Moon, Mars, and other deep-space destinations with no or minimal natural protection, mitigating radiation effects through shielding and other measures will be critical to mission success. Hence, detailed knowledge about the composition of the radiation environment and its temporal variations is a prerequisite for the design of new spacecraft, habitats, surface vehicles, and space suits. Real-time information about radiation levels inside a spacecraft or habitat is also required for moving astronauts to safety during brief but intense solar-radiation events. The RadMap Telescope is a technology-demonstration experiment whose main objective is to validate new radiation-sensing concepts for applications in manned and unmanned spacecraft. It is scheduled for deployment to the International Space Station (ISS) in 2020. Currently, the radiation environment aboard the ISS is monitored by a suite of active and passive dosimeters, particle telescopes, and small spectrometers. The RadMap Telescope combines several capabilities of these sensor types in one device and may even expand some of them. Due to its novel design, it also has new, unique capabilities; for example, the ability to monitor the radiation environment omnidirectionally without having to turn or relocate the sensor. The instrument comprises technologies that have only become sufficiently mature for large-scale applications in the past few years. These technologies enable the construction of compact yet highly capable radiation monitors. Much of the data is pre-analyzed on the instrument before being downlinked to the ground for detailed analysis. The centerpiece of this on-line pre-analysis is a framework of machine-learning algorithms that ensures the most important information, such as the radiation dose, is available with as little delay as possible. In this contribution, we present the overall design of the instrument, how it will be integrated into the ISS environment, and how it addresses the need for detailed studies of the space radiation environment. We show results from proof-of-principle ground tests that we performed during the development of the instrument and outline how we intend to use data from operational radiation sensors for validation. If proven to work as expected, the technology demonstrated in the RadMap Telescope may be used in new radiation detectors and help to reduce the number of sensors required in future spacecraft while increasing measurement capabilities at the same time.

2.1004 Calculating Ionizing Doses in Geosynchronous Orbit from In-situ Particle Measurements and Models

Yue Chen (Los Alamos National Laboratory),
Presentation: Yue Chen, Thursday, March 12th, 09:45 AM, Madison

Reliable and precise total ionization dose (TID) values are always pursued by the aerospace and satellite communities. The current common practice of calculating TID is to run radiation transport codes with the inputs of particle fluences specified by empirical statistical space radiation models given the satellite orbit as well as starting time and duration of the mission. In this way, uncertainties in particle fluences from the empirical models will propagate through to the final output TID values. Therefore, how large are those fluence uncertainties from empirical models and eventually how significantly they contribute to errors in calculated TID values are of great interest to satellite designers and instrument performance monitors. In this work, long-term electron and proton in-situ measurements made by Los Alamos National Laboratory Geosynchronous (GEO) satellites are used to calculate total ionization dose (TID) values and daily/yearly dose rate (DR) values in GEO orbit caused by the natural space environment, and these TID and DR values are compared to those calculated from empirical radiation models.Specifically, a Geant4 code is employed to calculate daily and accumulated TID on a small (with a radius of 0.1 mm) Si detector inside an Aluminum shielding sphere with a thickness of 100 mil. It is determined that electrons within the energy range of 1.4 -- 4 MeV and protons within 21 -- 84 MeV are the main TID contributors for this specific geometry in the GEO orbit. Results over the solar cycle 24 show that, for the selected solid sphere geometry, electron TID from measurements in LANL-04A GEO orbit has a mean of 17.3 krad/yr, about half of the values calculated from AE8 and AE9 models, while the TID on another GEO satellite 1994-084 is two times lower. Also, it is shown that even the few solar energetic proton events contribute significantly to the proton TID. Factors affecting those dose calculations are discussed. Results from this study provide out-of-sample tests on the reliability of empirical space radiation models and help estimate the margin factors of calculated ionization dose values in GEO orbit.

2.1005 Can Adaptive Response and Evolution Make Survival of Extremophile Bacteria Possible on Mars?

Lembit Sihver (Technische Universität Wien), S. M. Javad Mortazavi (University of Wisconsin Milwaukee),
Presentation: Lembit Sihver, Thursday, March 12th, 10:10 AM, Madison

The humidity on the surface of the red planet, Mars, drops steeply during the daytime as the temperature rises. In this situation, Martian microorganisms should have the capability to cope with desiccation. Extremophiles are microorganisms that are capable of surviving in extreme environmental conditions. It has previously been shown that a pre-exposure to low levels of either ionizing or non-ionizing radiation can induce resistance against subsequent exposure to high levels of different stressors (e.g. high doses of ionizing radiation) in a wide variety of living systems. Moreover, it has been shown that E. coli bacteria repeatedly exposed to a dose needed for 1% survival, and increasing the dose each time due to increased radioresistance for the same survival (1%), generates extremely radioresistant bacteria through directed evolution. Mortazavi et al. have warned that in a similar manner with extremophiles such as Deinococcus radiodurans, it would be very likely that this type of human-directed radioresistance makes E. coli bacteria resistant to all physical and chemical agents (generation of serious life-threatening micro-organisms). There are reports about the possibility of the existence of microbes in the salty puddles of Mars. On Mars, with its thin atmosphere and lack of the protective magnetic field, higher levels of space radiation cause more genetic mutations. Interestingly, these mutations in bacteria, which can make them resistant against radiation, can also make them resistant against desiccation. Moreover, the adaptive response to radiation in bacteria might play an important role in this process. As stated in a NASA report, the cells in the astronauts will be traversed by multiple protons before exposure to HZE particles. This sequential exposure might significantly increase the resistance against radiation. The same exposure in bacteria might not only induce resistance against the high levels of damage caused by HZEs, but also to other life-threatening factors for bacteria such as desiccation. In this paper, the current understanding of extremophiles and their capability of surviving in extreme environmental conditions as well as current findings about radioadaptive responses in bacteria will be discussed.

2.1006 GPS Constellation Energetic Particle Measurements

Matthew Carver (Los Alamos National Laboratory),
Presentation: Matthew Carver, Thursday, March 12th, 10:35 AM, Madison

The Global Positioning System (GPS) is one of the most ubiquitously available services in the world, but it provides far more than just location and timing services; many of the satellites carry instruments to directly measure the space environment. On October 13th, 2016, the White House issued Executive Order #13744 ‘Coordinating Efforts to Prepare the Nation for Space Weather Events’ which stated that responsible agencies 'shall make historical data from the GPS constellation and other U.S. Government satellites publically available.’ Los Alamos National Laboratory (LANL) has been designing, building, and operating energetic particle instruments in space for more than 50 years with two types of detectors on the current GPS constellation. As part of the 2016 Executive Order data collected by LANL sensors from 2001 through 2018 has been released and is archived by the National Oceanic and Atmospheric Administration. With more than 20 satellites operating LANL instruments during this period the dataset consists of more than 200 satellite-years of data that increases by roughly one satellite-year of data every two weeks and covers an entire solar cycle. We will present an overview of the available data as well as some initial studies to exemplify its utility.

2.1007 Cognitive Effects of Long-term Exposure of Human Brain to Alpha Particles

S. M. Javad Mortazavi (University of Wisconsin Milwaukee), Lembit Sihver (Technische Universität Wien),
Presentation: S. M. Javad Mortazavi, Thursday, March 12th, 11:00 AM, Madison

SMJ Mortazavi1,2 SMT R. Toosi3, P. Roshan-Shomal4, SA Mortazavi2, A. Kaveh2, G. Mortazavi2, and L. Sihver5 1. Fox Chase Cancer Center, USA 2. Shiraz University of Medical Sciences, Iran 3. Guilan University of Medical Sciences, Iran 4. University of Management, Iran 5. Technische Universität Wien, Austria *Corresponding author: Lembit Sihver E-mail: lembit.sihver@tuwien.ac.at Astronauts’ exposure to radiation is different from exposure to radiation on Earth. Besides cancer and acute radiation syndrome, there are concerns over the potential behavioral and cognitive impairments caused by exposure of the astronauts’ central nervous system to high levels of space radiation. Therefore, potential behavioral and cognitive impairments caused by astronauts’ brains exposure to high levels of space radiation and the possibility of developing dementia and other motor neuron diseases are getting more attention. As NASA is interested in studies on radium deposition in human brain, and exposure of the brain to high-LET alpha particles, we have assessed the cognitive effects of long-term exposure of human brain to alpha particles which mimics astronauts’ exposure to high HZE particles in upcoming mars missions. Dr. Boice, President of NCRP, and his colleagues, state that human brain exposed for years to alpha particles on Earth may be more relevant to a Mars mission than mouse brains exposed to heavy ions for a few minutes". Neither Boice, nor NASA did not pay enough attention to the fact that radium and other alpha emitters tend to accumulate in the bone. Since the alpha particles energies are typically ~5 MeV, they have a very short ranges, so the radiation dose would be localized to volumes near the cranium rather than being uniformly distributed throughout the cerebral and cerebellar parenchyma. We have previously reported extraordinary levels of Ra-226 in high background radiation areas of Ramsar, where people are consuming locally grown food. In this paper, we present data which provide the best human brain radiation exposure analogue for upcoming Mars missions. Normally the dose to the functional parts of the brain are not likely to be significant, even with higher uptakes of the radium or other alpha-emitting isotopes in the cranium. In this light, in this project only residents with calcium-rich diet were selected for the study. Measurements of background radiation was performed in houses, vegetable yards and gardens in areas with high levels of Ra-226 in the soil, and in a nearby control area with the same socio-economic factors. We show that exposure of human brain to high LET particles does not affect the reaction time and cognitive effects such as working memory. However, pre-exposure to gamma radiation might have played a role of adapting dose in the residents. Radio-adaptation might have made the residents resistant to subsequent detrimental effects of high LET particles. Although this hypothesis should be verified by further experiments, the same situation might occur in deep space, when astronauts' cells are pre-exposed to protons before being traversed by HZE particles.

2.1008 An Integrated Innovative 3D Radiation Protection Fabric for Advanced Spacesuits

Cody Paige (Massachusetts Institute of Technology),
Presentation: Cody Paige, Thursday, March 12th, 11:25 AM, Madison

Within the next five years NASA intends to be back on the moon and within the next decade, to have long-duration, deep-space exploration missions on Mars. Radiation doses predicted for current shielding systems exceed the allowable limits for these missions. In order to achieve these goals, we propose the novel use of nanomaterials in the development of a thermal radiation and micrometeoroid protection garment for advanced spacesuits with applications to radiation protection in space systems. Preliminary results from radiation transport modeling demonstrate the improved shielding capabilities of boron nitride nanotubes (BNNTs) over traditional space system shielding materials. Combining the novel BNNT material with Aerogels and more traditional materials such as carbon nanotubes and polyethylene, we have developed a material system which will be able to incorporate radiation shielding with thermal and micrometeoroid protection. A prototype was manufactured demonstrating the materials development capabilities and compatible applications for the proposed system.

2.11 Space Debris and Dust: The Environment, Risks, and Mitigation Concepts and Practices

Session Organizer: Kaushik Iyer (Johns Hopkins University/Applied Physics Laboratory), Douglas Mehoke (Johns Hopkins University Applied Physics Laboratory (JHU/APL)),

2.1103 Adaptive Detumbling Controller for Deorbiter CubeSat

M. Reza Emami (Luleå University of Technology), Houman Hakima (University of Toronto),
Presentation: M. Reza Emami, ,

Development of an attitude regulation controller is presented, which is utilized by a nanosatellite, called Deorbiter CubeSat, intended for the removal of sizable debris from low Earth orbit. The controller is used to detumble an uncooperative debris object to which the Deorbiter CubeSat is attached. The spacecraft performs a rendezvous maneuver, attaches rigidly to the exterior of the target debris, and detumbles and steers it toward the deorbit altitude. Three reaction wheels are used, in a mutually-orthogonal configuration, to control the attitude of the combined CubeSat and debris system. Each reaction wheel is capable of producing about 20 mN.m of torque, and has a maximum momentum capacity of 60 mN.m.s. Since physical parameters of the debris to be detumbled, e.g., mass and moment of inertia, are not known a priori, or there are large uncertainties in their values, the detumbling controller estimates the unknown parameters in order to reduce the regulation error to zero over time. Simulation results show that the controller is able to fully detumble the CubeSat-debris system in a matter of minutes, without knowing the debris physical parameters in the beginning of the maneuver.

2.1104 Efficiently Improved Guidance for Detumbling of Space Debris Using Thruster Plume Impingement

Yu Nakajima (Japan Aerospace Exploration Agency), Hiroumi Tani (Japan Aerospace Exploration Agency), Shinji Mitani (Japan Aerospace Exploration Agency), Toru Yamamoto (Japan Aerospace Exploration Agency),

Presentation: Yu Nakajima, Thursday, March 12th, 04:30 PM, Madison

This paper proposes a guidance approach for detumbling space debris using thruster plume impingement. It is difficult to capture rapidly rotating space debris. Previous studies have revealed the feasibility of reducing the rotational speed of such large debris as a rocket body or satellite. However, no study has presented concrete guidance during thruster plume impingement. This paper proposes an approach to rate damping from a e/i vector separated ellipsoidal trajectory. This trajectory is a safe trajectory with a low risk of collision in contingency cases. Moreover, it offers higher efficiency in reducing the rotational motion of a debris because the debris removal satellite flies around the debris and can inject a thruster plume from various directions. Conversely, if the debris removal satellite tries to damp the rotation from V-bar, the torque applied to the debris has strong directional sensitivity, thereby making it difficult in the worst case to damp the rotation from V-bar. Both situations were simulated and compared to verify the validity of the proposed approach. The torque and force applied to the debris were obtained by interpolating a predefined torque/force database. This database was obtained by conducting more than 900 cases of high-fidelity Computational Fluid Dynamics (CFD) simulations, changing the direction, distance, and point of thruster plume impingement. The simulation results revealed that rotation of the debris was reduced using the proposed approach. Rate damping from the e/i vector separated trajectory applied larger torque on the debris than those from V-bar. Hence, the rotation was reduced with less fuel and a shorter time. In addition, the e/i vector separated trajectory has less risk of collision with space debris even in a contingency case as compared to the V-bar hold. Thus, a safe and efficient rate damping approach to debris rotation was proposed, and will contribute to the probability of success for active debris removal missions.

2.1109 6-DoF Pose Estimation for Axisymmetric Objects Using Deep Learning with Uncertainty

Shintaro Hashimoto (Japan Aerospace Exploration Agency), Daichi Hirano (Japan Aerospace Exploration Agency), Nao Ishihama (Japan Aerospace Exploration Agency),

Presentation: Shintaro Hashimoto, Thursday, March 12th, 04:55 PM, Madison

Space debris is rapidly increasing in number. The most important thing in removing space debris is to observe the space debris with high resolution and accurately estimate its 6-DoF poses (positions and attitudes). However, when the shape of the debris is axisymmetric (such as a stage of a rocket) or when the debris is partially obscured, it is difficult to estimate its parameters. If the angle of a certain parameter is unknown, any parameter that cannot be estimated accurately affects all the parameters since each Euler angle and quaternion have a dependency, and the solution is not determined uniquely. Even if all parameters are known, there are multiple solutions with reversed signs. Therefore, this research proposed methods that make the solution and sign unique in other parameters even if direction or rotation parameters are unknown by decomposing the quaternion into a direction and rotation around the axisymmetry so that direction and rotation parameters can be estimated independently. The estimated parameters are the debris attitude of 6-DoF, which consists of the position (x, y, and z), direction (n_x, n_y, and n_z), and rotation angle (theta_z) based on the axis of the azimuthal direction. In addition, uncertainty is also calculated for each estimated parameter in order to express that a certain parameter cannot be estimated from the input image. A Bayesian neural network called MC dropout is used as a Bayesian approximation to estimate parameters from the input image. As a result, the 6-DoF pose estimation errors without uncertainty were x, y, z, n_x, n_y, n_z and theta_z were 1.65%, 1.77%, 4.31%, 3.19%, 3.20%, 4.30%, and 24.41% respectively. On the other hand, when an estimated value that has an uncertainty such that the error value exceeds 2% is deleted, the pose estimation errors were 1.25%, 1.35%, 3.76%, 2.27%, 2.64%, 3.06%, and 18.32% respectively. This research was able to adaptively improve accuracy based on a threshold of uncertainty. In addition, when we input bright and dark images to confirm the robustness, there was clearly an abnormal uncertainty value. In the case of dark images, the sensitivity of parameters x, y, and theta_z was high. In the case of bright images, the sensitivity of parameters z, n_x, n_y and n_z was high. Moreover, as a result of parameter theta_z estimating non-axisymmetric objects, the probability distribution of parameter theta_z was unimodal. On the other hand, when estimates of parameter theta_z were for axisymmetric objects, the probability distribution of parameter theta_z was bimodal or multimodal. This indicates whether the angle of the object is uniquely determined, whether there are two candidates, or whether there are more than two. From the results of these evaluations, we thought that 6-DoF pose estimation of axisymmetric objects could be applied to critical systems by using uncertainty.

2.1110 Performance of Space Debris Removal Satellite considering Total Thrust by Evolutionary Algorithm

Masahiro Kanazaki (Tokyo Metropolitan University),
Presentation: Masahiro Kanazaki, Thursday, March 12th, 09:00 PM, Madison

Space debris mitigation is a key technology for space development. It has been reported that further increasing the amount of debris could be avoided if five pieces of debris could be removed in each year. To remove multiple pieces of debris, one idea is to use one satellite to remove multiple pieces of space debris. This approach can reduce the launch cost and remove space debris efficiently, comparing with the idea using multiple satellite which can remove one piece of debris. To realize this idea, an optimization technique for the orbit transition is required. In this study, we developed a satellite trajectory optimization using an evolutionary algorithms (EAs). We applied the traveling serviceman problem (TSP) solution of an EA considering the similarity between this problem and TSP and we extended the TSP solution method to multiple objectives by coupling it with a satellite trajectory simulation. To improve the efficiency of the multiple debris removal, we considered the maximization of the total radar cross-section (RCS), which indicates the amount of space debris, as an objective function. To consider the total fuel consumption of the satellite, we considered the total velocity increment as a constraint. To evaluate the developed method, a set of 2000 pieces of space debris was selected from a database, and four cases were solved with changing the total velocity increment, 20m/s, 40m/s, 60m/s and infinity. As this result, RCS were reduced as the total velocity increments were reduced. Trends of solutions obtained through the EA process were visualized by means of the scatter plot matrix.

2.1112 Optimized Curvilinear Potential Field Based Multi-objective Satellite Collision Avoidance Maneuver

Ahmed Hamed (NARSS), Mahmoud Ashry , Ahmed Badawy (October University for Modern Sciences and Arts), Adel Omar (Military Technical College, Cairo Egypt),
Presentation: Mahmoud Ashry, Thursday, March 12th, 09:25 PM, Madison

the paper presentation will handle the principal technique beyond the paper work, including the integration between maneuver planning and genetic artificial potential field for creating a collision mitigation system.

2.12 Asteroid Detection, Characterization, Sample-Return, and Deflection

Session Organizer: Jeffery Webster (Jet Propulsion Laboratory), Paul Chodas (Jet Propulsion Laboratory),

2.1201 Using Precision Astrometry to Recover Near-Earth Object Candidates

Richard Wainscoat (University of Hawaii), Robert Weryk (University of Hawaii), Davide Farnocchia (Jet Propulsion Laboratory),
Presentation: Richard Wainscoat, Wednesday, March 11th, 04:55 PM, Dunraven

The Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) telescopes, located on Haleakala, Hawaii, spend much of their time searching the sky for Near- Earth Objects (NEOs) that may represent a hazard to Earth. The cameras on each telescope have small pixels and therefore deliver excellent astrometry. Some Near-Earth Object candi- dates that Pan-STARRS discovers are lost, because they are not recovered on subsequent nights. Over the course of the approximately 1 hour of observations when NEOs are initially discovered, many of the NEOs seen by Pan-STARRS display a small amount of non-linear motion (or curvature) in their path through the sky. This curvature arises due to the motion of the observer, and is a helpful diagnostic tool for establishing the approximate distance to the NEO and its size. At the present time, this curvature is not being fully used to tightly constrain the predicted position of the NEO one night later, and as a result, some NEOs are not recovered. A detailed study of the astrometric precision of Pan-STARRS was undertaken, using objects for which very precise orbits are known. The precision astrometry for NEOs from Pan-STARRS from a single night, and the curvature that it displays, was then used to better constrain the likely position of NEOs one night later. The predicted positions were compared to the real positions for these objects. For some objects, there was little change in the predicted position, but for four of the sample of eleven Near-Earth Objects evaluated, there was a major improvement in the predicted position. This technique will likely improve the discovery rate of all NEOs from Pan-STARRS, but with particular benefit to the smaller (nearby) NEOs.

2.1202 Neutron Energy Effects on Asteroid Deflection

Lansing Horan (Air Force Institute of Technology (AFIT)), Darren Holland (Air Force Institute of Technology),
Presentation: Lansing Horan, Wednesday, March 11th, 05:20 PM, Dunraven

This presentation inspects how energy deposition from neutrons affects asteroid deflection. This work examines how the spatial energy deposition profiles change as both the detonation distance and the neutron source energy is changed, along with the effects that profile shaping has in asteroid deflection scenarios. For studying the effects that standoff distance has on energy deposition, a detonation source is generated at standoff distances equal to 0.0001, 0.5, and 5 times the radius for a 500-meter-diameter notional silicon-dioxide asteroid target. For examining the effects that neutron energy has on generating blow-off momentum, two mono-energetic neutron sources, 14.1 MeV deuterium-tritium fusion neutrons and 1 MeV Watt-fission neutrons, were modeled at a detonation distance of 0.414 times times the asteroid radius for a 300-meter-diameter asteroid. Comparison of the resulting source-particle normalized energy deposition profiles reveals that the spatial distributions vary significantly as the neutron energies and distances change. The resulting material blow-off momentum in asteroid deflection scenarios was calculated via hydrodynamic simulations for two neutron source energies. These initial hydrodynamic results indicate that neutron energy can significantly affect overall asteroid deflection, thereby suggesting that tailored neutron spectra might be employed to enhance mitigation performance.

2.13 Orbital Robotics: On-Orbit Servicing and Active Debris Removal

Session Organizer: David Sternberg (NASA Jet Propulsion Laboratory),

2.1301 A Gecko-Like/Electrostatic Gripper for Free-Flying Perching Robots

Koki Tanaka (Illinois Institute of Technology), Matthew Spenko (Illinois Institute of Technology),
Presentation: Koki Tanaka, Monday, March 9th, 08:30 AM, Madison

This work describes the experimental evaluation of a robotic gripper's ability to perch on a variety of flat surfaces when used in conjunction with a free-flying robot in microgravity. The gripper is designed to be integrated with Astrobee, a free-flying robot deployed in the International Space Station (ISS) in April 2019. Astrobee was developed to help astronauts perform routine tasks while aboard the ISS. The robot has physical space for payloads such as a manipulator arm, which allows it to grasp grapple points such as handrails, in order to conserve energy while maintaining a given position. However, grapple points are not always readily available. As such, the goal of this work is to have Astrobee perch onto other surfaces. To enable extended perching times, the gripper described here uses a gecko-like/electrostatic adhesive coupled with a cam-actuated mechanism designed to consume little to no energy while engaged with a surface. The gecko-like adhesives allow the gripper to easily attach and detach to/from surfaces through the cam-actuation mechanism. The gripper was tested in a simulated microgravity environment where it was mounted on a platform equipped with air bearings. This work describes the gripper design and evaluates the gripper's attachment performance as a function of the platform's approach velocity and approach angle for several different target material types. The gripper perched on glass and acrylic substrates with over a 70\% success rate. For carbon fiber/epoxy laminate and Kapton sheets the success rate was approximately 50\%. The results showed a clear correlation between the approach velocity and approach angle for carbon and glass materials.

2.1302 Spacecraft Electrostatic Potential Sensing Using Fused X-ray and Electron Sensor Data

Kieran Wilson (University of Colorado Boulder), Hanspeter Schaub (University of Colorado, Boulder), Miles Bengtson (University of Colorado, Boulder),
Presentation: Kieran Wilson, Monday, March 9th, 08:55 AM, Madison

Touchless determination of electrostatic potential is an enabling technology for a wide variety of orbital robotics applications. This concept is useful for characterizing satellite surfaces during servicing missions, preventing electrostatic discharge during initial contact, and accounting for electrostatic perturbations that affect the relative motion during proximity operations. The electrostatic tractor concept proposes using these forces and torques to detumble or tow uncontrolled satellites to graveyard orbits. All of these applications require the ability to remotely sense the voltage on another spacecraft prior to any physical contact. Two methods have been proposed for remote monitoring of spacecraft electrostatic potential from a co-orbiting craft. This paper considers fusing data from both sensing methods to mitigate the limitations of each method and produce a robust estimate of the surface voltage. The methods involve observing x-ray and electron spectra emitted when energetic electrons, such as those from an electron gun, strike the surface of the target. The electron method provides a highly accurate estimate but is strongly sensitive to the relative geometry of the spacecraft which limits the times during which a usable signal is received. The x-ray method produces a less accurate estimate but is less affected by the target geometry. Experimental results demonstrate that fusing the datasets produces significant improvements in accuracy and geometrical coverage of the voltage estimate across a wide range of conditions, including a rotating target plate. These results are important for future missions which must remotely monitor the potential on a nearby object to ensure mission success.

2.1303 Development of On-orbit Assembly Demonstrator in 3U CubeSat Form Factor

Jin S. Kang (U.S. Naval Academy), John Gregory (United States Naval Academy), Michael Sanders (US Naval Academy),

Presentation: John Gregory, Monday, March 9th, 09:20 AM, Madison

This research focuses on the derivation of an autonomous control system for spacecraft assembly applications that blends Jacobian path following and visual servoing. This work proposes a hybrid approach that combines both approaches to improve the performance of a robotic manipulator in both know and unknown environments. This algorithm has been developed to be adapted by the U.S. Naval Academy's 3U CubeSat satellites that are equipped with two robotic arms with 6 DOF each. The presentation will describe the algorithm development, simulation results, and description of the CubeSat hardware that will utilize the developed algorithm.

2.1305 Experimental Evaluation of a COTS Time-of-Flight Camera as Rendezvous Sensor for Small Satellites

Markus Wilde (Florida Institute of Technology), Branden Blackwell (Florida Institute of Technology), Brian Kish (Florida Institute of Technology),

Presentation: Markus Wilde, Monday, March 9th, 09:45 AM, Madison

The paper describes an experimental study evaluating the use of a Microsoft Kinect v2 sensor as rendezvous and capture sensor. The sensor is used in a hardware-in-the-loop spacecraft maneuver simulator to detect position, velocity and attitude of an object representing a non-cooperative servicing or removal target. The paper describes the implementation of a sensor system built around the Kinect v2 sensor and the open source Open3D point cloud manipulation software. The paper then proceeds to describe the laboratory experiments run to test the performance of the system in determining the position of a chaser vehicle relative to the target object, with a twelve-camera OptiTrack system serving to establish ground truth. The tests in the controlled lab environment show that the system is readily able to measure relative position to within 0.005 m along its boresight axis at a rate on the order of 1 Hz, without any knowledge of the target geometry and without distinct reflectors or other fiducials placed on the target.

2.1309 Robotic Specialization in Autonomous Robotic Structural Assembly

Greenfield Trinh (NASA - Ames Research Center), Borbala Bernus (NASA - Ames Research Center), Olivia Formoso (NASA - Ames Research Center), Christine Gregg (NASA Ames Research Center), Kenneth Cheung (NASA - Ames Research Center),

Presentation: Greenfield Trinh, ,

Robotic in-space assembly of large space structures is a long-term NASA goal to reduce launch costs and enable larger scale missions. Recently, researchers have proposed using discrete lattice building blocks and co-designed robots to build high-performance, scalable primary structure for various on-orbit and surface applications. These robots would locomote on the lattice and work in teams to build and reconfigure building-blocks into functional structure. However, the most reliable and efficient robotic system architecture, characterized by the number of different robotic 'species' and the allocation of functionality between species, is an open question. To address this problem, we decompose the robotic building-block assembly task into functional primitives and, in simulation, study the performance of the the variety of possible resulting architectures. For a set consisting of five process types (move self, move block, move friend, align bock, fasten block), we describe a method of feature space exploration and ranking based on energy and reliability cost functions. The solution space is enumerated, filtered for unique solutions, and evaluated against energy and reliability cost functions for various simulated build sizes. We find that a 2 species system, dividing the five mentioned process types between one unit cell transport robot and one fastening robot, results in the lowest energy cost system, at some cost to reliability. This system enables fastening functionality to occupy the build front while reducing the need for that functional mass to travel back and forth from a feed station. Because the details of a robot design affect the weighting and final allocation of functionality, a sensitivity analysis was conducted to evaluate the effect of changing mass allocations on architecture performance. Future systems with additional functionalities such as repair, inspection, and others may use this process to analyze and determine alternative robot architectures.

2.1310 Multibody Simulation of REMORA CubeSat Docking to and Pushing a Spent Rocket Booster

Timothy Setterfield (Jet Propulsion Laboratory, California Institute of Technology), Ryan Mc Cormick (NASA JPL), Junggon Kim , Rudranarayan Mukherjee (Jet Propulsion Laboratory),
Presentation: David Sternberg, Monday, March 9th, 10:10 AM, Madison

This paper details the multibody simulation of three phases of critical importance to the feasibility of the REMORA CubeSat space debris mitigation concept: the final approach of the CubeSat to a spent rocket booster; the grappling of the spent rocket booster using a robotic arm; and the pushing of the spent rocket booster to divert its course from another on-orbit asset. The extension of a robotic mobility and manipulation modeling toolkit (M3TK) from multibody dynamics simulation of manipulators and ground vehicles to simulation of orbital robotics is outlined. This includes the identification of the appropriate parameters required to concisely and generically describe thruster loads, thruster mixing, spacecraft control, and spacecraft navigation for the purpose of on-orbit robotics simulation. A high-level spacecraft navigator commands maneuvers to target spacecraft states. A PID spacecraft controller takes the target states and calculates desired forces and torques. A thruster mixer solves a quadratic program to determine the optimal thruster firing times for the propulsion system. Pulse width modulated actuation of eight canted cold gas thrusters is used in the simulated approach to a rocket nozzle from a distance of 200 m. A five degree of freedom robotic arm is controlled to position a pair of pincers to grasp the rocket nozzle. Contact dynamics are used to accurately simulate the grasping of the rocket nozzle by the pincers. A similar, but separate simulation is performed to assess the ability of the REMORA CubeSat to push the large spent rocket booster. This diversion maneuver makes use of an additional, larger thruster, and pushes the rocket booster in excess of 400 m. Appropriate motor control gains on the robotic arm are found to be higher during the pushing phase than those which are appropriate during free motion; this increase promotes rigidity of the arm and allows it to properly direct the pushing force. Challenges encountered in time step selection for numerical stability of the simulation are also discussed.

2.1311 Coordinated Motion Planning for On-Orbit Satellite Inspection Using a Swarm of Small-Spacecraft

Benjamin Bernhard (University of Notre Dame), Changrak Choi (NASA Jet Propulsion Lab), Amir Rahmani (NASA Jet Propulsion Laboratory),

Presentation: Benjamin Bernhard, Monday, March 9th, 10:35 AM, Madison

This paper addresses the problem of how to plan optimal motion for a swarm of on-orbit servicing (OOS) small-spacecraft remotely inspecting a non-cooperative client spacecraft in Earth orbit. With the goal being to maximize the information gathered from the coordinated inspection, we present an integrated motion planning methodology that is a) fuel-efficient to ensure extended operation time and b) computationally-tractable to make possible on-board re-planning for improved exploration. Our method is decoupled into first offline selection of optimal orbits, followed by online coordinated attitude planning. In the orbit selection stage, we numerically evaluate the upper and lower bounds of the information gain for a discretized set of passive relative orbits (PRO). The algorithm then sequentially assigns orbits to each spacecraft using greedy heuristics. For the attitude planning stage, we propose a dynamic programming (DP) based attitude planner capable of addressing vehicle and sensor constraints such as attitude control system specifications, sensor field of view, sensing duration, and sensing angle. Finally, we validate the performance of the proposed algorithms through simulation of a design reference mission involving 3U CubeSats inspecting a satellite in low Earth orbit.

TRACK 3: ANTENNAS, RF/MICROWAVE SYSTEMS, AND PROPAGATION

Track Organizers: Farzin Manshadi (Jet Propulsion Laboratory), James Hoffman (Jet Propulsion Laboratory),

3.01 Phased Array Antenna Systems and Beamforming Technologies

Session Organizer: Janice Booth (AMRDEC Weapons Development and Integration Directorate), Glenn Hopkins (Georgia Tech Research Institute), Abbas Omar (University of Magdeburg),

3.0102 Experimental Validation of Swarm Array Results Using Mars Cube One (MarCO) Downlink Signals

Victor Vilnrotter (Jet Propulsion Laboratory),

Presentation: Victor Vilnrotter, Tuesday, March 10th, 08:30 AM, Lamar/Gibbon

In this paper, we investigate the feasibility of calibrating an orbiting phased array composed of CubeSat class spacecraft together with a larger Master spacecraft, comprising an overall Swarm Array. A coherently phased Swarm Array can potentially deliver comparable or even greater operational performance (such as increased data-rate for communications, or greater detector baseline for spatial resolution) than large monolithic spacecraft, thus increasing mission capability but with significantly enhanced flexibility, evolvability and robustness. Two CubeSats, designated as Mars Cube One (MarCO) A and B, were launched together with the InSight spacecraft on May 5th, 2018, and accompanied the InSight lander on its journey to Mars. A Swarm Array consisting of 30 MarCO class CubeSats can achieve performance comparable to Mars Reconnaisance Orbiter (MRO), and with 95 MarCO CubeSats a 10X MRO-level performance can be achieved, if phase-coherence can be maintained. Three deep-space antennas of the Madrid Deep Space Network (DSN) complex recorded downlink data from MarCO A/B simultaneously on Day-of-Year 330 of 2018, and these data were used for the

analysis reported in this paper. Six sets of complex baseband data were recorded on a wideband high-speed Radio Science recorder between 19:20 and 20:00 hours on DOY-330, and processed to determine the feasibility of phasing up the array using realistic data obtained from deep space, generated by MarCO A/B's on-board transmitters with realistic phase-noise and trajectory dynamics embedded in the received signals. Using three of the Madrid antennas (located several hundred meters apart) as proxies for three elements of a Swarm Array, and the downlink signals from MarCO A/B to simulate the phase reference distributed by the Master spacecraft, it was shown that accurate phase-calibration and phase-trajectory predicts can be obtained in a few seconds and used to maintain phase-coherence for the four elements (three CubeSats plus the Master spacecraft) of a simulated Swarm Array, for ten minute intervals. This suggests that frequent re-calibration will not be necessary, when the orbital dynamics are well known and a highly accurate reference-signal is available from the ground. However, the analysis also showed that similar array gains can be achieved even when the oscillator of the Master spacecraft is free-running, as in one-way mode, transmitting a noisy phase-reference to the Swarm Array elements. In this case the combined transmitted array phase will be noisier than in two-way mode, hence a wider loop-bandwidth will be required at the ground-station to track the received Swarm Array signal, potentially resulting in some radio loss. However, the array gain on received power will not be impacted even when a free-running Master oscillator is employed.

3.0103 Constructive Precoder Design for Single Beam Multiuser Satellite System with PSK Signals Signals

Yanwu Ding (WSU), Khanh Pham (Air Force Research Laboratory),
Presentation: Yanwu Ding, Tuesday, March 10th, 08:55 AM, Lamar/Gibbon

In satellite downlink communications, multiuser interference degrades performance of the system. The received signal at each user contains its own desired signal and the interference from other users. In general, the interference is often removed for the users in precoder designs. In this paper, we examine the interference for each user, and design a precoder so that the interference can contribute constructively to the desired detection zone at the receiver for each user. For the phase shift keying (PSK) transmit symbols, the design seeks to minimize transmit power while satisfying Given the QoS. Simulations on the transmission power versus the number of users and the received noise are carried out to verify the proposed scheme.

3.03 RF/Microwave Systems

Session Organizer: James Hoffman (Jet Propulsion Laboratory),

3.0301 Design of a GaN HEMT High Efficiency High Power Frequency Tripler Using a Class-F Technique

Fei Wang , Christopher Clark (The Aerospace Corporation), Donovan Le ,
Presentation: Fei Wang, Tuesday, March 10th, 09:20 AM, Lamar/Gibbon

The properties of Gallium Nitride HEMT technology allow for higher performance spacecraft RF payloads with lower size, weight and power. In this paper, we present a high efficiency, high output power, low phase noise class-F frequency tripler utilizing a GaN HEMT device. This frequency tripler converts a 750MHz input frequency into a 2.25 GHz output frequency. This paper applies the class-F design technique, conventionally used for high efficiency power amplifiers, to the design of frequency multipliers. An active harmonic load-pull system was built and utilized to explore the desirable harmonic load impedances presented to the GaN HEMT device, to achieve class-F operation for optimal RF/DC power efficiency. The results obtained from active load-pull tests show that the load network of the tripler should aim to achieve impedance match for the 3rd harmonic, while simultaneously maintaining an open for other odd harmonics and a short for even harmonics. Consequently, the drain voltage waveform is shaped as a square wave, and the drain current waveform is shaped as a half-sine wave at the 3rd harmonic. Based on the class-F harmonic tuning approach described above, a class-F frequency tripler was fabricated using a Cree CGH40006 GaN HEMT. Hardware measurements demonstrate that the tripler features a PAE of 23%, an unprecedented output power of 29.4 dBm, and a conversion gain of 8.1 dB. The designed tripler provides a minimum harmonic rejection of 7.3 dB at the fundamental frequency. The rejection at the higher order harmonics were all larger than 30dB. In addition, residual phase noise was measured to be less than –146 dBc/Hz at 10KHz.

3.04 Radio Astronomy and Radio Science

Session Organizer: Melissa Soriano (Jet Propulsion Laboratory), Mark Bentum (Eindhoven University of Technology),

3.0401 Feasibility Study on Inflatable Observational Antennas for CubeSat Applications

Cornelis Vertegaal (Eindhoven University of Technology), Mark Bentum (Eindhoven University of Technology),

Presentation: Cornelis Vertegaal, Tuesday, March 10th, 09:45 AM, Lamar/Gibbon

One of the many mysteries are the Dark Ages. It is expected that emissions from the hydrogen atoms originating from the Dark Ages have a frequency between 80 kHz and 30 MHz. Study towards these unknown times can't be done using the radio telescopes on Earth as our ionosphere distorts and blocks frequencies below 30 and 10 MHz respectively. That's why we need to design radio telescopes for use in space. By launching tens or even hundreds of small radio telescopes into space, it is possible to generate one large virtual dish using interferometry. However, how can we pack a large sensitive antenna into a box the size of a CubeSat? One solution is the use of Inflatable Antennas. In this presentation I will present a feasibility study regarding inflatable antennas. These antennas will be used as observational antennas and are designed for ultra-low frequency CubeSat applications. The novelty of the research is the use of active antenna elements on the thin film. The focus is mostly on inflation, rigidization, folding and the selection of material. Next, an antenna comparison is done on different designs and a scale model using generic cost-effective PCB material is shown which will be further investigated and tested.

3.05 Miniaturized RF/Microwave Technologies Enabling Small Satellite and UAV Systems

Session Organizer: Dimitris Anagnostou (Heriot Watt University), James Lyke (Space Vehicles Directorate),

3.0501 Miniaturized and Reconfigurable RF Electronics Architecture for SmallSat Applications

Fernando Aguirre (Radial Space),

Presentation: Fernando Aguirre, Tuesday, March 10th, 10:10 AM, Lamar/Gibbon

In order to meet the demanding needs of SmallSat cost and schedule constraints, a standardized process for complex SmallSat RF module designs has been developed. This need is addressed on two fronts, with the first being an integrated design process allowing for a reduction in design iterations and the second with the adaptation of a modular architectural approach. The design process to be presented will outline how the number of design iterations has been successfully reduced compared with those encountered in typical space application RF assembly designs. The architectural standardization approach will be presented in two parts, the first being at the prototype RF functional building block phase and the second at the engineering and flight model phase. A prototype Ka-band up and down converter example which is going through the standardized design process will be presented and will include both data and hardware photos.

3.0502 Compact Folded-Shorted Patch Antenna Array with PCB Implementation for Modern Small Satellite

Dimitris Anagnostou (Heriot Watt University), Symon Podilchak (The University of Edinburgh), YUEPEI LI (Heriot Watt University),

Presentation: Dimitris Anagnostou, Tuesday, March 10th, 10:35 AM, Lamar/Gibbon

A metohdology for highly miniaturized compact circularly polarized (CP) antenna arrays is presented. The presentation will include one design that uses folded-shorted patches (FSPs) on printed circuit board (PCB) technology for antenna miniaturization. The second design employes further miniaturization by meandering the top patch layer. Additional miniaturization is achieved by loading the top patch layer with a dielectric substrate. The antenna dimensions are in the order of λ/5 or less. The presented techniques lead to highly compact antennas that can fit on a side of a CubeSat and of a Pico-satellite.

3.0503 Inflatable Membrane Antennas for Small Satellites

Aman Chandra (Arizona State University), Christopher Walker (University of Arizona),

Presentation: Aman Chandra, Tuesday, March 10th, 11:00 AM, Lamar/Gibbon

Small satellites such as nano-satellites or CubeSats have seen increased interest as low cost platforms to access space. With advancements in commercial off the shelf (COTS) electronics, CubeSats have been growing in capability and are being considered for more challenging mission objectives. A significant challenge towards this advancement is limited data downlink rates available from CubeSat communication systems. This is due to volume and mass constraints imposed by CubeSat refence standards. The size of the platform also places constraints on the power system onboard. To maintain high transmit data-rates from CubeSats, high gain antennas (HGA) have emerged as a key technology. Conventional HGA technology for small satellites are restricted to reflect-arrays and mechanical linkage systems. Such systems do not package very efficiently into available payload volumes on CubeSats. Further, the complexity of the deployment mechanism introduces multiple points of potential failure. Hence such systems are not easily scalable to larger sizes needed for greater capability. FreeFall Aerospace along with the University of Arizona is focusing on the development of inflatable spherical antenna systems for small satellites. These systems are comprised of membrane spheres with a partially reflective surface inflated pneumatically from sizes ranging from half to 2 meters. The metallized portion of the sphere serves as a spherical reflector which, together with a custom line feed, forms a high gain, electronically steerable antenna system. This approach is unique in its ability to potentially provide the missing link in creating high bandwidth telecom systems for CubeSats. In the present work, we describe our development of deployment and packaging systems for inflatable antennas from CubeSats ranging in size from 6U and above. The focus of our approach has been on mechanical simplicity of deployment and scalability over a range of antenna sizes. The inflation system has been designed to prevent over-pressurization of the membrane. Packaging of the membrane has been tested with multiple folding patterns aimed at maximizing packing efficiency and minimizing wrinkles on the membrane's reflective surface. We present thermo-structural analysis of the inflated membrane's mode shapes in expected thermal environments for multiple deployment load cases. Results of packaging and deployment tests done in thermal vacuum environments cycled over expected temperatures in the Low Earth Orbit are presented which lead to an understanding of sensitive design variables. Reliability studies have

been conducted to understand the system's response to environmental factors such as micro-meteoroid damage, UV and oxidative degradation. Our work presents a mechanically simple membrane antenna system that can be scaled over varying small satellite sizes as a high gain, high bandwidth tele-communication system.

3.0505 Integrated GaN Power Switches for Pulsed PAs and Switching Power Converter Applications

Aaron Pereira (University of Adelaide), Said Al-Sarawi (The University of Adelaide), Derek Abbott (University of Adelaide), Neil Weste (University of Adelaide),
Presentation: Aaron Pereira, ,

In this paper we present a description and evaluation of commercial foundry Gallium Nitride RF HEMTs as power switches in high frequency switching circuits. The switches are used within the multi-functional blocks for a system-on-chip of the front-end of a pulsed VHF radar. The GaN power switches are evaluated in a voltage mode class-D (VMCD) RF amplifier and as a DC-DC converter. The power switches and its associated drivers are designed in a 0.25 µm commercially available RF GaN process technology. The efficiency of the circuit when evaluated as a Class D Power Amplifier is 74.5% at 250 MHz and delivers an output power of 39.5 dBm. The measured DC-DC converter circuit has an efficiency of over 92.4% at 100 MHz, delivering 40.8 dBm. These are the highest reported efficiencies for the RF PA and the switching modulator at its respective operating frequencies.

TRACK 4: COMMUNICATION & NAVIGATION SYSTEMS & TECHNOLOGIES

Track Organizers: Phil Dafesh (Aerospace Corporation), Shirley Tseng (Tseng LLC),

4.01 Evolving Space Communication Architectures

Session Organizer: Shervin Shambayati (Aerospace Corporation),

4.0101 Concept for a Distributed, Modular, In-space Robotically Assembled, Hosted RF Communication Payload

Spencer Backus (NASA Jet Propulsion Lab), William Walsh , Timothy Setterfield (Jet Propulsion Laboratory, California Institute of Technology), Brendan Chamberlain Simon (Jet Propulsion Laboratory), Rudranarayan Mukherjee (Jet Propulsion Laboratory),
Presentation: Spencer Backus, Sunday, March 8th, 04:30 PM, Amphitheatre

We present a concept for a Radio Frequency (RF) Ka band communications payload that is robotically assembled and serviced in space using a servicing vehicle such as the Robotic Servicing of Geosynchronous Satellites (RSGS) vehicle being developed by DARPA. Our work focuses on how to modularize a representative Ka band communications payload into discrete modules that are hosted on a persistent platform. In our concept, each module consists of a primary aperture and the associated RF and electronics required to serve a particular coverage area or type. These modules are notionally packaged in a form factor capable of launching as a secondary payload via an EELV Secondary Payload Adapter (ESPA) ring or a Payload Orbital Delivery System (PODS) module. The overall payload consists of an earth coverage module, regional coverage modules, high gain regional coverage modules, and a host interface unit (HIU). We discuss the notional capabilities and requirements of each module. We present two different architecture concepts corresponding to two different persistent platform concepts. In one concept, the persistent platform is made up of small, independent spacecraft that are connected together with structural members with communication channels. The payload modules are hosted on the individual spacecraft. In the second approach, the platform consists of a large central spacecraft with a structural truss that has power, communication and thermal loops. The payload modules are hosted on the truss through standard interfaces. We present aspects of the mission concept on how the payload may be modularized, launched (as secondary launch elements), acquired by the RSGS vehicle in space and assembled on to the persistent platform. We discuss the robotics aspects of assembly and servicing of the payload modules. A key aspect of this concept is the serviceability of the payload. Central to the modular and discrete payload design is an intent to refurbish the payload incrementally as technology evolves or the components fail. Existing geosynchronous communication satellites are designed and built as monolithic spacecraft which makes any servicing beyond refueling fairly complicated. This makes it hard to take advantage of the post launch evolution in technology, particularly in the electronics elements. Our concept is aimed at modularizing the payload such that the modules, particularly the electronics elements, can be easily serviced using the RSGS vehicle. Our concept attempts to take advantage of the long service life of high reliability system components in the core satellite bus while allowing rapid expansion and upgrading of the communications payload through the addition and replacement of individual payload modules.

4.0102 An Architecture for Advanced Networking Technology for Integrating Communications in Space

Brian Haberman (Johns Hopkins University/Applied Physics Laboratory), Edward Birrane , David Copeland (Johns Hopkins University/Applied Physics Laboratory), Philip Chimento (Johns Hopkins University/Applied Physics Laboratory),

Presentation: Brian Haberman, Sunday, March 8th, 04:55 PM, Amphitheatre

In the current model of space missions, the communications system can account for a significant percentage of the overall cost (2-7%). Many times, an entire communications system is developed for each new mission. The Advanced Networking Technology for Integrating Communications in Space project is focused on the development of a commodity communications capability that will allow new space missions to significantly reduce costs and provide a more robust ground infrastructure to support those missions. This paper describes a new architecture for ground-to-space communications based on the Long-Term Evolution (LTE) protocol suite that forms the primary basis for terrestrial cellular communications. By leap-frogging the state-of-the-art for space communications, this approach puts a more robust evolution path for space communications in place and provides space missions with a flexible, IP-based infrastructure capable of supporting a wide variety of applications. This paper provides the requirements & concepts of operation for space communications with LTE, an overarching architecture to utilize LTE in space mission communication systems, and the potential novel applications that are enabled by moving space communications towards the commercially successful LTE protocol suite.

4.0103 Feasibility of Weak GPS Real-Time Positioning/Timing at Lunar Distance

Kar Ming Cheung (Jet Propulsion Laboratory), Charles Lee (Jet Propulsion Laboratory),

Presentation: Kar Ming Cheung, Sunday, March 8th, 09:50 PM, Amphitheatre

There are multiple Global Navigation Satellite Systems (GNSS's), comprising over 100 navigation satellites in the Earth's medium and high orbits. Most of these satellites have antennas that point nadir to earth, and transmit navigation signals so vehicles on Earth's surface and in its vicinity can perform trilateration and estimate its 3-dimenional (3D) positioning. The sidelobes of these antennas can occasionally point to the Moon. It is postulated that a lunar vehicle carrying a large enough receiving antenna can occasion-

ally detects and receives four or more sidelobes of these weak GNSS signals, thus enabling the vehicle to perform 3D positioning using an onboard GNSS receiver. We propagate the orbits of the GNSS satellites from United States' Global Positioning Satellite (GPS) constellation, the Europe's Galileo constellation, and the Russia's GLONASS constellation, to a total of 81 satellites. We simulate the visibility of these satellites by a lunar vehicle in a Near Rectilinear Halo Orbit (NRHO), based on the assumption that the lunar vehicle is "in-view" of a GNSS satellite as long as it falls within the 40-degree beam width of the satellite. We also simulate the 3D positioning performance as a function of satellites' ephemeris errors and pseudo-range errors. The preliminary results show that the lunar vehicle can "see" 5 – 13 satellites, and achieve a 3D positioning error (one-sigma) of 200 – 300 meters based on reasonable ephemeris and pseudo-range error assumptions. We also consider the case of using relative positioning to mitigate the GNSS satellites' ephemeris biases; that is, we assume a reference receiver with accurately known positioning that is close to the lunar vehicle and then compute the relative position of the lunar vehicle with respect to the reference.

4.0105 Space and the Internet of Things

Barbara Braun ,

Presentation: Barbara Braun, Sunday, March 8th, 09:00 PM, Amphitheatre

The "Internet of Things" (IOT) revolution was based on the idea that common devices – such as light bulbs, thermostats, and household appliances – could be networked together using Internet Protocol (IP), eliminating dedicated connections and facilitating the "smart" use of devices and data. Whether or not one wants a light bulb that is controllable from a mobile phone, such features are easy to implement when networking is ubiquitous, and access is easy. The Internet of Things has proved so convenient and successful that even critical equipment such as medical devices and automobiles now routinely connect to the Internet. The convenience offered by the Internet of Things, however, comes with risk. The history of the Internet of Things is full of cautionary tales about what happens when devices previously connected by proprietary means (or not connected at all) suddenly become Internet accessible. IOT devices tend to follow a predictable path where the desire for quick and easy access leads to security issues that result in equally quick and easy exploitation, before more stringent security is implemented in a reactionary fashion. The same may soon become true for space. Many providers are developing space-based constellations to provide terrestrial Internet services [1]. Like the Global Positioning System, which was originally developed for ground use, but which is now used extensively for space-based navigation and timing, one can imagine these constellations ultimately providing an Internet-like service for satellites in space. Using a generic IP-based infrastructure could streamline communication and licensing and eliminate the need for specific ground hardware for each mission. In fact, some telecommunications companies already offer the equivalent of mobile phone towers in space [2,3], and some researchers are already foreseeing near-space and interplanetary data networks designed to ease data flow to the ground. [4] As it did for the Internet of Things, however, this opportunity comes with security risks. The good news is that the space industry can learn from the "lessons in blood" already experienced by the terrestrial Internet of Things. This paper will discuss the history of security in the Internet of Things and the typical path of new IOT devices. It will describe the analogies between terrestrial and space networking, and the potential for satellites – especially small satellites and CubeSats – to become the newest members of the Internet of Things. It will describe the steps needed to avoid the pitfalls of previous smart devices, from light bulbs to medical devices to automobiles, and reap the full benefits of Internet in space.

4.0106 Universal COTS Based SpaceVPX Payload Carrier for LEO Application

Michał Kuklewski (Warsaw University of Technology), Stanisław Hanasz (Warsaw University of Technology), Grzegorz Kasprowicz (Warsaw University of Technology), Marcin Bieda (Creotech Instruments),
Presentation: Michał Kuklewski, Sunday, March 8th, 09:25 PM, Amphitheatre

This paper presents a concept of the universal COTS based Payload Carrier for new microsatellite platform design in compliance with SpaceVPX (VITA78.0) standard. The card functionality can be extended by VITA 57.1 FMC Mezzanine cards and therefore cover wide spectrum of applications, which can be prototyped on off-the-shelf FMC evaluation boards. Selected assumptions of the design, which originate from minimum 2-year mission on LEO orbit and SpaceVPX standard, are described at the beginning. Further, they are followed by detailed description of selected components and proposed software required for reliable operation in space environment. Finally, example applications such as communication data link layer processor implemented according to CCSDS standard, DSP processor for Software-Defined-Radio and interface for dedicated payload computer are described.

4.0107 Concept of an Enhanced Accuracy Onboard Time Synchronization via Communication Link.

Stanisław Hanasz (Warsaw University of Technology), Michał Kuklewski (Warsaw University of Technology), Grzegorz Kasprowicz (Warsaw University of Technology), Konrad Traczyk , Marcin Bieda (Creotech Instruments),
Presentation: Stanisław Hanasz, Sunday, March 8th, 05:20 PM, Amphitheatre

The following paper describes the concept of an onboard time synchronization method for small satellites, as presented in the case of the Hypersat microsatellite platform. Although nowadays GPS receivers are a popular source of accurate time reference for Low Earth Orbit satellites, in our application an on-board Temperature Compensated Cristal Oscillator with RF-link based synchronization is also foreseen. A comparison of selected time synchronization methods is followed by considerations about their use in this application. A chosen method of time synchronization is analyzed step-by-step and expected sources of errors are highlighted. Finally, the planned development and accuracy verification method is proposed.

4.02 Communication Protocols and Services for Space Networks

Session Organizer: Shervin Shambayati (Aerospace Corporation),

4.0201 Utilizing Reinforcement Learning to Autonomously Manage Buffers in a Delay Tolerant Network Node

Marc Sanchez Net (Jet Propulsion Laboratory),
Presentation: Elizabeth Harkavy, Monday, March 9th, 08:30 AM, Amphitheatre

In order to effectively communicate with Earth from deep space there is a need for network automation similar to that of the Internet. The existing automated network protocols, such as TCP and IP, cannot work in deep space due to the assumptions under which they were designed. Specifically, protocols assume the existence of an end-to-end path between the source and destination for the entirety of a communication session and the path being traversable in a negligible amount of time. In contrast, a Delay Tolerant Network is a set of protocols that allows networking in environments where links suffer from high-delay or disruptions (e.g. Deep Space). These protocols rely on different assumptions such as time synchronization and suitable memory allocation.
In this paper, we consider the problem of autonomously avoiding memory overflows in a Delay Tolerant Node. To that end, we propose using Reinforcement Learning to automate buffer management given that we can easily measure the relative rates of

data coming in and out of the DTN node. In the case of detecting overflow, we let the autonomous agent choose between three actions: slowing down the client, requesting more resources from the Deep Space Network, or selectively dropping packets once the buffer nears capacity. Furthermore, we show that all of these actions can be realistically implemented in real-life operations given current and planned capabilities of Delay Tolerant Networking and the Deep Space Network. Similarly, we also show that using Reinforcement Learning for this problem is well suited to this application due to the number of possible states and variables, as well as the fact that large distances between deep space spacecraft and Earth prevent human-in-theloop intervention.

4.0203 Efficient and Secure Autonomous Communications for Deep Space Missions

Mehmet Adalier (Antara Teknik LLC),

Presentation: Mehmet Adalier, Monday, March 9th, 08:55 AM, Amphitheatre

For complex missions that are away from Earth's resources, there is an unmet need for more autonomous operations with minimal Earth contact. The presentation describes taraCoAP, an adaptation of the terrestrial IETF standard Constrained Application Protocol (CoAP) over the Bundle Protocol. taraCoAP, with its innovative Cyber-Physical Autonomous Asset Observation and Management extension, provides an efficient and secure RESTful delay and disruption tolerant communication framework. taraCoAP, currently at TRL-6, has been successfully tested with Jet Propulsion Lab's latest Interplanetary Overlay Network (ION) delay tolerant networking (DTN) solution. The presentation also covers Antara's Deep Space Autonomous Exploration DTN Simulator that utilizes taraCoAP Services to initiate and observe autonomous operations in deep space. Additionally, a case study in a relevant environment is presented where a cluster of satellites autonomously collaborate to form a large telescope aperture in deep space. The successful deployment of missions utilizing taraCoAP Services will enable various types of space vehicles to securely and efficiently communicate with other space vehicles independently and make possible entirely new classes of missions.

4.0204 A Blockchain-based Reputation System for Small Satellite Relay Networks

Lillian Clark (University of Southern California),

Presentation: Lillian Clark, Monday, March 9th, 09:20 AM, Amphitheatre

Space communications networks are attempting to move away from large geostationary (GEO) satellites towards large constellations of small satellites. This trend is observed both in government and commercial communications satellites. By relaying data across multiple constellations/networks, we may be able to reduce end-to-end latencies and reduce burden (mass, power, cost) for all users. However, this is only possible if networks across constellations can establish inter-satellite authentication and trust. The key to this trust is based on demonstrated ability of the relay satellites to meet performance requirements, i.e. ``reputation." In this work, we propose leveraging distributed ledger technologies (i.e. blockchains) to develop a secure, decentralized reputation system for satellite relay networks. This informs a reputation-aware routing protocol and reduces the average data latency across the network. In this presentation, we discuss designing the blockchain-based reputation system and routing protocol. We then analyze the resultant network performance with respect to average latency, computational complexity, and storage considerations for a variety of use cases.

4.03 Navigation and Communication Systems for Exploration

Session Organizer: David Copeland (Johns Hopkins University/Applied Physics Laboratory),
Patrick Stadter (Johns Hopkins University/Applied Physics Laboratory),

4.0301 Autonomous Navigation for Crewed Lunar Missions with DBAN

William Jun (Georgia Institute of Technology), Kar Ming Cheung (Jet Propulsion Laboratory), Julia Milton (Massachusetts Institute of Technology), Edgar Lightsey (Georgia Institute of Technology), Charles Lee (Jet Propulsion Laboratory),

Presentation: William Jun, Monday, March 9th, 09:45 AM, Amphitheatre

With the recent push for a crewed Lunar mission to descend, land, and ascend from the Moon, there is a need for real-time position, velocity, and attitude knowledge of a Lunar spacecraft. This presentation extends the previously published relative Doppler-based positioning scheme (Law of Cosines – LOC) and an absolute Doppler-based scheme (Conic Doppler Localization – CDL) with the aid of range measurements, an inertial measurement unit (IMU), and a star tracker to create the Doppler Based Autonomous Navigation (DBAN) architecture. DBAN allows for real-time, autonomous positioning with only a few Lunar orbiters and a reference station on the surface of the Moon. In this analysis, the Lunar Gateway and the Lunar Relay Satellite (LRS) were used with a pre-existing reference station located on the south pole of the Moon to localize a user during orbit, descent, and landing. Satellite ephemeris, velocity, and external and internal measurement errors were modeled as Gaussian variables and embedded in Monte Carlo simulations to increase fidelity. An Extended Kalman Filter (EKF) was used due to the non-linear effects during intervals of high user dynamics. Ultimately, the DBAN architecture can provide real-time position, velocity, and attitude knowledge with a minimal navigation infrastructure. DBAN can enable autonomous navigation for future crewed and uncrewed missions on other planets.

4.0303 Use of Navigation Beacons to Support Lunar Vehicle Operations

Evan Anzalone (NASA), Anand Iyer (NASA), Tamara Statham (NASA Marshall Space Flight Center),

Presentation: Evan Anzalone, Monday, March 9th, 10:10 AM, Amphitheatre

To support a wide variety of lunar missions in a condensed regime, solutions are needed outside of the use of Earth-based orbit determination. This research presents an alternate approach to in-situ navigation through the use of beacons, similar to that used on Earth as well as under technology development efforts. An overview of the current state of navigation aids included as well as discussion of the Lunar Node – 1 payload being built at NASA/Marshall Space Flight Center. Expected navigation results of this beacon payload for planned operation from the lunar surface are provided. Applications of navigation beacons to multiple stages of the proposed human lunar landing architecture are given, with initial analysis showing performance gains from the use of this technology. This work provides a starting point for continued analysis and design, laying out the foundation of how navigation beacons can be incorporated into the architecture to enable continued analysis, design, and future expanded capability.

4.0304 Quantifying Weather Effects on Ka-Band Communication Links: A Parker Solar Probe Study

Romina Nikoukar (Johns Hopkins University/Applied Physics Laboratory), David Copeland (Johns Hopkins University/Applied Physics Laboratory), Sean Sprouse (Johns Hopkins University/Applied Physics Laboratory), Matthew Cox (Johns Hopkins University/Applied Physics Laboratory), Katelyn Kufahl (Johns Hopkins University Applied Physics Laboratory),

Presentation: Matthew Cox, Monday, March 9th, 10:35 AM, Amphitheatre

A Ka-band communication channel provides a high capacity link critical for deep space science data downlink. However, data transmissions over Ka-band are highly susceptible to weather conditions (such as wind, clouds, water vapor, etc.). In this work, we conduct a comprehensive statistical analysis based on the first year of Parker Solar Probe measurements to quantify weather effects on a Ka-band science data downlink.

To this end, we compare the results of link models using Deep Space Network (DSN) aggregate annual and monthly statistics, and annual International Telecommunication Union (ITU) standards. Our results show a general agreement between monthly DSN and ITU models with a superior performance over annual DSN statistics. The Ka-band link models can match the observed carrier power to approximately 1 dB. However, the link models in general under-estimate the symbol signal to noise ratio (SSNR). Furthermore, using ITU standards, we examined the use of local weather parameters such as mean air temperature, humidity, and barometric pressure to model atmospheric gaseous attenuation. We find an excellent agreement between the measured and modeled system noise temperature (SNT) based on atmospheric attenuation due to gas for clear days. For cloudy days, one needs to account for cloud contribution to atmospheric attenuation using total columnar content of liquid water. In terms of mission operations, the results of our statistical analyses provide the first steps toward ingesting short-term weather predictions into the link models which will allow for an increased data rates during tracks with favorable weather forecasts, and will ultimately enhance the overall data return of science data with little increase in the percentage of dropped frames.

4.04 Relay Communications for Space Exploration

Session Organizer: Charles Edwards (Jet Propulsion Laboratory), David Israel (NASA - Goddard Space Flight Center),

4.0406 LunaNet: A Flexible and Extensible Lunar Exploration Communication and Navigation Infrastructure

David Israel (NASA - Goddard Space Flight Center), Kendall Mauldin (NASA GSFC), Christopher Roberts (National Aeronautics and Space Administration), Jason Mitchell (NASA - Goddard Space Flight Center), Lavida Cooper (NASA - Goddard Space Flight Center), Michael Johnson (NASA Goddard Space Flight Center), Steven Christe (NASA -Goddard Space Flight Center), Cheryl Gramling (US Government - NASA),

Presentation: David Israel, Monday, March 9th, 11:00 AM, Amphitheatre

NASA has set the ambitious goal of establishing a sustainable human presence on the Moon. Diverse commercial and international partners are engaged in this effort to catalyze scientific discovery, lunar resource utilization and economic development on both the Earth and at the Moon. Lunar development will serve as a critical proving ground for deeper exploration into the solar system. Space communications and navigation infrastructure will play an integral part in realizing this goal. This paper provides a high-level description of an extensible and scalable lunar communications and navigation architecture, known as LunaNet. LunaNet is a services network to enable lunar operations. Three LunaNet service types are defined: networking services, position, navigation and timing services, and science utilization services. The LunaNet architecture encompasses a wide variety of topology implementations, including surface and orbiting provider nodes. In this paper several systems engineering considerations within the service architecture are highlighted. Additionally, several alternative LunaNet instantiations are presented. Extensibility of the LunaNet architecture to the solar system internet is discussed.

4.0408 Communications with Curiosity during Solar Conjunction

Jackson Quade , Aseel Anabtawi (NASA Jet Propulsion Lab),

Presentation: Jackson Quade, Monday, March 9th, 11:25 AM, Amphitheatre

This presentation will step through the paper as-written -- first discussing solar conjunction's place in Mars Rover operations, and exploring current and future methods of communicating with Curiosity during this period of disrupted telecommunications.

4.0409 Simultaneous Optical Links with the Inter-Satellite Omnidirectional Optical Communicator

Alexa Aguilar (Jet Propulsion Laboratory), Jose Velazco (Jet Propulsion Laboratory), Kerri Cahoy (Massachusetts Institute of Technology),

Presentation: Alexa Aguilar, Monday, March 9th, 11:50 AM, Amphitheatre

As the onboard data volume for smaller platforms such as CubeSats increases, Radio Frequency (RF) communications systems may be unable to adequately support the required downlink demand. Optical communications systems (lasercom) can relieve the data bottleneck as they can support higher data throughput than RF for comparable Size, Weight, and Power (SWaP). Lasercom crosslinks are of particular interest for spacecraft swarms and constellations because they enable additional mission robustness for distributed science observations and remote sensing applications. The Inter-Satellite Omnidirectional optical Communicator (ISOC) is capable of supporting simultaneous lasercom crosslinks between multiple spacecraft at separations of up to thousands of kilometers in orbit. The ISOC architecture features a truncated dodecahedron chassis containing an array of photodetectors and gimbal-less MEMS mirrors, enabling full-duplex communications. The main objectives of the ISOC terminal include: 1) full sky coverage, 2) Gbps data rates, and 3) the ability to maintain multiple simultaneous links. We show ISOC can support up to 12 simultaneous links with the current architecture at 1 Gbps at 200 km separation with 10-9 BER. Compared to current lasercom transceivers (i.e., point-to-point), ISOC offers increased throughput performance for similar SWaP. A detailed link budget for both scenarios is presented, and the limiting factors for maximum number of simultaneous links are discussed.

4.06 Innovative Space Communications and Tracking Techniques

Session Organizer: Kar Ming Cheung (Jet Propulsion Laboratory), Alessandra Babuscia (NASA Jet Propulsion Laboratory),

4.0601 A Real-time Doppler Compensating Physical/data Link Layer Protocol for Satellite Communications.

Edwin Peters , Craig Benson (UNSW),

Presentation: Edwin Peters, Monday, March 9th, 04:30 PM, Amphitheatre

We propose a combined physical/data link layer protocol for satellite communications that contains markers which allow for real-time Doppler synchronization on the satellite. Traditionally, the communication protocols on many cube- and nano satellites utilize data link layer protocols such as AX.25 or CC11XX, which also are widely used in ground based communication networks. Ground based protocols, such as AX.25 and CC11XX utilize a synchronization sequence at the beginning of the packet for the demodulator to achieve carrier and symbol synchronization. This is sufficient for stationary or slow moving transceivers. However for satellite communications, the Doppler frequency is time-varying and can be in the excess of 100's of kHz. Most conventional spacecraft radios can not reliably obtain frequency synchronization with these frequency offsets. To mitigate this, the transmission from the ground is Doppler pre-compensated based on apriori information on the satellites trajectory. However in situations such as launch and early operations, for tactical users or for inter-satellite communications, this apriori information might be inaccurate or unavailable. To mitigate this, we propose a combined physical/data link layer protocol, that spreads markers across the entire packet. These markers allow for online Doppler estimation and correction directly on the satellite. The proposed packet structure features a 48 bit synchronization marker at the beginning of the packet. This synchronization marker consists of four 8 bit markers, spaced such that the hamming distance to a nearest match is large. The phase rotation between these four markers can be used to perform a course Doppler correction. Addi-

tionally, there are 8 bit markers placed at regular intervals throughout the entire packet. These are utilized to perform a fine Doppler compensation. The proposed system is robust and can maintain synchronization when the Doppler is time-varying. The current implementation has 64 bits of data between each marker, and can be received on low power, limited capacity receivers in real time. The proposed protocol includes a double forward error correction (FEC) scheme. The inner level FEC is applied individually inside each 64 bit block and can correct two out of 15 symbols using a (n=15, k=11, m=4) Reed Solomon scheme. If the FEC on a block fails, the entire block can be marked as an erasure. The high level FEC, currently implemented as a (n=255,k=223,m=8) Reed Solomon coder, can correct up to 32 bytes marked as erasures or up to 16 bytes as errors per packet, where we currently transfer 1kb of data with a 80 bit header in a packet of 2280 raw bits (including synchronization). The proposed protocol is suitable for implementation in FPGAs and in software defined radio on personal computers. We currently have an early version of the protocol implemented on a FPGA that is running a raw data rate of 100 kbps on S-band. The protocol is currently in the process of being implemented on a cube satellite that will be launched in the near future.

4.0602 Carrier-Phase Aided Pseudo-Noise Range Estimator Operating at RF Frequencies

Victor Vilnrotter (Jet Propulsion Laboratory),
Presentation: Victor Vilnrotter, Monday, March 9th, 04:55 PM, Amphitheatre

There is renewed interest in cislunar space exploration, including both robotic and human space missions in the near future. However, current CCSDS ranging standards do not include proximity links or spacecraft-to-spacecraft scenarios that will be required by future missions to the Moon and beyond. For example, the current CCSDS Pseudo-noise (PN) ranging standard assumes that a terrestrial ground station always defines one end of the link, achieving roughly one meter ranging accuracy under nominal conditions. However, spacecraft situational awareness and demanding docking operations require cm-level accuracy, far beyond the capabilities of current Earth-based PN-code based ranging techniques. The idea of using carrier phase in addition to PN code-phase to estimate range, operating at optical wavelengths and employing coherent optical detection, has been described and evaluated in several recent publications. In this paper, we translate this concept to RF carriers suitable for near-earth, lunar and deep-space applications, describe the modulation and detection algorithms, and evaluate ranging performance of the Carrier-Phase Aided PN Range Estimator via MATLAB simulations and Cramer-Rao bounds on range estimator performance. The simulation model assumes S-band (~2200 MHz) or X-band (~7200 MHz) carrier frequencies, with the PN code modulated coherently onto the RF carrier such that the start of each PN chip corresponds to the rising edge of the sinusoidal carrier waveform, and in addition maintaining an integer number of RF cycles per PN-code chip. Determining the range between two spacecraft, A and B, is initiated by spacecraft A transmitting a coherent BPSK-modulated PN code to spacecraft B, where it is transponded back to spacecraft A and processed to extract range. Phase-noise corresponding to the Allan variance of the transmitter oscillators was added to the received signal, downconverted to a convenient IF frequency while maintaining an integer number of IF cycles per chip, downsampled to the IF cycle and cross-correlated with a corresponding reference waveform to estimate PN range via the location of the magnitude of the complex cross-correlation peak. In addition, the phase of the cross-correlation peak is estimated via an optimal arc-tangent algorithm, and converted to range in order to refine the range estimate enabling cm-level accuracy. It is shown that phase noise, not receiver noise, ultimately limits the performance of the carrier-phase PN range estimator. Simulation results are verified via Cramer-Rao bounds on the variance of the Carrier-Phase Aided PN Range Estimator.

It is shown that high-quality oscillators enable sub-cm range estimates, provided that sufficiently high chip-SNR can be established over the proximity link.

4.0603 Miniature Optical Steerable Antenna for Intersatellite Communications Liquid Lens Characterization

Faisal Fogle (MIT STAR Lab), Ondrej Cierny (Massachusetts Institute of Technology), Kerri Cahoy (Massachusetts Institute of Technology), William Kammerer (Massachusetts Institute of Technology), Paula Do Vale Pereira (Massachusetts Institute of Technology),

Presentation: Faisal Fogle, Monday, March 9th, 05:20 PM, Amphitheatre

Laser communication (lasercom) enables more efficient links across larger distances compared with radio frequency (RF) systems. However, lasercom systems are typically point-to-point connections that would have difficulty interacting with several concurrently active spatially diverse users, where RF systems can more easily support such scenarios. Lasercom pointing, acquisition and tracking (PAT) systems have traditionally relied on mechanical beam steering devices, such as fast steering mirrors (FSMs) or gimbals, both of which are subject to potential mechanical failure. We investigate an alternative steering solution using liquid lenses. Liquid lenses are tunable lenses that can non-mechanically alter focal length based on an applied voltage or current. Currently available commercial off the shelf (COTS) liquid lenses are based on electrowetting (manufactured by Corning) or pressure-driven (manufactured by Optotune) operation. A series of liquid lenses, one on-axis to control beam divergence, and one each offset in the x and y-axes to steer, could be used to achieve laser pointing control. In this work, we analyze the suitability of both types of liquid lenses for use in a space based multiple access lasercom terminal. There is limited data on liquid lens survivability and operation in a space-like environment. Through vacuum testing, we have found that electrowetting-based liquid lenses continue to operate nominally in a very low-pressure environment. The pressure-driven liquid lenses appeared to have issues initially in vacuum testing, with gas bubbles forming in the lens aperture during pump-down. However, after extended exposure to vacuum of approximately two weeks, the gas bubbles diffuse through the lens membrane, and the lenses operate in vacuum. Steering transfer functions were developed both in ambient and in vacuum conditions for both lens types, and in each case, the differences between the two curves were largely negligible. The electrowetting lenses provide a steering range of 2.7 degrees with an approximate slope of 0.046 deg/V. In testing the Optotune lenses, the steering was limited by the camera detector size, but for a range of -92 mA to 144 mA on the steering lens, the lenses provide 8.6 degrees of steering with a slope of 0.0367 deg/V. Maximum hysteresis error was identified at 0.02 degrees for the Corning lenses and 0.05 degrees for the Optotune lenses. A Zemax beam quality analysis was conducted to see how transmit gain would be affected by refraction through the liquid lenses. Through this analysis, the worst-case link penalties were determined to be -0.5 dB for the Corning lenses at -0.8 degrees steering and -0.4 dB for the Optotune lenses at -1.0 degrees steering. Thus, we see that liquid lenses are likely good candidates for space applications and may perform well in nonmechanical beam steering. We discuss next steps in environmental testing as well as optical layout and control approaches for using liquid lenses in PAT systems for a nanosatellite based optical antenna.

4.0604 Introducing SatMF: The Satellite Metadata Format

Zachary Leffke (Virginia Tech), Seth Hitefield , Jonathan Black (Virginia Tech),

Presentation: Zachary Leffke, Monday, March 9th, 09:00 PM, Amphitheatre

This paper introduces the Satellite Metadata Format (SatMF) specification which provides a standardized method of combining signal, telemetry, or protocol metadata with raw data exchanged with a spacecraft during a mission. This additional metadata may

not be directly related to satellite operations, but could be of interest at a later point of the mission. It can be used to describe general information about satellite telemetry, the characteristics of a communications channel or the system itself, and different features of the given satellite or mission. Examples of this can include the timestamp when the packet was received, the ground station receiving the data, the strength of the signal, etc. The SatMF specification is only concerned with abstract metadata concerning the satellite communications and operations and does not prescribe the actual protocols or systems used to implement communication with a satellite itself. SatMF is intended as an additional tool for ground station systems and networks that is useful for storing and communicating this metadata in a standard manner allowing for easy interaction with other users or ground station systems. SatMF is inspired by both the Satellite Telemetry Protocol (STP) developed by the Radio Amateur Satellite Corporation (AMSAT) and the Signal Metadata Format developed by the GNU Radio community and provides a standard JSON (JavaScript Object Notation) format for structuring data. It provides several standard fields for each packet that are required, and also provides a few optional fields. The SatMF standard also provides an extensible structure that allows customization by end users to fit their mission's operational requirements. By implementing SatMF throughout ground station systems and networks, the processes of transferring metadata associated with raw signals and collaborating with other ground stations is greatly simplified.

4.07 Space Navigation Techniques

Session Organizer: Lin Yi (NASA Jet Propulsion Lab),

4.0702 Development of Cooperative Vision-Based Navigation Techniques Using Neural Networks

Jill Davis (Missouri University of Science and Technology), Henry Pernicka (Missouri University of Science and Technology),

Presentation: Jill Davis, Monday, March 9th, 09:25 PM, Amphitheatre

One key application of SmallSats identified by NASA and DoD is their use in spacecraft formation flight or swarm missions. Groups of SmallSats (with reduced launch costs and rapid development times), operating in swarms can reduce the need for typical monolithic spacecraft that take years to develop and launch, which are expensive, particularly if they fail prematurely and require replacement. SmallSat swarms are more robust, where the failure of one in the swarm can be mitigated by other swarm members assuming its duties. Envisioned spacecraft swarms can include tens to hundreds of satellites, and maintaining these swarms presents a variety of challenges for spacecraft guidance, navigation, and control. In order for swarms to function semi-autonomously, swarm members will need information regarding the pose relative to other spacecraft. A novel image processing chain is being developed to determine the full relative pose of multiple spacecraft in a cooperative swarm or formation using information from a single image. For cooperative SmallSats, vision-based navigation shows promising results. While vision processing algorithms can be computationally expensive, they typically consume less volume, mass, and power than other ranging systems such as radar or LiDAR. Of particular interest are systems that use monocular vision to perform relative satellite navigation. However, many proposed swarm and constellation missions would result in multiple spacecraft being imaged over short time spans. To effectively perform relative navigation, the spacecraft in each image must be properly classified and the pose must be estimated with high accuracy. This research addresses this problem by using a neural network to classify spacecraft in conjunction with traditional techniques for pose estimation. The process is enabled by leveraging cooperative mechanism between spacecraft, which may also reduce computation times. The image processing chain begins by capturing an image with a single camera in the visible, infrared, or ultraviolet spectrum. Any spacecraft in the image will then be identified using a neural network architecture. The architecture is trained as a classification network that will classify spacecraft in the images based off known pre-launch properties that are unlikely to change on-mission. The properties may include beacon patterns on spacecraft or fiducial identifiers similar to bar codes and QR codes. Once each spacecraft in the image has been identified, the relative pose will be estimated by solving the inverse perspective-n-point problem. This problem can be solved iteratively using the known locations of features or a wireframe model of the spacecraft, which can be assumed based on accurate identifications from the neural network. Facilitated by the cooperative nature of the swarm, beacons and fiducial markers are used to improve the accuracy of the pose determination. The image processing chain outlined above potentially enables a single spacecraft to determine the full relative pose of a large number of surrounding spacecraft. This capability will benefit proposed spacecraft swarm and cluster missions. Preliminary results have shown that the developed neural network can classify two spacecraft in an image as seen from the view of a third spacecraft without error.

4.0703 Autonomous Navigation for Small Body Landing Using Optical and Inter-spacecraft Measurements

He Jia (Beijing Institute of Technology), Shengying Zhu , Pingyuan Cui ,
Presentation: He Jia, Monday, March 9th, 09:50 PM, Amphitheatre

In this paper, an optical camera/inter-spacecraft measurement integrated navigation method to autonomously guide a formation of spacecraft for small body landing is proposed and the visual landmark recognition method is presented to improve the navigation performance. By introducing the relative range and line of sight (LOS) angle between spacecraft measured by radiometric and optical sensors, the states of two spacecraft are estimated, and the estimation performance degradation of velocity is reduced, which is caused by using LOS to the feature point on small body surface as the unique navigation information. The camera is used for state estimation of the spacecraft, and the inter-spacecraft measurement is introduced to improve the observability and accuracy of the onboard autonomous navigation system, which provides an effective way to guarantee the sufficient accuracy. The observability of the integrated navigation system has been proven based on the analysis of the observability matrix, which illustrates the improvement of observability of the navigation system. Furthermore, a high-accuracy center extraction method is used for crater landmark extraction to obtain accurate LOS measurement information, and the extraction error is less than 1 pixel. To verify the performance of the proposed navigation method, numerical simulations are set up. Simulation results illustrate that the novel navigation method proposed in this paper improves the observability and estimation accuracy of the navigation system.

4.08 Communication System Analysis & Simulation

Session Organizer: Yogi Krikorian (Aerospace Corporation),

4.0801 A Markovian Queueing Network Model of Multiple Access Communications in Space

Jay Gao (Jet Propulsion Laboratory),
Presentation: Jay Gao, Wednesday, March 11th, 08:30 AM, Lamar/Gibbon

Describe a Markovian queueing system model of multiple access communications for space exploration.

4.0802 Revenue Management for Communication Satellite Operator – Opportunities and Challenges

Markus Guerster (Massachusetts Institute of Technology), Joel Grotz (SES Satellites), Peter BELOBABA (MIT), Edward Crawley (Massachusetts Institute of Technology), Bruce Cameron (Massachusetts Institute of Technology),

Presentation: Markus Guerster, Wednesday, March 11th, 08:55 AM, Lamar/Gibbon

In this paper, we propose a Revenue Management framework for satcom operators and show with a proof-of-concept simulation that predicts a significant gain in revenues. New satellite operators, highly variable demand for data, digital payloads, and new phased array technologies are likely to remake the current satcom landscape. One of the challenges operators old and new will face is how to manage demand and capacity. Airlines faced a similar situation with deregulation in the 1970s – their response with tiered pricing and seat inventory control to allocate capacity (known as Revenue Management), which may offer lessons for the satcom market. The satcom industry shares many characteristics with the airline industry, such as inflexible capacity, low marginal sales cost, perishable inventory, heterogenous customers, and variable and uncertain demand. Generally, those characteristics favor the implementation of a Revenue Management system. However, the details of how Revenue Management can be used by satcom operators still need to be explored, which is the focus of this paper.

4.0804 A Mathematical Analysis of an Example Delay Tolerant Network Using the Theory of Shaves

Robert Short (John Carroll University), Alan Hylton (NASA),

Presentation: Robert Short, Wednesday, March 11th, 09:20 AM, Lamar/Gibbon

NASA's High-Data Rate Architecture (HiDRA) project is working towards a general yet practical toolkit and knowledge base to help usher in the era of new technologies for space systems communications, such as optical links. The High-Rate DTN (HDTN) implementation falls under the umbrellas of both the toolkit and the knowledge base, as its advancements illuminate more general areas of DTN that need growth. The goal of this paper is to explore the usage of particular mathematical machineries, namely temporal flow networks and sheaves, to identify fundamental, underlying structures in DTN for space systems. Satellites, space assets, ground stations, etc. give rise to a disconnected network, and it is the goal of DTN to glue disparate links together into a cohesive system, that is, a network. Depending on a given link, contact times might have one-way light times in excess of minute (perhaps greatly so) or the latencies might be on the order that the typical Transmission Control Protocol (TCP) can handle. Some links might be periodic (say, due to orbital mechanics) or they might not be. This diversity has made it difficult to probe the underlying structure. An immediate consequence is that DTNs in practice today are controlled by globally distributed schedules which are the input to the contact graph routing (CGR) algorithm. While this is effective for smaller networks, it will be very difficult to scale for future networks. Deeper and more rigorous theory is needed to bring DTN to the next evolutionary step. The tag-line for sheaves is that they are the mathematically precise way of gluing local data together into unique, global data. In this way it is clear that networking is a ``sheafy'' science. This paper introduces a simplified sheaf model, known as the cellular sheaf, and applies it to a space network that is simulated using an orbital analysis toolkit. The sheaf-theoretic analysis is presented and discussed, as it is hoped that this and related papers will help form the primordial ooze of DTN theory. Finally there is a section of future work suggesting follow-on research.

4.0807 Parker Solar Probe’s 1st Year of Ka-band Operations

Matthew Cox (Johns Hopkins University/Applied Physics Laboratory), David Copeland (Johns Hopkins University/Applied Physics Laboratory), Romina Nikoukar (Johns Hopkins University/Applied Physics

Laboratory), Sean Sprouse (Johns Hopkins University/Applied Physics Laboratory),
Presentation: Matthew Cox, Wednesday, March 11th, 09:45 AM, Lamar/Gibbon

Launched in 2018, NASA's Parker Solar Probe (PSP) mission has been described as "The Mission to Touch the Sun". Over a 7 year prime mission, the spacecraft will make 24 close encounters with the Sun. In order to meet requirements, PSP's telecom subsystem needed to incorporate a Ka-band downlink for radiometrics and science data return. PSP uses a 0.6 meter High Gain Antenna (HGA). This antenna is used only for a Ka-band downlink, and during its use is nominally the only time the science data is transmitted. Aspects of the mission design also restrict the use of the HGA to short periods in between each solar flyby. These constraints require the RF team and Mission Operations team to be extra diligent in optimizing the downlink data return. This presentation provides a summary of PSP's first year of operations at Ka-band. In addition to presenting the overall Ka-band performance, other items that will be focused on include: planning considerations for Ka-band coverage with the DSN, observed effectiveness of a HGA calibration, pre-launch link assumptions, and possible future work. With multiple future deep space missions utilizing a Ka-band downlink, this information will hopefully be beneficial to help with planning and optimizing the data return.

4.09 Wideband Communications Systems

Session Organizer: David Taggart (Self), Claudio Sacchi (University of Trento),

4.0901 Building Cellular Connectivity on Mars: A Feasibility Study

Claudio Sacchi (University of Trento),
Presentation: Stefano Bonafini, Wednesday, March 11th, 10:10 AM, Lake/Canyon

The recent literature has proposed a visionary and potentially disruptive idea, i.e. to deploy some sort of cellular networking infrastructure on Mars, based on terrestrial LTE principles. So far, the Martian communications are unidirectional. Data acquired by the surface sensors, mounted on landers and rovers, are sent to the Earth by means of low-rate direct connections, based on IEEE 802.15.4 standard, or using satellite-based relaying. Such kind of approaches does not consider the possibility of proactive cooperation between the different exploration vehicles present on Mars (landers, rovers, orbiters), enabling on-site data exchange and distributed information processing. Moreover, in the future perspective of manned missions, astronauts could profitably exploit the presence of networked connectivity to communicate among themselves and/or to exchange data with the processing devices already present on the Red Planet. Another key point of LTE is the support of mobility, totally unsupported by current wireless infrastructures operating on Mars surface. In this paper, we aim at improving some preliminary assessments concerning the efficient design of an LTE-based radio access interface that should operate on Mars. Link performance of standard LTE configuration - based on SC-FDMA with Localized FDMA (L-FDMA) for the uplink and OFDMA for the downlink - will be analyzed by means of in-lab simulations for two different Martian sites (Gusev 1 and Gusev 3) and two different link distances (100 m and 1 Km respectively). Moreover, the performance of non-standard multiple access strategies like Interleaved-FDMA (I-FDMA) will be assessed for the uplink in the Martian scenarios. Link budget and Quality-of-Service (QoS) analysis that concludes the paper will discuss in details the issue of the adaptability of terrestrial LTE to the Martian propagation environment. The main outcome of the proposed analysis is that LTE, as deployed on the Earth, can support high capacity in short-range cells with some modest upgrading (e.g. the use of I-FDMA for the uplink instead of L-FDMA), while, for long range transmission, the mobile radio interface should be substantially redesigned, especially for what concerns the RF section.

4.0902 Virtual Baseband Unit Splitting Exploiting Small Satellite Platforms

Riccardo Bassoli (Technische Universität Dresden),

Presentation: Claudio Sacchi, Wednesday, March 11th, 10:35 AM, Lake/Canyon

Recently, border monitoring and security has become an important topic since current methods against illegal immigration are expensive and inefficient. In particular, inefficiency and ineffectiveness increase when monitoring operations are focused on complex borders, where there is no available/reliable connectivity. In the last decade, the deployment of different kinds of unmanned aerial vehicles was seen as the main paradigm to provide on-demand wireless network access. Significant research work has been done on so called mobile base stations. Nevertheless, drones have specific technical limitations in terms, for example, of battery life and carried weight. Given above fundamental limits, network virtualization becomes a fundamental paradigm for system realization. In the last years, baseband processing was not seen any more as a monolithic block but has been studied as a chain of virtual functions. Especially, baseband unit can be split into five sub-blocks belonging to layer 1 to layer 3, where each degree of splitting implies more and more stringent requirements to be guaranteed, mainly in terms of throughput and latency. Split E is the logic separation of hybrid automatic repeat request from lower layers, which imposes the most flexible requirements. On the other hand, Split D (forward error correction, encoding/decoding logic functions) sets more stringent bounds on throughput and latency so that it requires careful study and detailed analysis for a correct system-level design. The main objective of this article is to study theoretically and numerically (i.e. via simulations) Split D to make it feasible with the help of small satellites. The paper will study the structure and the capabilities of small satellites to be used as small data centers to host radio access virtual network functions like forward error correction. The theoretical analysis is supported by simulations in order to highlight advantages and challenges of the proposed approach.

4.0905 UAV and Satellite Employment for the Internet of Things Use Case

Fabio Patrone (University of Genoa),

Presentation: Mario Marchese, Wednesday, March 11th, 11:00 AM, Lake/Canyon

This paper presents a study of deploying an IoT communication protocol (LoRaWAN) gateway onboard a UAV communicating with the terrestrial network through a simulated satellite link. The aim of the study is to propose and test UAVs together with satellites as possible means to, on one hand, extend the coverage of LoRa network, and, on the other hand, offer a common solution to allow data exchange with multiple devices implementing different IoT communication protocols.

4.0907 Wavelength Division Multiple Access for Deep Space Optical Communications

Dariush Divsalar (Jet Propulsion Laboratory), Samuel Dolinar (Jet Propulsion Laboratory), William Farr (Facebook Connectivity Labs), David Israel (NASA - Goddard Space Flight Center), Makan Mohageg , Matthew Thill (JPL), Erik Alerstam (Jet Propulsion Laboratory), Michael Peng (Jet Propulsion Laboratory), Matthew Shaw (Jet Propulsion Laboratory), Emma Wollman ,

Presentation: William Farr, Wednesday, March 11th, 11:25 AM, Lake/Canyon

In this paper, a high capacity wavelength division multiplexing (WDM) for high data rate optical communications, a WDM with 2-dimensional M- PPM to achieve a higher number of bits per photon transmission, an optical wavelength division multiple access (WDMA) for multiple CubeSats/small spacecraft for deep space optical communications, and a combined optical WDMA with optical code division multiple access (CDMA) are investigated. The signal processing components required for successful operation of above mentioned optical systems are defined. For WDMA, the performance of the uncoded case for N SmallSats/CubeSats is obtained. Software simulations are used to

obtain the performance of N SmallSats/CubeSats using a coded optical WDMA multiple access scheme. Results from successful completion of this investigation might be used in the future for deep space optical communication scenarios that require science data from SmallSats/CubeSats to be transmitted to Earth. An M-ary Pulse Position modulation (PPM) format is considered. For a hard decision optical receiver with photon counting detectors, a rate compatible protograph code is proposed. The code is optimized using the reciprocal channel approximation, which is a one-dimensional density evolution. The performance analysis is provided for the uncoded and simulated coded optical WDMA under background noise for up to N=16 SmallSat/CubeSats. Our results show, for example, that in the case of 2-PPM there is a 7 dB coding gain (with respect to the uncoded case) at a FER of 10^{-6}, for a rate 0.8 code, and 12 dB coding gain for a rate 1/6 code, depending on the received background noise intensity. Leveraging existing laboratory hardware to test the deep-space optical WDMA concept, an experiment is performed. Finally the concept of combining WDMA with optical CDMA to support more users is analyzed using short signature sequences and uncoded 2-PPM modulation and simulations are performed for coded system.

4.10 Communications and/or Related Systems: Theory, Simulation, and Signal Processing

Session Organizer: David Taggart (Self),

4.1002 Opportunistic Arraying

Clayton Okino (Jet Propulsion Laboratory),
Presentation: Zaid Towfic, Thursday, March 12th, 08:30 AM, Amphitheatre

This presentation discusses recent activities at JPL that are focused on extending the Opportunistic Multiple Spacecraft Per Antenna (OMSPA) concept to include arraying multiple antennas. We explore the ability to process multiple open loop recordings associated with multiple antennas and perform the appropriate alignment and combining. We focus on using the symbol stream combining technique and provide examples of performance measurements on actual spacecraft signals for MarCO A and B as well as the Mars Express.

4.1003 Mitigating Fading in Cislunar Communications: Application to the Human Landing System

Marc Sanchez Net (Jet Propulsion Laboratory), Kar Ming Cheung (Jet Propulsion Laboratory),
Presentation: Marc Sanchez Net, Thursday, March 12th, 08:55 AM, Amphitheatre

NASA's human exploration program is currently working towards landing astronauts on the surface of the Moon by 2024, close the lunar South Pole. To guarantee astronaut safety and maximize science data return, NASA is in the process of defining the communication architecture that will support all astronaut activities from launch to surface operations. Of particular interest to this paper are links from the lunar surface back to Earth without any intermediate relays. We show that the system geometry is such that antennas on the landing system will need to be pointed at low elevation angles, thus potentially causing multi-path fading effects not typically encountered in space communications. This paper is organized in three parts. First, we characterize the multi-path fading effects expected in links between the lunar South Pole and Earth and show that for moderate data rates (less than 1 Mbps) the links suffer from slow fading. We then show that for this operations regime the performance of forward error correction schemes is significantly worse for traditional Additive White Gaussian Noise channels. Finally, we investigate multi-copy mechanisms to mitigate the effects of fading, most notably repetition schemes and Automatic Repeat Request.

4.1005 A Control-Theoretic Approach to Precoding for Multicast Multibeam over Satellite

Khanh Pham (Air Force Research Laboratory),
Presentation: Khanh Pham, Thursday, March 12th, 09:20 AM, Amphitheatre

This work explores an initial step in defining a principled and control-theoretic framework for multi-beam broadband satellite systems in a novel and challenging scenario of hybrid terrestrial-satellite mobile system architectures. Advanced control-theoretic design principles for a bent-pipe satellite payload concept for forward paths will be highlighted for: i) broadcast (point-to-multipoint) downlink on forward paths; ii) trade-offs between terrestrial mobile network congestion and data transmission rates; and iii) judicious coordination of actual data rates and cognitive precoding strategies under uncertainty for achieving reliable feeder link transmission by the ground gateway. The expected results will also help to reveal new insights on risk-sensitive satellite-to-user downlinks and multicast transmission in the presence of frequency reuses as well as potential congestion from terrestrial mobile network counterparts.

4.1006 Risk-Sensitive Rate Correcting for Dynamic Heterogeneous Networks: Autonomy and Resilience

Khanh Pham (Air Force Research Laboratory),
Presentation: Khanh Pham, Thursday, March 12th, 09:45 AM, Amphitheatre

This work is proposing a unified framework for dy- namic and heterogeneous networks from a control engineering standpoint. Adaptive learning and risk-sensitive policies illustrate ways of dealing with: i) state-space realization to account for heterogeneous flow rates, bottleneck links with rate allocat- ing routers or switches, and coupling between queue regulation, stochastic and time lag effects; ii) centralized rate-based stabi- lization with explicit congestion indication feedback via partially noisy observations; iii) performance risk mitigation enabled by Minimal-Cost-Variance control theory; and iv) distributed adaptation based on companion window flow control mecha- nisms at sources. The expected results will help to reveal new insights on systematic designs and rigorous analysis of adaptive and scalable learning and management schemes for coordinated resilience across all layers and elements in networked systems.

4.1007 Design of Nonlinear Control for Active Queue Management in TCP Satellite Communication Networks

Jing Wang (Bradley University), Khanh Pham (Air Force Research Laboratory),
Presentation: Jing Wang, Thursday, March 12th, 10:10 AM, Amphitheatre

In this paper, we study the congestion control problem in TCP satellite networks, and present a new design for TCP network congestion control based on a nonlinear control and optimization framework. The proposed TCP/AQM control framework consists of two levels: the high-level generates the desired queue size for routers in the network by solving a network utility maximization problem using a distributed optimization scheme; the low-level provides a local nonlinear feedback control for the probability of packet mark/drop based on a typical fluid-flow model for TCP dynamical behaviors. The nonlinear control design is done using a backstepping method and its stability is proven by the Lyapunov direct method. Simulation results are included to show the effectiveness of the proposed new design.

4.1009 Data-Driven Solutions for Digital Communications

Donna Branchevsky (UCLA), Andres Vila Casado (The Aerospace Corporation), Eugene Grayver (Aerospace Corporation), Douglas Baney (Aerospace Corporation), Adam Belhouchat (The Aerospace Corporation), Andrew Braun (UCLA),
Presentation: Donna Branchevsky, Thursday, March 12th, 10:35 AM, Amphitheatre

In this paper, we show that data-driven communication methods can overcome limitations of pure model-based designs. Classical communication theory works well with 'ideal' channels (AWGN, Rayleigh, etc.). However, an open area of research exists in how to transmit across non-ideal channels, such as those with high Doppler, dynamic channels, or nonlinear channels, among other hard-to-model characteristics. Communications researchers have already started to make great progress using machine learning to address a variety of communications problems. We built on their findings and propose a variety of machine-learned communication techniques. We designed a transmitter that uses reinforcement learning algorithms, such as a modified Deep Deterministic Policy Gradient (DDPG) method, to learn efficient modulation schemes. The benefit of a reinforcement learned system is that it can change its transmission scheme based on the current characteristics of the channel. We show our reinforcement learned transmitter successfully able to learn an efficient modulation scheme given power constraints. We show our transmitter not only learning good modulation schemes for AWGN channels, but also adapting when suddenly presented with a non-linear amplifier in its path. In addition, while it takes a long time to initially train the transmitter, it relatively quickly adapts to the introduction and removal of non-linear amplification. This approach outperforms static modulation schemes that suffer when the non-linearities are introduced.Furthermore, we propose a receiver that uses a machine-learning classifier to decode either a fixed transmitter scheme or a learned transmitter scheme. We also implement and propose neural networks to simultaneously learn transmitter and receiving algorithms via supervised learning. Finally, we are using machine learning to select communication system parameters (modulation order, coding gain, etc.) based on current channel behavior.

4.1010 Ensemble Clustering for Unsupervised Learning of Time Series Data Using FPGAs

John Porcello (N/A),

Presentation: John Porcello, Thursday, March 12th, 11:00 AM, Amphitheatre

Ensemble Clustering for Unsupervised Learning of Time Series Data using FPGAs Abstract – Ensemble Clustering is a form of Unsupervised Machine Learning where several Unsupervised Learning Algorithms are combined in an ensemble to improve accuracy. Outputs from several Unsupervised Learning Algorithms are combined together to determine the final output of the ensemble. A consensus function is used for combining outputs from the Unsupervised Learning Algorithms to improve output from the ensemble. Selecting a consensus function without any apriori knowledge is difficult, and many types exist with various levels of computational complexity. In this paper, we consider the use Ensemble Clustering as an unsupervised learning approach of time series data. Specifically, in this paper the problem is to extract key relationships in time series data to derive key metrics. The paper considers the advantages and disadvantages of ensembles in machine learning followed by a discussion of clustering algorithms used in unsupervised learning. A discussion of consensus functions for ensembles of clustering algorithms is provided and followed by a discussion of unsupervised learning of time series data. Furthermore, this paper considers implementation of Ensemble Clustering using Field Programmable Gate Arrays (FPGAs). The approach described in this paper applies to high performance, high throughput and scalable implementations for big data. Design data is provided for FPGA implementation of Ensemble Clustering. Finally, an example is provided based on the Xilinx UltraScale+ FPGAs to illustrate the concepts in this paper. This document does not contain technology or Technical Data controlled under either the U.S. International Traffic in Arms Regulations or the U.S. Export Administration Regulations.

4.1013 Adaptive Sweeping Carrier Acquisition and Tracking for Dynamic Links with High Uplink Doppler

Dariush Divsalar (Jet Propulsion Laboratory), Marc Sanchez Net (Jet Propulsion Laboratory), Kar Ming Cheung (Jet Propulsion Laboratory),

Presentation: Marc Sanchez Net, Thursday, March 12th, 11:25 AM, Amphitheatre

In this paper, we propose an adaptive sweep signal acquisition and tracking algorithm that (1) takes into account high-order uplink signal dynamics (Doppler shift, Doppler rate, Doppler acceleration), (2) dynamically adapts the carrier search direction (positive or negative in frequency error) and (3) dynamically adapts the carrier search step. The combination of (2) and (3) are the main innovation of this paper, since radios do not need to restart at its initial search state when the carrier is missed. This, in turn, minimizes the time required for carrier lock and thus makes the system more robust to the loss of lock failures. Note that the proposed system improves upon the frequency sweeping algorithm used in current flight radios (e.g., JPL's Electra and IRIS) which use constant search direction and search step . There are three motivating applications for our proposed system: Proximity links at Mars or the Moon, support of Multiple Access per Antenna at the Deep Space Network, and generation of Doppler measurements for navigation purposes. As indicated later in the paper, all these scenarios require spacecraft to establish highly dynamic links for which no Doppler compensation can be performed on the ground. Therefore, the receiver's ability to properly acquire and track the received carrier is paramount for transfer of information, relative positioning and navigation.

4.1015 CCSDS Rate-Compatible Product Code for Ka-Band Satellite Communications

Ashraf Mahran (MTC), Ramy Samy (space technology center),

Presentation: Ashraf Mahran, ,

Ka-band Satellite communication performance is very vulnerable to different weather conditions especially the rain fade, one of the effective techniques against rain fade is the use of powerful channel coding with superior results. Since satellite is power-limited systems, it is appealing to use such techniques with reduced complexity. Reed-Solomon Convolutional Concatenated Code is a popular space communication error control system that has a powerful ability to correct errors and can be used to withstand rain fall but with a high decoding complexity. In this work, we introduce an analysis of the rainfall effect in Ka-band satellite communication and create the rain fade channel model. In addition to, we propose low-complexity Viterbi decoder based on the modified adaptive Viterbi algorithm (MAVA). The proposed work yields approximately the same error performance as the classical RSCC while needing substantially reduced computational load and memory requirements at wider range of signal-to-noise ratios. Our simulations are carried out using the RSCC codes CCSDS-recommended over Ka band fixed satellite channel model under different rain fade conditions. We will compare our proposed system with the standard RSCC, in terms of the BER performance and the complexity reduction. The complexity reduction measure will be considered as the average ratio of the eliminated paths to the total number of conventional VA paths throughout the whole trellis. The simulation findings over rain weather condition show that the appeared transmission errors cannot be fixed efficiently without coding. Generally speaking, BER reduces very slowly with the increase of Eb/No; all need more than 20dB to reduce the bit error rate to below 10-5. The suggested coding system can reach roughly 11.8dB and 13.3dB coding gains at BER 10-5 for hard and soft decision decoding, respectively. This can be argued by using such a coding scheme to accomplish the desired BER performance with a sensible value of the transmitted power that can be readily acquired by the satellite as a power-limited system. The decrease in complexity acquired to obtain BER 10-5 is 47% and 38.5% for hard and soft decision decoding. This decrease

in complexity contributes considerably in minimizing the overall computational load and memory demand for baseband processing, making the suggested scheme more appealing and appropriate for use in satellite communication systems. Our simulation results are extended to include more severe weather condition, the thunder shower. The uncoded signal BER reaches saturation at 10-4, no better performance can be accomplished for Eb/No higher than 30dB which is exceptionally large to be achieved by the satellite system. Using RSCC codes can attain 10-5 BER performance or better with a fair value of Eb/No i.e. 12.2dB and 10.7dB for hard and soft decision decoding, respectively. From the point of perspective of complexity decrease important improvement over standard VA can be obtained.

4.1016 Early Terminating Viterbi Decoding of Reed-Muller Codes

Ashraf Mahran (MTC), Ahmed Magdy ,
Presentation: Ashraf Mahran, ,

Reed - Muller codes are the oldest multiple error correction block codes that introduced in 1954. Recently, these codes have gained the interest of many researches in the field of error control coding. Researchers have focused their attention on achieving the capacity of erasure channel by using different decoding techniques. Moreover, the literature reveals different forms of RM code building such as multilevel lattice construction, Punctured RM, and the shortened projective RM. In spite of the trellis graphical representation of any block code that make it possible to implement maximum likelihood decoding (MLD), the time variant construction of trellis block code makes it more difficult in the decoding process. Reed-Muller codes can be constructed from smaller ones decoding by recursive scheme based on Plotkin construction. Many modifications have been applied to the trellis graphical representation of block code to treat this difficulty problem. Amongst these modifications are; the sectionalization of a trellis and parallel decomposition of minimal trellis into parallel isomorphic sub trellises. Although, the optimum permutation of trellis oriented form (TOF) that generates minimal trellis block code is very useful to decrease the complexity of trellis structure, the optimum permutation (bit ordering) of any block code is not easy to find. Meanwhile, the Viterbi algorithm (VA), as one of the optimum decoding algorithms for trellis representation, suffers from the decoding complexity as the trellis structure (number of states, number of branches) of the block codes exponentially increases in accordance with the increase in the number of information bits of the block code. The parallel decomposition is a parallel and structural identical (isomorphic) sub-trellis of smaller number of states without cross-connections between them. Consequently, identical sub-trellises Viterbi decoders of much smaller complexity can be decoded independently in parallel without internal communication between them. This not only simplifies the integrated circuit (IC) implementation, but also speeds up the decoding process. We have introduced a novel early terminating Viterbi algorithm for decoding Reed-Muller block code. The elimination concept of based on only one cross connection (selection wire), through all sub-trellis (IC), in the isomorphic construction at a specific position to carry on an optimal measure to eliminate some of the sub-trellis from the decoding process. The gain from the proposed early termination Viterbi algorithm (ETVA) not only reduces the decoding complexity of Reed-Muller codes, but also saves the energy of the non-functioning IC. The later benefit is or great interest to mainly the power limited space applications. The proposed algorithm will stop some sub-trellis that has been proven to be irrelevant, as they exceed the error correction capability of the code. The introduced algorithm not only maintains the MLD performance of the conventional VA, but also can achieve 30% reduction in terms of the number of eliminated branched over VA algorithm, while eliminating 50% of the sub-trellises of the parallel decomposition isomorphic trellis of the RM code.

4.1017 Implementation of Open-Loop Radio Frequency Record Feature on the JHU/APL Frontier Radio

Adam Crifasi (Johns Hopkins University/Applied Physics Laboratory),
Presentation: Adam Crifasi, Thursday, March 12th, 11:50 AM, Amphitheatre

Abstract—The John's Hopkins Applied Physics Laboratory (JHU/APL) Frontier Radio (JHU/APL FR), as flown on the Van Allen Probes and Parker Solar Probe missions, is a deep space communications platform designed to minimize size, weight, and power (SWaP) while maximizing radiation tolerance. This platform has historically only been used to support Deep Space Network communications and modulation formats. The receive chain was designed to support subcarrier PCM/PM waveforms and only forwarded demodulated symbols and uplink packets over to avionics. For the Europa Clipper mission, there was a desire to be able to record arbitrary segments of spectrum for post-processing on the ground, due to the real-time processing limitations of the low-SWaP JHU/APL FR. Therefore, a open-loop recording feature was added to the JHU/APL FR. The feature requirements dictated minimal firmware development, no additional hardware, and a packet stream to avionics using the existing spacewire interface. The open-loop record feature has differing bandwidths, ranging from the highest supported by spacewire to an eighth of that rate in order to capture as much data as possible or to reduce data volumes. The user can steer the center frequency of the recording window in order to capture a certain slice of spectrum. A simple post-processing algorithm was developed to fix a slight temporal shift during the recording data signal chain. An overview of the firmware design, algorithms, post-processing procedure, and analysis of the results are described below.

4.11 Global Navigation Satellite Systems

Session Organizer: Gabriele Giorgi (German Aerospace Center - DLR), Lin Yi (NASA Jet Propulsion Lab),

4.1101 Emergency Warning Services via GNSS (Global Navigation Satellite System) Signals

Keiko Shimazu (Advanced Institute of Industrial Technology (AIIT)), Kenji Makabe (Tokyo Metropolitan University), Naoki Nishii , Ryota Mori (Tokyo Metropolitan University), Naoki Harada (Tokyo Metropolitan University), Haruki Sashida (Tokyo Metropolitan University), Kohei Oikawa (Yokohama National University), Hamza Chaker (the Graduate School of Industrial Technology, Advanced Institute of Industrial Technology (AIIT)),
Presentation: Keiko Shimazu, Monday, March 9th, 04:30 PM, Lake/Canyon

Galileo is Global Navigation Satellite System developed by EU (European Union). It covers all over the world. The system is organized by 26 satellites now. It will be 30 in 2020. On the other hand, QZSS (Quasi-Zenith Satellite System) was produced by Japan. This system's positioning service covers not only Japan, but also South East Asia and Oceania. The main purpose of both systems is positioning service. Besides that, both sides, EU and Japan have been planning "double-use strategy" of their satellite systems. More precisely, Positioning service is for ordinary time. And then, danger notification and instruction to escape from devastated situation is for disaster time. Therefore, we call "double-use strategy." Most of attendees of GNSS international conference disagreed with our double use idea, at first. Although, they have been changing their mind recently. For instance, ISRO (Indian Space Research Organization) has decided to use our idea and to employ our emergency messages for their satellite. And they have plan to install on their satellite. While, EWS was named by EU. It's Emergency Warning Service. DC report was named by Japan. It's Report for Disaster and Crisis Management. We decided to name "common EWS" for both services, during our project. In this paper, we report an interim result of our joint project was development of common EWS message. The amount of information on positioning satellite is very small. We had to

design to express all necessary information at disaster in 122 bits. In other words, we have designed information structure of Emergency Warning for evolving to international standard in 122 bits. This message can be employed on small satellites. On the other hand, the limitation of 122 bits was according to constraint of Galileo system. QZSS has more 65 bits are available. Therefore, we will start to design for Asian Unique message (Figure 1). Now, we have been building some application system on QZSS and Galileo using the common EWS message to execute field test. We, Japanese experienced The Great East Japan Earthquake and giant Tsunami in 2011. Our broad band commutation network was totally destructed in critical damaged area. We would like to make big contribution by using Satellite for saving many lives at next disaster.

4.12 Software Defined Radio and Cognitive Radio Systems and Technology

Session Organizer: Eugene Grayver (Aerospace Corporation), Genshe Chen (Intelligent Fusion Technology, Inc),

4.1202 A Smart Hybrid AGC Scheme for Satellite System

Xingyu Xiang , Dan Shen (Intelligent Fusion Technology, Inc), Khanh Pham (Air Force Research Laboratory), Zhonghai Wang (IFT), Genshe Chen (Intelligent Fusion Technology, Inc),
Presentation: Xingyu Xiang, Wednesday, March 11th, 09:25 PM, Cheyenne

Satellite communication (SATCOM) has experienced increasingly rapid development in recent years due to its safety and reliability. Automatic gain control (AGC) is an essential regulating part in satellite communication systems with the aim of maintaining a suitable output amplitude as the input varies. In this paper, we propose a hybrid Automatic Gain Control (AGC) approach which combines the signal amplitude ratio technique and the signal amplitude difference technique in existing feedback and feedforward AGC schemes. The proposed AGC scheme is robust to different input signal amplitude variations and is applicable to other systems besides SATCOM system. The proposed AGC scheme can maintain the input signal within the desired range in the conditions of jamming with shorter response time compared to conventional AGC. To demonstrate the effectiveness of the proposed AGC scheme, simulations have been carried out based on the typical satellite transponder link. Jamming signals are considered in the simulation to evaluate the performance of the system with QPSK input signals.

4.1203 Extreme Software Defined Radio – GHz and Gbps in Real Time

Eugene Grayver (Aerospace Corporation), Alexander Utter (The Aerospace Corporation),
Presentation: Eugene Grayver, Wednesday, March 11th, 09:50 PM, Cheyenne

Software defined radio is a widely accepted paradigm for design of reconfigurable modems. The continuing march of Moore’s law enables real-time signal processing on general purpose processors feasible for a large set of waveforms. Data rates in the low Mbps can be processed on low-power ARM processors, and much higher data rates can be supported on large x86 processors. The advantages of all-software development (vs. FPGA/DSP/GPU) are compelling – much wider pool of talent, lower development time and cost, and easier maintenance and porting. However, the very high-rate systems (above 100 Mbps) are still firmly in the domain of custom and semi-custom hardware (mostly FPGAs). In this paper we describe an architecture and testbed for an SDR that can be easily scaled to support over 3 GHz of bandwidth and data rate up to 10 Gbps. The paper covers a novel technique to parallelize typically serial algorithms for phase and symbol tracking, followed by a discussion of data distribution for a massively parallel architecture. We provide a brief description of a mixed-signal front end and conclude with measurement results. To the best of the author’s knowledge, the system described in this paper is an order of magnitude faster than any prior published result.

4.13 CNS Systems and Airborne Networks for Manned and Unmanned Aircraft

Session Organizer: Denise Ponchak (NASA Glenn Research Center), Jamal Haque (Honeywell),

4.1301 Safety Assessment Process for UAS Ground-Based Detect and Avoid

Stephen Lloyd (Aviation Management Associates), Chris Wargo (Mosaic ATM, Inc.), Dylan Hasson , Jason Glaneuski (US DOT / RITA / Volpe Center),

Presentation: Dylan Hasson, Sunday, March 8th, 09:50 PM, Cheyenne

UAS Beyond Visual Line of Sight (BVLOS) capability with conflict detection and traffic avoidance technology is progressing through innovation and improved opportunity within the US National Airspace System and Internationally. However, the actual flight hours flown to gather statistically appropriate levels of real time safety data to quantitatively assess new technical system architectures and operational flight risk is lacking. In this presentation we will describe the safety risk based approach and airspace data assessment technology used to address the lack of live or real time data. This approach is used by the to develop a safe operational Ground Based Detect and Avoid (GBDAA) system for a wide variety of UAS operations in the US National Airspace System (NAS). This presentation will describe the studies used to determine acceptable safety risk levels using this approach and its effect of improved risk based decision making, and it can improve predictability of certain risks in safety assessments.

4.14 Aviation Cyber Security and Cyber-Physical Systems

Session Organizer: Denise Ponchak (NASA Glenn Research Center), Krishna Sampigethaya (Embry-Riddle Aeronautical University),

4.1401 Characterizing Radar Network Traffic: A First Step towards Spoofing Attack Detection

Théobald De RIBEROLLES (ENAC), Nicolas Larrieu (enac), Jiefu SONG (Activus Group), Yunkai Zou ,

Presentation: Théobald De RIBEROLLES, Monday, March 9th, 11:25 AM, Madison

4.14 Characterizing Radar Network Traffic A First Step towards Spoofing Attack Detection

4.1404 Identifying Attack Surfaces in the Evolving Space Industry Using Reference Architectures

Carsten Maple (University of Warwick),

Presentation: Carsten Maple, Monday, March 9th, 11:00 AM, Madison

The space environment is currently undergoing a substantial change and many new entrants to the market are deploying devices in space; this revolution has been termed as NewSpace. The change is complicated by technological devel- opments such as deploying machine learning based autonomous space systems and the Internet of Space Things (IoST). In the IoST, space systems will rely on satellite-to-x communication and interactions with wider aspects of the ground segment to a greater degree than existing systems. Such developments will inevitably lead to a change in the cyber security threat landscape of space systems. As such, there will be a greater number of attack vectors for adversaries to exploit and previously infeas- ible threats can be realised, and will need to mitigated. In this paper we present a reference architecture (RA) that can be used to abstractly model in situ applications of this new space landscape. The RA specifies high level system components and their interactions. By instantiating the RA for two scenarios we demonstrate how to analyse the attack surface using attack trees.

TRACK 5: OBSERVATION SYSTEMS AND TECHNOLOGIES

Track Organizers: Gene Serabyn (Jet Propulsion Laboratory), Ifan Payne (Magdalena Ridge Observatory),

5.01 Space Based Optical Systems and Instruments

Session Organizer: Ryan Mc Clelland (NASA Goddard Space Flight Center), Bogdan Oaida (Jet Propulsion Laboratory, California Institute of Technology),

5.0101 Thermally Formed Inflatable Membrane Reflectors for Space Telescopes

Aman Chandra (Arizona State University), Siddhartha Sirsi , Christopher Walker (University of Arizona), Phuoc Andy Phan , Heejoo Choi , Dae Wook Kim (University of Arizona), Yuzuru Takashima (University of Arizona),

Presentation: Aman Chandra, Sunday, March 8th, 04:30 PM, Elbow 1

Imaging distant objects with increasing spatial resolution has been instrumental in furthering space exploration abilities. Telescopic imaging of exoplanets and other objects require increasingly large collection surfaces in the form of mirrors. Such mirrors when used at terahertz frequencies can further capture object chemistry, mass structure and dynamics. Such technologies could play key roles in the detection of water and other elements in distant systems. However, large cost and development times have restricted the size of reflector mirrors on board on-orbit telescopes. Membrane mirrors could lead to a dramatic scale up in size of deployed surfaces much larger in size than the present state of art such as the James Webb space telescope. Very low areal density and high packing efficiencies have led pneumatically tensioned membrane mirrors being considered as a key- enabling technology towards realizing large space telescopes. Large membrane reflectors built in the past have faced fundamental challenges of unreliable surface shape and uncontrolled dynamics. A major contribution to such inaccuracies has been attributed to manufacturing techniques employed. The final shape attained by freeform membrane reflectors has been modelled as a Hencky surface or an oblate spheroid somewhere in between a perfect sphere and parabola. The conventional method of building a membrane out of smaller gore units also leads to faceted final shapes that deviate from the intended. They have also not been found to be repeatable in attained inflated shapes, thus making it difficult to design corrective optics. Additionally, gore assembly requires fixtures and jigs for precise location leading to poor scalability to large membrane sizes. To harness the ability of membranes as optical reflectors, a repeatable and reliable surface shape is necessary. Further, a scalable manufacturing method is required to construct membranes of sizes of the order of several meters. Our present work focuses on pneumatic-thermal forming of thermo-plastic membranes to desired shapes. Our efforts have been aimed at characterizing the effectiveness of this technique in producing reliable inflated membrane geometries. This method involves heating the membrane close to its glass-transition region with the heated membrane structure inflated pneumatically and held at a constant temperature. This leads to re-orientation of the membrane's internal bi-axial stress state causing a retention of induced curvature when cooled down. This method eliminates breaking down the membrane structure into smaller gore units and can be scaled over to vast membrane sizes. An experimental set-up has been designed and built to thermally form a 1-meter diameter Mylar membrane reflector and conduct shape measurement on its surface. We present results of optical deflectometry and laser ranging measurements used to determine attained membrane surface figures upon repeated inflation cycles. The results are used to validate thermo-structural simulations conducted on the expected membrane surface behavior. Further analysis is conducted to understand optimal circumferential stress distributions to improve the reliability of obtained membrane shapes. Our work contributes towards

an understanding of key design variables in the development of thermally formed large membrane reflectors.

5.0102 An Efficient Focal Plane Alignment Methodology with Application to the ASTERIA Space Telescope

Matthew Smith (Jet Propulsion Laboratory),
Presentation: Matthew Smith, Sunday, March 8th, 04:55 PM, Elbow 1

The process of aligning an instrument focal plane to precursor optics such as a telescope can be a difficult and time-consuming process. The final alignment must achieve sufficient performance at multiple locations across the field of view. In the case of instruments with infinite conjugates, such as a space telescope, there are practical challenges in illuminating the system at multiple off-axis field points simultaneously. Iteration during the alignment process can cause a lengthy search for local minima within the performance cost function. This paper will present a focal plane alignment methodology that avoids the above difficulties and obtains the desired level of optical performance in an efficient manner. The approach is based on systematically measuring spot size across a set of field points and defocus positions, and then using a least squares fit to determine the optimal location for the focal plane. This approach has the additional benefit of revealing the amount of field curvature present in the instrument. It also provides the analyst with a direct calculation of the shims needed to place the focal plane at the computed “best-fit” location. This approach was successfully applied to the Arcsecond Space Telescope Enabling Research In Astrophysics (ASTERIA) payload. ASTERIA is a cubesat mission that was deployed into low-Earth orbit in November 2017 and is still operational as of summer 2019. In addition to presenting the theoretical basis for the methodology, this paper will present laboratory measurements obtained during the payload alignment campaign, and will compare those measurements with images obtained in flight. This approach is applicable to future space-borne optical instruments that require an efficient methodology for focal plane alignment with limited cost or schedule resources.

5.0104 Impact of Remote Sensing Satellites Attitude Parameters on Image Quality

Walid Wahballah (MTC), Fawzy Eltohamy , Taher Bazan (Egyptian Armed Forces),
Presentation: Taher Bazan, Sunday, March 8th, 05:20 PM, Elbow 1

The image quality of very high-resolution optical satellites (VHROS) is affected by several factors, including optics, detector, pointing accuracy errors, attitude stability errors, and altitude variations. Though providing low noise and improved light sensitivity, the time delay and integration (TDI) charge-coupled devices (CCDs) employed in VHROS play an important role along with the satellite attitude parameters in characterizing the image quality. Failure of the satellite control system to maintain the required pointing accuracy and attitude stability during the imaging process leads to a serious degradation in the quality of the acquired images. Hence, it is required to investigate their impacts carefully during the satellite preliminary design phase. In this paper, the combined effect of the TDI steps, satellite attitude parameters, and orbital altitude variations on the image quality are investigated in detail. The results show that cross-track image quality is affected severely by yaw angle and roll angular velocity bias, whereas the along-track image quality is affected merely by pitch angular velocity bias. Furthermore, the proposed mathematical model in this paper reveals that total modulation transfer function (MTF), as a measure of image quality, is affected severely by the satellite altitude variation, especially when employing a high number of TDI steps. For example, for a given scenario, when employing TDI steps of 64 the effect of a satellite altitude variation of 10 Km will result in a 65% reduction in total system MTF.

5.0105 The Development of the 2.4-meter Class Mirror for Space-based and Ground-based Surveillance

Ifan Payne (Magdalena Ridge Observatory), Scott Teare (New Mexico Tech),
Presentation: Ifan Payne, Sunday, March 8th, 09:00 PM, Elbow 1

This paper traces an important part of the early history of space surveillance. ITEK and the Perkin-Elmer Corp were important providers of optics, including 2.4-meter class mirrors which were developed for use in space based telescopes typically used in earth-viewing or “spy” satellites. Two such satellite programs the KH-9, known as HEXAGON, which has now been declassified, and the KH-11, originally known as KENNAN and later in 1982 renamed CRYSTAL, and which remains classified. Perhaps the most well-known of these space-based 2.4 m mirrors was used on the Hubble Space Telescope which has steadily produced spectacular astronomical science and continues to do so today. Those same light weight 2.4-meter mirrors were also ideal for use in fast slewing, ground based telescopes for tracking and imaging ICBMs. One of those light-weight 2.4-meter mirrors found its way to New Mexico Tech and became the basis of the Magdalena Ridge Observatory. This paper traces the history of the light weight 2.4-meter class mirror, the intertwined relationships between ITEK and Perkin-Elmer. Both companies went through individual transformations, break-ups and acquisitions, only to finally come together in the Hughes Danbury Optical Systems company.

5.02 Balloon-based observatories

Session Organizer: J. Kent Wallace (Jet Propulsion Laboratory), Stefan Martin (Jet Propulsion Laboratory),

5.0201 Development of a High-Altitude Balloon Controlled Ascent System

Michael Fusco , Douglas Isenberg (Embery-Riddle Aeronautical University),
Presentation: Michael Fusco, Sunday, March 8th, 09:25 PM, Elbow 1

The objective of the High-Altitude Balloon Controlled Ascent System (HABCAS) is to release gas (e.g., helium) and ballast (e.g., sand) from a latex high-altitude balloon (HAB) system to achieve neutral buoyancy and thereby achieve a longer flight duration. The project described is the successful simulation of a full state-feedback, closed-loop controller. The research focuses on a feasibility analysis rather than a preliminary design. However, the mass control inputs from this analysis will be used to generate the requirements for a preliminary design of the actuation system. The control system uses experimental flight data to build a simplified state-space model, and in this regard the presented results have basis in observation. The paper presents a semi-empirical dynamic model with linearized equations of motion. The underlying assumption in the dynamics is that the ascent profile can be approximated by two regions, above and below 16 km (i.e., around the tropopause), with approximated steady-state velocities. With the dynamic model, feedback control is implemented through both pole placement and a linear quadradic regulator (LQR). In the pole placement approach, the balloon would have drifted to a burst altitude before it was fully controlled, prolonging simulated flight time by 27.5 minutes. The LQR approach would have reached steady state below burst, prolonging simulated flight time by three times longer than the original flight. In both control approaches, a large steady-state error is present. However, this error is successfully addressed with integral control. A discussion follows about the control implementation.

5.0203 Tethered Balloon-Based Experiment of Surface Water Height Using Satellite Signals of Opportunity

Hunter Hall (NASA Jet Propulsion Lab), Samuel Holt , Van Duong (Georgia Institute of Technology), Matthew Chamieh (Boston University), Rohan Daruwala (University of Wisconsin), Kyle Weng (California Institute of Technology), Christine Yuan , Michael Lally (New York University), Peter Soon Fah (California

State Polytechnic University Pomona), Chrishma Singh-Derewa (NASA JPL), Thomas Bewley (UC San Diego), Ryan Alimo (NASA Jet Propulsion Lab), Luan Nguyen , Ramin Rafizadeh (University of Maryland College Park),

Presentation: Hunter Hall, Sunday, March 8th, 09:50 PM, Elbow 1

Signals of Opportunity (SoOp) is an area of radio science that leverages existing ambient signals from spacecraft, aircraft, and ground-based radio systems to perform radio science without spending time or resources constructing new transmission infrastructure. It has been conceptualized that SmallSats or CubeSats can perform similar SoOp missions by augmenting pre-existing spacecraft missions — specifically radio/radar missions. During the summer of 2019, student-interns at the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL) under the Innovation to Flight (i2F) program tested the first airborne SoOp demo via a tethered aerostat — a valuable step towards getting a SoOp demo in orbit. The airborne SoOp demo received direct and bounced signals from multiple geosynchronous equatorial orbit (GEO) satellites by using two on-board wide-band grid antennas. One antenna was pointed at the sky at appropriate azimuth and elevation angles to receive a direct GEO signal. The other antenna was pointed at an identical azimuth angle with a mirrored elevation angle so as to receive the same GEO signal reflected from a body of water below. Both antennas were secured on adjustable mounts to allow for pointing changes and permit data collection from multiple satellites. This initial test proves the scientific and technological feasibility of doing further airborne SoOp tests, potentially on aircraft, unmanned aerial vehicles (UAV), high altitude balloons (HAB), and SmallSats or CubeSats.

5.03 Exoplanet Instruments, Missions and Observations

Session Organizer: William Danchi (NASA Goddard Space Flight Center), Stefan Martin (Jet Propulsion Laboratory),

5.0301 CubeSat Array for the Detection of RF Emissions from Exoplanets

Jose Velazco (Jet Propulsion Laboratory), Martijn Kok (Eindhoven University of Technology), Mark Bentum (Eindhoven University of Technology),

Presentation: Martijn Kok, Monday, March 9th, 05:20 PM, Lake/Canyon

We are presenting a CubeSat mission concept wherein a large number of small spacecraft furnished with Ultra-Long Wavelength (ULW) observation antennas is to be implemented to synthesize a large aperture for detecting ULW emissions from selected Exoplanets. The CubeSat Array for the Detection of RF Emissions from Exoplanets (CADRE) concept involves the placement of a swarm arrangement of CubeSats into small-amplitude Lissajous orbits around the Earth-Moon L2 point. In addition to the ULW receivers, each CADRE CubeSat will be furnished with a novel omnidirectional optical communicator which should allow data sharing at gigabit per second data rates. This presentation starts with the current state of the art in low-frequency radio astronomy and list the potential science objectives of a space-based interferometry array. Furthermore, the estimated interferometer requirements needed to detect exoplanet RF emissions are presented. While the detection of exoplanet emissions is CADRE’s ultimate goal, many other science cases could be explored during the gradual build-up of the large small spacecraft array. An outline of the potential architecture and key technical challenges of an eventual CADRE implementation is presented. One of CADRE’s main defining characteristics are the small-amplitude orbits at the Earth-Moon L2 point, which requires regular station-keeping to maintain orbit and a relay system to downlink measurement data to Earth. Another characteristic is the designed inter-satellite optical crosslink, which allows for fast sharing of the measured RF signals for subsequent on-board processing. The design and capacity of this optical communication network are discussed. A conceptual overview of a CADRE smallsat is presented, listing the required flight

hardware components. The presentation concludes by listing the operational phases of the CADRE mission and the next research and development steps required to realize this space-based radio interferometry array.

5.0302 Vector Vortex Waveplates with Tunable Spectrum and Switchable Topological Charge

Nelson Tabiryan (BEAM Engineering for Advanced Measurements Co.), David Roberts (Beam Engineering for Advanced Measurements Co.), Sarik Nersisyan (BEAM Co.), Gene Serabyn (Jet Propulsion Laboratory),

Presentation: Nelson Tabiryan, Monday, March 9th, 09:00 PM, Lake/Canyon

The contrast of astronomical coronagraphs based on vector vortex waveplates (VWs) depends critically on precision of fulfilment of half-wave retardation condition for the desired wavelength range. The structure of VWs designed for operation in broad bands of spectrum is typically rather complex comprising three-dimensional modulation patterns that in practice are obtained in layer-by-layer deposition of liquid crystal polymers (LCPs). Physical properties of each of those layers - thickness, retardation, and orientation modulation pattern, along with layer integrity and quality - need to be maintained with very high precision to ensure contrast requirements of coronagraphs. This inevitably reduces the yield and affects the quality of high contrast VWs. We discuss opportunities of tuning the retardation values of VWs using electric field for liquid crystal (LC) based VWs as well as temperature and optical radiation for LCPs. LC VWs allow also tuning the spectral range of operation and switching the topological charge of the effective VW system.

5.0303 The HabEx Telescope: Systems Engineering and STOP Modeling

H. Philip Stahl (NASA - Marshall Space Flight Center),

Presentation: H. Philip Stahl, Monday, March 9th, 09:25 PM, Lake/Canyon

Review of the HabEx baseline telescope opto-mechanical design and predicted performance.

5.0304 The HabEx Observatory: A Coronagraph and a Starshade for Exoplanet Science.

Stefan Martin (Jet Propulsion Laboratory), H. Philip Stahl (NASA - Marshall Space Flight Center), Gary Kuan (Jet Propulsion Laboratory), David Webb (JPL), Keith Warfield (Jet Propulsion Laboratory), Doug Lisman ,

Presentation: Stefan Martin, Monday, March 9th, 09:50 PM, Lake/Canyon

The National Academies' 2020 Decadal Survey on Astronomy and Astrophysics will provide a broad vision for future science in these disciplines and the Habitable Exoplanet Observatory (HabEx) is one of four major observatory missions extensively studied in preparation for the survey. HabEx is a space telescope with a 4 m diameter primary mirror, carrying a complement of two general astrophysics camera/spectrographs with coverage from the far UV to the near infrared as well as two key instruments for exoplanet science. These exoplanet instruments consist of a high performance coronagraph (that places stringent demands on the overall observatory design and performance) and a remote (tens of megameters distant) formation flying occulter, consisting of a 52 m diameter starshade deployed from a second launch vehicle. This paper discusses the specific features of the observatory that permit high contrast coronagraphy at the 10^-10 contrast level and the design considerations for the coronagraph itself. The starshade design is discussed in the context of the current technology development activities being undertaken by NASA to bring starshade readiness up to TRL5. Finally the design and performance of the starshade instrument itself is presented. The information given here is provided for planning and discussion purposes only. This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the

5.04 Atmospheric Turbulence: Propagation, Phenomenology, Measurement, Mitigation

Session Organizer: Jack McCrae (Air Force Institute of Technology), Noah Van Zandt (Air Force Research Laboratory),

5.0401 Wave Optics Simulations of a Dual Beacon Hartmann Turbulence Sensor

Jack McCrae (Air Force Institute of Technology), Santasri Bose Pillai (Air Force Institute of Technology), Steven Fiorino (AFIT), Christopher Rice ,

Presentation: Jack McCrae, Monday, March 9th, 08:30 AM, Elbow 1

Wave optics were used to simulate a dual beacon Hartmann Turbulence Sensor (HTS). The system simulated was used experimentally to measure turbulence profiles. These simulations were intended to help explain differences between the experimental results and theoretical predictions. The theoretically predicted results presume weak turbulence, a Kolmogorov power spectrum for the turbulence, and a geometric optics derived weighting of the turbulence along the path. The simulations carried out used a modified von Kármán spectrum, with finite inner and outer scales, so the effects of these scales could be readily studied. A number of interesting results were obtained. The simulations resulted in lower tilt variances in the HTS subapertures than expected, but this had little end effect on the turbulence profiles produced. The effect of the inner and outer scales on this point will be discussed. The profiling technique proved to be powerful enough to sometimes resolve individual phase screens used in simulation. While this result is very interesting, it points to the challenges in simulating a system like this, rather than any difference between theory and experiment. Finally, while the geometric optics presumption is seen as ignoring diffraction, no conclusion on the differences between theory and experiment (or simulation) based upon this point was made. The simulations concentrated on simulating an actual HTS system with a 32 x 32 subaperture array on a 16” telescope at a 1 km range.

5.0403 Impact of Measured Turbulence on Laser Beam Propagation

Benjamin Whetten (Air Force Research Laboratory), Noah Van Zandt (Air Force Research Laboratory),

Presentation: Benjamin Whetten, Monday, March 9th, 08:55 AM, Elbow 1

This study investigates the effects of atmospheric turbulence on laser beam propagation. It compares the effects of Kolmogorov turbulence to those of measured turbulence. A previous experiment took measurements of atmospheric turbulence using thermosondes beneath a weather balloon. The data shows elevated layers of increased turbulence strength. Within each layer, the power spectral density of the turbulence exhibits a power law differing from the -11/3 power law of Kolmogorov theory. To understand how these departures from theory impact optical propagation, we import the turbulence data into a wave-optics model. Additionally, we simulate two common types of turbulence measurement devices to test their usefulness against the non-Kolmogorov turbulence. One device is a scintillometer, while the other measures the Modulation Transfer Function (MTF). These simulated measurements produce a much simpler and lower resolution description of the turbulence compared to the data from the thermosondes, which we consider to be truth in this work. The wave-optics model uses the traditional split-step propagation method with phase screens that represent the turbulence for each segment of the path. We generate the phase screens using either the thermosondes’ truth measurements or the Kolmogorov statistics derived from the scintillometer and the MTF method. We propagate laser beams and point sources through both types of phase screens and compare the results. The metrics for the comparisons include scintillation index, Strehl ratio, and power-in-the-bucket. The results show that the Kolmogorov turbulence prescribed by the MTF method underestimates the strength of the turbulence. On the other hand, the scintillometer prescribes turbulence that is a good surrogate for the true non-Kolmogorov turbulence. These results will lead to a better understanding of optical turbulence, how it can be measured, and how it affects optical beams during propagation.

5.0404 Speckle Mitigation for Improved Optical Tracking Performance

Helena Franklin (USRA- AFRL Scholars Program), Noah Van Zandt (Air Force Research Laboratory), Presentation: Helena Franklin, Monday, March 9th, 09:20 AM, Elbow 1

Optical systems attempting to track distant objects face a number of challenges, including turbulence and speckle. Turbulence in the atmosphere causes phase perturbations that can severely distort the imagery. Additionally, natural illumination of the object is sometimes insufficient, and laser illumination must be used. Laser illumination leads to optical speckle, which causes the imagery to break up into bright and dark patches. Speckle is caused by the combination of the coherence of the laser light and the roughness of the object's surface, and it can be a severe source of noise for tracking systems. While theory exists to predict the impact of full-strength speckle on tracking performance for simple objects (i.e., a circle or a square), the effects of reduced speckle are largely unexplored. This work investigates the impact of partially mitigated speckle on object tracking over long paths through atmospheric turbulence. The speckle is mitigated using polychromatic illumination. Polychromatic speckle mitigation spoils the temporal coherence (i.e., the coherence length) of the laser light to produce a narrow band of wavelengths, thus reducing the strength of the speckle. This work uses wave-optics simulations in a software package known as PITBUL to investigate tracking performance over a range of coherence lengths from 1 mm to 1 m. The objects are unmanned aerial systems. First, pristine images are created. Then, the images are degraded by a number of effects, including atmospheric turbulence, atmospheric transmission, path and background radiance, speckle, and sensor effects. The resulting images are tracked using the Fitts correlation algorithm and the centroid algorithm. Tracking performance is analyzed over several seconds by comparing the tracker's estimate of aimpoint position to the actual aimpoint position on the object during both straight-and-level flight and turns. The results show that polychromatic speckle mitigation is sometimes necessary to maintain track of the object, and it significantly reduces both track jitter and track drift.

5.05 Image Processing

Session Organizer: Matthew Sambora (USAF),

5.0505 Earth Observation Satellite Learning to Video Compressor Complexity Reduction

Mohammadreza Bayat , Rongke Liu , Ladan Arman , Hossein Zarrini (University of Colorado Denver), Presentation: Hossein Zarrini, Monday, March 9th, 04:55 PM, Lake/Canyon

This study has discussed the importance of using a learning technique for satellites to ease video coding algorithms. On the one hand, satellites move in a very predictable manner and stay on schedule and on the other hand we need to eliminate similarities to better Video compression. Based on the evidence, MVs similarities suggest keeping detected MVs data at the Inter-Prediction stage of a compressing procedure for a built-in camera on a spacecraft can apply in the next orbital cycles.

5.06 Optical Detection and Analysis for Space Situational Awareness (SSA)

Session Organizer: Michael Werth (Boeing Company),

5.0601 Initial Orbit Determination Using Simplex Fusion

Patrick Handley (Ball Aerospace),

Presentation: Patrick Handley, Wednesday, March 11th, 10:10 AM, Lamar/Gibbon

A new Initial Orbit Determination (IOD) method for angles-only observations is presented. This method is based on an adaptive Nelder-Mead simplex optimization technique for fusion of multiple observations from one or more acquisition satellites. The resulting solution characterizes the target orbit as a standard state vector. The algorithm is tested under a variety of scenarios, including acquisition orbits in Low Earth Orbit (LEO) and Geostationary Orbit (GEO), as well as targets in GEO, both coplanar and non-coplanar cases, number of observations varying from 3 to 8, and time between observations varying from 60 to 1800 seconds. Observation error is varied in all cases to characterize the performance of the algorithm given varying angular resolution error. The simplex fusion algorithm is shown to perform well in a variety of cases when multiple acquisition satellites are used. Special emphasis is placed on GEO to GEO observations where the acquisition and target are in coplanar orbits. This new IOD method supports Space Situational Awareness (SSA) capabilities by enhancing performance in scenarios with multiple observation satellites for challenging GEO to GEO IOD scenarios.

5.0602 LUCID: Accelerating Image Reconstructions of LEO Satellites Using GPUs

Michael Werth (Boeing Company), Kevin Roe ,

Presentation: Michael Werth, Wednesday, March 11th, 10:35 AM, Lamar/Gibbon

We report on a new Multi-Frame Blind Deconvolution (MFBD) implementation developed to reconstruct high resolution images of Low Earth Orbit (LEO) satellites from short-exposure ensembles of images recorded from a large diameter ground-based telescope. This implementation, named Likelihood-based Uncertainty-Constrained Iterative Deconvolution (LUCID), uses NVidia's Compute-Unified Device Architecture (CUDA) to perform iterative blind deconvolution processing on Graphical Processing Units (GPUs). A single instance of LUCID is capable of using multiple GPUs to segment and process a large collection of image frames in parallel, achieving significant reductions in processing time and hardware cost compared to equivalent algorithms that only use Central Processing Units (CPUs). In this paper we describe how LUCID makes use of CUDA and GPU hardware to produce image reconstructions. We also show performance comparisons between the gold-standard Physically Constrained Iterative Deconvolution (PCID) implementation of MFBD running on all of the cores of an enterprise-class CPU and LUCID running on various target GPU platforms, including consumer-grade and datacenter-grade devices. The quality of image reconstructions produced by LUCID is demonstrated by showing data collected with the 3.6-meter Advanced Electro-Optical System (AEOS) telescope before and after processing.

5.0604 Automated Interpretability Scoring of Ground-Based Observations of LEO Objects with Deep Learning

Jacob Lucas (The Boeing Company), Michael Werth (Boeing Company), Trent Kyono (Boeing),

Presentation: Jacob Lucas, Wednesday, March 11th, 11:00 AM, Lamar/Gibbon

The Space-object National Imagery Interpretability Rating Scale (SNIIRS) allows human analysts to provide a quantitative score of image quality based on identification of target features. It is naturally difficult to automate this scoring process, not only because the scale is based on identifiable features but also because the images may be in an almost-resolved image quality regime that is difficult to handle for traditional machine vision techniques. In this paper we explore using a convolutional neural network to automatically produce SNIIRS scores. We use wave-optics simulations with varied turbulence strength to generate a dataset of images of Low-Earth Orbit (LEO) satellites observed from a ground-based optical observatory. SNIIRS scores are automatically generated for these images based on a combination of a priori knowledge of each object's simulated features and the simulated turbulence strength. A neural network is then trained to provide accurate SNIIRS scores from single images without being provided knowledge of the object model. We then transition this approach to real images collected at the Maui Space Surveillance Site on Haleakala, with initial results showing performance similar to that of a trained analyst.

5.0605 SILO: A Machine Learning Dataset of Synthetic Ground-Based Observations of LEO Satellites

Michael Werth (Boeing Company), Jacob Lucas (The Boeing Company), Trent Kyono (Boeing),
Presentation: Michael Werth, Wednesday, March 11th, 11:25 AM, Lamar/Gibbon

Images of space objects may have their interpretability assessed with a Space-object National Imagery Interpretability Rating Scale (SNIIRS) score. The rules for such scores are specific, but the process of rating a large number of images can be time-consuming even for a skilled analyst. As this scale is subjective and based on interpretability of resolved features, it is also difficult to provide automated SNIIRS assessments with a simple algorithmic procedure. A Convolutional Neural Network (CNN) may be able to solve this problem, but such an effort requires a large labeled dataset of images. In this paper we will describe the effort to use wave-optics simulations to generate a dataset of SNIIRS-scored images of Low Earth Orbit (LEO) satellites observed from a ground-based optical observatory with varied turbulence conditions. This first iteration of the Scored Images of LEO Objects (SILO) dataset is intended to serve as a foundation for deep learning efforts, similar to how MNIST and ImageNet have been foundational datasets in other machine vision domains. This dataset is already being used in numerous machine learning efforts, including those pertaining to using CNNs to perform image interpretability assessment and to produce higher-resolution image recoveries from degraded image sets. In this paper we also describe some of the other potential uses for this dataset.

5.07 Photonics and Lasers

Session Organizer: Aleksandr Sergeyev (Michigan Technological University), Joshua Shank (Sandia National Laboratories), David Peters (Sandia National Laboratories),

5.0701 Photonic Integrated Circuit TUned for Reconnaissance and Exploration (PICTURE)

Anthony Yu (NASA - Goddard Space Flight Center), Conor Nixon (NASA GSFC), Michael DiSanti (NASA - Goddard Space Flight Center), Michael Krainak (NASA GSFC), Igor Vurgaftman (Naval Research Laboratory), Jerry Meyer (Naval Research Laboratory), Aditya Malik , John Bowers (UCSB), Alexander Spott (University of California, Santa Barbara),
Presentation: Anthony Yu, Wednesday, March 11th, 11:50 AM, Lamar/Gibbon

The mid-infrared (MIR) spectral range (3-5 μm) is of particular interest for remotely sensing gaseous molecules such as H2O, CO2, CH4, N2O, CO, NH3, and many other compounds. The infrared spectra of planets, moons, comets and asteroids are rich in information, including gas composition and surface mineralogy. Significant advances in technology have emerged for ground-based telescopes, including the higher spectral resolution permitted by cross-dispersed instruments and heterodyne techniques. New technologies offer the opportunity to break this barrier, by using solid-state photonics. In the next three years, under the NASA ROSES PICASSO program, we plan to develop the key subsystems for a revolutionary MIR spectrometer Photonic Integrated Circuit TUned for Reconnaissance and Exploration (PICTURE) based on integrated photonics technology that offers ultra-small size, weight and power with non-moving parts and low cost for future planetary missions. In this paper, we will describe our program objectives in demonstrating the concept and functionalities of the PICTURE instrument, which comprises four major subsystems: (i) collection optic (telescope), (ii) fiber delivery subsystem using a photonic lantern (PL), (iii) Photonic Integrated Circuit Spectrometer (PICS) and (iv) electronics, data processing, storage and networking subsystem. PICS is a fully operational test unit that focuses on the CO spectral band at 4.6-4.8 μm that is of key importance to cometary science. Our 3-year program will focus on the development of a PICS subsystem designed for CO spectroscopic measurements near 4.65 μm. We will also explore a future instrument concept that exploits the broad wavelength potential of the PICS design to provide spectroscopy spanning the full MIR and longwave IR (LWIR) bands for wide applicability in planetary science, for example to probe CO2, H2O, and CH4, the strongest transitions from which are difficult (CH4) or impossible (CO2, H2O) to detect using Earth-based telescopes. Each integrated-photonics-spectrometer chip will feature a single heterodyne room-temperature laser with wide wavelength tuning range, or multiple local-oscillator lasers for much broader spectral coverage. The fully developed PICTURE instrument will provide a cost-effective high-resolution spectrometer for CubeSat and SmallSat, as well as larger satellites.

5.08 Techniques and instruments for extant life detection

Session Organizer: Chris Lindensmith (Jet Propulsion Laboratory, California Institute of Technology), J. Kent Wallace (Jet Propulsion Laboratory),

5.0801 An Integrated Dual-mode Digital-holographic/light-field-fluorescence Microscope for Life Searches

Gene Serabyn (Jet Propulsion Laboratory), Kurt Liewer (Jet Propulsion Laboratory), Chris Lindensmith (Jet Propulsion Laboratory, California Institute of Technology), J. Kent Wallace (Jet Propulsion Laboratory), Jay Nadeau (Portland State Universty),

Presentation: Gene Serabyn, Friday, March 13th, 10:35 AM, Jefferson

A promising way to search for microbial life in our solar system's Ocean Worlds is to use 3d microscopes, as these can provide single-image inventories of the complete contents of liquid sample volumes. Two applicable 3d microscopy techniques are digital holographic microscopy and light-field fluorescence microscopy. The former can provide high-resolution imaging information on cellular morphology and structure, index of refraction, and motility, while the latter can identify and locate targeted molecule families, such as lipids and nucleic acids. The combination of this pair of 3d techniques thus provides a powerful suite of diagnostic tools. We have recently combined both types of microscope into an integrated dual-mode microscope prototype aimed at demonstrating its utility at terrestrial field sites, and the combined instrument has already been taken on an initial foray into the field to assess its performance and shortcomings. Here we describe the design and capabilities of our dual-mode microscope, as well as initial performance measurements obtained during its first field trip to the local seashore

5.0802 Polarization Sensing in Digital Holographic Microscopy

J. Kent Wallace (Jet Propulsion Laboratory), Gene Serabyn (Jet Propulsion Laboratory),

Presentation: J. Kent Wallace, Friday, March 13th, 11:00 AM, Jefferson

Digital holographic microscopy is well suited to the search for microbial species due in part to its intrinsic stability, volumetric imaging capability, and sensitivity to very dilute samples. This is all done with a system having no moving parts, making it additionally attractive for flight instrumentation. Our devices have been field tested on several occasions, and have demonstrated robustness to extreme conditions. When bacteria are alive and moving, they are easy to detect. However, some measurements are subtler. Can we distinguish between a live yet nonmotile species and a mineral, for instance? To provide another method of discrimination, we have added the ability to measure object polarization. This will allow us to characterize the sample by polarization state with-

out any sacrifice in the spatial or temporal resolution (< 1um at 15 Hz). This snapshot polarization sensing is a new method for characterizing the sample under test. In this paper, we will describe the instrument design, the laboratory tests, and demonstrate its performance with live bacteria and crystalline samples.

5.0803 Microscopic Object Classification through Passive Motion Observations with Holographic Microscopy

Chris Lindensmith (Jet Propulsion Laboratory, California Institute of Technology), Jay Nadeau (Portland State Universty), Manuel Bedrossian (California Institute of Technology), J. Kent Wallace (Jet Propulsion Laboratory), Gene Serabyn (Jet Propulsion Laboratory),

Presentation: J. Kent Wallace, Friday, March 13th, 11:25 AM, Jefferson

Digital holographic microscopy provides the ability to observe throughout a volume that is large compared to its resolution element without the need to refocus through the volume. This capability enables simultaneous observations of large numbers of small objects within such a volume. We have constructed a microscope that can observe a volume 0.4 x 0.4 x 1.0 μm with submicrometer resolution for observation of microorganisms and minerals in liquid environments in earth and on potential planetary missions. Because environmental samples are likely to contain mixtures of inorganics and microorganisms that are of comparable sizes near the resolution limit of the instrument, discrimination of living and non-living objects may be difficult. The motion of motile organisms can be used to readily distinguish them from non-motile objects (live or inorganic), but additional methods are required to distinguish non-motile organisms and inorganic objects that are of comparable size but different composition and structure. Here we evaluate the use of passive motion to make this discrimination by evaluating diffusion and buoyancy characteristics of objects in the field of view.

TRACK 6: REMOTE SENSING

Track Organizers: Jordan Evans (Jet Propulsion Laboratory), Darin Dunham (Lockheed Martin),

6.01 Systems Engineering Challenges and Approaches for Remote Sensing Systems

Session Organizer: Karen Kirby (JHU-APL), Todd Bayer (NASA Jet Propulsion Lab),

6.0101 3D Simulator for Wind Interferometer Data-Model Comparison

Md Nurul Huda (Virginia Polytechnic Institute and State University,), Gustavo Gargioni (Virginia Tech),

Presentation: Gustavo Gargioni, Friday, March 13th, 08:30 AM, Dunraven

The connection between earth and space weather has numerous impacts on spacecraft, radio communications, and GPS signals. Thus, predicted & modeling this region is essential, yet models (both empirical and first principles) do a poor job of characterizing the variability of this region. One of the main objectives of the NASA ICON mission is to measure the variability of the ionosphere and thermosphere at low-mid latitudes. The MIGHTI instrument on ICON is a Doppler Interferometer that measures the horizontal wind speed and direction with 2 discrete MIGHTI units, separated by 90˚, mounted on the ICON Payload Interface Plate. This work focuses on building a simulation of wind interferometer data, similar to MIGHTI, using a first-principles model as the input dataset, which will be used for early validation and comparison to the MIGHTI data. Using a ray-tracing approach, parameters like O, O2, O+, O2+, T, wind, will be read for every point along every ray from the model and brightness and Line of Sight (LOS) wind will be calculated as functions of altitude and time. These data will be compared to the MIGHTI observations to both to establish the limitation of such models, and to validate the ICON data. ICON will help determine the physics of our space environment and pave the way for mitigating its effects on our technology, communications systems, and society. However, ICON is yet to launch and due to the unavailability of MIGHTI data, we have selected another instrument called WINDII (Wind Imaging Interferometer) from a different mission UARS (Upper Atmosphere Research Satellite) to demonstrate the utility of this data-model comparison. Similar to MIGHTI, WINDII measures Doppler shifts from a suite of visible region airglow and measures zonal and meridian winds, temperature, and VER (Volume Emission rate) in the upper mesosphere and lower thermosphere (80 to 300 km) from observations of the Earth's airglow. We will use a similar approach discussed for MIGHTI to calculate the vertical profile of Redline airglow, Wind velocity, emission rate and compare them with our simulated results to validate our algorithm. We initially thought asymmetry calculation along the Line of Sight (LOS) would be the limiting factor. We believe other things are going on such as variability in the winds associated with natural fluctuations in the thermosphere, atmospheric waves, inputs from the sun and the atmosphere below etc., that appear to be a more significant factor than just asymmetry along the line of sight.

6.0102 Statistical Classification of Remote Sensing Satellite Constellations

Ibrahim Sanad (University of British Columbia (UBC)), David Michelson (University of British Columbia), Zahra Vali ,

Presentation: Ibrahim Sanad, Friday, March 13th, 08:55 AM, Dunraven

In recent years, heterogeneous satellite constellations that use inter-satellite links (ISLs) between two different functional constellations, a remote sensing satellite constellation (RSSC) and a relay communication satellite constellation (RCSC) dedicated to command delivery and relay data back to Earth, have attracted considerable interest. The design of general purpose RCSCs that serve a range of RSSCs is complicated by the many different RSSCs that have been deployed to date and the effort required to test the performance of a candidate RCSC against each one. Accordingly, we have sought to determine whether a pattern in RSSCs exist that would allow us to represent the greater population by a much smaller set of representative classes. Based on a statistical analysis of NORAD Two-Line-Elements (TLEs) for 34 RSSCs and a thorough review of their missions, we propose a nine-class solution based upon orbital inclination (three categories) and the number of planes and different altitudes (three categories) although only seven of these classes are actually populated by actual RSSCs. The actual number of planes, orbital altitudes, and orbital inclinations are represented by simple distributions. The results allow the performance of RCSCs to be tested against a broad and representative set of RSSCs with far less effort than testing against an exhaustive set and far more confidently than against a random set.

6.0103 Pointing and Alignment for the Emirates Mars Mission

Michael Bonnici (LASP, University of Colorado), Mohsen Al Awadhi (Mohammed Bin Rashid Space Centre),

Presentation: Michael Bonnici, Friday, March 13th, 09:20 AM, Dunraven

The Emirates Mars Mission (EMM) will be the UAE's first mission to explore another planet in our solar system. The mission is designed to study the Martian atmospheric circulation and connections through measurements done using three instruments that image Mars in the visible, thermal infrared, and ultraviolet wavelengths. The measurements are collected at all times of day over a full Martian year. In this paper we will show the approach to defining, measuring, verifying and validating the pointing metrics and alignments for each instrument necessary to obtain a spatial resolution of 10 km for visible imagery, 300 km for infrared imagery, and 100 km for the ultraviolet measurements of the lower and upper atmosphere from orbital altitudes ranging between 20,000 and 43,000 km. We will detail the methods of specifying the alignment requirements to the spacecraft subsystems and the payload suite and go through the measurement process that shows EMM can achieve the pointing knowledge and control, jitter and stability metrics.

6.0104 Digital Elevation Model Enhancement Using CNN-Based Despeckled SAR Images

Shady Saied (MTC), Mohamed Elshafey (Military Technical College), Tarek Mahmoud (MILITARY TECHNICAL COLLEGE),

Presentation: Tarek Mahmoud, Sunday, March 8th, 09:50 PM, Dunraven

Synthetic Aperture Radar (SAR) imaging systems have the ability to acquire images of the terrain surface in all weather conditions and all day times. Digital Elevation Model (DEM) can be generated from two or more SAR images, and is considered essential in various recent applications. Acquired SAR images are often exposed to speckle noise, which has a negatively bad effect on the processing and interpretation of the SAR images, and hence on the DEM generation process. In this paper, a Convolution Neural Network (CNN) based preprocessing layer is suggested in the DEM generation process from SAR images. The main purpose of the suggested CNN based preprocessing layer is removing speckle noise from input SAR images, from which an enhanced DEM can be generated. Extensive experiments are carried out on SAR images, and different DEMs are generated from original SAR images and from despeckled ones. Comparative analysis is figured out, and results show significant enhancements in despeckled SAR images and in the subsequent generated DEMs.

6.0105 Instrument Data Metrics Evaluator for Tradespace Analysis of Earth Observing Constellations

Vinay Ravindra (NASA Ames Research Center), Sreeja Nag (NASA Goddard Space Flight Center / Ames Research Center (BAERI)),

Presentation: Vinay Ravindra, Friday, March 13th, 09:45 AM, Dunraven

There is currently a trend towards developing and commissioning satellite constellation missions, which has necessitated tradespace studies to design high-performance, low cost and low risk constellations. An open-source software tool called Tradespace Analysis Tool for Constellations (TAT-C) has been developed at the NASA Goddard Space Flight Center, which aims to facilitate pre-phase A mission studies by generating and optimizing the tradespace of the constellations, involving a multitude of possibly coupled parameters such as orbits, satellites, launchers, ground-stations, and instruments. The performance attributes investigated by TAT-C are instrument data metrics, coverage metrics, cost and risk. While previous research has explored optimization of the constellation satellite orbits using metrics associated with coverage (such as maximizing access duration, maximizing the number of revisits over a region), there is relatively less work on exploring the tradespace of instrument parameters and associated data metrics. Previous research has also used relatively rudimentary data-metrics such as imaged pixel resolutions, range, and angles at which observations are made. This paper describes the instrument datametrics evaluator of TAT-C which generates more sophisticated data metrics characteristic of the instrument type. The basic concept and the architecture of the evaluator have been developed to accommodate instruments without assuming specifics about the underlying technology. In this paper, we describe the modeling of the two most common types of Earth Observing instruments, namely passive optical sensors and synthetic aperture radars (SARs). The models allow for evaluation of commonly used data-metrics such as the signal to noise ratio, noise equivalent delta temperature, ground-pixel resolutions, dynamic range, noise-equivalent sigma0, etc. The challenges in making the models generic enough for wide usage, while

being able to appropriately mimic characteristics of complex real-world instruments, are described using examples such as the Landsat-8 Thermal Infrared Sensor and Operational Land Imager. Lastly, we present results from the instrument data metrics evaluator for three important use cases of mission design with passive-optical sensors and SARs. The first use case explores the tradespace of Sun-Synchronous Orbits from a perspective of data-metrics as opposed to commonly considered coverage metrics. The second use case explores the tradespace of SAR parameters and highlights quantitative trade-offs between instrument parameters influencing the performance, size, and complexity. Such tradespace analysis allows the user to appreciate and consider a fundamental constraint on the SAR antenna size depending on radar frequency. In the last use case, we explore the tradespace of pushbroom vs whiskbroom scanners, and evaluate the conditions under which their performance match.

6.0106 Applications of Failure and Anomaly Analysis for Space Systems

Kaden Loring (NASA-Goddard Space Flight Center/NOAA-NESDIS/the University of Florida),
Presentation: Kaden Loring, Friday, March 13th, 10:10 AM, Dunraven

Space missions are inherently high-risk and expensive. The space environment is harsh, making space system design and manufacture difficult. By studying past failures/anomalies (F/A), measures may be adopted in the concept and design mission phases to prevent reoccurrences. This could potentially save missions from premature failure and extend useful-life. The F/As considered in this research were studied by means of Failure Review Boards (FRB), F/A Review documents, NASA Lessons Learned, engineering handbooks, and science and engineering seminars. The project was meant to serve as an unbiased review of F/A root causes and as an educational resource for those interested in Applied Physics and Astronautical Engineering. Four major commonalities will be identified through studies of the Joint Polar Satellite System (JPSS) and many other space systems reviewed for comparison. The common root causes include 1) Written Procedures and Training, 2) Electrical Grounding and Conductance Design, 3) Material Incompatibility, and 4) Process Induced Contamination Including Foreign Object Debris (FOD). Publicly available examples for each root cause category will be explored and presented as a case study in how F/A analysis can be applied to improve the success rate of space systems. The findings from this research validates results from similar internal reviews. Additionally, we will discuss general preventative actions for each case study which could benefit future space missions. By developing a strong understanding of various F/As, space systems may be designed more robustly, and requirements for manufacture and operational performance written more effectively. For the designers of next generation space systems, the results of this project present an opportunity for accelerated success and avoidance of pitfalls by cognizant analysis and root cause investigation.

6.02 Instrument and Sensor Architecture, Design, Test, and Accommodation

Session Organizer: Matthew Horner (JPL), Keith Rosette (Jet Propulsion Laboratory),

6.0201 Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE) Mission Integration and Testing

Susanna Petro , Karen Pham (NASA - Goddard Space Flight Center),
Presentation: Susanna Petro, Monday, March 9th, 10:35 AM, Cheyenne

This presentation describes the plans, flows, key facilities, components and equipment necessary to fully integrate, functionally test and qualify the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Observatory. The PACE observatory is comprised of the spacecraft and three instruments, an Ocean Color Instrument (OCI) and two polarimeters, the Hyper-Angular Rainbow Polarimeter 2 (HARP2) and the Spectro-Polarimeter

for Exploration (SPEXone). The spacecraft and the OCI, which is the primary instrument, are developed and integrated at the NASA Goddard Space Flight Center (GSFC). The OCI is a hyper-spectral scanning (HSS) radiometer designed to measure spectral radiances from the ultraviolet to shortwave infrared (SWIR) to enable advanced ocean color and heritage cloud and aerosol particle science. The HARP2 and SPEXone are secondary instruments on the PACE observatory, acquired outside of GSFC. This presentation will focus on the Integration and Test (I&T) activities for the PACE mission at NASA GSFC. This I&T phase consists of mechanical, electrical and thermal integration and test of all the spacecraft subsystems and the integration of the instruments with the spacecraft. The PACE observatory environmental tests include electromagnetic interference (EMI)/electromagnetic compatibility (EMC), vibration, acoustics, shock, thermal balance, thermal vacuum, mass properties and center of gravity. This presentation will also discuss the observatory shipment to the launch site as well as the launch site processing.

6.0202 The Integration and Test of the TROPICS Flight Segment

Andrew Cunningham (MIT Lincoln Laboratory),
Presentation: Andrew Cunningham, Monday, March 9th, 11:00 AM, Cheyenne

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission was selected by NASA in 2016 as part of the Earth Venture Instrument (EVI-3) program and is now in development with planned launch readiness in late 2019. The TROPICS constellation consists of six CubeSats, two in each of three low-Earth orbital planes with a nominal circular orbit of 550 km and inclination of 30 degrees. Each CubeSat hosts a high-performance radiometer payload with twelve microwave channels, providing atmospheric temperature profiles, water vapor profiles, and rain rate. The TROPICS mission will produce rapid-refresh microwave measurements (median refresh rate of approximately 40 minutes for the baseline mission) over the Tropics that will enable observations of the entire tropical storm lifecycle. The radiometer design is similar to two other MIT Lincoln Laboratory (MIT LL) CubeSat programs, MicroMAS and MiRaTA, with improvements to meet enhanced performance requirements and longer mission life. The CubeSat bus is under contract with a commercial vendor who will integrate the MIT LL payload and their bus, and test the complete space vehicle. This paper will describe the integration and test of the payload and space vehicle. A novel characterization of the radiometer payload is described. A qualification space vehicle was used verify the design.

6.0205 Auroral Radio Emissions Simulation and Processing for AERO CubeSat Mission

Abigail Marek (Clemson University), Kristen Ammons (Morehead State University), Huda Irshad (University of Massachusetts Boston), John Swoboda (Massachusetts Institute of Technology),
Presentation: Kristen Ammons, Monday, March 9th, 11:25 AM, Cheyenne

Auroral Emission Radio Observer (AERO) is a 3U CubeSat that will observe the radio aurora using a novel vector sensor (VS). AERO will conduct a three-month mission in polar orbit to measure the direction of arrival, frequency spectra, and occurrence rates of radio frequency emissions from Earth’s aurora. The VS payload is comprised of three loop and three dipole antennas that are capable of detecting all six electromagnetic wave components, which is then used for direction of arrival calculations. In preparation for this mission, a method for testing signal processing algorithms and performing data validation for the VS is created. Thus, we have constructed a four part vector sensor simulator which acts as an effective end-to-end simulator. The four elements of the VS simulator are spacecraft orbit modelling, auroral signals simulation, signal generation with the software library SimVSR, and real-time signal processing implementation. A nominal spacecraft orbit is created using AGI’s Systems Tool Kit, constrained to altitudes of 450 to 550 km and a noon/midnight polar orbit with a target local time of midnight. This model is used to generate the position of the spacecraft at a given time in the mission life. A seven parameter model is developed to simulate auroral radio emissions. These sources are simulated in a randomized data set of time, position, and spectral intensity. In addition to the spacecraft location and orientation, these point sources are superimposed with expected ambient radio noise and then split into a six-channel VS simulator which produces voltage time series data. The generated voltage time series data is then input into a pipeline of three signal processing calculations in parallel in real-time. The simulation of the signal processing confirms the end result of the chain of AERO for data.

6.0206 50 Years of Spaceflight with Fourier Transform Spectrometers (FTS) from NASA GSFC

Conor Nixon (NASA GSFC), Shahid Aslam (NASA - Goddard Space Flight Center),
Presentation: Conor Nixon, Monday, March 9th, 11:50 AM, Cheyenne

Over the past 50 years, NASA Goddard Space Flight Center (GSFC) has been developing, building, testing and flying a series of Fourier Transform Spectrometers (FTS). This began with the IRIS instruments on the Earth-orbiting Nimbus satellites and progressed to more sophisticated designs optimized for interplanetary spacecraft sent to Mars and later to the outer solar system. Adaptions have been made over time, including progressively higher spectral resolution, sensitivity, numbers of detectors and complexity. Instrument operating temperatures have decreased to enable remote sensing of the cold giant planet systems. In this paper we describe the historical evolution of this instrument line, comparing and contrasting different aspects such as optical design and materials, detector types and data handling. We conclude by looking at challenges for the future. At present the CIRS-Lite prototype is being tested at NASA GSFC for potential use on a future mission to the ice giants, Uranus and Neptune. Surpassing the previous performance of the Voyager IRIS instruments remains challenging, and new technologies that could enable these measurements are discussed.

6.03 Imaging Spectrometer Systems, Science, and Science Applications

Session Organizer: Peter Sullivan (NASA Jet Propulsion Lab),

6.0301 GOLD: Far-UV Imaging Spectrograph Background at GEO

Katelynn Greer (LASP, University of Colorado),
Presentation: Katelynn Greer, Monday, March 9th, 09:20 AM, Cheyenne

The GOLD mission is a NASA mission of opportunity aboard the communications satellite SES-14. It provides an unprecedented new data set for expanding our understanding of the Thermosphere-Ionosphere system, as it is positioned in a geostationary orbit above the mouth of the Amazon river (47.5 degrees West). The GOLD instrument is an imaging spectrograph that measures the Earth’s emissions from 132 to 162 nm in the Far-UV on the limb and disk. These measurements are used to image thermospheric temperature and composition near 160 km on the dayside disk at half-hour time scales. These images are indicative of the changes in, and evolution of, the lower thermosphere. This is the region where some of the atmospheric thermal tides and waves from lower altitudes dissipate their energy and where the solar and geomagnetic changes can cause dramatic changes in the space environment. Daily observations began in October 2018, following instrument commissioning. This paper examines the types of background signals of the GOLD instrument. GOLD sees two types of background, that which depends on wavelength (spectral background) and that which does not (detector background). The spectral background is caused by both spectral features at shorter wavelengths than observed and imperfections in the optical design of the instrument.

Detector background is mostly gamma ray impacts on the "open faced" microchannel plate detector due to the radiation environment at geostationary orbit. This detector background can be examined through "non-illuminated" pixels on the detector. The detector background varies on a scale of minutes and the variability may be attributed to rapid changes in the solar wind, solar flares, and activity in the magnetosphere. GOLD data is publicly available at http://gold.cs.ucf.edu.

6.0302 The Arcstone Project to Calibrate Lunar Reflectance

Rand Swanson (Resonon, Inc.),
Presentation: Hans Courrier, Monday, March 9th, 09:45 AM, Cheyenne

The Arcstone project is devoted to calibrating the lunar spectral reflectance for an improved exo-atmospheric calibration standard. Beginning with concept, the project will be reviewed up to the current state of development.

6.0303 Miniaturized Spectral Imaging Instrumentation for Planetary Exploration

Antti Näsilä (VTT Technical Research Centre of Finland Ltd), Tomas Kohout ,
Presentation: Antti Näsilä, Monday, March 9th, 10:10 AM, Cheyenne

VTT Technical Research Centre of Finland has been developing miniaturized spectral imaging systems for nanosatellites since 2012. The first spectral camera operating in the visible- and near-infrared wavelengths (VNIR) was launched in summer 2017. The work was followed by development of nanosatellite compatible shortwave infrared (SWIR) spectral imager, which was successfully launched in November 2018. These demonstrations have been precursor missions to further planetary exploration utilizing nanosatellites. Together with European Space Agency, VTT has been developing spectral imaging systems for asteroid research. The Asteroid Spectral Imager (ASPECT) combines the tested visible and SWIR cameras with added measurement capability up to 2.5 µm in a single instrument suite. The ASPECT instrument aims to study the composition of planetary bodies and the effects of space weathering in order to gain understanding of the formation and evolution of the Solar System. The instrument has been primarily developed for the ESA/NASA AIDA mission (Asteroid Impact & Deflection Assessment) as a part of the European APEX CubeSat, but as the instrument concept is very flexible, it is suitable for any upcoming deep space exploration mission. The ASPECT instrument can fit inside a single CubeSat unit (1U), and it can have four separate measurement channels. Each of the four measurement channels can be tailored for the mission requirements, but in original ASPECT there is a single VNIR spectral camera (500 - 900 nm), two SWIR1 spectral imagers (ca. 800 - 1300 nm and 1200-1650 nm) and a SWIR2 spectrometer (1600 - 2500 nm). Other measurement options include UV (200 - 400 nm) and mid-wave infrared (2.5 - 4 µm). For APEX, the wavelength range 500 - 2500 nm has been selected because this wavelength range allows the mapping of surface composition with good accuracy. As the instrument is a spectral imager, it will also provide spatial information about the target, which helps in determining the composition differences over the planetary body. Knowledge of asteroid composition, the physical appearance of asteroids, and the correct interpretation of their reflectance spectra, are issues of key importance in planetary science. Secondary carry-on spacecraft are becoming more common (as demonstrated by the MarCO CubeSats), and for these kind of spacecraft, miniaturized instruments are crucial. By improving the instrumentation performance, these small spacecraft can perform tasks that are more complex and generate scientifically valuable data, while still being very cost effective. The ASPECT instrument aims to answer to this need.

6.04 Radar Signal Processing

Session Organizer: Thomas Backes (Thomas D. Backes), Donnie Smith (Waymo),

6.0403 UAS-supported Digitalized Search-And-Rescue Using Harmonic Radar Reflection

Jonatan Olofsson (Linköping University), Tomas Forssén (Recco AB), Gustaf Hendeby (Linköping University), Isaac Skog (Linkoping University), Fredrik Gustafsson (Linköping University),

Presentation: Jonatan Olofsson, Monday, March 9th, 08:30 AM, Cheyenne

Search-And-Rescue (SAR) is one of many fields with applications benefiting from the increasing availability of Unmanned Aerial Systems (UASs). Most UAS applications rely on the UAS's capability to carry a camera and stream video data for manual or automated processing. However, this relies on unobstructed views of the target, which limits the applicability of these systems. In this paper, we instead describe the development and initial application testing of a system with a UAS-carried harmonic radar. This sensor is designed to detect the presence of \recco{} radar reflectors, commonly found integrated into alpine clothes and gear. The reflectors can be detected through vegetation and snow and is independent of many external factors such as lighting conditions. The paper describes the system design and provides initial real-world results. The initial tests show fruitful results and opens up several avenues of continued research and development.

6.0404 A Maximum Likelihood Estimator for Coordinated Passive Radar System

Thomas Backes (Thomas D. Backes),

Presentation: Thomas Backes, Monday, March 9th, 08:55 AM, Cheyenne

A maximum likelihood estimator for a passive radar system having coordinated transmitters is presented. In passive radar, estimation of the time delay and Doppler shift of a signal is necessary for detection processing. A passive radar system employing multiple transmitters can geolocate targets based on this set of time delays. Typically, multiple transmitters each transmit an independent signal, and the receiver must observe the direct path to each transmitter. However, in the case of a coordinated set of transmitters, the receiver only has to observe a single direct path. Such a configuration may arise where there is control over the transmitters or where there are multiple repeaters setup with a known time delay between the transmissions. Using the presented estimator, the time delay estimation can be improved over the independent transmitter case.

6.05 Information Fusion

Session Organizer: Craig Agate (Toyon Research Corporation), Stefano Coraluppi (Systems & Technology Research),

6.0501 Distributed MHT and ML-PMHT Approaches to Multi-Sensor Passive Sonar Tracking

Michael Lexa (Systems & Technology Research), Stefano Coraluppi (Systems & Technology Research), Craig Carthel , Peter Willett (University of Connecticut),

Presentation: Stefano Coraluppi, Monday, March 9th, 04:30 PM, Cheyenne

This paper introduces a distributed multiple-hypothesis tracking (MHT) approach to passive sonar tracking with multiple sensors. Specific advances include the ability to contend with multiple emitted frequencies per target and the design of a statistically-consistent and stable sequential extended Kalman filter. We consider as well a maximum likelihood probabilistic multi-hypothesis tracker (ML-PMHT) and provide a qualitative comparison of the two methods with simulated sonar data. Directions for future work including a hybrid scheme that exploits the strengths of both tracking paradigms are provided.

6.0503 Approximate Track Automata -- Combining the Best of MHT and GBT for High Value Target Tracking

Lucas Finn (BAE Systems), Steven Schoenecker (BAE FAST Labs), Lake Bookman (BAE Systems), John Grimes (BAE Systems, Inc),

Presentation: John Grimes, Monday, March 9th, 04:55 PM, Cheyenne

Maintaining tracks on High-Value Targets (HVTs) in dense multi-target environments remains a computationally challenging problem. Approaches must trade off hypothesis management with state estimation accuracy in the presence of finite sensing and computational capabilities. This problem becomes more difficult when sensors provide additional, infrequent features: information that correlates track states over long timescales such as target size and color, or unique identifiers such as a license plate. Traditional real-time Multi- Hypothesis Tracking (MHT) algorithms must prune hypotheses before feature information arrives, often removing the correct association hypothesis from the solution space. Graph-Based Track stitching (GBT) algorithms suffer from two related problems: they rely on an upstream tracking algorithm to correctly associate measurements across short timescales, and must still associate tracks in the presence of infrequent feature information. As a result, the HVT tracking problem requires correctly assigning reports to tracks on both short and long timescales. In this paper, we extend the Approximate Track Automata (ATA) algorithm to perform dynamic hypothesis management given a set of HVT hypotheses and feature information models. The original ATA algorithm applied a single strategy to manage the entire hypothesis space; we tailor that approach here given HVTs and target features. We compare traditional tracking metrics such as root mean square error, probability of track, and track purity for HVT and background targets. In addition, we investigate the effect of scaling the number of Integer Linear Program (ILP) variables, i.e. the number of MHT and ATA hypotheses, on these metrics. Interestingly, we note that while solving ILPs is (in general) NP-complete, the ILP constraint matrices and cost vectors contain structure that often results in efficient runtimes in practice. We offer possible explanations as to why the ILP problem structure allows this near-polynomial runtime.

6.0505 Contextual Clustering for Automated State Estimation by Sensor Networks

Christopher Diggans (Air Force Research Laboratory),

Presentation: Christopher Diggans, Monday, March 9th, 05:20 PM, Cheyenne

An algorithmic approach to kernel engineering is taken for contextual spectral clustering of large partial state data sets. This approach to clustering incorporates the data as context for assigning a pairwise similarity measure, enabling the statistical association of partial state data that would otherwise not be possible. As a basic example for intuition, while two receivers may not be able to accurately locate a signal source, having a third would enable a proper source estimation; statistical analysis of all such triplet state estimations for that pair reveals a single likely state if the pair should in fact be highly associated. If not, the statistical results are akin to noise. A simple example is provided in the domain of space object tracking, but this general approach could be adapted to any domain and even cross domain data fusion given that the following holds: The data are not able to be associated on a pairwise basis due to being partially observed states; however, given higher order tuples of data (triplets or hgher), an accurate state estimation is possible. Furthermore, an expert in the domain may be able to employ heuristics and abstract associations through the intelligent design of an algorithm. The specific algorithm presented in this work is intended for defining a symmetric similarity matrix for a set of N position-only observations, say in Lower Earth Orbit made by radar. It is of O(N^3) time complexity and uses simple Keplerian heuristics. Thus, it is only useful for short time scales, such as monitoring an object break-up, but could be expanded

by a domain expert. Another potential application of this approach is in the domain of seismology.

6.0507 Multi-Target Blended Track Fusion in the Presence of Sensor Biases

Darin Dunham (Lockheed Martin), Terry Ogle (Georgia Tech Research Institute), William Blair (Georgia Tech Research Institute),

Presentation: Darin Dunham, Monday, March 9th, 09:00 PM, Cheyenne

In track to track correlation and fusion, the tracks are first correlated together, typically using one of the following approaches—greedy nearest neighbor, global nearest neighbor, or Murty's K-best hypothesis. Once the correlation relationships have been determined, then the tracks are fused together to improve the state estimate and covariance of the track representing each object. In the case of Murty's K-best approach, the correlation decisions from the best hypothesis are used to determine which tracks are then fused together. In this paper, we propose using a blending fusion approach using the correlation results from a set of the highest scoring hypotheses. This approach "hedges the bets" by using more than one hypothesis thus increasing the probability that the resulting covariance will contain the true target even in the case when the best hypothesis includes a miscorrelation. The result is that the blended fused tracks will in most cases have a larger covariance than the fused tracks from the best hypothesis with the tradeoff being a higher covariance containment probability. This paper builds upon the previous work by Ogle, et al. using a multiple level fusion system to investigate the effects of using blended fusion. Monte Carlo simulations were performed, and pattern metrics were used to assess the effectiveness.

6.06 Multisensor Fusion

Session Organizer: William Blair (Georgia Tech Research Institute), Laura Bateman (Johns Hopkins University/Applied Physics Laboratory),

6.0602 Heterogeneous Measurement Selection for Vehicle Tracking Using Submodular Optimization

Matthew Kirchner (Naval Air Warfare Center Weapons Division), Joao Hespanha (University of California, Santa Barbara), Denis Garagic (BAE Systems),

Presentation: Matthew Kirchner, Thursday, March 12th, 09:00 PM, Dunraven

We study a networked, heterogeneous, multi-senor tracking and estimation problem with bandwidth limitations. The scenario we consider is that of multiple sensors collecting measurements of a target vehicle, and the measurements are transmitted over a communication channel to a centralized node. The central node collects the measurements and estimates the motion of the vehicle. The communication channel presents an information-transfer bottleneck as the sensors collect measurements at a much higher rate than what is feasible to transmit over the communication channel. In order to minimize estimation error at the centralized node, the transmitted subset of measurements must be carefully selected. We seek to estimate the vector of unknown parameters that describes vehicle motion. Each of the measurements are noisy observations that are dependent on the parameters. Inspired by the connection to the Cramer-Rao lower bound, we propose to select measurements based on the Fisher information matrix (FIM), as "minimizing" the inverse of the FIM is required to achieve small estimation error. One can use the FIM as a criteria to select which subset of measurements are "best" by formulating a combinatorial optimization problem. This presents a computational challenge as finding the optimal selection of measurements is, in general, NP-hard. We show that one common criteria used to "minimize" the inverse of the FIM, maximizing log{FIM}, is both monotone and submodular and therefore allows the use of a greedy algorithm to find the selection of measurements. While the greedy algorithm returns a sub-optimal solution, it is guaranteed to be within 1-1/e ~=63% of the optimum and has the critical benefit of quadratic computational complexity. As an example, we derive the FIM for different sensor types to which we apply measurement selection. This includes the time-of-arrival and Doppler shift of passively received radio transmissions as well as detected key-points in camera images. We compare the track estimation of the vehicle with the FIM selected measurements with that of random selection and show selecting measurements based on the FIM greatly outperforms the estimation task when the bandwidth limitation becomes significant.

6.0604 Optimal Non-Assignment Costs for the GNP Problem

John Glass (Raytheon Company), Mark Levedahl ,
Presentation: John Glass, Thursday, March 12th, 09:25 PM, Dunraven

The global nearest pattern (GNP) approach to data association is closely related to the global nearest neighbor (GNN) problem, and both require that a cost of non-assignment of tracks be established. The existing theory for GNN can be reasonably applied to GNP problems, but adjustments are required to optimally account for bias estimation and uncertainty in GNP. These adjustments are presented along with Monte Carlo analysis showing the achieved performance is nearly optimal.

6.07 Applications of Target Tracking

Session Organizer: John Glass (Raytheon Company), Yaakov Barshalom (University of Connecticut),

6.0701 Practical Issues and Guidelines in Handling Erroneous IFF and Associated Radar Measurements in MTT

Sampath Kumar Gogulamudi (Bharat Electronics Limited), Viji Panakkal (Central Research Laboratory),
Presentation: Sampath Kumar Gogulamudi, Thursday, March 12th, 04:30 PM, Dunraven

This paper deals with handling various errors in the plot detection using innovative techniques in Radar Data Processing (RDP) for a 3D radar having Primary and Secondary detection. The output of radar consists of primary plot, secondary plot and associated plot corresponding to a target depending on the detection of target from primary & secondary radars. If the target is detected by primary radar and secondary radar and both the reports are at a distance less than the defined threshold distance then the associated plot is generated which consists of both the primary & secondary plot information. The associated plot generation is a combination of primary plot information and secondary plot information. If the primary plot and secondary plot are at a distance within the threshold distance then associated plot is generated by using primary plot azimuth and secondary plot range. Any slight deviation in the distances between primary and secondary plot while detection will result in generating separate primary and secondary plots corresponding to same target. The probable reasons for the above discussed deviation in distances between primary plot and secondary plot are: 1) Alignment of primary & secondary radars 2) Differences in bias errors between primary & secondary radars The majority of secondary radar target report may come from interference free circumstance. However a portion of secondary radar reports may have one or the other type of errors associated with it and this paper deals with identifying various errors and handling them at RDP. Few of the errors associated with secondary radar plots are due to: 1) IFF code error of the target due to garbling 2) IFF code error of the target due to code swapping and 3) IFF code error of the target due to ring around targets produced by side lobe replies which were not suppressed. 4) Poor Probability of Detection (PD). 5) Fruit replies The aforementioned errors in detection will cause the following abnormalities in detections: 1. Multiple targets with same secondary radar code (Mode 3/A IFF Code) 2. Presence of primary, secondary and associated plots for same target 3.

Presence of multiple secondary and associated plots for same target with valid code 4. Presence of multiple secondary and associated plots for same target with invalid code 5. Presence of invalid code for the secondary plots or associated plots This paper develops methods to circumvent the issues in track initiation and track maintenance that can be occur due to the aforementioned abnormalities in detection. This paper identifies the abnormal detection with the possible cause and then rectifies this abnormality by developing suitable logic and incorporating in the RDP. The developed logics are explained in this paper using detailed flow charts and the analysis results provided in this paper justifies the developed logics. The abnormal detections and the root cause analysis carried out in this paper are by the practical knowledge obtained by handling various real time radar recordings collected from the field.

6.0702 Optimal Range for Radar Tracking of Maneuvering Targets Using Nearly Constant Velocity Filters

Per Boström Rost (Linköping University), Daniel Axehill (Linköping University), William Blair (Georgia Tech Research Institute), Gustaf Hendeby (Linköping University),

Presentation: Per Boström Rost, Thursday, March 12th, 04:55 PM, Dunraven

For a given radar system on an unmanned air vehicle, this work proposes a method to find the optimal tracking range and the optimal beamwidth for tracking a maneuvering target. An inappropriate optimal range or beamwidth is indicative of the need for a redesign of the radar system. An extended Kalman filter (EKF) is employed to estimate the state of the target using measurements of the range and bearing from the sensor to the target. The proposed method makes use of an alpha-beta filter to predict the expected tracking performance of the EKF. Using an assumption of the maximum acceleration of the target, the optimal tracking range (or beamwidth) is determined as the one that minimizes the maximum mean squared error (MMSE) of the position estimates while satisfying a user-defined constraint on the probability of losing track of the target. The applicability of the design method is verified using Monte Carlo simulations.

6.0703 Single Satellite Emitter Geolocation in the Presence of Oscillator and Ephemeris Errors

Patrick Ellis (University of California, Santa Cruz),

Presentation: Patrick Ellis, Thursday, March 12th, 05:20 PM, Dunraven

This paper addresses high-accuracy geolocation of a ground-level, uncooperative RF emitter using a single low earth orbit (LEO) satellite. It is meant to be a real-time, single-pass solution that requires only a few seconds of Doppler and Doppler Rate measurements and resistant to erroneous ephemeris readings and oscillator errors from both the transmitter and receiver. The presented work can be expected to have a significant impact on search and rescue operations, spectrum monitoring, and tracking. Oscillator and ephemeris errors are inherent system flaws for satellite geolocation - heavily distorting error distributions, violating many symmetric and Gaussian assumptions that most estimation algorithms rely on. To deal with this, a constrained Unscented Particle Filter (cUPF) is provided. Using quoted oscillator errors, ephemeris error, analysis is provided with respect to geolocation accuracy. Each scenario compares the cUPF with a previously developed constrained Unscented Kalman Filter (cUKF). Validation is provided on both simulated data and off-the-air IQ data obtained from the TDS-1 Satellite operated by Surrey Satellite Technology. The cUPF algorithm outperforms the prior state-of-the-art cUKF in both accuracy and convergence time, often obtaining single kilometer geolocation accuracies with only a few seconds of acquisition time over a several hundred kilometer search space.

6.08 Guidance, Navigation and Control

Session Organizer: Christopher Elliott (Lockheed Martin Aeronautics Company and University of Texas at Arlington), Terry Ogle (Georgia Tech Research Institute),

6.0802 Reduction of Hamiltonian Systems with Involutory Functions

Michael Sparapany (Purdue University),

Presentation: Michael Sparapany, Sunday, March 8th, 04:30 PM, Cheyenne

Optimal control theory is a broad mathematical field whose main concern is the minimization of functionals, a generalization of variational calculus. Historical application of optimal control dates back to Queen Elissar of Carthage who studied the isoperimetric problem. In a more modern format, Newton, L'Hospital, Leibniz, and the Bernoulli brothers studied the Brachistochrone problem. The study of these problems resulted in the creation of groundbreaking analytic strategies due to the lack of digital tools commonly available today. The introduction of digital computers and efficient nonlinear programming strategies created a fork in optimal control theory. One school of solution processes are "direct" methods. Direct methods seek to solve optimal control problems (OCPs) by discretizing the infinite-dimensional mathematical problem into an approximate finite-dimensional computational problem. The other school of solution processes are "indirect" methods. Indirect methods seek to solve an OCP by solving a separate, but equivalent boundary-value problem (BVP). Ultimately, direct and indirect methods are intertwined, and progress in either school is of benefit to both. One such advancement that has been largely ignored in indirect methods is the mathematical theory of reduction. The primary goal of this paper is to provide a compact and scalable application of the mathematical theory of reduction to indirect methods for aerospace applications.
An OCP, problem possessing symmetries or constants-of-motion carries through to the indirect problem by the dualization procedure of indirect methods. The number of total constants-of-motion and symmetries in the dual problem is twice that of total constants-of-motion and symmetries in the original problem. Problem may eliminate the groups of constants-of-motion and symmetries resulting in a lower dimensional but equivalent formulation. This reduced dimensional problem may have several advantages: a lowered numerical error due to the elimination of some previously required numerical computations, a lowered time of convergence from the removal of some required propagations, and enhanced parallelization capabilities because of the elimination of some causal dependencies. On the other hand, the reduced system may have a much more complicated set of dynamics than the unreduced system, and therefore none of the benefits are guaranteed. Presently, there is no convenient manner of analyzing this problem. Indirect methods will benefit from a compact procedure for aerospace applications to generate reduced problems and results are shared with direct methods. The primary focus of this work is on the reduction of Hamiltonian systems possessing involutory symmetries.

6.0803 Extended Navigation Capabilities for a Future Mars Science Helicopter Concept

Jeff Delaune (Jet Propulsion Laboratory), Roland Brockers (Jet Propulsion Laboratory), David Bayard (Jet Propulsion Laboratory), Harel Dor (Caltech), Robert Hewitt (Jet Propulsion Laboratory), Jacek Sawoniewicz (JPL), Gerik Kubiak (Jet), Theodore Tzanetos (NASA Jet Propulsion Lab), Larry Matthies (Jet Propulsion Laboratory), J (Bob) Balaram (Jet Propulsion Laboratory),

Presentation: Jeff Delaune, Sunday, March 8th, 04:55 PM, Cheyenne

This paper introduces an autonomous navigation system suitable for supporting a future Mars Science Helicopter concept. This mission concept requires low-drift localization to reach science targets far apart from each other on the surface of Mars. Our modular state estimator achieves this through range, solar and Visual-Inertial Odometry (VIO). We propose a novel range update model to constrain visual-inertial scale drift in the absence of motion excitation using a single-point static laser range finder, that is designed

to work over unknown terrain topography. We also develop a sun sensor measurement model to constrain VIO yaw drift. Solar VIO performance is evaluated in a simulation environment in a Monte Carlo analysis. Range-VIO is demonstrated in flight in real time on 1 core of a Qualcomm Snapdragon 820 processor, which is the successor of the NASA's Mars Helicopter flight processor.

6.0805 Rendezvous Approach Guidance for Uncooperative Tumbling Satellites

Manwei Chan (Mit),

Presentation: Manwei Chan, Sunday, March 8th, 05:20 PM, Cheyenne

The development of a Rendezvous and Proximity Operations (RPO) guidance algorithm for approaching uncooperative tumbling satellites has multiple purposes including on-orbit satellite servicing, space debris removal, asteroid mining, and on-orbit assembly. This thesis develops a guidance algorithm within the framework of on-orbit satellite servicing, but is extendable to other mission scenarios. The author tests the algorithm in an RPO simulation with an uncooperative tumbling satellite near Geostationary Orbit (GEO) starting at a relative distance of 50m and ending at a relative distance of 5m. Examples of potential uncooperative tumbling clients include decommissioned satellites or satellites with malfunctioning thrusters. Due to the low Technology Readiness Level (TRL) of autonomous (RPO) missions, first missions prefer to use flight proven technologies. This thesis implements a guidance algorithm based on the flight proven Clohessy-Wiltshire (CW) and space shuttle glideslope equations which command a sequence of burns to close the distance between the servicer and client while matching the client satellite's rotation rate. The author validates the guidance algorithm through Monte Carlo (MC) analysis in a Three Degrees of Freedom (3DOF) simulation, which incorporates imperfect navigation, imperfect control, finite burn durations, and higher order gravity. The client satellite is modeled as a rotating object and knowledge of the behavior is based on current capabilities derived from commercial off the shelf sensors and publicly available computer vision algorithms. Fuel use metrics characterize the sensitivity of the algorithm. Fuel consumption is measured by the total velocity changes, or delta V, needed to complete the maneuvers. Cumulative delta V sensitivity is measured against navigational uncertainty in the rotational axis to summarize the key requirements and trade-offs associated with implementing this algorithm. Given state of the art technology in navigation and control, the guidance algorithm produces a 100 percent success rate, where failures are determined by the servicer violating a pre-determined keep out sphere. Trajectories generated in this environment used roughly 6m/s of delta V. As navigational errors are increased, so does the use of fuel and failure rate, but this can be partially offset by retargeting points more often at the expense of even more increased fuel use. This boundary is heavily investigated to find the delta V vs. failure rate tradeoff that can be used by mission managers who will have to decide between cost and risk of a servicing mission. The algorithm itself is also modifiable to accommodate different missions including but not limited to servicing, debris removal, and on-orbit assembly.

6.0807 Spacecraft Attitude Determination Using Terrestrial Illumination Matching

Liberty Shockley ,

Presentation: Liberty Shockley, Sunday, March 8th, 09:00 PM, Cheyenne

Powerpoint overviewing simulation set-up, position results, and diving into attitude and kalman filtering results.

6.0810 Localization–guaranteed Navigation in GPS-denied Environment via multi-UAV Closed-loop Coordination

Shenghao Jiang (Harvard University), Macheng Shen ,
Presentation: Shenghao Jiang, Sunday, March 8th, 09:25 PM, Cheyenne

Consider a scenario where multiple Unmanned Aerial Vehicles (UAVs) autonomously collaborate with each other to explore an unknown environment where GPS is not available. A visual fiducial marker with known geometry is fixed on each UAV to provide relative localization between any pair of UAVs. Nevertheless, the UAVs need to plan their motion to ensure that the marker always appears in camera's field-of-view so that they can be localized. Such requirement limits the trajectory space of UAVs when they are exploring the environment. To solve this issue, our first technical contribution is an innovative multi-UAV spatial closed-loop coordination mechanism, which provides guaranteed relative localization wherever they are in the unknown and texture-less environment. The coordination, however, requires that the environment satisfy line-of-sight (LOS) constraints, and therefore necessities the division of the global environment into different subareas such that LOS constraints are met within each subarea. Our second contribution is a novel temporal-spatial pose graph to register different subareas into one global environment accurately. Finally, we present an iterative strategy to simultaneously maximize the volume of exploration space and minimize the localization error under the line-of-sight (LOS) constraints. Comparison with STOA visual localization techniques in simulated unknown environment demonstrates that our method is robust, accurate and independent of the environment.

6.09 Fusion Integration of Sensor Harvesting

Session Organizer: Peter Zulch (Air Force Research Laboratory), Erik Blasch (),

6.0901 Sensor Network Target Detection with Unlabeled Observations

Peter Willett (University of Connecticut), Zachariah Sutton , Stefano Marano (University of Salerno),
Presentation: Peter Willett, Wednesday, March 11th, 04:30 PM, Lamar/Gibbon

Imagine a satellite acting as a sensor that sends measurements to a central processing center. Attached to each measurement would be data about the satellite's location when the measurement was taken as well as the time at which the measurement was taken. In a scenario with many sensors, this appended "labeling" data will take up a significant portion of the communication channel. For this reason, it is of interest to explore the possibilities and limitations of statistical decision- making without the use of the labeling information. We explore that here.

6.0902 Heterogeneous Sensor Fusion with Out of Sync Data

Biao Chen (Syracuse University),
Presentation: Biao Chen, Wednesday, March 11th, 04:55 PM, Lamar/Gibbon

This paper tackles sensor fusion when data from different sensors are out of sync - observations may be sampled asynchronously and there is no timing information at the fusion center for observations from some sensors. This may happen when sensors are heterogeneous in nature hence may employ different and even time varying sampling cycles. Furthermore, observations may need to go through wireless channels when tagging each observation with timestamp may be too expensive. Treating the timing information in out of sync data as a hidden variable, this paper employs the expectation-maximization (EM) algorithm to recover the posterior distribution of the timing information. Data fusion utilizing the out of sync data can subsequently be carried out. Using a simple two-sensor off-line state estimation experiment where one sensor's data is available but is out of sync at the other sensor, we demonstrate that the performance of the

EM based approach improves on the fusion performance when the out of sync data is discarded. Extensions to high dimensional observations, to system involving multiple out of sync data streams, and to online state tracking with out of sync data are discussed.

6.0903 Spectral Embedding for Memory-efficient Transmission of Multivariate Time Series

Lihan Yao (Geometric Data Analytics), Paul Bendich (Geometric Data Analytics, Inc.),
Presentation: Lihan Yao, Wednesday, March 11th, 09:00 PM, Lamar/Gibbon

We propose a graph spectral representation of time series data that 1) is parsimoniously encoded to user-demanded resolution; 2) is unsupervised and performant in data-constrained scenarios; 3) captures event and event-transition structure within the time series; and 4) has near-linear computational complexity in both signal length and ambient dimension. This representation, which we call Laplacian Events Signal Segmentation (LESS), can be computed on time series of arbitrary dimension and originating from sensors of arbitrary type. Hence, time series originating from sensors of heterogeneous type can be compressed to levels demanded by constrained-communication environments, before being fused at a common center. Temporal dynamics of the data is summarized without explicit partitioning or probabilistic modeling. As a proof-of-principle, we apply this technique on high dimensional wavelet coefficients computed from the Free Spoken Digit Dataset to generate a memory efficient representation that is interpretable. Due to its unsupervised and non-parametric nature, LESS representations remain performant in the digit classification task despite the absence of labels and limited data.

6.0904 Feature Level Sensor Fusion for Passive RF and EO Information Integration

Asadullah Vakil (Oakland University), Jenny Liu , Peter Zulch (Air Force Research Laboratory), Jia Li (Oakland University),
Presentation: Asadullah Vakil, Wednesday, March 11th, 05:20 PM, Lamar/Gibbon

Many different sensing modalities across the spectrum exist for collecting and processing data for the purposes of detection, tracking and target differentiation. However, each of these individual modalities from the electromagnetic spectrum contain benefits, limitations, and sources of uncertainty. While research has been conducted to integrate complementary data collected by electro-optical (EO) and radio frequency (RF) modalities, the processing of RF data usually applies traditional methods, such as Doppler. This paper explores the viability of using histogram of I/Q (in-phase and quadrature) data for the purposes of augmenting the detection accuracy that EO input alone is incapable of achieving. Processing of the histogram of I/Q data via deep learning, enhances feature resolution for neural network fusion. Using the simulated data from the Digital Imaging and Remote Sensing Image Generation (DIRSIG) dataset, the resulting Fusion of EO/RF neural network (FERNN) can achieve 95% accuracy in vehicle detection, which is a 23% improvement over the accuracy achieved by a standalone EO sensor.

6.0905 Joint-Sparse Heterogeneous Data Fusion for Target State Estimation with Weak Signals

Ruixin Niu (Virginia Commonwealth University), Peter Zulch (Air Force Research Laboratory), Marcello Di Stasio (AFRL), Genshe Chen (Intelligent Fusion Technology, Inc), Dan Shen (Intelligent Fusion Technology, Inc), Jingyang Lu (International fusion technology),
Presentation: Ruixin Niu, Wednesday, March 11th, 09:25 PM, Lamar/Gibbon

Recently, we developed a joint-sparse data-level fusion (JSDLF) approach to fuse heterogeneous sensor data for target detection and estimation. In this approach, the target state space is discretized and the data fusion problem is formulated as a joint sparse signal reconstruction problem, and solved by simultaneous orthogonal matching pursuit. In this paper, we continue our work on JSDLF, and our new work is different from our previous work in two aspects. First, the performance of the JSDLF is investigated for

cases with very low signal to noise ratio (SNR). Further, to compare the JSDLF approach with decision/feature level fusion approaches, we develop a new maximum likelihood (ML) decision-level fusion approach. In this approach, first each sensor makes its local detections, by comparing the signal's discrete Fourier transform amplitude at each frequency bin (or the image intensity at each pixel) with a threshold. The sensor detection results provide target Doppler shift estimates from radio frequency sensors and target location estimates from the video camera. Then a likelihood function is derived to statistically characterize the detected frequency bins or image pixels, by considering missed detections and false alarms. With the likelihood function, the sensor detections are fused using an ML estimator for target state estimation. We name this fusion approach, which considers both missed detections and false alarms, MLE-MDFA. The MLE-MDFA has assumed the perfect knowledge of the signals' distributions under both hypotheses, which in practice is very difficult to obtain. In contrast, the JSDLF approach requires minimum prior knowledge of the signal model. Hence, the MLE-MDFA only serves as a benchmark for the JSDLF approach. Our numerical results show that at high SNR, the MLE-MDFA provides similar performance as the JSDLF approach. At low SNR values, the JSDLF approach significantly outperforms the MLE-MDFA algorithm. This clearly demonstrates the benefits of data-level fusion over decision-level fusion.

6.0906 Joint Sparsity Aided Joint Manifold Learning for Sensor Fusion

Dan Shen (Intelligent Fusion Technology, Inc), Ruixin Niu (Virginia Commonwealth University), Peter Zulch (Air Force Research Laboratory), Marcello Di Stasio (AFRL), Jingyang Lu (International fusion technology), Genshe Chen (Intelligent Fusion Technology, Inc),

Presentation: Dan Shen, Wednesday, March 11th, 09:50 PM, Lamar/Gibbon

This paper presents a joint sparsity aided joint manifold learning (JCAJML) approach for distributed sensor fusion of image and radio frequency (RF) data. A typical scenario includes several objects (with RF emitters), which are observed by a network of platforms with Medium Wavelength Infrared (MWIR) cameras and/or RF Doppler sensors. In the past, we developed two heterogeneous approaches for mixed and/or mixed sensor modalities. The joint sparsity (JC) approach for cases without ground truth and joint manifold learning (JML) for cases with ground truth. In this paper, we unify the abovementioned methods. We propose an interactive learning/training of JML based on joint sparsity results. We use the joint sparsity support recovery to generate estimated ground truth and train the JML framework. On the other hand, the joint sparsity can use the JML results to improve the data fusion results and speed up the processing as well. The JCAJML approach is tested and verified on AFRL datasets.

TRACK 7: AVIONICS AND ELECTRONICS FOR SPACE APPLICATIONS

Track Organizers: Harald Schone (Jet Propulsion Laboratory), John Samson (Morehead State University), John Dickinson (Sandia National Laboratories),

7.01 High Performance Computing and Data Processing for Space Applications

Session Organizer: Dmitriy Bekker (Johns Hopkins Applied Physics Laboratory), Robert Merl (Los Alamos National Laboratory), Jamal Haque (Honeywell),

7.0101 MAARS: Machine Learning-Based Analytics for Automated Rover Systems

Masahiro Ono (JPL), Brandon Rothrock (NASA Jet Propulsion Lab), Kyohei Otsu , Yumi Iwashita , Annie Didier (NASA Jet Propulsion Lab), Tanvir Islam , Vivian Sun , Christopher Laporte (JPL), Kathryn

Stack (Jet Propulsion Laboratory), Shoya Higa (Jet Propulsion Laboratory), Jacek Sawoniewicz (JPL), Shreyansh Daftry (California Institute of Technology), Chris Mattmann (NASA Jet Propulsion Laboratory/ California Institute of Technology), Virisha Timmaraju (NASA Jet Propulsion Lab), Sami Sahnoune (Jet Propulsion Laboratory), Olivier Lamarre (University of Toronto), Dicong Qiu (Carnegie Mellon University), Sourish Ghosh (Carnegie Mellon University), Shunichiro Nomura (The University of Tokyo), Hemanth Sarabu (Georgia Institute of Technology), Sean Suehr (North Carolina A&T State University), Larkin Folsom (North Carolina A&T State University), Gabrielle Hedrick (West Virginia University), Hyoshin Park (North Carolina A&T State University), Hiya Roy (University of Tokyo),

Presentation: Masahiro Ono, Sunday, March 8th, 04:30 PM, Gallatin

MAARS (Machine leaning-based Analytics for Automated Rover Systems) is an ongoing JPL effort to bring the latest self-driving technologies to Mars, Moon, and beyond. The ongoing AI revolution here on Earth is finally propagating to the red planet as the High Performance Spaceflight Computing (HPSC) and commercial off-the-shelf (COTS) system-on-a-chip (SoC), such as Qualcomm's Snapdragon, become available to rovers. In this three year project, we are developing, implementing, and benchmarking a wide range of autonomy algorithms that would significantly enhance the productivity and safety of planetary rover missions. The purpose of this paper is to provide the latest snapshot of the project with a broad and high-level description of every capability that we are developing, including scientific scene interpretation, vision-based traversability assessment, resource-aware path planning, information-theoretic path planning, on-board strategic path planning, and on-board optimal kinematic settling for accurate collision checking. All the on-board software capabilities will be integrated to JPL's Athena test rover using ROS. The main roadblock to a Mars exploration rollout is that the best computers are on Earth, but the best data is on Mars. High-Performance Spaceflight Computing (HPSC) - a new generation of radiation-hardened multi-core processor qualified for space - is currently being developed by NASA and the Air Force, and would enable a vast suite of new mission concepts. In the meantime, the Mars Helicopter Scout, the first vehicle to fly on Mars, uses Qualcomm's Snapdragon system-on-a-chip (SoC) for visual navigation. The computation power of such modern commercial off-the-shelf (COTS) SoCs for mobile devices far surpasses the existing spacecraft computers such as the RAD750. There is an urgent need for significantly enhancing on-board autonomy of future rover missions. For example, the sample fetch rover of the Sample Retrieval and Lander (SRL) mission concept is expected to drive up to ~1 km per Sol, more than a ten-fold extension of the average per-sol driving distance of the Curiosity rover. Faster driving generates data at an increased rate, while the capacity of Mars-Earth communication remains limited by the laws of physics as well as the availability of relay orbiters and the Deep Space Network. Science opportunities might be passed up by necessity or missed entirely simply because the data cannot be fully downlinked to Earth. Furthermore, since the majority of the driving distance will need to be covered by AutoNav (autonomous navigation), complex safety assessments that are currently performed on the ground must be performed on-board the rover. Given these challenges, the MAARS project aims at developing autonomy software capabilities that would significantly enhance the safety, productivity, and cost efficiency of future Mars rovers by fully exploiting the computation power of HPSC and space-qualifed modern SoCs. What is described in this paper is the snapshot of our development effort at the end of the second year of the three-year project.

7.0102 Nebulae: A Proposed Concept of Operation for Deep Space Computing Clouds

Joshua Vander Hook (NASA Jet Propulsion Lab), Dmitriy Bekker (Johns Hopkins Applied Physics Laboratory), Richard Doyle (Jet Propulsion Laboratory), Julie Castillo Rogez (JPL/Caltech), Tiago Vaquero ,

Presentation: Joshua Vander Hook, Sunday, March 8th, 04:55 PM, Gallatin

In this paper, we describe an ongoing multi-center study in using emplaced computational resources such as high- volume storage and fast processing to enable instruments to gather and store much more data than would normally be pos- sible, even if it cannot be downlinked to earth in any reasonable time. The primary focus of the study is designing science pipelines for on-site summarization, archival for future downlink, and multi- sensor fusion. A secondary focus is on providing support for increasingly-autonomous systems, including mapping, planning, and multi-robot collaboration. Key to both of these concepts is treating the spacecraft not as an autonomous agent, but as an interactive batch processor, which allows us to avoid "quantum leaps" in machine intelligence required to realize the designs. Our goal is to discuss preliminary results and technical di- rections for the community, and identify promising new op- portunities for multi-sensor-fusion with the help of planetary researchers.

7.0103 COSMIC: Content-based Onboard Summarization to Monitor Infrequent Change

Gary Doran (Jet Propulsion Laboratory), You Lu (Jet Propulsion Laboratory), Maria Liukis (JPL), Kiri Wagstaff (Jet Propulsion Laboratory),

Presentation: Gary Doran, Sunday, March 8th, 05:20 PM, Gallatin

We are developing a system called COSMIC (Content-based Onboard Summarization to Monitor Infrequent Change) that will opportunistically analyze data onboard a Mars orbiter to alert scientists when meaningful changes have occurred. COSMIC will allow future spacecraft to continuously collect data to search for rare, transient phenomena such as fresh impacts or seasonally changing polar landforms under a constrained downlink budget. We describe the overall goals and architecture of COSMIC, plans to enable specific scientific studies, label acquisition to enable supervised approaches to surface landform classification, a new machine learning evaluation framework for analyzing the trade-offs between classifier accuracy and computational requirements, and lessons learned about constraints that COSMIC will face operating onboard a spacecraft. In particular, we discuss design considerations surrounding computational and storage constraints, change detection strategies, and localizing detected landforms of interest within a global coordinate frame. Finally, we describe challenges and open research questions that must be addressed prior to deploying COSMIC.

7.0105 LEON4 Based Radiation-Hardened SpaceVPX System Controller

Robert Merl (Los Alamos National Laboratory),

Presentation: Robert Merl, Sunday, March 8th, 09:00 PM, Gallatin

The Processing and Communications team at Los Alamos National Laboratory has designed and manufactured a new system controller that complies with the 6U SpaceVPX (ANSI/VITA 78) specification and can function as a command- and data-handling single-board computer. The design meets the radiation hardness requirements for application in geosynchronous (GEO) and medium earth orbit (MEO), employs QMLV and Class-S components, has a conduction cooling frame, and is mechanically hardened against typical shock and vibration profiles encountered during launch. The system controller is based on the space grade GR740 quad-core LEON4 processor ASIC with a MicroChip RTG4 field programmable gate array (FPGA) to support hardware coprocessing and supply the gigabit /s serializer-deserializers (SerDes) needed for the VPX control and data planes. This module was designed to allow interoperability between OpenVPX (ANSI/VITA 65) and SpaceVPX so that lower cost hardware from the commercial world can be used during the prototyping process instead of more expensive flight like hardware. This design has 1 GByte of SDRAM with an additional ½ GByte of error detection and correction memory (EDAC). Since SDRAM is susceptible to singe event functional interrupts (SEFIs), the design team used byte-wide aspect ratio memories with individual power control for recovery. This paper will discuss the performance, power consumption, and initial application of this design.

7.02 Peripheral Electronics, Data Handling, and Interconnectos for Space Applications

Session Organizer: Mark Post (University of York), Patrick Phelan (Southwest Research Institute),

7.0201 Building Blocks for the Future: TRL 10 and 11 Commercial Spacecraft Avionics

Leif Kirschenbaum (Maxar), Yann Renault (Maxar Space Solutions), Jose Andrada (Maxar Space Solutions), Peter Lord (SSL), Laurie Chappell (SSL),

Presentation: Leif Kirschenbaum, Sunday, March 8th, 09:25 PM, Gallatin

One of the obstacles to achieving a cost-effective high-reliability paradigm has been the need to reinvent the command and data handling infrastructure on a spacecraft by spacecraft basis. The availability of a family of commercial spacecraft avionics units with extensive reliable flight heritage offers an attractive approach to efficiently implement a spacecraft bus tailored to support specific mission needs without the concomitant redesign, redevelopment, or requalification of the avionics framework. In 2019 P. Lord et al. [1] defined Technology Readiness Levels (TRL) 10 and TRL 11 by expanding upon the need identified by J. Straub in 2015 [2] for a TRL beyond level 9. They extended TRL 9 ("Flight Proven Technology") by defining TRL 10 as "Reliable Flight Proven Technology" and level 11 as "Mature Flight Proven Technology". Maxar's avionics units, with extensive flight heritage in the commercial GEO market, offer TRL 10 and TRL 11 building blocks enabling a customized architecture to accommodate varied missions, from a deep space asteroid rendezvous (Psyche), to robotic servicing in LEO (Restore-L), to forming the basis of the Lunar Gateway with the Power and Propulsion Element (PPE). The Maxar catalog includes a RAD750 based central processor and a hardware level commanding unit as well as units specialized for temperature sensor acquisition, analog voltage measurement, digital control and monitoring, pyrotechnic device control and monitoring, heater control, generic relay control, launch vehicle umbilical discharge event isolation, and ESD hazard mitigation. The Maxar avionics family is integrated via a highly scalable serial data bus architecture. Every unit offers redundancy and full cross-strapping may be implemented for even higher mission reliability. This presentation illustrates the scalability of the Maxar avionics family and includes details of unit capabilities on-orbit data based failure rate estimates, and TRL level as well as their itemization on the Psyche, Restore-L, and PPE spacecraft. [1] P. Lord, et al., "Beyond TRL 9: Achieving the Dream of Better, Faster, Cheaper Through Matured TRL 10 Commercial Technologies", 2019 IEEE Aerospace Conference, Big Sky, MT, 2019, pp. 1-17. [2] J. Straub, "In search of technology readiness level (TRL) 10", Aerospace Science and Technology, 46, (2015), pp. 312–320.

7.0203 FPGA-Based Back-End Electronics for the Imaging X-Ray Polarimetry Explorer Mission

Hikmat Nasimi (INFN), Mattia Barbanera (Istituto Nazionale di Fisica Nucleare, Universitá di Pisa), Saverio Citraro , Carlo Magazzu' (INFN - Pisa), Alberto Manfreda (Istituto Nazionale Fisica Nucleare sez. Pisa), Massimo Minuti (INFN-Pisa),

Presentation: Hikmat Nasimi, Sunday, March 8th, 09:50 PM, Gallatin

The Imaging X-Ray Polarimetry Explorer (IXPE) is the next NASA small explorer mission, due to be launched with a Falcon 9 rocket in May 2021. IXPE will perform polarization measurements in the 2-8 keV band, complementing the unprecedented polarimetric capabilities with moderate-to-good imaging, spectroscopy and timing. The scientific payload consists of three identical telescopes, each including a mirror module assembly

and a detector unit at the focal plane. At the core of each detector unit is a Gas Pixel Detector (GPD). We designed the GPD back-end electronics based on a radiation-tolerant FPGA for data acquisition and processing, event sequencing, and on-line data compression. Two custom digital serial interfaces - the Command and Control Interface (CCI) and the Science Data Interface (SDI) - implement the communication of the units with a central on-board computer. We designed and manufactured a comprehensive test equipment, based on a commercial FPGA hosted on a custom VME board, to emulate the functionality of the on-board computer that will operate the detector in flight. In this paper we shall discuss the basic architectural choices behind the design of the GPD back-end electronics, as well as the tests with X-rays performed in the lab using the aforementioned test equipment.

7.04 Avionics for Small Satellites, Nano-Satellites, and CubeSats

Session Organizer: James Lumpp (University of Kentucky), John Dickinson (Sandia National Laboratories),

7.0401 Miniaturized Fiber Optic Gyroscopes with Multiplexing for Micro/Nano-Satellites Application

Jin Jing , Jiliang He (Beihang University), Kun Ma , Kong Linghai ,
Presentation: Jin Jing, Wednesday, March 11th, 09:00 PM, Dunraven

The interferometric fiber optical gyroscopes (IFOGs) have already proved to adapt to space application due to many advantages including insensitivity to electromagnetic interference, immunity from sparking electrostatic discharge, low power requirement, high measurement accuracy, freedom from mechanical vibrations and shock from launch, etc. In the past ten years, the IFOGs have widely served for various space missions, and the developed products and technologies have been mainly oriented toward high precision, long life period and high reliability applications. As the use of small satellites became increasingly common in commercial space missions, the demand for miniaturized, low-cost and robust gyroscopes surged. The cost effective IFOG with very light weight, small size and low power consumption is a potential choice for small spacecrafts including micro-satellites (10-100kg), nano-satellites (<10kg) and cube satellites. Especially in harsh environments and high performance applications, the mini IFOGs can still provide a moderate precision with closed-loop control and guarantee a relatively high reliability as solid state technique, simple configuration and modular assembly, which makes it possible to outperform their conventional counterparts. This paper will report the recent progresses in the research and development of the digital closed-loop IFOGs with components sharing and time division multiplexing approaches and briefly demonstrate our miniaturized off-the-shelf products and their applications in small commercial and scientific satellites. Based on our previous research works, the configurations of multi-axis IFOG using components sharing and time division multiplexing will be proposed. Compared with typical single axis IFOG these configurations may achieve unprecedented light weight, small dimension, low cost and power dissipation, which are crucial feathers for micro/nano-satellites. A novel modulation method for time division multiplexing will be shown to improve the signal to noise ratio significantly. An alternate loop closure control will be discussed correspondingly. Finally the miniaturized space products and their specification, performance and application will be introduced. A minimum three-axis IFOG overcoming the constraints of 200 grams weight and 2 watts power consumption demonstrated the performance of ≤0.2deg/hr bias instability, ≤0.03deg/hr random noise and ≤200ppm scale factor error. These products already served for more than ten micro-satellites including two commercial micro-satellite clusters ZHUHAI-1 and JILIN-1 and several scientific experimental micro-satellites.

7.0402 Interfacing Architecture between Telemetry and On-board Computer for a Nanosatellite

Abhishek Prasad , Yash Jain , Neelanchal Joshi , NISHANT GUPTA (Birla Institute of Technology and Science, Pilani), Varsha Singhania (Birla Institute of Technology and Science, Pilani), Yatharth Sreedharan (Bits Pilani, Pilani campus),

Presentation: NISHANT GUPTA, Wednesday, March 11th, 09:25 PM, Dunraven

The paper goes over a possible solution for providing an architecture of the interface between two subsystems of a nanosatellite (On-board computer and Telemetry), one of which runs on RTOS and the other on a Linux based OS. It reasons the use of UART over other serial protocols based on ease of implementation and efficiency of communication as the amount of data being exchanged is not memory extensive. It also exemplifies an approach of using FIFO memory to simplify the architecture of the interface between any two microcontrollers or SoCs for serial data transfer. This is also an asynchronous mode of data transfer as the two subsystems can send and receive data at different rates.

7.0403 On-board and Ground-station Telemetry Architecture Design for a LEO Nano-satellite

NISHANT GUPTA (Birla Institute of Technology and Science, Pilani), Umang Garg (Birla Institute of Technology and Science,Pilani), Sakshi Agarwal , Mohit Vyas (BITS Pilani),

Presentation: NISHANT GUPTA, Wednesday, March 11th, 09:50 PM, Dunraven

The presentation will detail the communication system architecture for a 3U hyper-spectral imaging CubeSat. It begins with discussions on objectives and requirements from the communication system. Based on these, architecture has been proposed. The architecture has been designed to ensure that the system works even in the case of emergencies, including, but not limited to antenna deployment failure or other component failures. This has been done by introducing multiple redundancy provisions. The architecture is broadly classified into three sections - Uplink, Downlink, and Beacon transmission. The satellite implements a full-duplex UHF-VHF architecture using Gaussian Minimum Shift Keying (GMSK) modulation scheme for data downlink and uplink, while a Morse coded, simplex, On-O Keying (OOK) scheme is used for beacon transmission. Onboard the satellite, a single monopole antenna is used for receiving uplink, while the other antenna doubles as a turnstile and dipole for downlink and beacon transmissions respectively. All the components to be used in the system, both onboard the satellite and at the Ground Station (GS) will be discussed. The reasons for selecting and details regarding the interfacing of these components will be elucidated. Further, we will also describe the flight plan for TTC and how the microcontroller switches between the modes of operations. Entry and exit conditions for each mode are defined. Discussions on terrestrial testing of individual modules and architecture of the system will also be included.

7.05 Power Electronics for Space Applications

Session Organizer: Christopher Iannello (NASA - NESC), Peter Wilson (University of Bath),

7.0502 Survey of Cryogenic Power Electronics for Space Applications

Haider Mhiesan , Md Maksudul Hossain (Univ. of Arkansas, Faytteville), Arman Rashid (University of Arkansas,), Yuqi Wei , Alan Mantooth (University of Arkansas),

Presentation: Haider Mhiesan, Monday, March 9th, 04:30 PM, Jefferson

Whether power electronics operate at room or at ultra-low temperatures, the design considerations and requirements are the same for highly reliable and efficient systems with high power density. For many years, researchers have evaluated power electronics under cryogenic temperature, and the outcome promised better performance. Power electronics at cryogenic temperatures have many applications, such as deep space and medical diagnostics. To date, power electronics operating at ultra-low temperatures has been evaluated for semiconductor devices, where the semiconductor devices show faster performance due to fact that the carrier mobility and the saturation velocity are increased. Power electronics operation at cryogenic conditions requires simpler thermal management and the lower operation temperature improves the thermal conductivity. This results in lower conduction losses, higher and more reliability [1]. Much research has been conducted to evaluate the WBG power semiconductors at cryogenic temperatures. In [2], GaN was characterized at cryogenic operation. At cryogenic temperatures, the on-resistance is 20% less. Additionally, there are 31.25% less switching losses. Si IGBTs and SiC MOSFETs operating at low temperature were compared in [3]. The comparison results show that SiC has smaller on-resistance which leads to lower conduction losses at cryogenic temperature. Several studies have focused on developing accurate modeling strategies to estimate the effects on the MOSFETs characteristics at cryogenic temperatures [4]-[5]. High-speed PWM chips have been evaluated in [6] as a function of temperature from 25°C to -190°C and they show better performance and stability at lower temperatures. Another key advantage of operating at low temperature is the reduction of the cable size, which leads to an increase in the system efficiency and power density [7]. Some power electronics applications have also been evaluated at cryogenic temperature. In [12], 1-kW single phase 3-level GaN inverter was tested at different temperatures. This work shows that the total losses are 16% less at -60°C compared to room temperature. In [13]- [14], H-bridge converter has been evaluated for low temperature applications. Buck converter has been tested at low temperature and the results show that the total system efficiency is increased from 95.8% to 97% [15]. Buck converter, synchronous rectifier, 3-level diode clamped converter, and 3-level (ZVS) were compared at low operation temperatures in [16]- [17]. The ZVS topology offers 18% switching loss reduction compared to other topologies while operating at low temperatures. To date, little research has been conducted for evaluation of power electronic topologies using WBG devices. Power electronic components have temperature dependent properties. Therefore, power electronic circuit topologies are temperature dependent. However, some power electronic topologies are more sensitive to temperature dependent device properties. This paper presents investigations required to reveal how the changes in topologies affect the circuits sensitivity to temperature dependent device properties. Results for the selected topologies for the purpose of comparison will be included in the final version of this paper.

7.0503 Robust Design of Emirates Mars Mission’s Electrical Power Subsystem

Essa Almehairi (Mohammed Bin Rashed Space Centre), Reid Gurnee (Johns Hopkins University/Applied Physics Laboratory),

Presentation: Essa Almehairi, Monday, March 9th, 04:55 PM, Jefferson

The presentation will give an overview of the robustness of the Emirates Mars Mission's electrical power subsystem and its autonomy. It will go over the different components that the subsystem is comprised of and their operation in terms of controlling the input/output power and managing the charging. The presentation will start with introducing the electrical power subsystem specifications followed by component selection and features. There will be an emphasis on the redundancy that each component has, in addition to the safety that is implemented against failures. Furthermore, the interaction of the subsystem will be touched upon, such as power distribution, battery charge management, bus voltage set-points, solar array performance, and autonomy of the charging algorithm, etc. Lastly, the presentation will explain the reasoning behind sizing the subsystem, which is based on driving scenarios and more specifically the worst case orbit.

7.0504 Evaluation of Point of Load Converters for Space Computational Loads

Thomas Cook (University of Pittsburgh), Aidan Phillips (University of Pittsburgh), Christopher Siak , Alan George (University of Pittsburgh), Brandon Grainger (University of Pittsburgh),

Presentation: Thomas Cook, Monday, March 9th, 05:20 PM, Jefferson

Space experiments in low earth orbit (LEO) are becoming more ambitious and the power electronic systems for these missions are quickly becoming outdated when compared to the power-dense and highly efficient commercial solutions used to power modern processors. In this work, a comparison is presented between several radiation-hardened (rad-hard) and commercial-off-the-shelf (COTS) point-of-load (PoL) converters with a focus on Gallium Nitride (GaN) switching FETS. The converters were designed and evaluated based on their electrical and thermal performance when supplying power to computational loads in a LEO environment. This work is presented in the context of supplying power to a 1U FPGA- based computing platform that features a mix of COTS and rad-hard components, and a modular power system.

7.06 Electronics for Extreme Environments

Session Organizer: Gary Bolotin (NASA Jet Propulsion Lab), Mohammad Mojarradi (Jet Propulsion Laboratory),

7.0601 Cold Survivable Current Sense Multi-Chip Module

Malcolm Lias (NASA Jet Propulsion Laboratory), Gary Bolotin (NASA Jet Propulsion Lab), Don Hunter (Jet Propulsion Labortory),

Presentation: Malcolm Lias, Tuesday, March 10th, 08:30 AM, Amphitheatre

Cold Survivable Current Sense Multi-Chip Module Gary Bolotin Jet Propulsion Laboratory, California Institute of Technology. Abstract – This paper will present the design of a Current Sense Module (CSM) capable of surviving the harsh ambient environment of ocean worlds, such as Europa and Enceladus that may see temperatures down to -184° C. This module is to be fabricated by i3 Electronics using their Multi-Chip Module (MCM) technology. JPL together with i3 Electronics have developed techniques to allow this module survive to temperatures down to -184° C. This module greatly improves the ability to measure current, phase current and bridge current which can be problematic in extreme environments. In addition, by packaging these electronics at the die level, we achieve significant weight and size savings. This module is one several modules that employ similar techniques for weight and size savings and are integrated into a distributed or centralized motor controller. The cold survivability allows the motor control electronics which results in the advantage of being able to be co-located with the motors in a robotic arm. This module is can also be used on its own where current sensing is needed in harsh environments. The paper will discuss the modules design along with a summary of our test results.

7.0602 The Roadmap from Concept to Infusion for a Cold Survivable Distributed Motor Controller

Gary Bolotin (NASA Jet Propulsion Lab), Don Hunter (Jet Propulsion Labortory), Malcolm Lias (NASA Jet Propulsion Laboratory),

Presentation: Gary Bolotin, Tuesday, March 10th, 08:55 AM, Amphitheatre

The Roadmap From Concept to Infusion for a Cold Survivable Distributed Motor Controller Gary Bolotin, Malcolm Lias, Don Hunter, Ben Cheng, Yutao He Jet Propulsion Laboratory, California Institute of Technology Abstract — This paper will present JPL's effort of working towards a distributed motor controller capable of working out in the ambient environment of in-situ missions to icy worlds such as Europa and Enceladus. Placing electronics out at the actuators has been a long time goal for JPL because it

enables a significant reduction in cable mass and its associated complexity. Learning from the previous efforts in this area we have developed a pragmatic approach based upon developing incremental deliveries that are complete products that could be sold on their own merits. These products take us closer by tackling a particular challenge in a tangible product that can be infused on its own long before we are ready to infuse the product that addresses our entire goal. A distributed motor controller requires a number of technologies to meet the goal. The controller needs to talk over a common interface network. The electronics needs to be miniaturized to fit in the unused volumes at the actuators. The electronics need to survive the ambient environment. Ultimately we would like the electronics to operate in the cold ambient environment as well. To date we have develop Multi-Chip Modules (MCMs) that address current sensing, motor drive, positon sensing and an FPGA based controller. We have developed a card that incorporates all these MCMs into a single 10cm x 16cm design. This design is ready for infusion into a miniaturized centralized motor controller. In this paper we will discuss the goal we are trying to achieve along with the roadmap for getting there. We will present the products we have produced along with the projects that have baselined these products into their designs. We will finish by discussing our plans for the future.

7.0603 First Iteration Communications Circuit for a Long-Lived In-situ Solar System Explorer (LLISSE)

Jennifer Jordan (NASA - Glenn Research Center), George Ponchak (NASA Glenn Research Center), Philip Neudeck (NASA - Glenn Research Center), David Spry (NASA),

Presentation: Jennifer Jordan, Tuesday, March 10th, 09:20 AM, Amphitheatre

The first iteration communication system circuitry for the Venus Long-Lived In-situ Solar System Explorer (LLISSE) lander was developed using NASA Glenn Research Center SiC JFET technology. The Long-Lived In-situ Solar System Explorer (LLISSE) lander is meant to land on the surface of Venus, where it will remain for 60 Earth days, and measure the wind speed and direction, temperature, pressure, radiance and chemicals periodically and transmit the data to the orbiting satellite. With the data from these sensors, planetary scientists hope to better understand the atmosphere super-rotation, the evolution of the Venus climate, and the interaction between the surface and the atmosphere.

7.0604 Select Electronic Parts Operation at Extreme Low Temperature

Jean Yang Scharlotta (Jet Propulsion Laboratory), Mohammad Ashtijou (JPL), Michael Han (Jet Propulsion Laboratory), Benjamin Blalock (The University of Tennessee), Mohammad Mojarradi (Jet Propulsion Laboratory), William Norton , Linda Del Castillo (Jet Propulsion Laboratory),

Presentation: Jean Yang Scharlotta, Tuesday, March 10th, 09:45 AM, Amphitheatre

The purpose of the study presented in this paper is to extend the test period of a selected set of electronics parts at cryogenic condition to dwell period of about 24 hours to demonstrate extreme cold operational capability of these components. The parts tested are tantalum polymer, BX and P90 type ceramic capacitors, thick film resistors, analog multiplexers, a digital inverter, and a D-flip-flop. These parts were tested to assist identifying candidate components that can be used for development of a cold capable telemetry board. There are several past investigations that have shown that COTS (commercial-off-the-shelf) capacitors and resistors tested at cryogenic temperatures and frequencies up to 10MHz did not exhibit significant changes in capacitance and resistance values. Also, there are several test results for active parts. These past tests collected measurements during a temperature sweep from room temperature down to cryogenic temperature with very short dwell time at cryogenic temperature, and back to room temperature. This study extends the operational dwell time to at least 24 hours and returning to room temperature operation without significant degradation in perfor-

mance for most parts. Thus, demonstrating the potential for actual operation in these extreme cold temperatures and a method for identifying the cold operability.

7.0605 A Universal Behavioral Model for COTS ADCs with Predictive Cold Temperature Performance Capability

William Norton , Jean Yang Scharlotta (Jet Propulsion Laboratory), Benjamin Blalock (The University of Tennessee),

Presentation: William Norton, Tuesday, March 10th, 10:10 AM, Amphitheatre

To further enable exploration of Cold Worlds, this paper seeks to develop a universal model for CMOS Nyquist rate COTS analog to digital converters (ADCs) that is predictive with respect to temperature. The modeling methodology is optimized to enable rapid model construction from readily available data sheet information without COTS ADC data collection to produce a behavioral model with predictive cold temperature performance estimation. Thorough temperature characterization of two different popular architecture COTS CMOS ADCs from two different manufacturers is used to add predictive temperature performance capability to this universal behavioral model for Nyquist rate CMOS ADCs. The model consists of two main blocks, namely a block modeling analog capture of the input by the track and hold (THA) amplifier, and a second block implementing an ADC's quantization transfer curve composed of offset error, gain error, and nonlinearity (INL) errors. The ADC's reference voltage temperature impact on quantization has been measured and included as well. To use the model, one must first identify a candidate part and extract as much information from the part's datasheet. For populating various components of the THA block, it is necessary to know or estimate basic technology information in addition to specifics regarding sampling capacitor size, transistor switch characteristics, and tracking amplifier dynamics. Many of these parameters have ranges which can be estimated from requirements on the converter's resolution and settling time. The next step is to implement the converter's nonideal quantization function, the transfer curve. The transfer curve is a record of the converter's decision locations. Again, directly using datasheet values, and by also extracting INL from a datasheet graph, one can build up the initial ADC model purely from literature and datasheet information. Parametric trends in ADC transfer curve, which have been measured and established across temperature, are applied to the initial parameters of the ADC's datasheet transfer curve. This allows the initial transfer curve to evolve across temperature in a similar fashion to what has been observed. From this, the simulated output and performance of the device may be computed. The paper concludes with a comparison of part to part variations for several DUTs along with simulated results. Under certain conditions, it may be possible to predict a rough estimate of a part's performance beyond datasheet temperature ranges.

7.0606 Cryogenic Temperature Induced Instability of 200MHz CMOS Operational Amplifier

Michael Han (Jet Propulsion Laboratory), Jean Yang Scharlotta (Jet Propulsion Laboratory), Mohammad Ashtijou (JPL),

Presentation: Michael Han, Tuesday, March 10th, 10:35 AM, Amphitheatre

Recent interest in LEO (Low Earth Orbit) communication systems and success in deep space exploration such as the Mars INSIGHT have spurred interest in using commercial off the shelf electronics (COTS) for space applications. In general, COTS parts are only guaranteed to operate over a limited range of temperatures, typically 0°C to +85°C for commercial applications or -40°C to +125°C for industrial applications. The majority of these commercial parts are typically not rated for space environment with extreme low and high temperature. Temperatures in space can be much colder than -40°C, or even at the cryogenic temperature (comparable to liquid nitrogen temperature 77K/-196oC) that exists on the moon or Mars during night, or the moons of Jupiter and Saturn. Thus there is a growing need to systematically evaluate these commercial off the shelf parts for their capability to work at cryogenic temperature ranges. This work investigates the electrical performance of a high speed general purpose operation amplifier, OPA2356, operating under cryogenic temperature ~-180oC. Evidence of cryogenic-induced instability of OPA2356 was experimentally observed and several rounds of hardware and test routines were modified and fine-tuned in order to experimentally capture and reproduce this instability phenomenon; the increase in Isupply's variability after extended -180oC cold dwell for more than 24 hours. Figure 1 shows snap shots of the monitored Isupply under extended cryogenic soak of OPA2356 at -180oC/24hrs and -70oC/16hrs, which caused increased random fluctuation of Isupply as compared to its initial room temperature current. This is exemplified by ~2X δ25C-initial at -180oC and 4X δ25C-initial at -70oC. Possible causes of this cryogenic induced instability are also discussed in this paper. This work also suggests using the static supply current (Isupply), also commonly known as DC standby current, of the analog chip as a good monitor of analog chip's instability operating under cryogenic operations. We also found that increasing voltage headroom by maximizing allowable VDD in analog chips will enable proper cryogenic operation of analog chips, which can be a critical trade-off for a space electronic system to consider between long term reliability and operating window.

7.07 Fault Tolerance, Autonomy, and Evolvability in Spacecraft and Instrument Avionics

Session Organizer: Didier Keymeulen (Jet Propulsion Laboratory), Tom Hoffman (Jet Propulsion Laboratory),

7.0702 Using Probabilistic AI with Local Awareness Sensors to Improve Satellite Resiliency

Michelle Simon (Air Force Research Laboratory),

Presentation: Michelle Simon, Friday, March 13th, 10:10 AM, Lake/Canyon

With 20,000 trackable orbital objects and hundreds of thousands of orbital debris too small to be cataloged, satellites today operate in an increasingly congested environment as more and more launches are performed. It is also common for a satellite to not be in 24/7 contact with the ground, this break in the communication network implying that when there is an anomalous event, there is often a longer downtime than desired. By monitoring the local structural state health of the satellite using sensors, the satellite could be alerted when it has been struck by debris and which area of the satellite has been effected. The information from the monitoring local structure state health system can be used by the on-board autonomous system to not only update the operator but it can also plan around the damaged area, if possible, so the overall mission can still be accomplished., To reduce the chances of the satellite being struck by debris the autonomous system could use local cameras to plan and execute maneuvers around reducing the chance of an on-orbit collision. By coupling a probabilistic AI system with local awareness sensors running onboard the vehicle, it will enable the satellite to execute maneuvers to reduce the chances of an on-orbit collision, and have higher resilience to the effects and dangers of space. At the Space Vehicle Directorate in the Air Force Research Laboratory, software has been built to support aspects of this concept. This software has been designed to be modular with each executable performing a specific function. Each executable falls into one of three different categories: processing sensor data, analysis on the processed data, and decision making using the analyzed information (data fusion). Probabilistic model are used to infer and recommend a proper course of actions. Initial capabilities of this concept have been tested with a local hardware in the loop testbed. This testbed allows us to work with real attitude information, simulated orbital dynamics, and emulated local awareness sensor hardware. Future work will focus on taking version of this software and implement it on repeated 6U cubesat missions, expanding our software and hardware library and improving the resiliency of the satellite.

7.0703 Towards an FDIR Software Fault Tree Library for Onboard Computers

Sascha Müller (German Aerospace Center - DLR), Kilian Hoeflinger (German Aerospace Center - DLR), Michal Smisek (German Aerospace Center - DLR), Andreas Gerndt (German Aerospace Center (DLR)),
Presentation: Sascha Müller, Friday, March 13th, 10:35 AM, Lake/Canyon

The increasing complexity of space missions, their software architectures, and hardware that has to meet the demands for those missions, imposes numerous new challenges for many engineering disciplines such as reliability engineering. Affected by the ever growing demand for more onboard computation power are the onboard computers. They in return require Fault Detection, Isolation, and Recovery (FDIR) architectures to support their fault tolerant operation in the harsh environment of space. Especially high performance commercial processing units face the challenge of dealing with negative radiation effects, which may significantly degrade their operation. To design performant and fault tolerant onboard computers, it is of high interest to assess the effectiveness of the FDIR architecture in the early phase of system design. This can be achieved using Fault Tree Analysis (FTA). However, to create complete fault trees manually is an error prone and labor intensive task. In this talk, we present a refined methodology for assessing the FDIR design of onboard computers in space systems, using a library of FDIR routines. The routines are modeled using fault trees and are composed into a software system fault tree using a basic fault model and a design configuration chosen by the reliability engineer. We demonstrate the feasability of our approach on the basis of a case study on the rover of the Martian Moons eXploration (MMX) mission. For the chosen case study, we obtain a reduction of up to 80% in terms of modeling effort.

7.0705 Hierarchical Distributed Autonomy: Implementation Platform and Processes

Fernando Figueroa (NASA Stennis Space Center), Lauren Underwood (NASA - Stennis Space Center), Ben Hekman (Northrop Grumman Corporation), Jonathan Morris (D2K Technologies, Inc),
Presentation: Fernando Figueroa, Friday, March 13th, 11:00 AM, Lake/Canyon

This work approaches autonomous implementation from a perspective different than that used for traditional NASA applications, i.e. for robotics and rovers. Autonomous operations are vital capabilities and critical technologies required for the success, safety and crew survival of NASA deep space missions beyond LEO. This is relevant since NASA is implementing the President’s Space Policy Directive, and a key objective is sustainable space exploration with reusable spacecraft and architecture, which could later take humans to Mars. This capability will require not only autonomous operations of spacecraft, but also systems that will be needed for habitation on the Moon and Mars. The future of “true” autonomous systems requires independent thinking and reasoning to eliminate the need for persistent updates and oversight by humans. It is also important to enable passive monitoring of the progress of a task when desirable, to make possible awareness for rapid comprehension and action by operators. Because of the complexity of these systems, an architecture that accommodates multiple autonomous systems hierarchically organized so that systems in the higher levels of the hierarchy have authority to manage systems at lower levels, when decisions that affect the higher-level systems are considered is required. The paper will describe a software platform called the NASA Platform for Autonomous Systems (NPAS), along with processes; that make possible implementing hierarchical distributed autonomy. NPAS enables implementation of “thinking” autonomy as model-based analysis is achieved by the autonomous system application. This in contrast with typical autonomous systems or Brute-Force Autonomy (BFA) strategies that consists of considering all possible cases for autonomous decisions and applying those specific strategies to generate solutions offline. In BFA, these cases and solutions are then incorporated in the processor for implementing autonomy, and the processor simply chooses the decisions which correspond to each prescribed case. An interpretation of this methodology suggests that the “thinking” is done offline by experts. NPAS is a platform that integrates all functions required for autonomy: (1) Integrated System Health Management (ISHM); (2) autonomy strategies, guided by system health and concepts of operations; (3) domain objects (system elements) and infrastructure to create complete application domain knowledge models (4) infrastructure to create, schedule, and execute mission plans; (5) infrastructure to develop user interfaces for comprehensive awareness; and (6) infrastructure to integrate distributed autonomous applications across networks. The paper will also discuss how NPAS has been used to implement autonomy, and how these capabilities developed could be leveraged and used to implement autonomy for Gateway. Demonstration results from specific NPAS prototype applications will be described. One implementation, conducted at NASA’s Johnson Space Center’s integrated Power Avionics and Software (iPAS) lab, validated application for a generic space habitat encompassing three NPAS autonomy applications: a vehicle manager, a power system, and an avionics system. A second implementation, which leveraged the iPAS autonomy application, demonstrated distributed hierarchical autonomy for a space habitat mockup built by Northrop Grumman Intelligent Systems (NGIS).

7.0706 LiveView and P2serialcmds Co-Verification Software for NGIS and Embedded MPSoC Instrument Avionics

Eugene Shao (Caltech), Joshua Anderson , Vanessa Mechem (Jet Propulsion Laboratory), Jacqueline Ryan (Jet Propulsion Laboratory), Didier Keymeulen (Jet Propulsion Laboratory), Elliott Liggett (NASA/JPL), Robert Valencia (Jet Propulsion Laboratory), Michael Bernas (Jet Propulsion Laboratory), Matthew Klimesh (Jet Propulsion Laboratory / Caltech), David Dolman (Alpha Data Parallel Systems Ltd.),
Presentation: Jacqueline Ryan, Friday, March 13th, 11:25 AM, Lake/Canyon

The emergent technology of Multi-Processor System-on-Chip (MPSoC) devices promises lighter, smaller, cheaper, more capable and reliable space electronic systems that could help to unveil some of the secrets in our universe. This paper describes the automation and the integration of hardware/software co-verification tools (LiveCheckHSI) for the Xilinx Zynq-based SoC and UltraScale MPSoC avionics system that have been developed at the Jet Propulsion Laboratory (JPL) for Next-Generation Imaging Spectrometers (NGIS). The flight NGIS avionics acquires and compresses images in real-time, in addition to reporting telemetry and programming the spectrometer, focus step motor, and heaters. This paper describes the new development of LiveCheckHSI: comprising a data visualization tool, as well as command and telemetry software. In addition, the deployment of LiveCheckHSI to flight avionics is described. The heavy reliance on the ability to discern instrument behavior in real time for displaying data transmitted by an imaging spectrometer led to the development of LiveView, a co-verification tool that executes real-time data processing and visualization on hyperspectral imaging data. This paper documents progress on current LiveView development, including the implementation of features that allow LiveView to be compiled without a CameraLink driver installed, enable the dragging and dropping of files into LiveView, and enable subframe sampling rates in the fast Fourier transform widget. Furthermore, this paper details the Qt-based p2serialcmds GUI and its development, which includes enhancements to the remote recording and automated test scripting capabilities. The p2serialcmds GUI serves as a comprehensive user interface for interacting with the LiveView software, NGIS, and supporting devices, and its development, which includes enhancements on the recording and scripting abilities and implementations of new features. This paper also describes the integration of the Qt-based LiveView application and the Qt-based p2serialcmds GUI onto the MPSoC. This installation was made possible by building the Yocto Linux

operating system (OS) onto the MPSoC, which thereby enabled C++ applications such as the Qt framework, LiveView, and p2serialcmds to be compiled and run on the device.

7.0707 Design and Construction of Power Distribution Architecture of Cubesat Using Genetic Algorithm

Sameeksha Rao (RV College of Engineering), Ankitha Selvam , Rithika Varma , Aayushii Goswami (RVCE),

Presentation: Sameeksha Rao, Friday, March 13th, 11:50 AM, Lake/Canyon

The power distribution system of a nanosatellite consists of various integrated circuit components arranged and connected in a way that leads to its maximum optimization. To achieve maximum optimization, the integrated circuits need to be selected by keeping various power requirement parameters and physical parameters in mind. The goal of this paper is to carry out a trade off analysis to select various ICs used in the power distribution architecture of RV-SAT1, which is a cubesat carrying a biological payload, and find out pathways in which the power distribution system can function if one or more of the components falter,using an innovative method called genetic algorithm. Genetic algorithm provides a multi-faceted outlook at optimization problems which is very useful in carrying out the trade off analyses to select components as there are various parameters that need to be considered in the process of component selection. Once the information of the power requirements of various loads in RV-SAT1 is obtained, the selection of ICs is done on the basis of its various fundamental properties by applying genetic algorithm. The simulation of the power distribution architecture is done using the genetic algorithm toolbox in MATLAB SIMULINK. Furthermore, this technique is applied to consider various scenarios of component malfunctioning and provide unique solutions for each one of those cases.

7.08 Guidance, Navigation, and Control Technologies for Space Applications

Session Organizer: Giovanni Palmerini (Sapienza Universita' di Roma), John Enright (Ryerson University),

7.0802 High Precision Fiber Optic Gyroscope Based on Photonic-Crystal Fiber for Space Application

Kong Linghai , Jin Jing , Wei Cai , Fuyu Gao , Kun Ma , Jiliang He (Beihang University), Ningfang Song , Chunxi Zhang ,

Presentation: Kong Linghai, Wednesday, March 11th, 08:30 AM, Dunraven

Interferometric Fiber Optic Gyroscopes (IFOGs) have been widely used in space spacecraft such as satellites because of their particular advantages including high performance, low power consumption, large dynamic ranges and high reliability as a solid state technology without any moving parts. With the continuous development of space technology, higher-performance IFOGs are required to keep up with the demand, especially the ones with high precision and better environmental adaptability. However, IFOGs are susceptible to external perturbations such as radiation, temperature and magnetic field, which most limits the application of high precision IFOGs in space. The advent of photonic-crystal fiber (PCF) offers a new means to solve these problems. The PCF is a new type of optical fiber with a different guiding mechanism from the conventional polarization-maintaining fiber (PMF). Its environmental adaptability is better than that of the conventional PMF. Here, we present a comprehensive introduction to our latest research about photonic crystal fiber optic gyroscope(PCF-IFOG) aiming for space applications. First, this paper reports the detail design schemes of the high precision PCF-IFOG made by the low-loss small-diameter photonic crystal fiber. In addition to the PCFs, other special designs for space applications are also performed in this IFOG.

Secondly, the performance parameters of the low-loss small-diameter photonic crystal fiber with the size of φ100/135um are shown. Finally, the tested and analyzed data of the newly developed high-precision photonic crystal fiber optic gyroscope are given. All the test data show that the random walk coefficient (RWC) of the PCF-IFOG is better than 0.0002 °/h.

7.0803 Investigation of Instabilities in Detumbling Algorithms

Jeet Yadav , Tushar Goyal (Birla Institute of Technology and Science),
Presentation: NISHANT GUPTA, Wednesday, March 11th, 08:55 AM, Dunraven

Detumbling refers to the act of dampening the angular velocity of the satellite. This operation is of paramount importance since it is virtually impossible to nominally perform any other operation without some degree of attitude control. Common methods used to detumble satellites usually involve magnetic actuation, paired with different types of sensors which are used to provide angular velocity feedback. Team Anant is a group of undergraduate students working to build a 3U CubeSat with a hyperspectral imager as its primary payload. The team explored two detumbling algorithms, keeping in mind their efficiency and power used. This paper presents the adverse effects of time discretization on the stability of these detumbling algorithms. The first algorithm (Bdot) uses only magnetometer information as an input, while the second algorithm uses both magnetometers and Inertial Measurement Unit (IMU) for the magnetic field and angular velocity feedback. An extensive literature review revealed that both algorithms achieve absolute stability for systems involving continuous feedback and output. However, the physical components involved impose limitations on the maximum frequency of the algorithm, thereby making any such system inconceivable. This asserts the need to perform a discrete-time stability analysis, as it is better suited to reflect on the actual implementation and dynamics of these algorithms. The first section of this paper presents the current theory and views on the stability of these algorithms. The next section describes the discrete-time stability analysis performed by the team and the conclusions derived from it. Theoretical investigation led to the discovery of multiple conditions on angular velocity and operating frequencies of the hardware, for which the algorithms were unstable. These results were then verified through various simulations on MATLAB. The paper concludes with a discussion on the various instabilities posed by time discretization and the conditions under which the detumbling algorithm would be infeasible.

7.0808 Learning-based Warm-Starting for Fast Sequential Convex Programming and Trajectory Optimization

Somrita Banerjee (Stanford University), Thomas Lew (Stanford University), Riccardo Bonalli (Stanford University), Abdulaziz Alfaadehl (KACST), Ibrahim Alomar , Hesham Shageer (Stanford University), Marco Pavone (Stanford University),
Presentation: Somrita Banerjee, Wednesday, March 11th, 09:20 AM, Dunraven

Sequential convex programming has recently emerged as an effective tool to quickly compute locally optimal trajectories for robotic and aerospace systems alike, even when initialized with an unfeasible trajectory. In this paper, by focusing on the Guaranteed Sequential Trajectory Optimization (GuSTO) algorithm, we propose a methodology to accelerate SCP-based algorithms through warm-starting. Specifically, leveraging techniques from imitation learning, we devise a neural-network-based approach to predict a locally optimal state and control trajectory, which is used to warm-start GuSTO. This approach allows one to retain all the theoretical guarantees of GuSTO while simultaneously taking advantage of the fast execution of the neural network and reducing the time and number of iterations required for GuSTO to converge. The result is a faster and theoretically guaranteed trajectory optimization algorithm.

7.0812 Attitude Stabilization during Retargeting Maneuver of Flexible Spacecraft Subject to Time Delay

Chokri Sendi (University of Alaska Anchorage),
Presentation: Chokri Sendi, Wednesday, March 11th, 09:45 AM, Dunraven

This paper investigates the attitude stability of a flexible spacecraft made of a rigid platform and multiple flexible appendages during retargeting rest to rest slew maneuver. In addition to the attenuation of external disturbances and model uncertainties, the designed fuzzy controller goal is to suppress the vibration caused by the minimum time maneuver of the appendages, and to stabilize the attitude of the spacecraft subject to independent time delay and actuators saturation. The fuzzy controller-observer is formulated as a set of linear matrix inequalities and utilizes the parallel distributed compensator to obtain the feedback control and the observer gains. Numerical simulations are provided to measure the performance of the proposed controller.

7.0813 Quaternion Based Optimal Controller for Momentum Biased Nadir Pointing Satellite

Salahudden Qazi (Indian Institute of Technology Kanpur), Dipak Giri , Vijay Shankar Dwivedi (IIT Kanpur), Ajoy Ghosh , Praful Kumar (University of Toronto),
Presentation: Salahudden Qazi, ,

We proposed a robust LQR controller for a Nadir Pointing Satellite. Dynamics and framework for controller design have been discussed, and a generalized state-space derived for the controller. Simulations have been carried out for the proposed controller over various satellite classes. Through simulations, we observed that even in case of highly elliptical orbits, a single controller design could yield optimal results and the variation of angular rates on control output is minimal. Even in case of extreme variations in Inertia matrix and orbital rates, the controller performs as intended.

7.0814 Performance Determination of a Multi-Mode Thruster Using GPS and Star Tracker Data

Kyle Craft (Missouri University of Science and Technology), Jacob Darling (The Boeing Company), Henry Pernicka (Missouri University of Science and Technology),
Presentation: Kyle Craft, Wednesday, March 11th, 10:10 AM, Dunraven

Abstract—A key element of the Advanced Propulsion Experiment (APEX) spacecraft mission is the accurate thrust determination of a Multi-Mode Ionic Monopropellant Electrospray (MIME) thruster payload. The MIME thruster payload operates in high thrust, low specific impulse chemical mode and low thrust, high specific impulse electric mode, making standard thrust determination processes by accelerometer or attitude maneuver not feasible. The development of a batch filter to determine thrust from an orbit changing maneuver is presented. The batch filter estimates a constant thrust magnitude along with the dynamic states of the vehicle, the coefficients of drag and solar reflectivity and the time biases of the GNSS receiver. To improve accuracies in GPS pseudorange measurements, the International GNSS Service Final Product GPS ephemeris and clock biases are used to improve position and thrust determination. The statistical consistency of the batch filter was verified using a Monte Carlo analysis. An initial investigation of desired maneuver duration and attitude was performed in order to assist in APEX mission design and concept of operations development.

7.0816 Intrinsic Desensitized Optimal Control

Hans Seywald (AMA),
Presentation: Hans Seywald, Wednesday, March 11th, 10:35 AM, Dunraven

The Desensitized Optimal Control (DOC) approach enables the simultaneous optimization of a physical reference trajectory and the associated transition matrix describ-

ing the sensitivity of the physical states in the neighborhood of the optimal reference trajectory. In the context of DOC, the gains appearing in the differential equations for the sensitivity states are treated like additional controls, and are subject to optimization. In the standard DOC approach, the optimization of the DOC gains is performed with no attention paid to the optimality of the continuation of a trajectory after a perturbation is encountered. This limitation is overcome in the present paper by introducing a condition that forces the DOC control gains to become equal to the DOC problem's neighboring optimal control gains. The newly introduced condition cannot be considered an optimality condition since it acts as a constraint, and hence, can never cause an improvement in the DOC problem's performance index. The condition cannot qualify as a state constraint or control constraint either since it involves the DOC problem's costates. The condition is dubbed a "design condition", since it enforces a desirable behavior of the optimal solution that is not otherwise compelled by the minimization of the DOC performance index alone.

7.0817 An Experimental Approach to Mapping of Magnetic Fields of CubeSat Attitude Actuator Representations

August Williams , Sharanabasaweshwara Asundi (Old Dominion University),
Presentation: August Williams, Wednesday, March 11th, 11:00 AM, Dunraven

In a compactly designed satellite, particularly those hosting magnetic or electric motor based actuators, the magnetic field distribution is continuously changing and can adversely affect the sensor/instrument measurements captured for attitude/orbit computations or science data collection. The purpose of this study is to elaborate on a 2-step process for mapping the magnetic field of a compactly designed satellite. The 2-step process involves, (i) carrying out experiments in a Helmholtz cage (HHC) to obtain discrete measurements of the satellite magnetic field, and (ii) perform a Fourier analysis to extrapolate the discrete measurements into a continuous map. A tri-axial HHC with precision magnetometers is set up to facilitate the measurement of magnetic field of CubeSat components – permanent magnets, magnetic torquers, etc, in a three dimensional (3D) space. Upon satisfactory calibration of the HHC, an electromagnet emulating a CubeSat magnetic torquer is placed on a rotating platform inside the HHC. The HHC is pre-configured to negate the effect of Earth’s magnetic field. Using a DC supply as a power source, various intensities of currents are passed through the torquers. For various values of the current flowing through the torquers, precision magnetometers are used to measure the magnetic field generated by the torquers. The discrete magnetometer measurements are used in a Fourier analysis to develop continuous maps of magnetic fields. The magnetic maps, thus developed, facilitate an understanding of the adverse effects of satellite magnetic field on sensors, instruments. The underlying intent of the underlying research is to investigate compensation approaches to address the adverse effects of the satellite magnetic field on its sensors and instruments.

7.09 Emerging Technologies for Space Applications

Session Organizer: Michael Mclelland (Southwest Research Institute), William Jackson (Sierra Nevada Corp.),

7.0901 Near Field Wireless Power Transfer via Robotic Feedback Control

Carl Greene (Michigan Technological University), Wayne Weaver , Jeremy Bos (Michigan Technological University), John Naglak (Michigan Technological University), Casey Majhor (Michigan Technological University),
Presentation: Carl Greene, Monday, March 9th, 09:00 PM, Jefferson

Unmanned rover application plays a key role in planetary exploration, where power and efficiency is paramount. The approach utilized in this work allows for near field wireless power transfer in remote locations with minimal support. The ability to establish a micro-grid power system connection autonomously using wireless power, eliminates the arduous task of designing a complex, multiple degrees of freedom (MDOF) robotic arm. The work presented in this paper, focuses on both the hardware and software within the micro-grid system. This particular near field wireless system consists of a primary and secondary set of modules, comprised of Litz wire coils, which are inductively coupled to complete the circuit. Both the primary and secondary modules contain a shunt resistor circuit, as well as a potential divider circuit and an Arduino controller (used to collect and analyze recorded data). The aforementioned hardware, allows for quantitative measurement of voltage, current, and power of the primary and secondary modules. Robot rover docking is accomplished using camera visualization, wheel odometry, and GPS data; all of which, are provided by the Robot Operating System (ROS). Various docking poses are used to characterize overall power transfer and efficiency at diverse alignments. Using collected data from the near field power modules' Arduino controllers and ROS, power from the coils is measured as functions of both the distance between coils and associated yaw angle. Power transfer efficiency is then evaluated using compiled power data. A dynamic feedback control system optimizes power transfer efficiency and docking alignment. The feedback control system acts as the driving force for re-docking the robot and further enhancing efficiency of the proposed near field power connection. In its entirety, the research paper explores the physical and mathematical relationships used to develop the dynamic feedback control system.

7.0902 RADSoM - a System on Module Approach for Reusable Spacecraft Processing Elements

Jeffrey Boye (JHUAPL),

Presentation: Jeffrey Boye, Monday, March 9th, 09:25 PM, Jefferson

Presentation and overview of progress to date on the RADSoM development - a proof of concept approach to modularizing spacecraft processing elements ongoing at the Johns Hopkins University Applied Physics Lab.

7.0903 Designing Printed Circuit Boards to Drastically Reduce the Occurrence of Tombstoned Components

Donald Schatzel (Jet Propulsion Laboratory/California Institute of Technology),

Presentation: Donald Schatzel, Monday, March 9th, 09:50 PM, Jefferson

Designing Printed Circuit Boards to Drastically Reduce the Occurrence of Tombstoned Components Electronic components continue to shrink as electronic printed circuit boards become denser. Smaller discrete passive devices such as surface mount capacitors and resistors are increasing in use and approaching sizes that require magnification to recognize. Unfortunately, during the Surface Mount Technology (SMT) assembly process these smaller devices are the primary source of defects during soldering. One of the leading defects during SMT is “Tombstoning,” a condition where a capacitor or resistor only solders on one end due to vertical rotation of the component creating an open circuit. Rework is costly and potentially induces additional factors that can decrease overall reliability because rework requires heating the defect location multiple times with a soldering iron; once to remove and once to replace for each pad. This defect can be drastically reduced by using the correct printed circuit board design parameters when laying out the board pad geometries. Printed Circuit Board pad size and geometry play a significant role in reducing and eliminating “tombstoning.” This paper presents the results from a comprehensive Designed Experiment illustrating the effects of different pad designs and their effect on the amount of defects. The results show that smaller pad geometries are a major factor in the reduction of “tombstoning.” This combined with the elimination of solder mask between the pads yield significant reduction in SMT soldering defects. This paper will delineate the major factors involved and how a comprehensive Design of Experiment (DOE) was planned and performed to drastically reduce this type of defect.

7.10 COTS Utilization for Reliable Space Applications

Session Organizer: Douglas Carssow (Naval Research Laboratory), Harald Schone (Jet Propulsion Laboratory), Eric Bradley (Naval Research Lab),

7.1002 Evaluation of Algorithm-Based Fault Tolerance for ML and CV under Neutron Radiation

Seth Roffe (NSF Center for Space High-performance and Reliable Computing), Alan George (University of Pittsburgh),

Presentation: Seth Roffe, Tuesday, March 10th, 11:00 AM, Amphitheatre

In the past decade, there has been a push for adaptation and deployment of commercial-off-the-shelf (COTS) electronic systems on space systems and missions due in part to improved affordability, performance, and energy-efficiency. Traditionally used radiation-hardened processors are expensive and only provide limited processing capability compared to modern COTS options. Therefore, COTS-based solutions are highly attractive for these missions. Furthermore, the deployment of COTS technology on spacecraft has enabled machine-learning and computer-vision applications, which are emerging technologies for on-board data analytics. However, COTS electronics are highly susceptible to radiation, which can lead to single-event upsets corrupting computational data. As a result, reliability in the underlying computations for machine-learning applications becomes a concern. Specifically, the typically long run-time and large amounts of memory needed for machine-learning applications makes them even more susceptible to single-event upsets. The bottleneck in computationally intense machine-learning applications falls to the underlying matrix multiplication. Therefore, measures need to be taken to ensure data reliability in the on-board processing of machine-learning applications. In this paper, we will apply and evaluate algorithm-based fault tolerance (ABFT) to mitigate silent data errors in a matrix-multiplication kernel to evaluate ABFT's efficacy for reliable machine-learning applications in a radiative environment. ABFT is a methodology of data-error detection and correction using information redundancy to augment the primary data. In matrix multiplication, ABFT consists of storing checksum data in vectors separate from the matrix. These checksums can then be used to verify the contents of matrices before and after operations. To evaluate this research, fault injection into a 500×500 matrix-multiplication kernel was performed prior to irradiation. The CPU side of the Xilinx Zynq 7020 SoC processor on the Digilent PYNQ-Z1 board is used. This platform was selected to emulate the CSP space computers developed by the NSF SHREC Center and currently deployed on the International Space Station, where this technique will be used for on-board machine-learning. Irradiation was performed on the kernel under wide-spectrum neutrons at Los Alamos Neutron Science Center to observe the mitigation effects of ABFT. Fault injections targeted towards the general-purpose registers showed a ~45x reduction in data errors using data-error mitigation with ABFT with a negligible change in run-time. Similarly, ABFT was shown to reduce data errors by ~10x in beam testing. The results of this experiment demonstrate that ABFT is a viable solution for active data reliability in matrix multiplication for machine-learning and computer-vision applications in future spacecraft.

7.11 Designing Spacecraft Hardware for Electromagnetic Compatibility, Signal Integrity, and Power Integrity in Space Applications

Session Organizer: Pablo Narvaez (NASA Jet Propulsion Lab), Paul Edwards (a.i solutions), Jeffrey Boye (JHUAPL), James Lukash (Lockheed Martin Space),

7.1101 Application of Fault Containment Principles to Electromagnetic Compatibility

Reinaldo Perez (Jet Propulsion Laboratory),

Presentation: Reinaldo Perez, Wednesday, March 11th, 04:30 PM, Jefferson

A hardware fault in aerospace is an undesired response to a designed engineering function in hardware. Therefore, in aerospace systems fault management is of prime importance. An important aspect of hardware faults is fault propagation. Fault propagation (also known as failure propagation) is a condition where a fault will not only produce an undesired hardware response, at its location of origin, but the fault will also propagate to other interfaced hardware and cause additional faults, or failures. Fault containment is necessary to avoid fault propagation. A fault containment region is an electronic or electromechanical region within a given hardware assembly where a fault in that region will not physically propagate to other regions of the assembly, and beyond. Rather, the fault will cause a functional failure of the hardware, where the fault occurred, without causing any additional propagated failures. Electromagnetic Compatibility (EMC) is a desired state in aerospace hardware. Electromagnetic Interference (EMI) in aerospace hardware is a fault condition of EMC. Like other faults EMI can also propagate to other aerospace hardware unless it occurs inside an EMI containment region. The paper addresses the concepts of fault containment region and introduces the concept of EMI containment region with examples of both.

7.1103 An Approach to Magnetic Cleanliness for the Psyche Mission

Maria De Soria Santacruz Pich (Jet Propulsion Laboratory),

Presentation: Maria De Soria Santacruz Pich, Wednesday, March 11th, 04:55 PM, Jefferson

Psyche is a Discovery mission that will visit the asteroid (16) Psyche to determine if it is the metallic core of a once larger differentiated body or otherwise was formed from accretion of unmelted metal-rich material. The spacecraft will launch in August 2022 and arrive at the asteroid in January 2026. Psyche will carry three science instruments: a gamma ray and neutron spectrometer, a magnetometer, and a multi-spectral imager. Additionally, the spacecraft will host the Deep Space Optical Communications payload, which is a technology demonstration not required to meet Psyche's science objectives. The magnetometer is composed of two identical high-sensitivity magnetic field fluxgate sensors mounted in a gradiometer configuration that enables the rejection of meter-scale stray fields from the spacecraft. The instrument is key to meeting mission objectives since measurements of a strong asteroid remanent magnetic field will unambiguously indicate that (16) Psyche is an iron core. The magnetic signature from the spacecraft is the main source of noise for the magnetometer, both for DC and AC magnetic fields. Limiting and characterizing spacecraft-generated magnetic fields is therefore essential to the mission. This is the objective of the Psyche's magnetics control program described in this paper. The first step towards a successful program was to establish a set of magnetic cleanliness requirements directly derived from the magnetometer science performance and Psyche's range of expected fields. Test and modeling efforts of DC and AC fields of spacecraft components were then put in place to characterize and understand the spacecraft fields and enable verification of the cleanliness requirements. In this paper we describe the derivation of these requirements, test and analyses methods, and more generally the processes and procedures that govern the magnetics program for Psyche.

7.1104 Shield to Pin Coupling of Lightning-like Transients on Payload Umbilical Cables on a Launch Pad

Dawn Trout (NASA - Kennedy Space Center), Paul Edwards (a.i solutions),

Presentation: Dawn Trout, Wednesday, March 11th, 05:20 PM, Jefferson

In this paper we describe in-situ testing of a long payload umbilical, on a launch site, injected with "lightning-like" transients and describe resulting pin-to-pin voltages. Injections and voltage measurements near the ground support equipment room, as well as at a location near the payload junction box, are made. The umbilical cables tested include an outer over-braid and the inner conductor coupling is examined for open circuit, short-circuit and various loads representative of spacecraft input impedances. This testing is important because the Kennedy Space Center (KSC) where the lightning occurrence is the highest in the United States, is the primary launch site for Launch Services Program spacecraft customers. Lightning planning is essential but developing a lightning plan is often overlooked or not adequately analyzed leaving the spacecraft vulnerable to time delays or even damage when lightning occurs. At other popular launch sites like Vandenberg Air Force Base (VAFB) where lightning occurs less often, although at the same or greater intensity when it does occur, lightning planning is often completely ignored by the spacecraft. The two major questions to be addressed in the lightning plan are what retesting should be done to establish a "goodness" level and what is the trigger criteria for this testing? The spacecraft will typically use a standard spacecraft check-out procedure to address the necessary retesting, but determining the trigger criteria is often an issue. For instance, a spacecraft needs to understand what their immunity is to a certain lightning magnitude and location. Determining the amount of current that can be coupled onto a spacecraft umbilical can be calculated by using worst case assumptions or measured with current probes and current measurement devices. Spacecraft can also determine what pin-to-pin voltages they are sensitive to, however pin-to-pin voltage measurements are not typically taken during the strike due to the invasive nature of this measurement. In this paper, we present detailed data on the shield to pin voltage transfer functions to provide insight to the spacecraft developers for lightning retest criteria planning. The results from this unique testing opportunity provide essential details on specific coupling mechanisms affecting spacecraft hardware that interfaces with the ground support equipment. This missing link between cable shield currents and payload susceptibility voltages has been methodically tested and representative data presented.

7.1105 Electromagnetic Compatibility Considerations for International Space Station Payload Developers

Matthew McCollum (NASA - Marshall Space Flight Center), Christopher Lowe (Jacobs Space Exploration Group), Larry Kim (ESSCA),

Presentation: Matthew McCollum, Wednesday, March 11th, 09:00 PM, Jefferson

The International Space Station (ISS) is a laboratory for scientific research, innovative technology development, and global education. The ISS provides a number of facilities and platforms for payload developers and investigators to conduct biological, microgravity, and Earth and space observation science, as well as for performing technology development. Due to the unique nature of the ISS vehicle and its electrical power and data systems, achieving electromagnetic compatibility (EMC) with the vehicle requires special considerations by the payload developer. The ISS electromagnetic interference (EMI) requirements and test methods are based on MIL-STD-461, "Electromagnetic Emissions and Susceptibility Requirements for the Control of Electromagnetic Interference," Revision B, and MIL-STD-462, "Electromagnetic Interference Characteristics, Measurement of," respectively. The low source impedance of the test setup requires special attention when designing or selecting EMI power filters and switched mode power supplies. Many filters, suited for later revisions of MIL-STD-461, will result in non-compliant designs. ISS electrical power system power quality requirements, imposed to protect the stability of the system, can also affect EMI filter design. The selection and use of commercial-off-the-shelf (COTS) equipment for ISS applications requires forethought and scrutiny to meet both EMC and crew safety requirements. Furthermore, the ISS environment can provide unique immunity challenges; if the payload developer ignores these challenges, the result is a possible loss of science or impact to technology demonstration. The ISS provides a unique opportunity for the science and technology development community. However, in order to be successful, the payload developer must incorporate special EMC considerations, many of which will be presented.

TRACK 8: SPACECRAFT & LAUNCH VEHICLE SYSTEMS & TECHNOLOGIES

Track Organizers: Robert Gershman (JPL), Bret Drake (The Aerospace Corporation),

8.01 Human Exploration Beyond Low Earth Orbit

Session Organizer: Kevin Post (The Boeing Company), Bret Drake (The Aerospace Corporation), John Guidi (NASA), Douglas Craig (NASA),

8.0101 NASA's Lunar Exploration Enterprise

Marshall Smith (NASA HQ), Erin Mahoney (Stardog Union), Douglas Craig (NASA), Jonathan Krezel , Kandyce Goodliff (NASA), Nicole Herrmann (Valador), Jacob Bleacher (NASA - Goddard Space Flight Center), Nathanael McIntyre (NASA - Headquarters),

Presentation: Marshall Smith, Wednesday, March 11th, 08:30 AM, Jefferson

NASA is developing a two-phased approach to quickly return humans to the Moon and establish a sustainable presence in orbit and on the surface. The two phases run in parallel, and both have already begun, with selection of the first Gateway element, the Power and Propulsion Element, solicitation activities focused on an American-built, industry-provided integrated Human Landing System, and discussions with industry and international partners about potential opportunities for collaboration. Phase 1 is driven exclusively by the administration's priority to land the first American woman and the next American man on the lunar South Pole by 2024. In this phase, NASA and its industry partners will develop and deploy two Gateway components: the Power and Propulsion Element (PPE) that will launch in 2022, and a minimal habitation capability that will launch in 2023. Both will launch on commercial rockets. This initial Gateway configuration represents the beginning of its capability buildup, and the primary components required to support the first human expedition to the lunar South Pole. The first Human Landing System will aggregate and dock to the Phase 1 Gateway, in preparation for deploying 2024 astronauts to the lunar surface. Phase 2 is focused on advancing the technologies that will foster a sustainable presence on and around the Moon – a lasting and productive presence enabled by reusable systems, access for a diverse body of contributing partners, and repeatable trips to multiple destinations across the lunar surface. In this Phase, we will pursue reusable landing system vehicles to make surface expeditions more repeatable and affordable. While the Gateway is the first of its kind to be funded, the concept has been proposed for decades as a necessary and foundational capability for a sustainable return to the Moon, and a port for vehicles embarking to farther destinations. It supports every tenet of Space Policy Directive-1 and the infrastructure it provides is critical to an accelerated return to the Moon, and access to more parts of the Moon than ever before. The Gateway also provides a unique platform to conduct cross-discipline science. Science instruments, both internal and external to the Gateway, will gather new space science, Earth science, and biological research data from deep space. Additionally, the broad science community will be able to utilize the communications and data relay capabilities of the Gateway, beginning with the PPE in Phase 1. This paper will outline the cross-discipline activities NASA is currently conducting, and those the agency anticipates conducting in the future to successfully implement Phases 1 and 2 in the lunar vicinity, all while preparing for humanity's next giant leap: Mars.

8.0102 NASA's Human Landing System: The Strategy for the 2024 Mission and Future Sustainability

Greg Chavers (NASA / MSFC), Lisa Watson-Morgan (NASA - Marshall Space Flight Center), Marshall Smith (NASA HQ), Tara Polsgrove (NASA Marshall Space Flight Center), Shawn McEniry (ASRC for NASA Marshall Space Flight Center),

Presentation: Greg Chavers, Wednesday, March 11th, 08:55 AM, Jefferson

In response to the 2018 White House Space Policy Directive-1 to lead an innovative and sustainable lunar exploration, and to the Vice President's March 2019 direction to do so by 2024, NASA is working to establish humanity's presence on and around the Moon by: 1) sending payloads to its surface, 2) assembling the Gateway outpost in orbit, and 3) demonstrating the first human lunar landings since 1972. NASA's Artemis program is implementing a multi-faceted and coordinated agency-wide approach with a focus on the lunar South Pole. The Artemis missions will demonstrate new technologies, capabilities and business approaches needed for future exploration, including Mars. Assessing options to accelerate development of required systems, NASA is utilizing public-private engagements through the Human Exploration and Operations Mission Directorate's NextSTEP Broad Agency Announcements. The design, development and demonstration of the Human Landing System is expected to be led by a commercial partner. Utilizing efforts across mission directorates, the Artemis effort will benefit from programs from the Science Mission Directorate (SMD) and Space Technology Mission Directorate (STMD). SMD's Commercial Lunar Payload Services (CLPS) initiative will procure commercial lunar delivery services and the development of science instruments and technology demonstration payloads. The Space Technology Mission Directorate (STMD) portfolio of technology advancements relative to HLS include lunar lander components and technologies for pointing, navigation and tracking, fuel storage and transfer, autonomy and mobility, communications, propulsion, and power. In addition to describing the objectives and requirements of the 2024 Artemis Mission, this paper will discuss the , NASA's approach to accessing the lunar surface with an affordable human-rated landing system, current status, and the role of U.S. industry in 2024 and for a sustainable lunar presence.

8.0103 Crewed Lunar Lander Missions Enabled by the NASA Space Launch System

Ben Donahue (Boeing Company),

Presentation: Ben Donahue, Wednesday, March 11th, 09:20 AM, Jefferson

NASA's New Human Landing System (HLS) return to the Moon plan involves the development and launch of lunar lander elements and an in-space transfer stage element. These are to be aggregated at the cis-lunar Gateway. The Gateway will host the crew and Orion, and consist of, at a minimum, a habitation module, Power and Propulsion Element (PPE) and a Logistics Module. In this paper, the NASA HLS architecture, with the cis-lunar Gateway located in a Near-Rectilinear Halo Orbit (NHRO), are explained and illustrated, and brief technical descriptions of trajectory phases, staging events, and operational features of the architecture are discussed. The planned NASA HLS system is a 3 stage system, it includes the Lunar Ascent Stage Element (AE), with its Crew Cabin, the Descent Stage Element (DE), and a Transfer Stage Element (TE). For the current architecture the HLS elements are launched separately; each on a different launch vehicle, along with the Orion. This "3 Launch" HLS architecture is presently under evaluation. Also under consideration, and presented in this report, is a similar, but alternative "2 launch" simplified HLS architecture. Utilizing two NASA Space Launch

System (SLS) launchers will enable the HLS Elements (AE, DE and TE) to be launched in 2 launches rather than 3, and will allow the DE to be launched fully fueled. This "Two launch" scenario eliminates one launch per lunar sortie, and eliminates the necessity (in the reference plan) to transfer propellant to the DE at the gateway. Also In this report, a lander sizing evaluation is presented for the "2 launch" integrated (AE and DE) crewed lander (launched together not separately) that would fulfill HLS requirements. The evaluation includes a propulsion system trade study comparing five propellant / engine combinations. The first SLS (Block 1B, 8.4 m diameter, cargo version) boosts the Lander to Trans-Lunar Injection (TLI); the DE provides propulsion for the transfer to the Gateway. That launch is followed by a second SLS (Block 1B, crew version), which injects the Orion and a co-manifested payload TE to TLI, also traveling to the Gateway. There the TE and the Lander are joined and a sortie to the lunar South Pole is conducted. After the surface mission the AE ascends directly back to the Gateway. In this paper the current HLS architecture and this alternative, simplified HLS one are compared, and the relative sizes and propulsion features for the AE, DE and TE elements are given. How Lander and TE mass and performance varies with propellant choice and engine cycle is discussed. Lander and TE features and illustrations are briefly discussed. The advantages of the "2 Launch" and "3 Launch" options are listed. Other closely related items such as crew size, surface duration, payloads, mission objectives and robustness to weight growth or payload increases are also touched on. This work has been done under Boeing Internal Research & Development, Exploration Launch Systems division.

8.0104 Capabilities Development: From the International Space Station and the Moon to Mars

Kathleen Boggs , Kandyce Goodliff (NASA), Darcy Elburn (Freedom Information Systems),
Presentation: Kathleen Boggs, Wednesday, March 11th, 09:45 AM, Jefferson

This presentation discusses the activities required to advance critical exploration capabilities, focusing on selection of demonstration and test location based upon the unique environments and characteristics of the ISS, Gateway, and potential lunar surface assets. The optimal strategy will be a combination of ISS/LEO, Gateway, and lunar surface testing; however, not all capabilities require all these steps on their path to deep space exploration missions.

8.0105 Launch Availability Analysis for Project Artemis

Kandyce Goodliff (NASA), William Cirillo (NASA - Langley Research Center), Grant Cates (The Aerospace Corporation), Chel Stromgren (Binera, Inc.),
Presentation: Grant Cates, Wednesday, March 11th, 10:10 AM, Jefferson

On March 26, 2019, Vice President Pence stated that the policy of the Trump administration and the United States of America is to return American astronauts to the Moon within the next five years i.e., by 2024. Since that time, NASA has begun the process of developing concepts of operations and launch campaign options to achieve that goal as well as to provide a sustainable human presence on the Moon. Whereas the Apollo program utilized one Saturn V rocket to carry out a single lunar landing mission of short duration, NASA's preliminary plans for the Artemis Program call for a combination of medium lift class rockets along with the heavy lift Space Launch System (SLS) to achieve a lunar landing by 2024 as well as subsequent missions. This presentation will review how discrete event simulation is used to model the launch campaigns and provide metrics on launch availability and mission duration for each element being launched. Possible methods for improving launch availability are presented.

8.0106 Gateway Lunar Habitat Modules as the Basis for a Modular Mars Transit Habitat

David Smitherman , Andrew Schnell (NASA Marshall Space Flight center),
Presentation: David Smitherman, Wednesday, March 11th, 10:35 AM, Jefferson

This paper provides a summary of the results from a recent concept study of various configurations for a Mars Transit Habitat. The designs considered are composed of modules based on published contractor concepts proposed for the lunar Gateway through NASA's NextSTEP program. Using these Gateway concepts as a starting point for the design of a Mars Transit Habitat has potential advantages. Both Gateway and Mars Transit Habitats will have similar requirements for long-term operations in deep space, autonomous and remote operations when the crew is not onboard, and similar requirements for transferring crew to and from a planetary surface—the Moon and Mars respectively. The contractor designs for Gateway were traded against a monolithic transit habitat previously proposed by NASA's Mars Integration Group. In addition, these concepts were considered for a "shakedown" mission for the transit habitat hardware in cislunar space to build confidence in new systems, including the advanced environmental control and life support systems needed for Mars missions. The results presented include overall vehicle configurations, mass, and volume estimates for the selected design concepts. Two concepts using large expandable modules are identified as leading candidates for a Mars Transit Habitat and the remaining elements are identified as representative of the habitable pressure vessels needed for safe haven configurations, logistics modules, surface habitats, rovers, and descent and ascent crew cabins in the overall Mars Architecture.

8.0107 Defining the Required Net Habitable Volume for Long-Duration Exploration Missions

Chel Stromgren (Binera, Inc.), Michelle Rucker (National Aeronautics and Space Administration), Jason Cho (Binera Inc.), Callie Burke (Binera), Robert Calderon ,

Presentation: Chel Stromgren, Wednesday, March 11th, 11:00 AM, Jefferson

As the National Aeronautics of Space Administration continues planning for long-duration space missions, specifically to Mars, it will be necessary to understand the requirements for a "transit habitat", the element that the crew will live in as they travel to and from Mars. In particular, understanding of volume requirements for the transit habitat is of significant importance because the volume is a first order driver of the habitat size and mass, and therefore the propulsion and propellant requirements for future Mars missions. Despite this importance, there is significant uncertainty regarding how much habitable volume is required to support the crew on these missions. Prior studies provide valuable background, but their focus has largely been on investigating historical analogs in order to develop parametric sizing formulas. While this type of data is valuable, there is large variability in the derived results. Other research has focused on specific drivers of habitat volume and stressors to the crew. However, there have been limited efforts to establish a comprehensive minimum required habitable volume based on crew activity needs and crew health requirements. This paper will describe a detailed effort to establish the minimum required net habitable volume for the Mars Transit Habitat employing a "bottom-up" methodology. The process used to establish volumetric requirements involves the definition of a set of specific "crew activities" and the assignment of required volumes to each activity. This type of "bottom-up" approach is the most accurate method to establish required habitat volume and is specifically recommended by the NASA Chief Medical Officer for future space missions. The authors established a taxonomy of crew activities that could be required during a Mars transit. These activities include direct operational activities, such as command and control or system maintenance, habitation activities, such as eating and sleeping, or health maintenance activities, such as exercise and leisure. Health maintenance activities also include "pseudo-activities", such as psychological well being, that are directly related to habitat volume. The authors then defined required volumes for each defined activity, based on habitat analogs, prior research, and SME input. The potential for various activities to share volumetric space was then evaluated, based on temporal usage, compatibility of

tasks, and crew health. Finally, the required minimum net habitable volume for a 4-crew Mars Transit Habitat was assessed, including consideration of specific geometrical constraints. Results of this study will be used to evaluate deep space habitat options, and also help formulate future Mars missions requirements. Ultimately, results of this study will support the refinement of NASA's Mars DRAs, and help realize future long duration exploration missions.

8.0109 Design of a Microgravity Airlock with Integrated Inflatable Crew Locks

Douglas Litteken , Damien Calderon , Carlos Gaytan (NASA - Johnson Space Center), Michael O'Donnell (NASA - Johnson Space Center), Khadijah Shariff (NASA - Johnson Space Center), Mallory Sico (NASA - Johnson Space Center),

Presentation: Douglas Litteken, Wednesday, March 11th, 11:25 AM, Jefferson

Spacewalks, or extra-vehicular activities (EVAs), are a critical component of human space exploration for science activities and habitat construction and maintenance. For NASA's proposed lunar Gateway system, an airlock module is required for vehicle maintenance, repair, and exploration. Traditional airlock structures are fully metallic, with two chambers, known as an equipment lock and a crew lock. The larger volume, called the equipment lock, serves as the storage, logistics and electronics area, while the smaller volume, called the crew lock, serves as the volume to transition from the vacuum of space to the pressurized cabin. A traditional metallic structure design offers mass efficiency for these elements, but cannot offer volume efficiency. The potential to use an inflatable fabric pressure shell supplemented by a metallic support structure allows for efficiency in both mass and volume. Inflatable structures are being used for human habitable space modules, starting with the Bigelow Expandable Activities Module on the International Space Station. They are high-strength fabric-based structures that are compactly stowed for launch and then, once in space, they are expanded and rigidized with internal pressure. They provide significant launch volume savings over metallic structures. For Gateway, a hybrid airlock design is proposed with both metallic and inflatable structural elements, taking advantage of each material's capabilities. A metallic equipment lock serves as both a docking node and provides pressurized volume for pre-EVA activities including pre-breathe and suit donning/doffing. A rigid equipment lock offers stowage space during launch for integrated hardware and suits. Adding an integrated inflatable crew lock provides the volume required for EVAs with minimal use of launch volume. Using dual inflatable crew locks provides redundancy and the capability to move large pieces of equipment into and out of the vehicle for repair and maintenance. The inflatable crew lock is deflated and packaged in the launch shroud and expanded after installation on the Gateway. This packing capability allows additional volume to be added to the equipment lock and fully utilize the capability of the launch vehicle. This presentation will outline the work completed to design, analyze, and test the systems of a microgravity airlock with inflatable crew locks. In detail, it will include launch vehicles, structural sizing of the metallic equipment lock, the fabric layers of the inflatable crew lock, the internal structure of the crew lock, the space suit interface elements, the crew restraint system, the hatches and pass-throughs, the material and thermal elements, and the crew operations for the usage of the system. This presentation is meant to offer a reference design for a hybrid microgravity airlock design for deep space human exploration.

8.0111 America Back to the Moon and on to Mars: Australian, Japanese and Indian Perspectives

Aaron Pereira (University of Adelaide), Brett Biddington (Biddington Research Pty Ltd), Kazuto Suzuki (Hokkaido University), David Vaccaro (Aurora Global Ventures), Rajeswari Rajagopalan (Observer

Research Foundation), Rahul Krishna ,
Presentation: Aaron Pereira, ,

NASA has welcomed the participation of other space nations on its bold venture back to the Moon and then to Mars. The compressed time frame for such a complex and herculean effort calls for international collaboration. This paper probes the key questions of national significance in Australia, Japan and India with attention to public policy, internal dynamics of various agencies within the space sectors, the role of private venture, areas of proposed collaboration as well as strategic interests of the nations within the region.

8.02 Human Exploration Systems Technology Development

Session Organizer: Stephen Gaddis (NASA - Marshall Space Flight Center), Andrew Petro (NASA - Headquarters), Jonette Stecklein (NASA - Johnson Space Center),

8.0202 Benefits of In-Space Manufacturing Technology Development for Human Spaceflight

Matthew Moraguez (Massachusetts Institute of Technology),
Presentation: Matthew Moraguez, Sunday, March 8th, 04:55 PM, Jefferson

Future human deep space exploration will be faced with the challenges of long mission endurance, as well as demand for robust surface infrastructure, increased solar power generation, and reliable high data rate communications, just to name a few. In-space manufacturing (ISM) can potentially address these challenges, and thus revolutionize human spaceflight, by opening up design freedom previously limited by launch vehicle constraints. For example, ISM can drastically reduce spares logistics mass with on-demand manufactured spare parts, utilize in-situ resources for surface infrastructure, and manufacture high-gain antenna reflectors and solar array structures that are larger than existing deployables. This paper aims to understand how ongoing ISM technology development efforts can benefit human spaceflight by assessing the utility of different technology development paths. This analysis involves identifying the needs of a mission scenario, limitations on allowable manufacturing processes, the theoretical benefit from ISM for that case (including minimum capability thresholds and points of diminishing return), and the tracing of achieved benefit back to technology development parameters. For the case of on-demand spares, benefit is measured in terms of the spares logistics mass savings relative to the conventional carry-along strategy for a desired probability of sufficient spares over the mission duration. Increasing benefit is gained as more spares become manufacturable by ISM using manufacturing processes with increasing capability, such as larger build volumes, wider range of materials, and improved resolution. This same process is applicable for the other case studies of surface infrastructure and large external structures. This work can thus inform the way in which ISM technologies are pursued with the specific purpose of yielding the maximum benefit for future human space exploration.

8.0203 Booster Obsolescence and Life Extension of SLS Boosters

David Griffin (Northrop Grumman Corporation), Terry Haws (Northrop Grumman Corporation), Mark Tobias (Northrup Grumman Innovation Systems), Mike Fuller (Northrop Grumman Corporation),
Presentation: David Griffin, Sunday, March 8th, 05:20 PM, Jefferson

Human exploration beyond low earth orbit (BEO) has been a long-term goal of the United States and the international community since the end of the Apollo program. NASA has set in motion the Artemis program, meant to return humans to the lunar surface in 2024, followed by a sustainable presence in 2028. NASA and the current administration have stated that these lunar missions are just part of the larger goal of sending humans to Mars. To achieve this goal, NASA has been developing the Orion crew capsule and Space Launch System (SLS) as key elements in the architecture designed to advance human spaceflight from our current capability in low earth orbit to returning to the moon

and eventually landing humans on Mars. This aggressive goal is complicated by the need to optimize the use of precious public financial resources during a period when budgets are challenged. Defining and prioritizing the technology and hardware needed is crucial to achieving the goal of landing humans on Mars. SLS consists of a liquid oxygen/liquid hydrogen powered core with two strap-on solid rocket boosters designed and built by Northrop Grumman Innovation Systems. The SLS boosters are based on the reusable/redesigned solid rockets motors (RSRM) designed and built for the Space Shuttle using many of the same technologies, including the heritage steel cases. Eight flight sets of steel cases were retained from the Shuttle Program for use on SLS launches. New cases will then be needed for the ninth and subsequent launches of SLS. Northrop Grumman Innovation Systems continues to study Booster Obsolescence and Life Extension (BOLE) of the SLS boosters. The study is looking to replace obsolete materials, such as the steel cases and thrust vector control systems, and includes technologies to improve the life and performance of the boosters, including upgrades to the propellant and liner system. This paper will discuss on-going BOLE efforts at Northrop Grumman Innovation Systems. It will discuss the upgraded technologies that have been studied, as well as the changes to performance, focusing on how BOLE enables lunar sorties and Gateway missions. It will include analysis performed by Northrop Grumman Innovation Systems under its internal efforts and under contract to NASA.

8.0204 Advancing towards Human Torpor Capabilities in Support of Future Space Settlements

John Bradford (SpaceWorks Enterprises, Inc.),
Presentation: John Bradford, Sunday, March 8th, 09:00 PM, Jefferson

SpaceWorks is an advocate for the development of advanced habitat systems for transporting crews between the Earth and various destinations in space. This new and innovative habitat design is nominally capable of placing crews and passengers into inactive, non-cryonic torpor sleep states during the transit phases of a mission. The idea of “suspended animation” for interstellar human exploration has often been shown in the realm of science fiction as the solution for extremely long-duration spaceflight. However, recent medical advancements have demonstrated our ability to induce inactive, sleep-like states with significantly reduced metabolic rates for humans over extended periods of time requiring only moderate reductions in core body temperatures to 32-34C from our nominal 37.5C. While metabolic reduction and body cooling with clinical Therapeutic Hypothermia is currently achieved using heavy sedation and invasive cooling systems, new pharmaceuticals inspired from hibernating animals have the potential to achieve this state more naturally and for longer periods by significantly lowering sedation levels and achieving cooling via ambient temperatures surrounding the crew. In achieving this inactive state, a number of benefits can be realized for the crew and mission. On the medical side, the metabolic rate is lowered by 50-70%, reducing food, water, and oxygen demand. A number of ancillary systems can also be eliminated from the habitat, thus reducing the pressurized volume and power requirements for the primary systems. Ultimately, habitat mass savings of more than 50% can be achieved compared to a non-hibernating crew. On the medical side, reduced rates of muscle atrophy and bone loss are believed to occur with the reduced metabolism. Body cooling can also reduce intracranial pressure (ICP), thus providing a possible solution for vision impairment and degraded visual acuity currently suffered by many astronauts. While this new approach to spaceflight can offer numerous benefits to the crew and mission, it also provides an affordable and sustainable path towards settlement-class missions. Enabling the transport of not just a few passengers, but hundreds using current technologies and propulsion. This paper will discuss the overall vision and rationale for advancing a human torpor (or stasis) capability for spaceflight. Engineering analysis results for both near-term and far-term missions will be high-lighted, along with the potential for programmatic costs savings.

8.0205 Building the Single-Person Spacecraft for Future Weightless Operations

Brand Griffin (Genesis Engineering Solutions),

Presentation: Brand Griffin, Sunday, March 8th, 09:25 PM, Jefferson

For weightless operations, the Single-Person Spacecraft (SPS) offers significant advantages over traditional suited EVA. There is no risk of the "bends," it doesn't not require an airlock, it is sized for all astronauts. and it uses the proven Manned Maneuvering Unit propulsion system. The SPS is being built and this presentation will describe the progress leading to a flight demonstration.

8.03 Advanced Launch Vehicle Systems and Technologies

Session Organizer: Melissa Sampson (Ball Aerospace), Daniel Dorney (NASA), Jon Holladay (NASA),

8.0303 An EDR Subsystem for the AA2 Test Flight of the Orion LAS

Kristina Rojdev (NASA),

Presentation: Kristina Rojdev, Monday, March 9th, 04:30 PM, Gallatin

NASA is developing the Space Launch System (SLS) and the Orion capsule to send people to the moon in 2024. One important aspect of the Orion capsule is the Launch Abort System (LAS), which safely separates the Orion crew module from the SLS during an ascent abort situation. The LAS is scheduled to be tested in a flight demonstration, known as the Ascent Abort 2 (AA-2) test flight, on July 2, 2019. The purpose of AA-2 is to perform an ascent abort with the LAS under flight-like, high dynamic pressure conditions. The successful demonstration of the LAS and the flight test data obtained from the flight test will be used to certify the LAS for crewed missions. To ensure the data is collected, the AA-2 vehicle employs a communications system with several antennae distributed around the vehicle and a buffer and rebroadcast capability, as well as an ejectable data recorder (EDR) subsystem. The EDR subsystem consists of a recorder system and an ejection system. The ejection system has a dual-string COTS military system situated 180 degrees from one another in the forward bay of the crew module. The recorder system consists of a breakout box with a computer to record the instrumentation data, and a payload, which contains a memory card to store the data and a beacon to locate the payloads. There will be a total of 12 payloads ejected. The recorder system will record the data from initialization until the payloads are ejected. Each string of the ejection system will eject a payload simultaneously and the payloads will be ejected in a staggered fashion at 10 second intervals until all payloads are ejected. The beacon in the payloads is turned on at ejection. When the payloads land in the ocean, they will self-orient with the beacon antennae pointed towards the sky. Post-flight, the payloads will be recovered from the ocean and the data will be extracted from them. The recorded data will be combined with the downlinked data from the communications system to create a single set of complete data. EDR was a unique development opportunity at NASA with challenges that necessitated innovation. EDR employed a “skunkworks” development approach in which we designed, built, and delivered 47 end items, not including ground support equipment. We used as many COTS components as possible, we looked for process efficiencies to meet our tight deadlines, and the EDR team was involved in the flight operations of the AA2 test flight and responsible for the recovery operations of the ejected payloads. This paper will discuss the design and development of the EDR subsystem, as well as the results of the system performance during the AA-2 test flight.

8.0305 Investigation of Atmospheric Boundary-Layer Effects on Launch-Vehicle Ground Wind Loads

Thomas Ivanco (NASA),

Presentation: Thomas Ivanco, Monday, March 9th, 05:20 PM, Gallatin

A launch vehicle ground-wind-loads program is underway at the NASA Langley Transonic Dynamics Tunnel. The objectives are to quantify key aerodynamic and structural characteristics that impact the occurrence of large wind-induced oscillations of a launch vehicle when exposed to ground winds prior to launch. Of particular interest is the dynamic response of a launch vehicle when a von Kármán vortex street forms in the wake of the vehicle resulting in quasiperiodic lift and drag forces. Vehicle response to these quasiperiodic forces can become quite large when the frequency of vortex shedding nears that of a lowly-damped structural mode thereby exciting a resonant response. Wind approaching the vehicle can be characterized by a varying speed with height and turbulence content. The combination of both the varying speed and turbulence content is referred to herein as the atmospheric boundary-layer. The importance of the atmospheric boundary-layer upon launch vehicle wind-induced oscillation response has long been contested, and its effects are not well understood. Although there are several facilities around the world dedicated to replicating atmospheric boundary layers, the development of such a boundary layer in a wind tunnel capable of producing flight-representative Reynolds numbers for aeroelastically-scaled launch vehicle models has only recently been accomplished. The NASA Langley Transonic Dynamics Tunnel is capable of simulating flight-representative Reynolds numbers of launch vehicles on the pad and is uniquely capable of replicating many fluid-structure scaling parameters typical of aeroelastic tests. Recent test efforts successfully developed representative atmospheric boundary-layers for three launch sites in the Transonic Dynamics Tunnel, thereby allowing all known aerodynamic and fluid-structure coupling parameters to be simultaneously simulated for those sites. Dynamic aeroelastically-scaled models representative of typical large launch vehicles were constructed for testing. Aeroelastic scaling includes matching geometry, mode shapes, reduced frequencies, damping, running mass ratios, and running stiffness ratios. The models were tested in smooth uniform flow and then immersed in the atmospheric boundary-layer for comparison of these effects. Dynamic data were acquired measuring unsteady pressure, acceleration, and base bending moment. It was discovered that peak dynamic loads resulting from resonant wind-induced oscillation response are similar when acquired in either smooth uniform flow or an atmospheric boundary-layer. This indicates that resonant lock-in events are minimally impacted by turbulence and/or wind profile. Alternately, nonresonant wind-induced oscillation response events are stronger when acquired in an atmospheric boundary-layer. This indicates that a lowly-damped structural response will increase when exposed to an increased magnitude of random excitation, which is consistent with historical comparisons. Loads created by the resonant response events were substantially stronger than those from the nonresonant response events. Therefore, if testing is done to simply identify worst-case conditions and load magnitude, then smooth uniform flow is likely an adequate test technique. However, if nonresonant response loads are of primary interest, then atmospheric boundary-layer simulation is important.

8.0306 SLS Block 1B and Block 2 with Kick Stages for Outer Planet Science Missions & Beyond

Terry Haws (Northrop Grumman Corporation),

Presentation: Terry Haws, Monday, March 9th, 09:00 PM, Gallatin

Interest in the outer planets of our solar system remains high following several recent high-profile missions. These science missions to the outer planets require significant energy to deliver payloads. This energy typically results in either multiple planetary flybys or very small payloads or both. NASA's Space Launch System (SLS) heavy launch vehicle is being developed as part of NASA's directive to return to the moon, followed by crewed missions to Mars. Along with delivering crew to cislunar space, SLS will also have the capability to launch science payloads for high-energy outer planet missions. Adding a kick stage on top of SLS further increases SLS's capability for these missions. This paper discusses the capability of SLS, both alone and with kick stages, to deliver payloads for outer planet missions. There are currently a number of solid motors that could be used as kick stages, and this paper analyzes the results, advantages, and disadvantages of using these motors along with SLS Block 1B to deliver larger payloads with shorter mission times for outer solar system science missions.

8.0310 Flow Interaction between Adjacent Elements in High Speed Roller Bearing for Rocket Turbine Pump

Wenjun GAO (Northwestern Polytechnical Univerisity),
Presentation: Wenjun GAO, Monday, March 9th, 04:55 PM, Gallatin

High speed roller bearing plays an critical role in rocket turbine pump, which needs lubricating and cooling fluid (like the fuel or lubricant oil) to insure its function. For each roller element, it's surrounded by another two rollers in upstream and downstream respectively, while the flow interaction between adjacent roller elements is however unclear, that may cause significant error for bearing behavior analysis. In this article, a numerical method is employed to analyze the effect of different geometrical parameters, including the gap between two elements and the length/diameter ratio. Flow pattern with different Reynolds numbers is revealed. And the simulated result is verified with experimental data. It's found that, with sharp circular ends and relative short gap, the flow passing one roller bypasses the next roller rather than entering in the region between two adjacent elements. Differential pressure is almost offset between the windward side and the leeward side of the roller with several local vortex in the gap.

8.04 Human Factors & Performance

Session Organizer: Jessica Marquez (NASA Ames Research Center), Kevin Duda (The Charles Stark Draper Laboratory, Inc.),

8.0402 RxEVA: Prescribing Human Performance Exploration Limits for Surface Operations

Ryan Kobrick (Embry-Riddle Aeronautical University), Diego Garcia (Embry-Riddle Aeronautical University), Claas Olthoff (NASA - Johnson Space Center), Daniel Pütz (Technical University of Munich), Lea Miller (Embry-Riddle Aeronautical University), Laura Bettiol (Österreichisches Weltraum Forum), Kirby Runyon (Johns Hopkins APL), Gernot Groemer (Austrian Space Forum), Chase Covello (Embry-Riddle Aeronautical University), Nicholas Lopac (Embry-Riddle Aeronautical University),
Presentation: Ryan Kobrick, Thursday, March 12th, 04:30 PM, Gallatin

Abstract—Future human space exploration missions will see crewmembers perform extravehicular activities (EVA) more frequently and with a higher degree of autonomy than ever before. This change requires new tools for mission planning to be developed that take the increased physical and mental stress associated with numerous EVAs into account. The Prescription (Rx) Extravehicular Activity (EVA) Project, or RxEVA, is an interdisciplinary approach with the goal of creating a human-centric model that will encourage safe, long duration, surface EVA operations. This model is hypothesized to allow mission planners to continually update the cadence and difficulty level of extravehicular crewmember's tasks by using biometric and environmental factors as feedback, thus creating individualized thresholds or EVA limits. RxEVA endeavors to output mission planning recommendations for subsequent operations that will prevent crew physical and/or mental overload (or burnout) and reduce potential injuries or compromised performance on EVA. The desired output of the RxEVA Project is the creation

of a computer or tablet-based application that can be used primarily for long duration spaceflight, but can also be applied to terrestrial spinoffs involving human performance and personal health. This paper serves as a roadmap for the RxEVA project. First, it lays out the foundational knowledge and data sources that already exist that can be used to create the RxEVA model. Second, it highlights the gaps that the research needs to address with respect to the model itself and finally it discusses the next steps that need to be taken to fulfill the project goal.

8.0403 Tradespace Exploration of Geometry for a Spacesuit Hip Bearing Assembly

Patrick McKeen (Massachusetts Institute of Technology), Leia Stirling ,
Presentation: Patrick McKeen, Thursday, March 12th, 04:55 PM, Gallatin

Extravehicular activity (EVA) spacesuits are a crucial component of human spaceflight, allowing crew members to exit vehicles for maintenance, observation, scientific experiments, and sample collection. While spacesuits keep astronauts alive, they currently restrict motion, require additional energy to change body posture, and are a factor in some astronaut injuries. Previous planetary suits were based largely on flexible components, which generate additional forces on the wearer due to volumetric changes when the components flex. The NASA Mark III spacesuit technology demonstrator addresses this problem with a hip brief assembly (HBA) composed of rigid sections connected by bearings, an approach shared with other spacesuit technologies under evaluation (e.g., the Z2). However, previous analysis shows that the hip range of motion (ROM) for the current suit geometry is not well-aligned with the nominal human hip ROM during gait. Most significantly, the suit severely limits adduction, which is the motion of the leg towards the body mid-line. We considered how the geometry of this suit could be altered to improve alignment between the suit's ROM and nominal human gait. A method of parameterizing the geometry of the hip brief assembly (HBA) was developed using an expansion upon Denavit-Hartenberg (DH) yielding 13 total variables. By adjusting these variables, different suit geometries were explored. A set of tests were derived to estimate the feasibility of a given HBA section from these parameters and bound the parameter trade space (e.g., testing for section edges that were too close for bearings to fit and ability for the human leg to fit through the components). As the parameter space is complex, it was sampled instead of optimized. Over 1.3 billion variations of suit geometry were considered. The valid geometries were rotated through their possible bearing orientations, while a human leg was simulated inside and tested for intersection with the suit. From the leg's orientation in these positions, the suit's ROM was estimated. This region (transferred to the unit sphere) was compared with the region corresponding to nominal human gait. The size of the overlap of these regions indicates the available human-suit mobility. Of the valid geometries examined, 10,912 were found to improve upon the current HBA geometry. The connections and similarities of these geometries are considered and discussed. The top performing geometry increased the overlap area by 567%. Many of these suit geometries allow for greater adduction, meaning the wearer could walk with their feet closer to the body mid-line, allowing a more natural gait. This design could improve mobility and comfort as well as reduce injury risk and astronaut energy expenditure. Additionally, based on the ROM estimates, many designs also allow the wearer to kneel without combined abduction and external rotation, allowing easier sample collection, analysis, and observation. These and similar advantages are analyzed.

8.0404 Impact of Automation on General Aviation Rotorcraft Mishaps: A Human Factors Analysis

Mattie Milner , Christopher Brill (U.S. Air Force Research Laboratory), Stephen Rice ,
Presentation: Mattie Milner, Thursday, March 12th, 05:20 PM, Gallatin

As technology continues to advance, the aviation industry has seen an exponential growth in 'glass cockpits,' representing the move to automated systems within the cockpit. While automation often helps relieve pilots' workload and increase safety, inappropriate or inaccurate automation can also cause potentially fatal mishaps. The purpose of this study was to identify general aviation rotorcraft accidents caused by negative automation events and conduct a human factors analysis to determine additional influential factors. Using archival data from the National Transportation Safety Board, over 3,000 rotorcraft mishaps were examined for their contributory and causal factors. To help maintain objectivity, only cases with a 'Final Report' were considered as these contained contributory and causal factors identified by accident investigation experts. Using the Human Factors Analysis and Classification System, researchers identified additional errors contributing to the accident and the specific type of automation event. Analysis of the mishap data revealed that 24% of all mishaps resulted in a fatality, and using HFACS as a framework, majority of these accidents occurred due to organizational influences. Furthermore, 17 cases were identified as having experienced a negative automation event that significantly contributed to the mishap. Overall, automation seems to benefit pilots; however, automated systems were designed by humans; therefore, human error is still a part of the system. It's impossible to know the outcome of these mishaps had there not been automation involved but negative automation events are significantly contributing to rotorcraft mishap fatalities. Pilots tend to over rely on the automation to either provide them with the appropriate information and/or take the appropriate corrective action. When the automation did not respond appropriately/ accurately, pilots were unable to handle degrading scenario. Automation is often seen as a solution to human error and inefficiency, so it gets implemented without fully understanding its impact on the user and the system, as a whole. The current study provides insight into pilots' relationship with automation and the burgeoning consequences.

8.0408 Evaluating the Effect of Spacesuit Glove Fit on Functional Task Performance

Seamus Lombardo (Massachusetts Institute of Technology), Kevin Duda (The Charles Stark Draper Laboratory, Inc.), Leia Stirling ,

Presentation: Seamus Lombardo, Thursday, March 12th, 09:00 PM, Gallatin

As the number of suited operations per mission increases with exploration beyond low Earth orbit (LEO), it is essential that crewmembers conduct suited activities in a manner that enables acceptable performance and minimizes the risk of injury. Currently, knowledge gaps exist in how to define optimal suit fit, how to more effectively incorporate fit into the suit design process, and how fit is related to performance. While it is understood that fit influences suited performance, the relationship between fit and performance has not been quantified. This research effort investigates the effects of spacesuit glove fit on tactile performance. This study adapted functional performance tasks from the literature and developed novel tasks to assess tactile performance. Through these tasks, the hypothesis that static fit (as derived from glove and human anthropometry dimensions) is related to spacesuit glove performance was evaluated. Subjects wore prototype gloves, developed by David Clark Company, Incorporated (DCCI). These gloves are similar to the DCCI Orion Crew Survival System intravehicular activity (IVA) gloves that will be utilized on NASA's Orion spacecraft. Participants completed a battery of functional assessment tasks in a glovebox vacuum chamber (4.3 psid). The subject's prescribed fit within the DCCI glove sizing scheme specific to this design was determined using their anthropometry. The subjects then conducted the tasks in gloves one size below their prescribed fit, their prescribed fit size, and gloves one size larger than their prescribed fit in both a pressurized and unpressurized state. To evaluate general tactility, blindfolded subjects attempted to detect bumps of different widths (0.59 in, 0.39 in, 0.20 in) and heights (0.05 in, 0.20 in,0.39 in) while the correct detection was recorded. An operationally-relevant tactility task was also designed. A mock spacecraft control panel was created in consultation with subject matter experts and designed to NASA specification. Blindfolded subjects then actuated a pre-defined sequence of these controls on the switchboard. The accuracy and completion time of the sequence was recorded. It was found that direct measures of static fit derived from hand length and glove length had a significant relationship to performance on the switchboard tactility task. Additionally, it was found that in the unpressurized case, subjects performed significantly better on the switchboard task when wearing the glove size larger than the prescribed fit as compared to small and prescribed fit. This study also reaffirms tactile performance decreases with a spacesuit glove, with larger decrements when the gloves are pressurized versus unpressurized.

8.0410 Trust in an Autonomous Guidance System for a Planetary Rover Task

Jamie Voros (University of Colorado Boulder),

Presentation: Jamie Voros, Thursday, March 12th, 09:25 PM, Gallatin

As crewed space missions explore deeper into space, it will become increasingly necessary for astronauts to rely on autonomous systems for tasks that ground controllers currently carry out with minimal communication delays. A crewed mission to Mars, however, would involve roundtrip communication times of up to 45 minutes, rendering traditional ground control infeasible. Autonomous intelligent systems on board the spacecraft may perform some tasks traditionally done by ground control (e.g., planning, information transfer, decision support) without any communication delays. It will be important that the human crew is able to establish a functional level of trust in such systems. In order to assess trust in autonomous systems, we performed an experiment using a task that required participants to drive a lunar rover to a series of set locations. Subjects had to navigate the rover, from a first-person camera view, around terrain obstacles (e.g., craters) without getting stuck or running out of battery. Subjects were provided navigational assistance via an overlaid arrow. Trust was measured objectively by examining the average angle between the displayed arrow (recommended direction of travel) and the rover's current travel direction. Subjects also self-reported trust in the guidance in a post experiment questionnaire. We used a 2x2 between-subjects experimental design: 1) Our primary independent variable was the source of the navigational assistance, either an autonomous system or a human (analogous to a ground controller). 2) To isolate subjective perceptions of the two systems from the objective guidance quality, the second independent variable was the source of the guidance as briefed to the subject (perceived autonomous vs. perceived human). The autonomous guidance used a Markov decision process based upon an accurate, but reduced resolution, hazard map to direct the subject. When human guidance was provided, the same conducive research assistant sat in the adjacent room (mimicking the role of a ground controller) and provided directions with a thumb-stick while using the same hazard map. In addition, we tested control subjects who were provided no displayed guidance and could be compared against both guidance systems. Our results suggest that perceived guidance source did not change subject behavior. Specifically, objective propensity to follow guidance remained similar for both perceived autonomous and perceived human groups. However, the control group (who were never actually shown any guidance) indicates that the actual source of guidance does change subject behavior. Interestingly, we found subjects who were shown guidance from an autonomous intelligent system were more willing to follow it compared to controls, while those shown guidance from a human were no more willing to follow it than controls. These results suggest that, when accounting for natural unguided behavior, subjects were actually more willing to follow guidance from an autonomous intelligent system (i.e., higher functional trust) than directions from another human.

8.0411 Evaluating Accuracy of Eye Gaze Controlled Interface in Military Aviation Environment

Pradipta Biswas (Indian Institute of Science),

Presentation: Pradipta Biswas, Thursday, March 12th, 09:50 PM, Gallatin

Eye gaze controlled interfaces allow to directly manipulate a graphical user interface just by looking at it. It has already been explored for assistive technology. Eye gaze controlled interface has great potential use in military aviation, in particular operating different displays in situations where pilots' hands are occupied with flying the aircraft. This paper reports two studies on analysing accuracy of eye gaze controlled interface inside aircraft undertaking representative flying missions. We reported that pilots can undertake representative pointing and selection tasks at less than 2 secs on average and the accuracy of COTS eye gaze tracking glass is less than 5º of visual angle up to +3G although it is less accurate at -1G and +5G. We used these results in developing a multimodal head and eye gaze movement based HMDS and in a user study involving standard ISO 9241 pointing task, the average pointing and selection times was significantly lower in the proposed system compared to traditional TDS.

8.05 Space Human Physiology and Countermeasures

Session Organizer: Ana Diaz Artiles (Texas A&M University), Andrew Abercromby (NASA Johnson Space Center),

8.0503 Metabolic Modeling in Altered Gravity

Richard Whittle (Texas A&M University), Ana Diaz Artiles (Texas A&M University),

Presentation: Richard Whittle, Tuesday, March 10th, 08:55 AM, Lake/Canyon

This paper explores the extension of an existing 21-compartment lumped parameter hemodynamic model of the cardiovascular system in altered gravity (including both hypogravity and artificially induced gravity gradients) during exercise to incorporate pulmonary function and metabolic gas transport. The existing model allows study of the acute responses of cardiovascular system parameters (pressures, volumes, resistances, heart rate) to exercise under a variety of conditions. Based on the identified risk to operational performance for future exploration class missions from reduced aerobic capacity, the extended model can greater aid in understanding human physiology in space, as well as future development of integrated countermeasures. By incorporating pulmonary function, a gas transport model, and a respiratory control system, the existing model capabilities will be enhanced to be able to determine the dose response curves for additional parameters such as respiration rate, tidal volume, oxygen uptake, and carbon dioxide output. The modeling will follow a six-stage development process with all stages integrating into the existing computational model, using techniques and elements either developed from scratch or adapted from a broad range of human and animal physiological modeling studies. This paper outlines the requirement, a thorough literature review of modeling various aspects of pulmonary and metabolic physiology, before describing in detail our approach to building the model. Having demonstrated our plans, our future intention is to finish coding the remaining aspects of the model before validating the modeling effort in both constant simulated hypogravity and artificial gravity gradient fields via human experimentation using both a tilt platform and a short-radius centrifuge combined with cycle ergometer exercise. The work aims to inform research on both acute responses to hypogravity and exercise, along with chronic responses due to hypovolemia and reduced hematocrit, and also has many applications outside the space domain.

8.0504 Design of an External Compensatory Breathing Bladder for the BioSuit

Jeremy Stroming (Massachusetts Institute of Technology), Dava Newman (National Aeronautics and Space Administration),

Presentation: Jeremy Stroming, Tuesday, March 10th, 09:20 AM, Lake/Canyon

Mechanical counterpressure (MCP) spacesuits offer several advantages over traditional gas-pressurized suits including lower energy cost of transport, greater mobility and range of motion, reduced risk of decompression due to suit tear or puncture, and increased astronaut comfort. The BioSuit is an MCP concept being developed at MIT primarily for Martian extravehicular activity (EVA). A key part of this design is an external breathing compensation bladder on the chest of the astronaut. This bladder acts as a counter-lung to ease the burden of breathing while wearing a constrictive garment and adapts to the changing volume of the chest to provide equalized pressure application. This paper details the engineering analysis, prototype design and fabrication, and benchtop component and system testing plan of a compensatory breathing bladder for the BioSuit. Additionally, concepts for a helmet neck seal and integrated airflow system between a portable life support system (PLSS) backpack, helmet, and bladder are presented. The BioSuit breathing bladder advances the development of life support systems for a full MCP spacesuit and lessons learned will be applied for future engineering prototypes. During this presentation, the physical prototype will be on display and initial testing results discussed.

8.0506 Soft Exoskeleton Knee Prototype for Advanced Space Suits and Planetary Exploration

Allison Porter (Massachusetts Institute of Technology), Barnaba Marchesini (D-Air Lab), Irina Potryasilova (D-Air lab), Enrico Rossetto (D-Air Lab srl), Dava Newman (National Aeronautics and Space Administration),

Presentation: Allison Porter, Tuesday, March 10th, 09:45 AM, Lake/Canyon

Existing gas-pressurized space suit designs aim to provide astronauts with a wide range of joint motion while minimizing joint torque during extra-vehicular activity (EVA). However, current space suits have limited joint range and stiff knee and elbow joints, which impedes performance. Future designs should consider that some joint torque can be beneficial in storing elastic energy for locomotion in reduced gravity planetary EVAs. Though current gas-pressurized space suits restrict astronaut movement, they are capable of partially supporting their own mass and storing elastic energy in the lower body, allowing metabolic cost reduction during locomotion in reduced gravity, such as on Mars or the moon. The BioSuit™, developed by the Massachusetts Institute of Technology (MIT), is an advanced, skin-tight compression garment concept, which exerts mechanical counterpressure (MCP) directly on the astronaut's skin with the benefits of increasing motion and performance and reducing mass as compared to gas-pressurized space suits. We designed a BioSuit™ soft knee exoskeleton with tunable knee-joint stiffness to minimize metabolic expenditure during locomotion in partial gravity, maximize mobility, and enhance performance of astronauts. This paper summarizes the design and development of prototype actuation in a soft exoskeleton, in collaboration with the Dainese D-Air Lab (Vicenza, Italy), that can apply varying stiffness/torque to the knee while permitting full range of motion for flexion and extension. Additionally, a proof-of-concept sleeve was produced to investigate and demonstrate the capability of WholeGarment knitting to aid in producing sufficient mechanical counterpressure for safe use in space. Design criteria, fabrication techniques, and performance metrics are discussed. The soft knee exoskeleton was shown to exert stiffness in parallel to the knee, analogous to stiffness exerted by a space suit. Range of motion of the knee and arm was significantly larger for the MCP prototypes when compared to current space suits. These prototypes were developed to maximize locomotion in reduced gravity while minimizing metabolic cost expenditure associated with locomotion and space suit inflexibility. The results of

this paper demonstrate the ability to integrate a soft knee exoskeleton into the BioSuit™ to improve space suit design to enable longer, safer, and more complex EVAs in partial gravity.

8.0508 Artificial Gravity in Mars Orbit for Crew Acclimation

Justin Rowe (Jacobs Engineering),
Presentation: Justin Rowe, Tuesday, March 10th, 08:30 AM, Lake/Canyon

NASA's current baseline plan for a crewed Mars mission anticipates a transit time of up to three hundred days in microgravity and 3-14 days on the Martian surface for gravity acclimation before the crew can safely perform their first Extra-Vehicular Activity (EVA). While there are multiple options for how initial surface operations will be performed, all current designs involve acclimation on the surface, and the impacts on the mission schedule, required supplies, and crew lander systems are significant. This paper proposes an alternative option utilizing artificial gravity, which offers benefits in terms of mission scope, mass savings, crew health, and long-term strategic vision. By moving the acclimation requirement to the orbiting habitat's existing systems, rather than adding redundant systems to the lander, the Mars Descent Vehicle (MDV) can be a much smaller, simpler, and lighter design. Rather than the lander being designed to support crew for days, it would be mere hours. While ambitious, the concept of pre-acclimation in orbit can be not only safe and feasible, but done with fairly minimal changes to the planned architecture and overall mass requirements. The data used draws on decades of established research and demonstrates how this capability can be not only used for pre-acclimation, but also to support crew during early orbital-only missions, surface abort contingency scenarios, return-to-orbit abort scenarios, and as an early proof of capability into larger and more ambitious artificial gravity designs needed for extended exploration missions in the future.

8.0509 Design of an Augmented Reality Visor Display System for Extravehicular Activity Operations

Neil McHenry (Texas A&M University), Leah Davis (Texas A&M University), Gregory Chamitoff (Texas A&M University), Ana Diaz Artiles (Texas A&M University),
Presentation: Leah Davis, Tuesday, March 10th, 10:10 AM, Lake/Canyon

An Extra-Vehicular Activity (EVA) is one of the most challenging operations during spaceflight. The current technology utilized during a spacewalk by an astronaut crewmember includes real-time voice loops and physical cuff checklists with procedures for the EVA. Recent advancements in electronics allow for miniaturized optical displays that can fit within a helmet and provide an alternative method for a crewmember to access mission data. Additionally, cameras attached to helmets provide EV astronauts' several Point of Views (POVs) to Mission Control Center (MCC) and Intra-Vehicular (IV) astronauts. These technologies allow for greater awareness to protect astronauts in space. This paper outlines the design and development of a custom augmented reality (AR) visor display to assist with human spaceflight operations, particularly with EVAs. This system can render floating text checklists, real-time voice transcripts,and waypoint information within the astronaut's Field of View(FOV). These visual components aim to reduce the limitations of how tasks are communicated currently. In addition, voice commands allow the crewmember to control the location of the augmented display, or modify how the information is presented.The team used the Microsoft HoloLens 1 Head Mounted Display(HMD) to create an Augmented Reality Environment (ARE)that receives and displays information for the EVA personnel.The ARE displays the human vitals, spacesuit telemetry, and procedures of the astronaut. The MCC and other astronauts can collaborate with the EVA crewmember through the useof a 3D telepresence whiteboard, which enables 2-way visualcommunication. This capability allows interaction with the environment of the EV astronaut without actually having to beoutside the spacecraft or even onboard. Specifically, mission personnel in a Virtual Reality (VR) Oculus Rift head mounted display could draw shapes in the EV members' view to guide them towards a particular objective. To test the system, volunteers were asked to proceed through a mission scenario and evaluate the user interface. This occurred both in a laboratory setting and in an analog mockup at the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC), using both the Microsoft Hololens and Oculus Rift in coordination with the NASA Spacesuit User Interface Technologies for Students (SUITS) Competition. The major goal of testing the User Interface (UI) was determining features contributing to a minimized cognitive workload and improving efficiency of task completion. AR technology has the potential of dramatically improving EVA performance for future manned missions. With the HoloLens, the team implemented an efficient and elegant design that can be individualized by the user. The system provides as much functionality as possible while remaining simple to promote user-friendliness.

8.0510 Comfort, Mobility, and Durability Assessment of a Wearable IMU System for EVA Suit Evaluation

Young Young Shen (University of Colorado Boulder), Allison Anderson (Massachusetts Institute of Technology),

Presentation: Young Young Shen, Tuesday, March 10th, 10:35 AM, Lake/Canyon

Improving the design of spacesuits to reduce the rate of musculoskeletal injury to the wearer proves challenging due to the inability to observe human motion inside the suit. Past efforts have investigated the use of wearable inertial sensors to observe the motion of the wearer relative to the suit. However, none of these investigated the potential for the sensors themselves to interfere with human motion inside the suit. Additionally, these past systems were found to fail frequently in the harsh in-suit environment. The authors are developing a new in-suit wearable inertial sensor system in order to address the shortcomings faced by previous efforts. The current work describes two test campaigns to evaluate the comfort, mobility, and durability of the new system. Methods and data analysis plans are presented for each test campaign along with results for the comfort and mobility study. It is demonstrated that the presence of the devices have no significant effect on suited comfort and mobility of the arm ($p < 0.05$, $N = 11$). These tests serve not only to provide verification of the performance of the new system, but also provide some confidence about the validity of past work using similar devices. The work advances the development of a reliable tool for observing human motion inside the spacesuit, which facilitates the design of safer suits that will be needed for planetary extravehicular activity.

8.0511 Multi-modal Stochastic Resonance to Enhance Astronaut Perceptual Performance: Experimental Design

Jamie Voros (University of Colorado Boulder),

Presentation: Jamie Voros, Tuesday, March 10th, 11:00 AM, Lake/Canyon

Astronauts on future deep space exploration mission will need to maintain optimized performance to ensure safety and mission success. To enhance neurocognitive and task performance, stochastic resonance (SR) may be used to enhance "information transfer" to the brain across multiple sensory modalities, reducing the cognitive workload associated with complex tasks. SR is achieved when white noise is added to a perceptual channel (e.g., auditory, vestibular, visual, etc.), and resonates with the underlying primary signal. As a result, the signal's message is enhanced, allowing the human to perceive the primary signal more easily. SR has been shown to improve balance, hearing, vision, and sensations of touch. Our overarching study seeks to examine SR in the context of improved perceptual thresholds; specifically, we hypothesize humans can

perceive smaller stimuli with the addition of SR white noise. Here we introduce a novel approach to experimental design aimed at reducing the time necessary for accurate and precise perceptual threshold measurement. The detection of SR-performance enhancements requires extensive measurement of perceptual thresholds, across a range of SR noise exposures. This is complicated by the fact the optimal SR noise level, in terms of improving thresholds, may vary substantially across individuals. Measuring perceptual thresholds at multiple SR noise levels is time consuming. Furthermore, the expected improvement from SR is moderate (15-30%), thus accurate threshold measurements are necessary requiring many trials. We will measure thresholds with both one and two interval tasks. In a one interval task, the subject must determine the direction of the stimulus (direction recognition). In a two-interval task, the subject must indicate which of the two intervals they thought the stimulus occurred in (stimulus detection). Direction recognition and stimulus detection tasks have been chosen to avoid biases in the subject's decision criteria. Each one or two interval sequence is called a trial; by collecting binary (correct, not correct) data on a given subject (at a given SR noise level) over a series of trials, a threshold can be estimated by fitting a psychometric curve. Measurement of thresholds can be exhausting for subjects, especially if many thresholds are measured in quick succession. Therefore, to avoid fatigue confounding performance it is important that the number of trials, and thus time, are minimized. To this effect, we use computational methods to simulate threshold measurement. The simulations seek to show how many trials are necessary for a threshold measurement accurate and precise enough to discern the presence of SR. With such simulations, we have developed an experimental design that is likely to identify SR if it exists while minimizing the number of trials required. We will present results from this approach for detecting SR, in an effort to enhance human perception in challenging environments, such as astronauts on deep space exploration missions.

8.0512 ASSESSING the FEASIBILITY of an ARTIFICIAL MARTIAN MAGNETOPAUSE

Scott Carpenter (CognitiveCybernetics), Edrea Jiang , Katherine Lu , Mason Cai , Jesse Yao (NuForensics), Johnry Zhao (NuFORENSICs), Xia ("Shaw") Liu (NuForensics), David Zhao (NuFORENSICS), Matthew Li (NuFORENSICs), Nathaniel Lao (NuFORENSICs),

Presentation: Scott Carpenter, Tuesday, March 10th, 11:25 AM, Lake/Canyon

The primary objective of the "MarsB" project is to model and assess planetary-scale artificial magnetic-fields that induce a magnetopause shield to deflect the solar wind and enable build-up and protection of a future modest Martian atmosphere. Such an artificial magnetopause is one important part of a larger project for terraforming Mars, which is of great public interest. The MarsB extensible trade-study environment was developed and successfully benchmarked against spacecraft-measured empirical data and other models for magnetic fields and magnetopauses of Earth and the other solar system dipole-bearing planets, against measured data for solar-flare buffeting of Earth's magnetopause, and against estimates for Earth's magnetopause retraction during the ancient Brunhes-Matuyama magnetic field reversal. Using MarsB, we assessed surface and subsurface superconducting coil configurations. We show that a modest superconducting cable current can protect a future Martian atmosphere from the solar wind, requiring far less amperage (~1 MA for a 1.9-Mars-radii-distant magnetopause) than that commonly discussed in the informal literature. For comparison, a surface current-ring around Earth's equator, equal in effect to Earth's intrinsic dynamo-driven current-ring, would require 622 MA. We review and discuss the 'convenient and simple' math of 'true' dipole magnetic-field topology related to current rings, and demonstrate why one should avoid such math when less than 17 ringRii distant from the current-ring's center. For distances closer than 17-ringRii, we describe in detail one method that implements elliptic integrals, a precise mathematical method for determining magnetic flux density,

magnetopause-standoff distance, ring current, and many other system properties. Notionally, a thin superconducting cable could be ‘printed’ around Mars by automated machines, and the construction materials could be obtained and processed in situ. For subsurface superconducting-cables, we consider a notional tunnel-boring strategy that includes a large-volume reserve for oxygen, a high-speed equatorial transport system, and research for subsurface discovery.

8.06 Mechanical Systems, Design and Technologies

Session Organizer: Alexander Eremenko (Jet Propulsion Laboratory), Lisa May (Murphian Consulting LLC),

8.0602 Real-Time Full-Field Photogrammetry Implementation during the Mars 2020 Heat Shield Acceptance Test

Sotiris Kellas (NASA - Langley Research Center), David Dawicke (Analytical Services and Materials, Inc.), Nathaniel Gardner (NASA - Langley Research Center / Analytical Services & Materials, Inc.), Michael Mc Neill (Science and Technology Corporation/NASA), William Johnston (STC), Benjamin Jabola , Derek Shannon (Lockheed Martin Space), Mohamed Abid (Jet Propulsion Laboratory),

Presentation: Sotiris Kellas, Friday, March 13th, 08:55 AM, Gallatin

NASA’s next science mission to Mars (Mars 2020) utilizes a similar entry vehicle as Mars Science Laboratory, or MSL. In fact, the intention was that Mars 2020 utilize the spare MSL heat shield (HS) structure termed HS1. Unfortunately, HS1 failed during static testing in April 2018. Failure investigation concluded that there were multiple contributors to the root cause including testing methodology. The redesigned Mars 2020 heat shield, HS3, adopted a simpler load application process compared to the method used in HS1. Entry load was simulated by applying external pressure through vacuum, a technique previously used for the MSL flight heat shield (HS2), instead of external pressure applied via a pressurized airbag. To monitor HS3 response to the applied load, and anticipate non linearities in real time, full-field photogrammetry coverage of the entire OML surface of the HS was proposed by the NASA Engineering and Safety Center (NESC) team who participated in the HS1 failure investigation. The paper describes the technical and programmatic challenges associated with the implementation of the technique during the acceptance test for flight hardware the scale (D=14.5 ft) of the Mars 2020 heat shield structure. Examples of how the real-time results were used to assess the health of the hardware as well as test/analysis correlation at critical load-holds are also presented. Finally, advantages and limitations of the full-field measurement technique as applied to flight hardware acceptance tests are discussed. There were two objectives for full-field photogrammetry application. The primary objective was real-time monitoring of full-field deformations and strains during loading. In essence the technique was used as real time non-destructive evaluation. A secondary objective was test/analysis correlation. To meet the primary objective, a near 100% coverage of the heat shield outer surface was required. This was achieved with the use of commercially available digital correlation software, VIC-3D, and three 29 M-pixel video camera-pairs located 120° apart around the heat shield. At the completion of the proof test, post-processed images from the three systems were merged (stitched) together and full-field displacements and/or strains were mapped onto the structural Finite Element model for test/analysis correlation.

8.0603 Thermal-Mechanical Stability of a Large Spacecraft Structure within a Jovian Orbit

Anthony Licari (NASA Jet Propulsion Lab),

Presentation: Anthony Licari, Friday, March 13th, 09:20 AM, Gallatin

Pointing stability of spacecraft payloads is a vital part of ensuring high quality science return. This is especially true for flyby missions that rely on precise pointing knowledge and control among a suite of elements to provide appropriate co-alignment between both optical and in-situ instruments. The Europa Clipper mission plans to execute over 45 flybys of Jupiter's moon Europa. To do this, the spacecraft will be put into highly elliptical orbits around Jupiter. Throughout each orbit, the Clipper spacecraft will experience a variety of thermal environments near 5 AU. It will be commanded to operate in a wide range of power cycles, experience cold soaks of up to nine hours in eclipse and then immediately impacted by direct solar flux, and then ultimately pass within 25 km of Europa's icy surface. The most stressing duration for the spacecraft from a distortion perspective will be within +/-48 hours of closest approach to the Europan surface due to the increased power demand from the instruments on the Nadir-pointed deck as well as the electronic boxes in the Avionics Vault. Despite the structural distortions due to evolving thermal environments and demanding power schedules, the spacecraft is expected to maintain adequate pointing of its instruments throughout the orbit, especially during the flyby where a majority of science is captured. The objective of this work was to identify the driving thermal scenarios and analyze the Spacecraft-level thermal-mechanical distortions. The JPL Clipper Mechanical and Thermal teams have analyzed the thermal gradients of the Clipper spacecraft throughout an entire orbit of Jupiter. This transient analysis included appropriate power profiles, spacecraft attitudes and external albedo loads of orbit E41 of the 17F12v2 mission schedule. A thermal model (TM) of the spacecraft was linked to the NASTRAN structural finite element model (FEM). Thirty strategic points along the orbit were selected to map thermal gradients from the TM to the FEM and assess distortion of the structures. This integrated modeling and analysis effort provided confidence in the mechanical system design of the Europa Clipper spacecraft. It also highlighted sensitive areas that led to design modifications which aim to provide thermal-mechanical stability robustness moving forward. This paper will discuss the modeling and analysis approach, results, design improvements, and lessons learned.

8.0606 Novel Contamination Control Model Development and Application to the Psyche Asteroid Mission

Maxwell Martin (NASA Jet Propulsion Laboratory), William Hoey (NASA Jet Propulsion Laboratory), John Alred , Carlos Soares (NASA Jet Propulsion Laboratory),

Presentation: Maxwell Martin, Friday, March 13th, 09:45 AM, Gallatin

In this work, a model that was developed for JPL's Psyche Mission is presented that enables direct derivation of contamination control requirements specifically tailored to meet mission science objectives while minimizing cost and schedule impacts to the project. This is accomplished using a novel method of geometric model processing and analysis as well as a newly developed approach to materials contamination data characterization that enables extrapolation across all mission environments. Spacecraft missions have traditionally followed one of two approaches to contamination control engineering: low-sensitivity missions that rely on non-data-driven heritage practices to meet mission objectives, or flagship-class missions that can afford to implement highly-conservative contamination control programs that may not be optimized to meet mission requirements. In contrast, this model enables teams to evaluate the risk of not meeting bakeout requirements, trade contamination degradation budget allotments between spacecraft subsystems, and provide a mission-specific contamination control program suited for missions of all contamination sensitivity levels. This model incorporates instrument contamination requirements, materials information, spacecraft geometry, thermal predictions and mission operations timelines. Both internal and external spacecraft models are developed in order to account for bus venting, and different cases for stowed and deployed configurations and solar array orientations are analyzed to identify the driving mission phases for contamination. The spacecraft is subdivided into subsystem groups to make outgassing rates independently changeable by a table input and parametrically

assess the impact of different components on each instrument. JPL's in-house view factor code is used to perform direct and reflected contamination transport modelling, allowing outgassing rate data to be updated without needing to re-run a simulation and enabling real-time analysis iteration compared to the weeks or months-long analysis life cycle seen on comparable missions. The contamination behavior of the materials is obtained by identifying the contaminant chemical species from a single materials test. The material behavior across all mission environments is subsequently extrapolated from the knowledge of the constituent contamination species. As projects move from detailed design into manufacturing and baking out real hardware, model predictions can be updated with as-measured outgassing data to adjust future bakeouts on-the-fly to meet mission requirements. Results from the Psyche mission are presented, as well as the application of this model to future missions.

8.0609 Androgynous Fasteners for Robotic Structural Assembly

Greenfield Trinh (NASA - Ames Research Center), Olivia Formoso (NASA - Ames Research Center), Christine Gregg (NASA Ames Research Center), Arno Rogg (NASA - Ames Research Center), Kenneth Cheung (NASA - Ames Research Center),
Presentation: Greenfield Trinh, ,

We describe the design and analysis of an androgynous fastener for autonomous robotic assembly of structural components. These fasteners prioritize ease of assembly through simple actuation with large driver positioning tolerance requirements while producing a reversible mechanical connection with high strength and stiffness per mass. This enables the creation of high strength to weight ratio structures, such as discrete building block based systems that offer reconfigurability, scalability, and efficiency. Such periodic structures are suitable for navigation and manipulation by relatively small mobile robots. The integration of fasteners, which are lightweight and can be robotically installed, into a high performance robotically managed structural system is of interest to reduce launch energy requirements, enable higher mission adaptivity, and decrease system life-cycle costs.

8.0620 Development, Testing and In-Orbit Verification of a Large CFRP Helical Antenna on the AISat Mission

Tom Sproewitz (German Aerospace Center), Siebo Reershemius (German Aerospace Center - DLR),
Presentation: Tom Sproewitz, Friday, March 13th, 08:30 AM, Gallatin

A deployment strategy for a 4 m long, ultra-light, high-gain, helical Antenna made from fiber-composite material will be presented. The antenna was designed to fly on the DLR NanoSatellite AISat for the receiving of signals from the Automatic Information System (AIS) for maritime applications. A description of the antenna deployment strategy including release mechanisms will be given. The proof of concept will be presented based on experimental results gained during the 15. DLR parabolic flight campaign (PFC) in March 2010. Aim of this campaign was to verify the antennas' and the release mechanisms' performance in weightlessness for the following space mission. Tests with gravity compensation devices in a laboratory are not well suited due to the very complex deployment behaviour like coupled dynamic longitudinal and torsion motions. Final, in-orbit demonstration was performed during the two years of operation after the successful launch of the DLR satellite AISat June 30, 2014 with a PSLV launcher from Shriharikota (India). The AISat was developed at DLR Institute of Space Systems aiming at the worldwide receiving of AIS signals from ships. These signals provide identity, position, velocity and heading of ships and can therefore be used for ship tracking. A number of AI-satellites already exist but especially in areas with high ship fluctuation identification problems arose due to the high signal density. AISat has a distinctive ultra-light, high-gain, helical antenna which allows to focus on comparably small areas and thus enables a receiving of Class A and B and SART signals in dense traffic areas. The antenna is a 4 m long and 0.57 m in diameter deployable helix antenna made from fiber composite material, which can be stowed in a very flat volume with a height of 100 mm. Based on its design with 8 windings the total length of the wire itself is approx. 16 m. Through the dedicated usage of fiber composite materials this wire weighs less than 1 kg including the copper cord. In stowed configuration, held down by 3 release mechanisms, the antenna has stored elastic energy like in a spiral spring. After releasing the structure it deploys autonomously in orbit to a length of 4 m. When deployed, the antenna is still prestressed by means of control cords to increase its bending stiffness. During the 15. DLR PFC the deployment of the helix structure was verified. Four structures with different materials and different wire diameters for differing stiffness properties were tested. Additionally the prestressing of the most promising structure was altered. The deployment behaviour was video taped and reaction forces were recorded. This is a basis for further deployment predictions with changing designs and for reaction force predictions acting on the satellite for guidance and navigation control. The contribution will be concluded with a summary of the data received and lessons learned during the two years of operation of the AISat from 2014 to 2016.

8.07 Spacecraft Propulsion and Power Systems

Session Organizer: John Brophy (Jet Propulsion Laboratory), Erica Deionno (The Aerospace Corporation),

8.0703 Design of an Integrated Solar Thermal System for Micro Satellite Orbit Insertion

Fiona Leverone (Delft University of Technology), Angelo Cervone (Delft University of Technology), Matteo Pini (Delft University of Technology), Eberhard Gill (University of Technology),

Presentation: Fiona Leverone, Tuesday, March 10th, 08:30 AM, Madison

Small satellites with increased capabilities in terms of power and propulsion are in demand for future missions. This paper proposes the possible solution of designing a novel integrated solar thermal system that co-generates propulsion and power on-board micro satellites. The proposed system consists of a solar thermal propulsion (STP) system coupled with a micro-Organic Rankine Cycle (ORC) system to harness the waste heat from the STP receiver to provide electrical power and mitigate the need for solar panels. STP provides an alternative to conventional propulsion systems for missions requiring velocity changes of between 800 m/s and 2.5 km/s. Additional advantages include higher specific impulses than chemical propulsion systems, throttability, re-start capabilities, and faster transfer times than electrical propulsion systems. The faster transfer times are especially useful for missions that travel across high radiation regions such as the Van Allen Belt. This unique configuration shares resources such as the concentrator and receiver to potentially extend the power and propulsion capabilities while adhering to the strict mass and volume constraints of micro satellites. However, there is currently no literature available on the design process of the proposed bi-modal system. This paper, therefore, presents an integrated solar thermal design methodology for a GTO to lunar orbit insertion mission. The system is designed to provide a velocity increment of 1.6 km/s and electrical power of 500 W to a 500 kg spacecraft. The STP system uses water as the propellant due to its safety and performance attributes. Toluene has been selected as the working fluid for the ORC due to its high thermal efficiency. By incorporating the use of a high-temperature receiver, propellant temperatures around 2500 K can be achieved that can produce high specific impulse values of approximately 300 s. An optimization has been conducted for various design parameters, such as propellant temperature, nozzle area ratio, burn time, concentrator design, and cycle pressures. The optimization provides an initial framework in the selection of an optimal integrated solar thermal design for the proposed lunar mission. An analysis of variance

(ANOVA) has also been conducted to identify which system parameters, such as optical efficiency and turbine efficiency, have the most influential effect on the system. The largest components of the system are the concentrator, receiver, condenser, propellant and propellant tanks. The performance of an integrated solar thermal system design is also compared against an existing satellite to identify the benefits and pitfalls of the proposed system. The design methodology is described in detail to assist with future evaluations of integrated solar thermal systems for other applications and missions.

8.0704 Utilization of Polychromatic Laser System for Satellite Power Beaming

Michael Sanders (US Naval Academy), Jin S. Kang (U.S. Naval Academy),

Presentation: Michael Sanders, Tuesday, March 10th, 08:55 AM, Madison

Most modern space systems use multi-junction solar cells to better utilize the entire solar spectrum. Since a monochromatic laser does not match the solar spectrum, a multi-junction solar cell would not generate power efficiently from a single wavelength laser. This paper addresses the design for a polychromatic laser system to beam power to a multi-junction solar cell for space applications and the power levels needed of the different laser wavelengths to optimize the spectral response of a space-grade solar cell. Since the wavelengths will be selected to best match the spectral response of each junction and the currents matched across all junctions, the efficiency of the multi-junction cell would increase to 51% without concentration while still being able to use the solar spectrum for power production. Three matched lasers were able to beam power at a 38% increase over a single wavelength laser.

8.0705 Commercial Solar Electric Propulsion:A Roadmap for Exploration

Peter Lord (SSL),

Presentation: Scott Tilley, Tuesday, March 10th, 09:20 AM, Madison

1.5 kW Solar Electric Propulsion (SEP) systems in commercial production for over a decade enable cost-effective and mass-efficient in space transportation. Today's Second Generation 5 kW class Hall Effect thrusters, share a common flight proven design and production legacy that has been carefully evolved by a factor of three. Providing 300% more thrust these flight proven systems are suitable for Discovery class exploration missions carrying significant sensors and/or targeting faraway objects. The recent emergence of a third generation of commercial technology is being achieved through a second 300% growth in scale making possible low-risk steps toward 15-kW class thrusters. When combined with large scale, high power solar arrays and higher voltage power processing equipment, large in space mass transportation missions can be achieved at dramatically lower cost compared to chemical propulsion missions. Fielding these highly reliable technologies for exploration missions is made possible by commercial bottom line driven product development approaches which are strongly focused on early product configuration decisions, modularity and scalability. To succeed in the highly competitive global market, commercial practices demand high reliability features be demonstrated over 15 year missions with rigorous qualification to an envelope of application environments and products designed for manufacturability. To date Maxar has flown well over 100 hall thruster engine systems on commercial spacecraft, without a system level failure impacting Spacecraft performance. Anchoring these emerging technologies in ongoing commercial production across the full SEP power spectrum is vital to maintaining the legacy of low cost and high reliability introduced by the 1st generation of commercial SEP. In addition to a commercial SEP roadmap covering the evolution of smaller planetary, and enhanced large space transportation capabilities, two examples are highlighted of exploration missions enabled by commercial SEP optimized for deep space operations. One illustrates how the Psyche Discovery mission's 20kW SEP chassis design was extracted from Maxar's Space Solutions commercial product line for the exploration of then main belt asteroid 16 Psyche. The second features the much larger third generation Power Propulsion Element (PPE) or “space tug” being developed for the Deep Space Gateway. PPE is a 50 kW class state of the art SEP spacecraft that is capable of Cislunar and Mars missions.

8.0709 Optimizing Directional Power Deposition of Antenna in RF Excited Helicon Plasma Thrusterer

Md Mahbubur Rahman (Skolkovo institute of science and technology), Divya Shankar (Nitte Meenakshi Institute of Technology),
Presentation: Md Mahbubur Rahman, ,

Plasma thruster operating with high-density helicon source expected to mitigate the problems of the finite lifetime of electric thrusters and shows a possibility to be incorporate in spacecraft for long-duration interplanetary missions. Helicon wave a low-frequency whistler wave, where the frequency lies in between lower hybrid frequency and electron cyclotron frequency. The generated electromagnetic wave from helicon antenna penetrates to the plasma and transfer energy to the particles. Helicon waves are excited by an rf driven antenna, which couples the transverse mode structure across the plasma chamber. The mode propagates along the discharge column, and the energy absorbed by plasma electrons due to the collisional or collisionless damping. This research work tends to investigate plasma antenna coupling for maximizing power deposition and frequency dependence for the proposed helicon plasma thruster. To investigate the directional power deposition of rf antennas in helicon plasma source, HELIC, a C++ program is used that simulates wave excitation and propagation, which is developed by Donald Arnush and Francis Chen. In HELIC code, plasma creation and transport are not considered, rather plasma response and resistivity calculated as a function of a static uniform magnetic field for particular plasma density. The antenna considered infinitely thin. The underlying theoretical model solves Maxwell’s equations for radially non-uniform plasma with standard cold plasma dielectric elements. Non-uniform plasma density profile fitted into the three-parameter function. The results depict that power deposition is much higher in the core of the plasma. Comparing the three widely used antennas, in the case of half helix antenna, relative power deposition is higher than nagoya III and single loop antenna. The efficient antenna and plasma coupling depend on the driving frequency and magnetic field strength. These driving parameters reflect directly with the coupling strength of the antenna and plasma plume. The total loading resistance calculated for a wide range of parameters. The result shows an increase of resistance with the higher frequency, which co-relates with the previous studies. The results show an increase in resistance over the increment of the magnetic field. In conclusion, this research paper we investigated the driving parameters for the efficient coupling of the rf antenna to helicon plasma. The directional power deposition for different antenna geometry computed. The effects of parametric functions (volume, edge, and density) on the density profile studied. The result shows that half helix antenna produces overall higher power deposition in both radial and axial directions. The power deposition in the axial direction shows symmetric patterns expect the half helix antenna. Half helix antenna shows an axial preference, which is because of the direction of the magnetic field and the twist of the antenna shape. The maximum loading resistance computed as a function of the driving parameters. The loading resistance exhibits an increase with higher frequency and higher magnetic field strength. The finding of these studies will serve as a useful reference to choose the optimal values for the proposed helicon plasma thruster.

8.0712 Non-nuclear Based Thermoelectric + Battery System Concepts for Space Power Systems

Alexander Morgan (University of Dayton Research Institute),

Presentation: Alexander Morgan, Tuesday, March 10th, 09:45 AM, Madison

The application of a thermoelectric based RTG (Radioisotope Thermoelectric Generator) to recharge or supplement a space battery power system is a proven technology that has been successfully employed and is currently powering the Curiosity rover on Mars. Similar systems are integrated into the upcoming Mars 2020 rover and Dragonfly rotorcraft missions. These hybrid systems utilize the heat generated from the decay of plutonium-238 to generate electrical power, and are tailored to the particular needs of each mission. A similar non-nuclear based thermoelectric + battery hybrid system concept would employ thermoelectrics to capture heat from other thermal sources, such as the large amounts of excess thermal energy emitted from rocket exhaust during a particular mission profile, to augment the power needs of the mission. This may bring additional design freedom and/or power generation to systems that have large amounts of waste heat generation. In this paper, UDRI will present preliminary work on measurements of power generation from commercial thermoelectric devices exposed to radiant energy heat fluxes of up to 67 kW/m2. Further, new total solid-state battery technologies developed at UDRI utilizing new ceramic electrolytes and thermally stable lithium based chemistry will be discussed. This includes battery technology being optimized for planetary space surface missions in very high operational environments (up to 350 °C). Initial calculations on power generation to augment for short durations these new solid-state batteries, along with some of the potential design freedom that may be enabled by such non-nuclear based thermoelectric + battery hybrid power systems will be presented.

8.0713 Self-directed Energy Management System for an Islanded Cube Satellite Nanogrid

Mohammad Yaqoob (Aalborg University),

Presentation: Mohammad Yaqoob, Tuesday, March 10th, 10:10 AM, Madison

Cube satellites in the modern day space missions, are gaining more attraction by both academia and industry due to their low cost of manufacturing and easy deployments compared to previous large spacecraft. These are trustworthy for scientific research, remote sensing, imagery and aeroplane tracking, etc. Nanosatellites with a limited size and weight comprises of some sub systems, communication link (COMM), Attitude Controls (ADCS), on-board data handling (OBDH), payloads and of course, the electrical power system (EPS) which powers and store energy, needed for subsystems and payloads. In this sense, the EPS is the perfect example of a LVDC Nanogrid with distributed energy resources (DERs), which is the holistic lifeline of the other subsystems in the satellite. In fact, many space missions have failed due to the lack of proper coordination of each of the components in the satellite, e.g. solar array, batteries, power control units, etc. The main causes were deficiency in power bus connection with solar panels and/or batteries, power system interaction, the insufficient generated power to operate the transmitter, lack of protection from over current and voltage fluctuations. Furthermore, burn wires are common deployment mechanisms. These are prone to short circuits, a malfunction and overall system failures. Cube satellite nanogrid, DERs power conditioning and power management is a unique challenge because of limits in powers, mass and size constraints. In this work, we consider an islanded low voltage, Nanosatellite Nanogrid. To ensure energy efficiency, regulated voltage and power balancing a self-directed energy management system (EMS) is proposed. The EMS with a robust infrastructure is used to control generation, storage and utilities. The establishment of logical basis for the EMS operations and proposing functionality defining operation modes that encompass all situations. Load prioritization and disconnection are maintained at the time of loss of power conditions. For the proposed EMS validation, simulations are demonstrated to show energy balance in the network.

8.08 Nuclear Space Power Generation

Session Organizer: David Woerner (Jet Propulsion Laboratory), June Zakrajsek (NASA - Glenn Research Center),

8.0801 Empirical Analysis of MMRTG Power Production and Decay

Chris Whiting (University of Dayton),
Presentation: Chris Whiting, Monday, March 9th, 09:45 AM, Lamar/Gibbon

MMRTG is the only flight qualified radioisotope power system available for use by NASA. Recently, telemetry from the first flight unit (F1) was analyzed to obtain a performance prediction at 17 years of life. Despite this analysis, it is difficult to have high confidence in a life prediction from a single system. In this paper, measurements from the MMRTG engineering unit (EU) will be analyzed to improve confidence in the F1 power predictions. The EU has experienced multi-year life testing under two different conditions: simulated thermal vacuum and diurnal cycle testing similar to F1 conditions on Mars. Analysis of the EU thermal data indicates that the unit is experiencing a steady increase in hot junction temperature, which is most likely due to a concurrent decrease in thermal conductivity. Power analysis indicates that temporary degradation mechanisms play a major role in the degradation rate of MMRTG. These mechanisms produce different rates at different temperatures, but once they reach completion, the total degradation will be the same. In other words, units operated at cooler temperatures will have higher power early in life, but all units should produce similar power late in life. EU power data was adjusted to account for the differences between EU and F1 operational conditions. These results provide a prediction of power out to the end-of-design life (EODL) at 17 years after fueling. Results from the simulated thermal vacuum data predict a monthly average EODL power of 75.2 + 0.4 We, while the diurnal cycle data predicts 76.0 + 0.4 We. These results are very similar to the 75.2 We prediction previously provided for F1. The EU was also placed into conditions equal to F1 10.0 years after fueling. In this F1 simulation test, the EU produced an average 90.1 We, which is similar to the 89.7 We monthly average produced by F1. These results suggest that the EU is a very good indicator for the degradation behavior of F1. In addition, the fact that two different MMRTG units produce similar performance and degradation results significantly increases confidence in the F1 predictions, suggesting that F1 could be a leading indicator of performance for other MMRTG flight units. While the EU appears to be a good predictor of flight unit performance, it is important to note that the EU has experienced significantly more physical and thermal stresses compared to a flight unit. This makes a statistical comparison of EU and F1 difficult. In addition, it is possible that the EU may produce anomalous behavior when the unit experiences conditions outside the nominal flight envelope.

8.0802 System Integration of Stirling Convertors into a Dynamic Radioisotope Power System

Joseph Vander Veer (Teledyne Energy Systems), Robert Sievers (Teledyne Energy Systems),
Presentation: Joseph Vander Veer, Monday, March 9th, 11:00 AM, Lamar/Gibbon

Free piston Stirling convertors offer increased efficiency over radioisotope thermoelectric generators at the potential expense of increased risk to reliability and robustness. Steps in reducing that risk are system studies that integrate Stirling convertors into a generator. System integration of a Stirling convertor into a generator requires trade studies and in depth system analysis of a variety of subsystems. Subsystems focused upon here are the GPHS to convertor heating mechanism, convertor and system level heat rejection system, and the overall physical/mechanical configuration. An overview of several system design options and rationale for the down selection of the final configuration will be presented. Included in the analysis is several off-nominal conditions and effects of failed convertors upon the system. Initial trade studies indicate 21% system conversion efficiency and 3.9 W/kg specific power, updated higher fidelity models and details indicate a system efficiency of 23% and a specific power of 3.0 W/kg for the reference condition are possible.

8.0803 Higher Power Design Concepts for NASA's Kilopower Reactor

Marc Gibson (NASA), Paul Schmitz (Vantage Partners),
Presentation: Marc Gibson, Monday, March 9th, 11:25 AM, Lamar/Gibbon

The need for higher power reactors to support human exploration missions to the moon and Mars has become increasingly important due to the urgency to put boots on the moon by 2024 and have a sustainable presence in the following years. This desire has prompted NASA to continue the development of the Kilopower reactor to extend the power up to 10 kilowatts of electricity in support of a lunar base. These 10 kilowatt units are expected to be used as standalone units or be ganged together to create a modular power grid for propellent production, human habitats, and robotic exploration to name a few. The Kilopower reactor was originally designed to produce electrical power from 1 to 10 kilowatts using the same highly enriched uranium fuel, sodium heat pipes, and Stirling convertors at the proper scale. Consideration has also been given to the use of low enriched uranium fuel for these missions and will be studied along with the other aspects of the reactor. This paper will focus on the design concepts and trades associated with the scale up of the Kilopower power conversion system and heat transfer system to support human exploration of the moon and Mars.

8.0804 Official Release of the Radioisotope Power System Dose Estimation Tool (RPS-DET)

Michael Smith (Oak Ridge National Laboratory),
Presentation: Michael Smith, Monday, March 9th, 10:35 AM, Lamar/Gibbon

This talk will present the development, utility, and release of the Radioisotope Power System Dose Estimation Tool (RPS-DET). RPS-DET serves as a user interface that simplifies building and simulating radiation transport models of radioisotope power systems (RPS) for various terrestrial, planetary, and spaceflight scenarios. This talk will describe relevant nuclear engineering fundamentals, modeling methodologies, simplified model development, and where these analytical tools are applicable to the aerospace industry. Examples of the RPS-DET user interface, underlying particle transport codes, geometry libraries, and analysis tools will be demonstrated and explained.

8.0805 Concept for a Cascaded Multi-Mission Radioisotope Thermoelectric Generator

Chadwick Barklay (University of Dayton Research Institute), Daniel Kramer (University of Dayton Research Institute), Chris Whiting (University of Dayton), Richard Ambrosi (University of Leicester), Ramy Mesalam (The University of Leicester),
Presentation: Chadwick Barklay, Monday, March 9th, 10:10 AM, Lamar/Gibbon

A multi-mission radioisotope thermoelectric generator (MMRTG) powers Curiosity, the National Aeronautics and Space Administration (NASA) Mars Science Laboratory rover on Mars, and will also power the upcoming Mars 2020 and Dragonfly missions. Recent studies have determined the feasibility of integrating a second thermoelectric circuit of bismuth telluride (Bi2Te3) into the MMRTG design in order to improve the beginning-of-life (BOL) and end-of-design life (EODL) performance. Initial studies indicate that the integration of a second stage Bi2Te3 thermoelectric circuit could potentially provide an approximate 20% increase in power output at BOL and EODL. In order to provide a low-risk system upgrade approach, a concept was refined to integrate the second stage Bi2Te3 thermoelectric circuit on the external MMRTG housing. However, this concept is accompanied by a number of performance trades, the most notable being a 36.1 kg mass increase, which would reduce the BOL specific power from 2.37 to 1.68 We/kg. This paper summarizes the results of that study, and discusses activities that should be pursued to validate the technical feasibility and potential performance gains that could be obtained.

8.0806 EVOLUTION of SPACE REACTOR QUALIFICATION METHODS and a PATH FORWARD for NEW SPACE REACTORS

Andrew Zillmer (Idaho National Laboratory), Stephen Johnson (INL), Venkat Dasari (Los Alamos National Laboratory),

Presentation: Andrew Zillmer, Monday, March 9th, 11:50 AM, Lamar/Gibbon

This paper outlines the evolution of space reactor system qualifications and provides a potential framework for qualification of current space reactor concepts. Qualification approaches for SNAP 10A, SP-100, TOPAZ II, and Prometheus reactor systems will be discussed. Several qualification approaches from past reactors will be reviewed including: a component qualification approach demonstrated in the SNAP reactor program, a system level approach in the SP-100 program, adding additional features to an existing design in the TOPAZ program, and a combination of a computational and basic testing approach for the Prometheus reactor. Past and present test facilities will also be discussed and the impact of test facility availability (or existence) is discussed. A suggested approach that complies with the updated Presidential Directive (NSPM-20, August 2019) that is derived from previous program approaches will be discussed for qualification of future space reactors.

8.09 Systems and Technologies for CubeSat/Smallsats

Session Organizer: Michael Swartwout (Saint Louis University), Kyle Kemble (Air Force Research Laboratory),

8.0902 Feasibility of a Deep-Space CubeSat Mission with a Stage-Based Electrospray Propulsion System

Oliver Jia-Richards (Massachusetts Institute of Technology), David Sternberg (NASA Jet Propulsion Laboratory), Daniel Grebow (NASA Jet Propulsion Lab), Swati Mohan (NASA Jet Propulsion Laboratory), Paulo Lozano ,

Presentation: Oliver Jia-Richards, Friday, March 13th, 10:10 AM, Gallatin

Independent deep-space exploration with CubeSats, where the spacecraft independently propels itself from Earth orbit to deep-space, is currently not possible due to the lack of high-DeltaV propulsion systems compatible with the small form factor. The ion Electrospray Propulsion System (iEPS) under development at the Massachusetts Institute of Technology's Space Propulsion Laboratory is a promising technology due to its inherently small size and high efficiency. However, current electrospray thrusters have demonstrated lifetimes (500 hours) below the required firing time for an electrospray-thruster-propelled CubeSat to escape from Earth starting from geostationary orbit (8000 hours). To bypass this lifetime limitation, a stage-based approach, analogous to launch vehicle staging, is proposed where the propulsion system consists of a series of electrospray thruster arrays and fuel tanks. As each array reaches its lifetime limit, the thrusters and fuel tanks are ejected from the spacecraft exposing a new array to continue the mission. This work addresses the technical feasibility of a spacecraft with a stage-based electrospray propulsion system for a mission from geostationary orbit to near-Earth asteroid 2010 UE51 through a NASA Jet Propulsion Laboratory Team Xc concurrent design center study. Specific goals of the study were to analyze availability of CubeSat power systems that could support the propulsion system and any other avionics as well as requirements for attitude control and communication between the spacecraft and

Earth. Two bounding cases, each defined by the maturity of the iEPS thrusters, were considered. The first case used the current demonstrated performance metrics of iEPS on a 12U CubeSat bus while the second case considered expected near-term increases in iEPS performance metrics on a 6U CubeSat bus. A high-level overview of the main subsystems of the CubeSat design options is presented, with a particular focus on the propulsion, power, attitude control, and communication systems, as they are the primary drivers for enabling the stage-based iEPS CubeSat architecture.

8.0905 Heat Control System Development for Two-Phase Cold Gas Thruster Tank in CubeSat

Kamil Dąbrowski (Warsaw University of Technology), Krzysztof Zając (Warsaw University of Technology), Marcin Pulik (Warsaw University of Technology), Aleksander Kipiela (Warsaw University of Technology), Łukasz Kuryłowicz (Warsaw university of technology), Radosław Trzepałka (Warsaw University of Technology),

Presentation: Kamil Dąbrowski, Friday, March 13th, 10:35 AM, Gallatin

The purpose of this paper is to explain the process of designing a heat control system which will be able to maintain a thruster tank at a suitable temperature. The system will be used on PW-Sat3, a 3U CubeSat developed by the Students' Space Association at the Warsaw University of Technology. The aim of this project is to demonstrate the two-phase cold gas propulsion technology. The primary payload requirements include the use of a tank, with the temperature maintained in the assumed range, dependent on fuel vapor pressure with butane as a chosen propellant. The implementation of temperature control is necessary in order to eliminate the risk of only one (liquid) phase forming inside the tank, as well as the butane pressure dropping too much, which leads to non-effective thrust. The initial thermal analysis was conducted in ESATAN software. Based on the Preliminary Design, the calculations were performed. They included three cases - a steady state and with no thrust applied, a transient state with no thrust applied, and a transient state with the thruster working. Thanks to these analyses, required thermal constraints were determined. Based on the received temperatures, the heat control system was designed. This system is combined of passive and active thermal-control elements such as insulation, sensors and heaters. The selection of the heaters was made according to the tank design and the requirements stemming from the usage of butane. The next step was to create a control module which enables to achieve the desired range of temperatures in the tank. This device is composed of two parts. Both of them are responsible for the stabilization of temperature, but one of them is active when the thruster does not work and the second one is active otherwise. The paper includes a detailed description of the heating system components, as well as the analyses and calculations performed to verify the functioning of the system. An additional series of tests for the tank heat control will be performed before the launch of the CubeSat. The results will be compared to computational studies of the design, in order to further improve the methodology applied. This research is of significant value, as the achieved results can lead to a more complex development of this system or to the unification of the heat control system with the cold gas thruster.

8.0911 Shape Morphing Microbots for Planetary Exploration

Rachel Moses (University of Arizona), Jekan Thangavelautham (University of Arizona),

Presentation: Rachel Moses, Friday, March 13th, 11:00 AM, Gallatin

NASA has expressed a demand for new explorative robotic technology as the search for previously habitable environments progresses. Exploration, utilizing one or few rovers may restrict the scouting range causing a lack of discovery of hidden environments. Current planetary robotic systems contain single robots that have rigid and prebuilt components. All of which have high launch costs and are incapable of exploring extremely rugged environments. Utilizing innovative and low-cost inflatable robot technologies it is possible to conceive short, low-cost, high-risk, high-reward missions. Our current work focuses on networks of cost efficient inflatable microbots with the intent of rugged environment exploration. These robots deploy inflatables filled with regolith which vary softness allowing them to crawl over obstacles. The generic architecture of these shape-morphing microbots has been developed and is suitable as sub-payloads on board satellites of size 1U and above. Each microbot is packaged into the size of a chocolate bar, 9 cm x 3 cm x 1 cm. A single 1U CubeSat can deploy 27 of these microbots and a 3U can deploy 81 microbots. These microbots utilize in-situ sand to inflate into a sphere of 10 cm diameter. Using swarms of ground robots we have previously shown maximal area-coverage algorithms and ability to gather around an impact event. Once these microbots have run out of life, they can serve as beacons on the perimeter of dangerous terrain or around high-value or historical locations on the Moon. Our future analysis, points towards the feasibility of such systems being distributed in large numbers on planetary surfaces while being packaged into CubeSat-sized carriers. The results of our present work will provide insight into the structural dependability and lead to prototype development.

8.0913 Educational Nanosatellite Hacking

Thibault Gateau ,

Presentation: Thibault Gateau, Friday, March 13th, 11:25 AM, Gallatin

Security issue concerning telecommunication with educational nanosatellite missions is currently underestimated or not considered critical and often neglected. Loosing contact with a nanosatellite in the academic world is, until now, pretty common. Without thrusters, safety studies on LEO orbits usually guaranty their atmospheric re-entry. Even hacking a nanosatellite would have low impact concerning others spacecraft, apart for being a space debris doing random attitude changes. That may change. For example, electrical propulsion allows to significantly modify an orbit, and opens new possibilities, and therefore new threads. While classic space actors are taking a great care for securing telecommunications, academic teams usually lake of funding, expertise and knowledge. This paper aims at providing a warning for academic nanosatellite conceptors, and provide some recommendations and concrete methods. This work is relying on a concrete use-case, a space mission involving an academic nanosatellite: the NIMPH project. Platform is a 3U Cubesat. It is planned to be operated by radio-amateur on UHF/VHF bandwidth. We conducted a security analysis in order to identify the current and future threats for this kind of specific space mission (academics nanosatellite). We also recommend procedures that can be used to protect against such risks, with as low effort as possible for the development, and minimal cost. This paper also describe symmetric key cryptography schemes. They are not yet deployed in the framework of academic projects to our knowledge, but they could be easily usable. Two cryptographic procedures have been especially identified to authenticate and/or encrypt telecommands on the up-link. As a proof of concept, Authenticated Encryption with Associated Data construction based on the Advanced Standards Algorithm in Galois Counter Mode (AES/GCM) has consequently been implemented. We simulate how a telecommand would be processed through this cryptographic procedure, from authenticated encryption on the ground to verification and decryption by the On-Board-Computer.

8.10 Planetary Exploration Using Small Spacecraft

Session Organizer: Carolyn Mercer (NASA - Glenn Research Center), Andrew Petro (NASA - Headquarters), Young Lee (Jet Propulsion Laboratory),

8.1002 MarCO Radio Occultation: How the First Interplanetary Cubesat Can Help Improve Future Missions

Kamal Oudrhiri (Jet Propulsion Laboratory), Dustin Buccino (Jet Propulsion Laboratory), Yu Ming Yang (NASA Jet Propulsion Lab), Daniel Kahan , Norman Lay (Jet Propulsion Laboratory), Joseph Lazio (Jet Propulsion Laboratory), Joel Krajewski (Jet Propulsion Laboratory), Andrew Klesh (Jet Propulsion Laboratory),

Presentation: Dustin Buccino, Thursday, March 12th, 09:20 AM, Jefferson

Smallsats and cubesats have been suggested as low-cost alternative means to achieve scientific goals for interplanetary missions. On May 5, 2018, NASA launched the first interplanetary cubesat: Mars Cube One (MarCO). MarCO-A and MarCO-B are twin communications-relay cubesats designed to monitoring InSight during its Entry, Descent and Landing (EDL) on November 26, 2018. After InSight's EDL, MarCO continued to flyby Mars and conduct a radio occultation of the planet. This is the first-ever radio occultation of a planet other than Earth performed, and also the first planetary science measurement taken by an interplanetary cubesat. This research presents a performance assessment of the MarCO radio science measurements, results of MarCO radio occultation task, and the expected radio science capability of MarCO-like cubesat. Future interplanetary radio science missions can investigate planetary atmospheres, ionospheres, and rings using radio occultation measurements; probe the interior of a planetary body with gravity measurements; and surface characteristics with bistatic scattering. Observations made by tracking MarCO from NASA's Deep Space Network using an open-loop recordings of the X-band radio signal collected during cruise, InSight EDL, and the MarCO radio occultation are presented. Although the noise level of the MarCO radio occultation was too high for precise remote sensing of the atmosphere, the noise patterns are presented and analyzed against simulations. We compared observations with the spacecraft dynamics, Earth atmospheric and ionospheric calibrations, Martian atmospheric and ionospheric model simulations to evaluate the performance of the MarCO radio occultation. This investigation will improve our understanding of engineering and science constraints for future interplanetary cubesats.

8.1005 An Inter Planetary Network Enabled by Small Spacecraft

Jose Velazco (Jet Propulsion Laboratory),

Presentation: Jose Velazco, Thursday, March 12th, 09:45 AM, Jefferson

This paper describes the implementation of an unparalleled large sensor and communications platform along the solar system that we call the inter planetary network (IPN). The proposed IPN consists of thousands of small spacecraft (e.g. CubeSats) strategically deployed around planetary bodies in the solar system where each spacecraft is furnished with fast communications and sensor systems. The IPN concept is being proposed as an avant-garde science and communications platform that could allow for continuous fast communications and remarkable science returns. The IPN spacecraft, furnished with suitable miniaturized sensors, could form an amazing deep space platform for unique observation of the solar system, stars, galaxies and universe. A key feature of the IPN architecture is the use of swarms of spacecraft as network units. Super-high-speed intra-swarm communications could be achieved via omnidirectional optical links. The swarms act as autonomous network nodes and are capable of forming large synthetic apertures that enable high data rate communications among the IPN nodes. Depending on the sensors they carry, these swarms may also be capable of forming large synthetic sensors by rapidly combining data among the spacecraft. We envision distances between spacecraft forming a swarm to be in the range of 1E2-1E4 kilometers, whereas distances of 1E6-1E8 kilometers among swarms (IPN nodes) are expected.

8.1006 Architecture Trades for Accessing Small Bodies with an Autonomous Small Spacecraft

Sandro Papais (NASA Jet Propulsion Lab), Benjamin Hockman (NASA Jet Propulsion Laboratory, California Institute of Technology), Saptarshi Bandyopadhyay (Jet Propulsion Laboratory), Reza Karimi (NASA Jet Propulsion Lab), Shyam Bhaskaran (Jet Propulsion Laboratory), Issa Nesnas (Jet Propulsion Laboratory),

Presentation: Sandro Papais, Thursday, March 12th, 10:10 AM, Jefferson

Characterizing the composition, properties, and environments of Small Bodies is key to understanding the origins and processes of the Solar System. Traditionally, our knowledge has been limited to ground observations and selected few missions which cannot fully characterize the diversity of Small Bodies. Advances in miniaturized spacecraft technologies have recently enabled small spacecraft to perform missions in deep space, as demonstrated by Mars Cube One in 2018. Additional missions are being developed to further mature these technologies and expand their capabilities. We investigate a new approach to exploring Small Bodies, where standalone small spacecraft can be used as a more affordable approach to autonomously navigate, rendezvous, and characterize them. We review relevant mission concepts, available targets, architecture trade-offs, and required technologies for baseline mission design options. Using near-term technologies that will be available in less than 3 years, our results indicate that it is possible for standalone small spacecraft to rendezvous with one of several Small Bodies. It was found that a 24 kg and 180 kg spacecraft would be capable of delivering payloads of 1.5 kg and 10 kg, respectively, to several near-Earth asteroids candidates. With a departure window of 2022 to 2030, the number of available targets for the 24 kg and 180 kg architectures are 9 to 177 and 104 to 1,132 respectively. The number of targets depends on additional requirements, such as orbit uncertainty, composition, and diameter. Enabling technologies include high-delta-V (> 3 km/s) miniature electric propulsion system, high-efficiency (> 100 W/kg) deployable solar arrays, and improved computational hardware and software for autonomy. Advances in miniaturized instruments, high-performance radiation-tolerant avionics, and interplanetary communications systems can also be leveraged. In the long term, a standardized autonomous small spacecraft architecture could enable a fleet of spacecraft to perform a cursory exploration of a representative sample of Small Bodies.

8.11 Systems and Technologies for Ascent from Planetary Bodies, a Multidisciplinary Problem

Session Organizer: Ashley Karp (Jet Propulsion Laboratory), Tara Polsgrove (NASA Marshall Space Flight Center),

8.1101 Mars Ascent Vehicle Hybrid Propulsion Configuration

Darius Yaghoubi (NASA - Marshall Space Flight Center), Andrew Schnell (NASA Marshall Space Flight center),

Presentation: Darius Yaghoubi, Thursday, March 12th, 10:35 AM, Jefferson

As part of a Mars Sample Return (MSR) campaign, two Mars Ascent Vehicle (MAV) configurations have been designed in parallel. Each ascent vehicle configuration has a different propulsion system which ultimately leads to two unique vehicle designs. As part of a Preliminary Architecture Assessment (PAA), these vehicle designs were developed to the same level of maturity in order to inform the selection of one of the vehicles as the point of departure design for the campaign. The selection will be made in November 2019. The initial MSR architecture called for a hybrid-based propulsion MAV. This type of propulsion system calls for a solid wax motor that would utilize liquid MON-25 as an oxidizer. Hybrid rocket propulsion allows for more flexibility than traditional solid or liquid propulsion options, and typically benefits from the advantages of both. A hybrid motor can be throttled and shut down easily, and avoids significant risk in manufacturing and handling. On a theoretical level, hybrid motors perform at a higher specific impulse (Isp) than solid motors. The primary disadvantage of hybrid motors comes from additional complexity and significantly less flight heritage and low Technology Readiness Level (TRL). This paper describes the design of the hybrid propulsion configuration. An additional paper will be published describing the design of the solid propulsion configuration*. The hybrid propulsion configuration MAV was developed in 2019 by NASA Marshall Space Flight Center (MSFC) in association with NASA Jet Propulsion Laboratory (JPL). It features a Single Stage to Orbit (SSTO) design with an SP7A solid wax fuel and MON-25 liquid oxidizer. The liquid portion of the vehicle allows for a Liquid Injection Thrust Vector Controller (LITVC) as well as hypergolic propellant additives for ignition. The vehicle was designed to deliver approximately 0.31kg of Martian geological samples to a circular orbit at Mars of 343km at a 25o inclination. Although hybrid propulsion in general has been used on launch vehicles in the past, the integrated vehicle subsystems that operate in conjunction with these propulsion elements do not typically operate in a Martian environment, which in this application can get as cold as -40oC. The PAA advanced the maturity of these subsystems by performing detailed design and analysis on the vehicle with respect to structures and mechanisms, Guidance/Navigation/Control (GNC) systems, avionics, Reaction Control System (RCS), LITVC, thermal environments, and advanced Computational Fluid Dynamics (CFD). This paper will summarize the results of these studies. *Mars Ascent Vehicle Solid Propulsion Configuration, IEEE Aerospace Conference, March 2020

8.1102 Mars Ascent Vehicle Solid Propulsion Configuration

Darius Yaghoubi (NASA - Marshall Space Flight Center), Andrew Schnell (NASA Marshall Space Flight center),

Presentation: Darius Yaghoubi, Thursday, March 12th, 11:00 AM, Jefferson

As part of a Mars Sample Return (MSR) campaign, two Mars Ascent Vehicle (MAV) configurations have been designed in parallel. Each ascent vehicle configuration has a different propulsion system which ultimately leads to two unique vehicle designs. As part of a Preliminary Architecture Assessment (PAA), these vehicle designs were developed to the same level of maturity in order to inform the selection of one of the vehicles as the point of departure design for the campaign. The selection will be made in November 2019. Although the initial MSR architecture called for a hybrid-based propulsion MAV featuring solid wax fuel with liquid oxidizer, a configuration using more traditional solid propulsion was developed as an additional risk mitigation option. Though lacking in the single stage to orbit (SSTO) and throttle flexibility of a hybrid configuration, a solid configuration vehicle allows a simpler design with significantly longer flight heritage and higher Technology Readiness Level (TRL). This paper describes the design of the solid propulsion configuration. An additional paper will be published describing the design of the hybrid propulsion configuration*. The solid propulsion configuration MAV was developed in 2019 by NASA Marshall Space Flight Center (MSFC) in association with NASA Jet Propulsion Laboratory (JPL). It features two stages with a modified STAR-17 motor for the second stage and a traditional electromechanical actuator Thrust Vector Controller (TVC). The vehicle was designed to deliver approximately 0.47kg of Martian geological samples to a circular orbit at Mars of 343km at a 25o inclination. Although solid motor designs in general are at a relatively high TRL, the integrated vehicle subsystems that operate in conjunction with these propulsion elements do not typically operate in a Martian environment, which in this application can get as cold as -40oC. The PAA advanced the maturity of these subsystems by performing detailed design and analysis on the vehicle with respect to structures and mechanisms, Guidance/Navigation/Control (GNC) systems, avionics, Reaction Control System (RCS), TVC, thermal environments, and advanced Computational Fluid Dynamics (CFD). This paper will summarize the

results of these studies. *Mars Ascent Vehicle Hybrid Propulsion Configuration, IEEE Aerospace Conference, March 2020

8.1104 Guidance and Navigation Challenges for a Martian Ascent Vehicle

Evan Anzalone (NASA), Dane Erickson (NASA - Marshall Space Flight Center), Jason Everett , Joseph Powers ,

Presentation: Dane Erickson, Thursday, March 12th, 11:25 AM, Jefferson

This work presents studies and analysis in support of a Mars Ascent Vehicle as part of a Martian Sample Return campaign. The vehicle design has been ongoing, with rapid development of a 6 Degree of Freedom simulation to capture full vehicle dispersions and integrated performance of vehicle, guidance, navigation and control. The maturation of this simulation is presented to provide an overview of its capabilities added over the past year of effort. The results describe in detail guidance algorithm development to increase the system's robustness to thrust sensitivities. Navigation performance and sensitivity analysis are included to describe the capabilities of the current design as well as identify primary drivers of insertion performance. Lastly, integrated vehicle 6DOF statistical results are presented to provide insight into the nominal performance of the current vehicle and insight into system-level drivers. Future work is described to outline the continuing maturation and development of the MSR MAV ascent vehicle.

TRACK 9: AIR VEHICLE SYSTEMS AND TECHNOLOGIES

Track Organizers: Kendra Cook (C2 International, LLC), Tom Mc Ateer (NAVAIR), Christian Rice (Naval Air Systems Command, Patuxent River, MD.),

9.01 Air Vehicle Flight Testing

Session Organizer: Brian Kish (Florida Institute of Technology), Christopher Gavin (AIRTEVRON TWO ONE), Daniel Short (HX-21),

9.0104 Flight Testing of Predictive Energy Management Displays for Light Aircraft

Isaac Silver (Florida Institute of Technology), Markus Wilde (Florida Institute of Technology), Brian Kish (Florida Institute of Technology),

Presentation: Isaac Silver, Monday, March 9th, 09:25 PM, Gallatin

Loss of control at low altitude in the traffic pattern is one of the main causes of fatal accidents in general aviation. A large number of loss-of-control accidents can be attributed to the pilot loosing awareness of the energy state of the aircraft. An intuitive and accessible display for energy state and specific excess power can potentially remedy these types of accidents. As general aviation aircraft are not equipped to measure a large number of dynamic parameters, such a predictive energy display must be based on an algorithm running on a reduced set of parameters readily available from the current generation of light aircraft avionics. This paper discusses the challenges associated with designing a predictive projection-based or screen-based display for light aircraft and presents prototype solutions. Furthermore, the paper presents a number of energy state prediction algorithms and reports the flight test results producing the underlying aircraft performance database. The work presented has great potential of resulting in low-cost, easy-to-use, energy state prediction, warning and guidance displays based on available aircraft parameters.

9.0105 Proposed Part 23 Means of Compliance Based on Flight Testing of Level 2 and Level 3 Aircraft

Brian Kish (Florida Institute of Technology), Markus Wilde (Florida Institute of Technology),
Presentation: Brian Kish, Monday, March 9th, 09:50 PM, Gallatin

General aviation suffers from an alarmingly high rate of fatal loss-of-control accidents. For a number of years, the aviation community has been working on developing new airworthiness certification standards and means of compliance to move the safety needle. This paper proposes a new Part 23 means of compliance based on flight testing of single-engine Level 2 and Level 3 aircraft, crafted to address the low-altitude and startled-pilot loss-of-control problem. This means of compliance encourages good low-speed handling qualities, promotes flight characteristics over warning devices, redefines roll limits to appropriate values, eliminates the ambiguous term “uncontrollable nose down pitching motion”, allows cost-effective flight testing with appropriate minimum standard flight test methodology, specifically emphasizes the qualitative assessment of the certification authority test pilot for compliance determination, and achieves a higher standard than previous Part 23 amendments. The means of compliance combines minimum thresholds for coordinated stall characteristics with point-based scoring for uncoordinated “feet-on-the-floor” stalls, longitudinal trim force changes along with free-pitching response during configuration changes, and warning devices. The paper reports on the flight tests executed in the development of this means of compliance and discusses the motivation and thought processes.

9.02 UAV Systems & Autonomy

Session Organizer: Frances Zhu (Cornell University), Luis Gonzalez (Queensland University of Technology), Will Goins (dynetics),

9.0202 3-D Adaptive Navigation: Multirobot Formation Control for Seeking and Tracking of a Moving Source

Robert Lee (Santa Clara University), Christopher Kitts (Santa Clara University), Michael Neumann , Robert Mcdonald (Santa Clara University),
Presentation: Michael Swartwout, Thursday, March 12th, 08:30 AM, Dunraven

Adaptive navigation enables a vehicle to autonomously modify its direction or motion path based on real-time measurements. This may be advantageous to achieve more time- and energy-efficient exploration of the scalar characteristics of an unknown and possibly dynamic region of interest (e.g., temperature, magnetic field, concentration level, etc.). Capabilities include finding local maximum/minimum points and following contours within the scalar field of interest. These capabilities have the potential to benefit a variety of applications such as environmental monitoring, disaster response, and exploration. This paper documents the initial results of a comprehensive program to develop, verify, and experimentally implement 3-dimensional adaptive navigation capability using the author’s multilayer control architecture. This initial work focuses on source seeking/tracking, and describes the approach used for formation control of an appropriate multirobot formation, estimation of a field gradient, and the adaptive navigation control policy. Simulation results verify the functionality of this work for a fixed formation geometry navigating in both static and dynamic scalar fields.

9.0203 Towards Simulating Semantic Onboard UAV Navigation

Nicolas Mandel (Queensland University of Technology), Fernando Vanegas Alvarez (Queensland University of Technology), Luis Gonzalez (Queensland University of Technology),
Presentation: Nicolas Mandel, ,

In recent years the field of robotic navigation has increasingly harnessed semantic information in order to facilitate the planning and execution of robotic tasks. The use of semantic information focuses on employing representations more understandable by humans to accomplish tasks with robustness against environmental change, limiting memory requirements and improving scalability. Contemporary computer vision algorithms extracting semantic information have continuously improved their performance on benchmark datasets, however, most computations are expensive, limiting their use for robotic platforms constrained by size, weight and power such as unmanned aerial vehicles (UAVs). Recent advances have demonstrated the potential for navigation systems based on semantic information to be included into real-time operation of UAVs. This paper describes the development of a processing pipeline to incorporate the use of semantic information into a UAV navigation system. A navigation framework that uses the Robot Operating System (ROS) and semantic information is being developed, with simulations as a primary evaluation mechanism preceeding deployment on hardware. The proposed system takes inputs from RGB images generated on-board the UAV and processes them in real-time to generate a semantic representation of its environment. The UAV executes subsequent actions autonomously by reasoning about the semantic content of the environment in order to accomplish a goal. Results from simulation indicated that the system is capable of extracting semantic information from camera images alone and infer plausible motion inputs for the flight controller to execute. The results also show that the system is capable of processing data in real-time and is able to enhance navigational capabilities to drive UAVs towards a higher level of autonomy.

9.0205 Efficient Terrain following for an MAV with Ultra-Wide Stereo Cameras

Marcus Müller (German Aerospace Center - DLR),

Presentation: Marcus Müller, Monday, March 9th, 08:30 AM, Lake/Canyon

In recent years, Micro Aerial Vehicles (MAVs) have drawn attention to the aerospace community. With such autonomous flying platforms, it is possible to explore foreign extraterrestrial bodies in an efficient and faster manner than other robotic platforms, like rovers. In addition, they can be equipped with a variety of different sensors. Cameras are especially well suited, since they are light, energy efficient and deliver a broad spectrum of information. Following the underlying terrain in a defined height is a fundamental task for any exploring MAV. To accomplish this, many systems possess a designated height sensor, which in most cases only delivers a single height estimation taken from nadir. In such a setup, the MAV is just adjusting its height based on the current height estimation and does not take any terrain lying ahead into account, which results in delayed height adjustments. In this presentation, we propose a novel method based on a wide-angle stereo camera setup, which is attached to the MAV, to overcome such problems. Due to the wide vertical field of view, the vehicle is able to not only measure its current height, but also the terrain lying ahead. Therefore, the MAV is able to perform a better terrain following compared to other methods, which use just a single nadir height sample. Our algorithm only needs to take the depth image, calculated by the stereo cameras, and the estimated gravity vector into account. Therefore, our method is very fast and computationally efficient, compared to other methods, which build up an entire map beforehand. As a result, the procedure presented here is also suitable for tiny flying systems with low computational capabilities and memory resources. The terrain following algorithm runs in real-time and on board the system, and is therefore also suitable for confined environments, like caves, and where communication delays are present. We evaluate our method with real tests on an MAV.

9.0207 UAV Formation Flight for In-Air-Capturing Maneuver

Stefan Krause (German Aerospace Center - DLR), Sebastian Cain (German Aerospace Center - DLR),
Presentation: Stefan Krause, Monday, March 9th, 08:55 AM, Lake/Canyon

Implementation of reusable launch vehicle (RLV) missions is a major goal in current aerospace research. One conceptual idea to return a booster stage is the so-called “in-air capturing” (IAC), where a winged stage is captured by an aerial vehicle and towed back to the final destination. This approach has the advantage that a towed winged stage does not need a propulsion system or fuel reserves to arrive to a destination point, compared to alternative approaches as demonstrated by SpaceX. The concept of capturing the RLV in air is based on earlier IAC missions for satellite photo capsules and the probe-and-drogue refueling method. A key difference is that in an air-to-air-refueling procedure a highly dynamic fighter tries to connect to a trailing drogue or rigid boom from a sluggish tanker. Opposite to this procedure, it can be assumed that in IAC case two aerodynamically sluggish aircraft need to be coupled. The challenge is to build up a formation which enables a connection between a gliding RLV and a dynamic coupling device trailing from a large aircraft. To investigate this IAC approach, the German Aerospace Center (DLR) built a scaled demonstration system with smaller unmanned aerial vehicles (UAV) to research different aspects of IAC flight tests. Based on the assumption that at an IAC approach would involve two large aerodynamically sluggish systems, a third highly dynamic vehicle should be introduced to enable a safe and reliable connection. Therefore, the trailing system, which is known from the air-to-air refueling, was modified by DLR with aerodynamic control surfaces and an independent flight control system. This enables a dynamic and independent motion of the coupling device relative to the towing aircraft, as well as the RLV. This paper gives an overview about IAC investigations of DLR, which are validated in experimental flight test demonstrations with scaled unmanned systems. The focus of this work is on building up the formation, from the rough approach with GNSS up to the final approach, where the global, absolute localization is supported by an image based relative position estimation of the coupling device. A major aspect in the formation implementation is the active coupling device (ACD). Therefore, the paper will show the construction of the ACD, its functionality and operation during the formation flight and a validation of its behavior at the flight demonstration. The first flight test results show that our research is heading in the right direction and further tests are expected to provide comprehensive results for the validation of the IAC concept.

9.0214 Autonomous UAV Navigation for Active Perception of Targets in Uncertain and Cluttered Environments

Juan Sandino (Queensland University of Technology), Fernando Vanegas Alvarez (Queensland University of Technology), Luis Gonzalez (Queensland University of Technology), Frederic Maire (Queensland University of Technology),
Presentation: Fernando Vanegas Alvarez, Monday, March 9th, 09:20 AM, Lake/Canyon

The use of Small Unmanned Aerial Vehicles (sUAV) has grown exponentially owing to an increasing number of autonomous capabilities. Automated functions include the return to home at critical energy levels, collision avoidance, take-off and landing, and target tracking. However, sUAVs applications in real-world and time-critical scenarios, such as Search and Rescue (SAR) is still limited. In SAR applications, the overarching aim of autonomous sUAV navigation is the quick localisation, identification and quantification of victims to prioritise emergency response in affected zones. Traditionally, sUAV pilots are exposed to the prolonged use of visual systems to interact with the environment, which causes fatigue and sensory overloads. Nevertheless, the search for victims onboard a sUAV is challenging because of noise in the data, low image resolution, illumination conditions, and partial (or full) occlusion between the victims and surrounding struc-

tures. This paper presents an autonomous Sequential Decision Process (SDP) for sUAV navigation that incorporates target detection uncertainty from vision-based cameras. The SDP is modelled as a Partially Observable Markov Decision Process (POMDP) and solved online using the Adaptive Belief Tree (ABT) algorithm. In particular, a detailed model of target detection uncertainty from deep learning-based models is shown. The presented formulation is tested under Software in the Loop (SITL) through Gazebo, Robot Operating System (ROS), and PX4 Firmware. Tests are conducted in a simulated SAR GPS-denied scenario, aimed to find a person at different levels of location and pose uncertainty.

9.0217 Uncertainty Velocity Obstacle Avoidance for sUAS Trajectory Planning in a 2D Plane

Jaron Ellingson (Brigham Young University),

Presentation: Jaron Ellingson, Monday, March 9th, 09:45 AM, Lake/Canyon

To guarantee safe autonomous-navigation of multiple small unmanned aircraft systems (sUAS) within a limited airspace, collision avoidance algorithms must be robust enough to handle uncertainties in aircraft states. The velocity obstacle (VO) concept is a popular avoidance algorithm which uses a collision cone to effectively determine if two objects will collide in the near future. The VO method is an excellent choice for collision avoidance because it is a fast algorithm which allows for avoidance of dynamic obstacles. This paper proposes a novel approach to the decentralized VO collision avoidance method by addressing uncertainties in the position and velocity of sUAS. Two scenarios are presented to illustrate the utility of this method for a sUAS encountering cooperating and noncooperating vehicles. In the first scenario the vehicles use automatic dependent surveillance broadcast (ADSB) like messages to communicate position and velocity between cooperative vehicles. In the second, the vehicles rely on a ground based networked radar system which relays estimate positions and velocities of all the vehicles to subscribing sUAS. Each vehicle uses this information in a constant-jerk Kalman filter to estimate other vehicle's positions and velocities. The main contributions of this paper include (1) augmenting the VO's collision cone to handle position and velocity uncertainty, (2) addressing the limitation of current VO methods when the collision cone is undefined, and (3) recommending the appropriate speed and transmission range a vehicle must operate at to guarantee safe operations. Each of these contributions will now be expanded upon. (1) Current VO methods assume perfect and instantaneous knowledge of the opposing vehicles position and velocity. In real-world operations this is never the case. To prevent collisions, the sUAS must augment the current VO method to account for uncertainty in of the collision cones. The Minkowski sum is applied to position and velocity ellipses of uncertainty providing a dynamic collision cone that changes to account for varying vehicle uncertainty. (2) When dealing with sUAS dynamics in traditional VO methods, the collision cone between two vehicles has the potential to become undefined. This occurs at a critical time when the vehicles are close together. To augment this deficiency and ensure safe operations, the VO algorithm is augmented with an artificial potential field that prevents vehicles from reaching this degenerate state. (3) In scenarios with many cooperative vehicles, estimating the position and velocity of another vehicle may be costly. Therefore, the sUAS might only care about another vehicle if it is within a certain range. This portion of the research focuses on finding the appropriate range for communicating ADSB-like messages and corresponding speeds at which the sUAS should fly to prevent collisions. Finally, this paper validates this new VO method through numerical simulations.

9.0218 Multi-UAV Target-Finding in Simulated Indoor Environments Using Deep Reinforcement Learning

Ory Walker (Queensland University of Technology), Fernando Vanegas Alvarez (Queensland University of Technology), Luis Gonzalez (Queensland University of Technology),

Presentation: Fernando Vanegas Alvarez, Monday, March 9th, 10:10 AM, Lake/Canyon

Searching indoor environments in the presence of obstacles while using multiple UAV agents remains a challenge. This work presents a framework that combines traditional POMDP planning and deep reinforcement learning based control to enable target-finding using multiple UAV agents in simulated environments containing unknown obstacles. Agents are aware of the general shape of the environment, but must respond to hidden unknown obstacles as they traverse the environment in search of the target.

9.0222 Drivocopter: A Concept Hybrid Aerial/Ground Vehicle for Long-endurance Mobility

ARASH KALANTARI (NASA Jet Propulsion Lab), Thomas Touma (California Institute of Technology), Leon Kim (Columbia University), Rianna Jitosho (Stanford University), Kyle Strickland (California State University), Brett Lopez , Ali Agha ,

Presentation: Brett Lopez, Wednesday, March 11th, 05:20 PM, Amphitheatre

Aerial robots show promise for increased capabilities in exploring unstructured and challenging environments.However, they are limited by payload capacity, flight times, and susceptibility to damage in case of collision. On the other hand,ground robots are able to carry larger payloads and have a lower cost of transport, at the price of limited mobility over challenging terrain. This paper presents a hybrid aerial/ground vehicle that combines the capabilities of both types of vehicles to enable multi-modal mobility in diverse and challenging environments,a lower cost of transport compared to purely aerial vehicles,increased payload capacity, and a design that is more robust to collisions and physical interaction within potentially cluttered and narrow spaces. The design consists of a UAV with four independently actuated spherical wheels which, in addition to providing traction for ground mobility, protect the propellers in collision. In comparison to hybrid vehicles with passive wheels presented in other designs, actuated wheels mitigates perception degradation in dusty environments caused by downwash from thrusting close to the ground. In addition, the integration of an end-to-end autonomy stack is presented which enables the control, planning, and autonomous navigation of the hybrid vehicle in unknown environments. The controls framework em-ploys a geometric tracking controller for aerial trajectories and a cascaded position and velocity controller for ground mobility.We leverage motion primitives to locally plan collision-free paths and a differential flatness mapping to generate kinodynamically feasible trajectories for both terrestrial and aerial modalities in a unified manner. Lastly, we utilize a grid based A* search and probabilistic 3D mapping based on octrees to plan geometric aerial/ground paths to a goal. With this framework, we hope to demonstrate the capabilities of this hybrid aerial/ground vehicle in challenging unknown environments and improved energy efficiency for hybrid mobility over purely flying.

9.0224 Urban Air Mobility System Testbed Using CAVE Virtual Reality Environment

Panadda Marayong (California State University, Long Beach), Praveen Shankar (California State University Long Beach), Jessica Wei (California State University Long Beach), Hanson Nguyen (California State University), Thomas Strybel (California State University, Long Beach), Vernol Battiste (San Jose State University Foundation),

Presentation: Panadda Marayong, Wednesday, March 11th, 09:00 PM, Amphitheatre

Urban Air Mobility (UAM) refers to a system of passenger and cargo transportation within an urban area, as well as other Unmanned Aerial Systems (UAS) services that will be supported by a mix of onboard, ground-piloted and autonomous operations.

The UAM operation framework, with small electric-powered vertical takeoff and landing vehicles, offers an on-demand innovative transportation option that can reduce traffic congestion and pollution and increase mobility in metropolitan areas. Market studies funded by NASA Aeronautics Research Mission Directorate identified use cases of UAM for passenger and cargo transport that are viable and potentially profitable. NASA, in partnership with the UAM community, established the vision and framework for UAM that address several key developments and barriers, including vehicle development and production, airspace system design and implementation, community integration, air traffic and fleet operations and management, and individual vehicle management and operations. UAM will require increasing autonomous systems, known to improve the capacity, safety and efficiency of complex systems. Although industry partners, such as Uber and Boeing, are designing smart air vehicles, the concept of airspace operations and human-automation teaming in UAM operations remain an area of active research. In this paper we report on the development of a Cave Automatic Virtual Environment (CAVE) system as a testbed for human-automation teaming and airspace operations research for UAM. The CAVE consists of a four-wall projection system, motion capture, and a control software for generation of immersive virtual environments with real-time full body tracking capability [Visbox, Inc., IL]. A CAVE-like system offers advantages over head-mounted displays in that it provides better presence through a greater field of view that can be shared with multiple users and allows an operator to interact immersively in a real user volume. Our virtual reality (VR) is created with Unity 3D [Unity, CA]. The testbed provides a virtual simulation of the city of San Francisco. Currently, the vehicle is generated as a scaled model of a drone to simulate vertical take-off and landing from a location in downtown area to the SFO International Airport. The pilot can maneuver the vehicle via a Logitech ATTACK 3 joystick that maps to its roll, pitch, and yaw movement and can change speed with an input button. The system is set up for a single pilot; however, potential passengers can enter the VR space with the view seen by the pilot. Vehicle heading, location, and speed are also simulated. The system can record simulation events and flight data for post-processing. The VR simulation provides a flexible testbed to conduct research in various areas of UAM including concepts of operation, human-automation teaming, vehicle and cockpit design, and passenger experience. We will be conducting a validation test of the VR system in a flight scenario between downtown San Francisco to SFO, followed by an integration of Air Traffic Management operations.

9.0225 Feasible Polynomial Trajectory Planning for Aerial Manipulation

Kye Morton (Queensland University of Technology), Aaron Mc Fadyen (Queensland University of Technology), Luis Gonzalez (Queensland University of Technology),
Presentation: Kye Morton, ,

A method is proposed to extend a feasible trajectory planning technique for thrust vectoring UAV, such that it can be applied to aerial manipulators. This method utilizes high-degree polynomials to calculate the system dynamics that would be necessary to perform a trajectory in a time-constrained manner. The use of this method provides a high quality trajectory that can be used in conjunction with an almost global exponential stable tracking controller. A two-step method is proposed to optimize flight time based on actuator constraints of the system, and allows for flight aggressiveness to be tuned based on a minimal set of parameters.

9.0226 Assessment of Tracking Small UAS Using IR Based Laser and Monocular-Vision Pose Estimation

Minzhen Du (Virginia Tech), Gustavo Gargioni (Virginia Tech), Daniel Doyle (Virginia Tech), Jonathan Black (Virginia Tech),

Presentation: Minzhen Du, Wednesday, March 11th, 09:25 PM, Amphitheatre

Global Navigation Satellite System (GNSS) is a widely available tracking solution from aircraft to smartphones. Small Unmanned Aerial Vehicles (sUAVs) are also heavily dependent on GNSS to fly autonomously from location to location. However, sUAVs have limited battery life and most sUAVs change batteries and pick up cargo manually by human operators. However, GNSS is insufficient when sUAVs are used in large quantities for patrol, delivery, and construction were picking up various payloads and changing batteries are frequently required. GNSS is sufficient for taking the sUAVs from point A to point B in open air space with communication to the satellites. If the fully autonomous operation were to only rely on GNSS navigation, the landing hubs would be limited to open spaces such as rooftops or parking lots. Commercial grade GNSS receivers also have limited update rates of 1-10Hz, limiting the capability of the landing sUAV. The purpose of this project is to investigate tracking methods available for supplementing the existing GNSS solution that will assist the sUAVs in landing at more flexible locations. Methods include: 1) ground-based IR LED array markings identified by a monocular camera onboard the sUAV, and 2) IR laser sweeping identified by IR photodiodes onboard the sUAV. Each of these methods is capable of localizing the sUAVs at rates of 15Hz to 120Hz without location limitations such as using GNSS. These methods can expand the landing capability of the sUAVs to confined spaces such as warehouses and building floors under construction, or mobile locations such as delivery trucks and patrol cars, even landing/docking for aerial vehicles on Mars. The scope of this paper includes implementation and assessment of SteamVR tracking and IR marker-based monocular-vision pose estimation on sUAV platforms to perform two types of maneuvers, a continuous circular flight path and a flight path based on stop-and-go waypoints. Findings suggested that Lighthouse can achieve high accuracy and tracking fidelity in an ideal environment, but subject to interference from large reflective surfaces. The IR marker-based pose estimation can achieve centimeter accuracy in ideal conditions but largely limited by its hardware specifications.

9.0227 Lévy Flight Foraging Hypothesis-based Autonomous Large-scale Memoryless Search under Sparse Rewards

Kostas Alexis (Univeristy of Nevada, Reno),

Presentation: Kostas Alexis, Wednesday, March 11th, 09:50 PM, Amphitheatre

Autonomous aerial robots are commonly tasked with the problem of area exploration, surveillance and search for certain targets or objects of interest to be detected and tracked. Traditionally, the problem formulation considered is that of complete coverage and thus - ideally - identification of all targets of interest. However, an important problem which is not often addressed is that of memoryless time-efficient search under sparse rewards that may be worth visited any number of times. An indicative application scenario relates to surveillance for moving and possibly camouflaged targets thus making map coverage an inherently memoryless process. In this paper we specifically address the largely understudied problem of optimizing the “time-of-arrival” or “time-of-detection” to robotically search for sparsely distributed rewards (detect targets of interest) within large-scale environments and subject to memoryless exploration. At the core of the proposed solution is the fact that a search-based Lévy walk consisting of a constant velocity search following a Lévy flight path is optimal for searching and identifying distributed target regions in the lack of map memory. A set of results accompany the

presentation of the method, demonstrate its properties and justify the purpose of its use towards large-scale area exploration autonomy using aerial robots.

9.0228 UAV Implementation of Distributed Robust Target Location in Unknown Environments

Hannah Mohr (Virginia Polytechnic and State University),

Presentation: Hannah Mohr, Wednesday, March 11th, 08:30 AM, Lake/Canyon

This paper presents the implementation of a target seeking application on a multi-agent unmanned aerial vehicle (UAV) testbed, in which the target to be located emits a signal that attenuates with increasing distance from its source. A heterogeneous swarm of multirotors collects local measurements of the signal emanating from the target, and each UAV shares its information with neighboring UAVs in a fully distributed manner to form an estimate of the signal's gradient, informing the direction of travel to move toward the target. The UAVs navigate around obstacles in an unknown environment, implementing a localized robust hybrid controller for obstacle avoidance when an obstacle is within the UAV's detection radius. The hybrid controller enables the UAVs to robustly avoid obstacles in the presence of potentially adversarial exogenous inputs through the use of overlapping control modes which preclude the topological obstructions that can arise in traditional obstacle avoidance schemes. The algorithms are implemented on the VT SpaceDrones platform, using mulitrotors equipped with Raspberry Pi microcontrollers. Each UAV performs its own target seeking and obstacle avoidance calculations in a distributed architecture, receiving position data from an OptiTrack motion capture system. The distributed implementation illustrates the adaptation of the control law to real world challenges, including unsynchronized clocks among different UAVs, limited computational power, and communication latency. Experimental and theoretical results are compared.

9.0230 Autonomous Search for Underground Mine Rescue Using Aerial Robots

Tung Dang (University of Nevada, Reno), Frank Mascarich (University of Nevada, Reno), Shehryar Khattak (University of Nevada, Reno), Dinh Huan Nguyen (University of Nevada, Reno), Hai Nguyen (University of Nevada, Reno), Satchel Hirsh (University of Nevada, Reno), Russell Reinhart (university of nevada reno), Christos Papachristos (University of Nevada, Reno), Kostas Alexis (Univeristy of Nevada, Reno),

Presentation: Tung Dang, Wednesday, March 11th, 08:55 AM, Lake/Canyon

In this paper we present a comprehensive solution for autonomous underground mine rescue using aerial robots. In particular, a new class of Micro Aerial Vehicles are equipped with the ability to localize and map in subterranean settings, explore unknown mine environments on their own, and perform detection and localization of objects of interest for the purposes of mine rescue (i.e., “human survivors” and associated objects such as “backpacks”, “smartphones” or “tools”). For the purposes of GPS-denied localization and mapping in the visually-degraded underground environments (e.g., a smoke-filled mine during an accident) the solution relies on the fusion of LiDAR data with thermal vision frames and inertial cues. Autonomous exploration is enabled through a graph-based search algorithm and an online volumetric representation of the environment. Object search is then enabled through a deep learning-based classifier, while the associated location is queried using the online reconstructed map. The complete software framework runs onboard the aerial robots utilizing the integrated embedded processing resources. The overall system is extensively evaluated in real-life deployments in underground mines.

9.0232 A Self-deployed Multi-Channel Wireless Communications System for Subterranean Robots

Frank Mascarich (University of Nevada, Reno), Dinh Huan Nguyen (University of Nevada, Reno), Tung Dang (University of Nevada, Reno), Shehryar Khattak (University of Nevada, Reno), Christos Papachristos (University of Nevada, Reno), Kostas Alexis (Univeristy of Nevada, Reno),

Presentation: Tung Dang, Wednesday, March 11th, 09:20 AM, Lake/Canyon

In this paper we present an experimental results-driven system design to enable more robust and self-deployed wireless communications for robotic systems autonomously operating in underground environments such as mines, caves, and tunnels. Subterranean environments pose severe challenges for wireless communications as wireless signal suffers extra power loss due to tunnel's curvatures; the existence of corners, junctions and large obstacles inside the mines; the changes in cross section of a passage and the tilt of sidewalls. This is especially the case when high-bandwidth and low-power wireless communications are considered as commonly found in autonomous robots. In response to these challenges, we present a multi-modal communication solution that a) relies on the integration of both dual 5.8GHz WiFi radios (high bandwidth channel), as well as 915MHz telemetry modules (low bandwidth channel), while at the same time b) utilizes both high-gain directional antennas outside of the underground environment and communication "breadcrumbs" within the subterranean setting. The communication breadcrumbs correspond to a highly integrated, lightweight and self-contained solution of dual radio WiFi and small patch 6dBi antennas, a 915MHz ultra low-power module with a 3dBi wire antenna, alongside battery for approximately 2 hours of operation. Finally, we present an integrated robotic solution – the "Aerial Scouts"- that are not only capable of autonomously exploring in the underground domain but also ferrying and dropping the aforementioned communication breadcrumbs on their own – thus autonomously extending their network as they go. For evaluation purposes we present experimental results from underground exploration missions where we relate the location of the robot, the self-deployed communications network and the measured received signal strength indicator (RSSI) over several points of the 3D reconstructed map of the environment.

9.0233 Multi-modal Visual-Thermal Saliency-based Object Detection in Visually-degraded Environments

Maria Tsiourva , Christos Papachristos (University of Nevada, Reno),

Presentation: Maria Tsiourva, Monday, March 9th, 10:35 AM, Lake/Canyon

In this work we present a new approach on the fusion of multi-modal data from visible-light and thermal camera sensors in order to efficiently detect objects in visually-degraded environments using aerial robots. Through a bottom-up approach inspired by the principles of visual saliency and how it models the attention mechanism of mammals, a novel algorithm that builds individual conspicuity maps across color channels and across visible-light and longwave infrared spectra is proposed. More specifically, two input images - a radiometric thermal image and a visible-light RGB image - are fed respectively into an intensity channel, and a set of intensity and color-opponent channels. For every channel, image pyramids are computed to allow searching in different scales. The eventual feature maps are subsequently combined into one saliency map. The approach is computationally efficient and tailored to the limited processing capacities found onboard Micro Aerial Vehicles, while at the same time providing fast real-time object detections as required for the purposes of autonomous navigation and object search. Integrating thermal vision together with visible-light data, the method builds on top of a rich representation that allows resilient operation even in conditions of visual degradation and specifically in cases of low-light or obscurant-filled (e.g., dust, fog) settings which can be penetrated using thermal vision. The presented algorithm and overall

system-level solution is built to facilitate efficient, fast and reliable object detection during autonomous aerial robotic exploration of subterranean environments, contributing novel capacity beyond the context of aerial robotic navigation. Our approach is extensively evaluated in the framework of real-life field deployments in underground metal mines in Northern Nevada.

9.0236 Smart & Integrated Management System - Smart Cities, Epidemiological Control Tool Using Drones

Rodrigo Rangel (BRVANT / BRV UAV & Flight Systems),
Presentation: Rodrigo Rangel, Monday, March 9th, 11:00 AM, Lake/Canyon

This paper describes the development of a real application using Drones over urban regions to help the authorities at epidemiological control through a disruptive solutions based on a customizable Smart & Integrated Management System (SIGI), devices and software based on the Enterprise Resource Planning (ERP) concept, initially applied to public sector management. Compound by management software, Drones and specific IoT devices, both referred to as sensors, the sensors collect the data of the interest areas in real time, creating a specified database. Based on the data collected from the interest areas, SIGI software has the ability to show real-time situational analysis of these areas and allows that the administrator can optimize resources (material and human) improving the efficiency of resource allocation in these areas. In addition to the development of the management software, the development of sensors to collect the information in the field and update these information to the database of the management software, are considered. The sensors will be recognized as IoT devices for the collection of meteorological data, images and command / control Drones. Considering the technological challenges proposed, the use of IoT and Drone sensors to monitor and to control the epidemiological risk areas, (this was a request of our local R&D Agency - Brazil), initially the system will be customized, using an Artificial Intelligence tool, to collect data and identify the outbreaks of the dengue mosquito, zika and Chikungunya, nominee by risk areas. After the definition of the potential risk areas, in a complementary way, a totally customized Drone will be used to map these areas of interest, generating aerial photographs, identifying and geotagging the potential “targets”, which will allow the agents to identify potential mosquito breeding sites. After the identification of breeding areas, the next step will be the effective combat of the vectors, using the Drones to fly over the areas of interest, where biological defenses will be “dropped “ over the targets to combat mosquitoes. Due some Drone flight restrictions over the cities, the whole process will be monitored by a situation room, that will be able to control de Drone remotely, access the air space controller, reads the sensors installed in the city (field), that will measure, for example, rainfall through weather stations installed in risk areas and subsequently processed by Intelligent System Integrated Management (SIGI), which will result to the information public official reflecting the situational analysis of the areas, which will enable a better management of available resources. This system can be expanded to new areas and functionalities, according to the operational needs of the sector, it will be fully integrated to map the areas of interest of the city and provide a more accurate situational analysis to the public agent, helping him preventively in the decision making. Since the first employment of this system in 2015, for the Police application, it has proved to be efficient in real missions, for now we will demonstrate at full paper the use for epidemiological control, with the results of real operation.

9.0238 Mission-Driven Simulation of a Multi-rotor Unmanned Aerial System for Energy Consumption Analysis

Calin Badea (Delft University of Technology), Nirmit Prabhakar (Argonne national Lab), Dominik Karbowski ,
Presentation: Calin Badea, ,

This paper presents a high-frequency dynamic model of a multi-rotor unmanned aerial system (UAS) that simulates mission-specific energy consumption and power-plant performance. The full aircraft model is discretized in blocks that model the subsystems, including the rotational dynamics, the propellers, motors and battery. Motors draw current from the battery to generate torque, resulting in rotation of propellers, which in turn generate thrust. The sum of each propeller thrust defines the attitude and motion of the aircraft. Energy losses are calculated for each subsystem, in order to accurately predict energy consumption and battery state-of-charge evolution. The dynamic model allows the inclusion of a cubic payload, which affects the drag and inertia of the vehicle. A mission controller accepts waypoints in three dimensional space as an input and low-level controllers control the speed of each propeller in order to produce the desired thrust. The model outputs the energy required to fulfill the given mission, as well as the states of each of the subsystems along the mission. Factors such as air density, temperature and stochastic atmospheric turbulence are modeled throughout the mission to include the effect of the environmental conditions. The UAS model is set up to simulate an actual hexacopter, running hover and cruise missions with various payloads carried in a box underneath the main body of the aircraft. The simulation results are then compared with the energy consumption values from real-world experiments. In the hover test, simulation results are within 4% of the experimental values. In the cruise test, the predicted energy consumption was relatively close to the experimental value, with a maximum discrepancy of 10% for the heaviest payload. It is therefore shown that the proposed mathematical model is capable of predicting mission-specific energy consumption within a low relative error range.

9.0239 A Dispersed Autonomy Architecture for Information-Gathering Drone Swarms

Eric Frew (University of Colorado, Boulder), Katherine Glasheen (University of Colorado, Boulder), Camron Hirst (University of Colorado, Boulder), John Bird (University of Colorado Boulder), Brian Argrow (University of Colorado Boulder),
Presentation: Eric Frew, Thursday, March 12th, 08:55 AM, Dunraven

Teams of cooperating unmanned aircraft can perform spatial-temporal sampling of complex phenomena at scales not achievable by single platform sensor systems. In highly-dynamic environments, like severe storms, the sensing platforms must adapt in response to the evolving phenomena. Because onboard computation is limited, a dispersed computing architecture en- ables inclusion of high-performance models and computation- ally expensive algorithms in the decision-making loop. This paper presents the design and implementation of components of a dispersed autonomy architecture for information-gathering drones. Components of this architecture are described and demonstrated for several field campaigns, including the sampling of severe supercell thunderstorms by loosely coordinated UAS teams in order to study tornado formation.

9.0240 Effects of Propwash on Horizontal Tail Aerodynamics of Pusher UASs

Hady Benyamen (University of Kansas), Aaron McKinnis (University of Kansas), Shawn Keshmiri (University of Kansas),
Presentation: Aaron McKinnis, Thursday, March 12th, 09:20 AM, Dunraven

In this paper, the propwash phenomenon for pusher configuration unmanned aerial systems (UASs) is studied. The SkyHunter UAS has the propeller placed aft of the fu-

selage and in front of the horizontal tail with no offset from the zero lift plane. Thus, the propeller slipstream directly flows over the horizontal tail affecting its aerodynamics. To validate the physics based model developed for propwash impacts and to quantify the effects of propwash, the SkyHunter UAS was equipped with an extra pitot tube. The first pitot tube was placed at the nose of the aircraft where the air is undisturbed and it was measuring the aircraft's velocity. The second pitot tube was placed at different locations on the horizontal tail and three flight tests were conducted. Flight test data showed that the current configuration of the SkyHunter: (A) has large variations in the horizontal tail dynamic pressure ratio along the span of the horizontal tail. (B) had the dynamic pressure ratio higher than 1.7 in two of the three investigated locations along the span of the horizontal tail . This suggests that the theoretical estimate of the dynamic pressure ratio (which is 0.93) may be an under estimation. (C) The dynamic pressure ratio varied with time during flight. A change in the horizontal tail dynamic pressure ratio directly leads to a shift in the location of the aerodynamic center of an aircraft as well as changes in the stability and control derivatives of an aircraft. The implication of these changes in small UASs can be significant since they affect the aircraft longitudinal stability, trim elevator, and flight characteristics. In order to mitigate such changes during flight, a redesign was made to the original empennage design where is an offset was added between the zero lift plane and the aerodynamic center of the horizontal tail. This redesign intends to move the horizontal tail above (and away from) the propeller slipstream. Manufacturing of the redesigned horizontal tail was completed recently and it was flight tested. Flight test data from the new design show that the new design successfully mitigates the effects of the propwash.

9.0241 A Review of Current Approaches for UAV Autonomous Mission Planning for Mars Biosignatures Detection

Julian Galvez Serna , Luis Gonzalez (Queensland University of Technology), Fernando Vanegas Alvarez (Queensland University of Technology), David Flannery (Jet Propulsion Laboratory),

Presentation: Fernando Vanegas Alvarez, Thursday, March 12th, 09:45 AM, Dunraven

Autonomous mission planning for unmanned aerial vehicles (UAVs) aims to leverage the capabilities of UAVs equipped with on-board sensors to accomplish a wide range of applications, including planetary exploration where greater science yields can be achieved at lower costs over shorter time periods. A significant body of research has already been performed with the aim of improving the autonomy of UAV missions, particularly in the areas of navigation and target identification. In this work, we review current approaches to drone navigation and exploration for planetary missions, with a focus on Mars and the main autonomy levels/techniques employed to achieve these levels. Recognising the importance of astrobiology in Mars exploration, we highlight progress in the area of autonomous biosignature detection capabilities trialed on Earth, and discuss the objectives and challenges in relation to future missions to Mars. Finally, we indicate currently available software tools and future work to improve autonomous mission planning capabilities.

9.0242 Dynamic Modeling and Flight Test Validation of an In-House Design UAS Built for Polar Research

Aaron McKinnis (University of Kansas), James LaGue (University of Kansas), Shawn Keshmiri (University of Kansas),

Presentation: Aaron McKinnis, Thursday, March 12th, 10:10 AM, Dunraven

This presentation will detail the design and build process of the Astrid Unmanned Aerial System as well as the guiding principles behind the design decisions. A brief description of the developed dynamic model will be expanded upon to showcase the unique

handling qualities of this UAS. Finally, the flight test results and associated system identification will be shown.

9.0243 Identify, Surround, and Overwhelm Enemy Drones via Cognitive Swarm of Heterogenous UAS

Jeffrey Xu (University of Kansas), Thomas Le Pichon (University of Kansas), Dustin Hauptman , Shawn Keshmiri (University of Kansas), Isaac Spiegel (University of Kansas),

Presentation: Jeffrey Xu, Thursday, March 12th, 10:35 AM, Dunraven

Low-flying unmanned aerial systems (UAS) are regarded as extremely serious threats to critical military sites and large industrial facilities. This work presents bio-inspired and cognitive navigation methods for collaborative swarm of heterogeneous UAS to counteract adversaries posing serious threats using low-flying drone strikes. Standard UAS navigation algorithms are limited by their inability to adapt. Classical path planning and navigation methods are developed assuming predefined missions and fixed objectives; additionally, relying heavily on a priori information, they lack robustness in dynamically changing environments. With such constraints, an adaptive, distributed, and collaborative swarm is unattainable. Increasingly complex and sophisticated UAS require influence from some of the most well-developed and oldest cognitive and autonomous systems, boasting impressive adaptation, robustness, and resiliency: “Superorganisms”, formed by collaborative groups of individuals, such as flocks of birds or schools of fish. Eusocial animals and/or migrating birds in flight formations very efficiently optimize time, energy, and distribute tasks. We have developed metaheuristic optimization techniques for a swarm of UAS where tasks are assigned and distributed between heterogeneous systems of different sizes and resources. Function based optimizations satisfy competing objectives using available assets. UAS paths are solely optimized around defined functional goals (i.e. tracking, identification, surrounding, etc.). Path planning algorithms determine optimal point(s) as direct functions of mission goals and produce navigation commands based on all agents’ positions, effort required (energy) to accomplish a task, and likelihood of mission failure. The metaheuristic foundation allows for rapid and reliable response in unstructured environments with dynamic goals. For years, metaheuristic optimizations have been used in Computer Science applications however constraining agents using aircraft 6DoF dynamics add a layer of authenticity to the metaheuristic methods, necessary in Aerospace applications. The metaheuristic optimization uses iterative generation processes to efficiently explore the search space with a goal to converge to near-optimal solutions. In the heterogeneous swarm, learning strategies are used for cognitive exploring and exploiting search based on the UAS functions and spatial positions. Scenarios are simulated to assess capabilities developed navigation algorithms. In the simulations, three types of UAS are used: (1) G1X class UAS with high payload capacity and endurance, equipped with radars for tracking purpose (2) SkyHunter UAS, with higher maneuverability characteristics, equipped with a camera for identification (3) A 33% scaled Yak-54 UAS acting as an intruder UAS. Simulation results will be presented in the full version of paper.

9.0245 Leveraging ASTM Standard F3269-17 for Providing Safe Operations of a Highly Autonomous Aircraft

Mark Skoog (NASA - Armstrong Flight Research Center), Loyd Hook (University of Tulsa),

Presentation: Mark Skoog, Thursday, March 12th, 11:00 AM, Dunraven

This paper expands upon the ASTM industry standard F3269-17 to outline a run-time assurance (RTA) network architecture for use in ensuring safe flight operations of a highly autonomous aircraft. An RTA network architecture is proposed and critical features discussed to implement functions where automation is primarily responsible for the safety of the aircraft instead of a pilot. This shift in responsibility, made possible

by the proposed architecture, is key to highly resilient automation and is a core enabler for future “pilotless” transportation concepts. The findings in this paper stem from the researcher’s experiences with ASTM in the generation of the standard and some seven years of RTA system development on various flight programs leveraging the RTA concepts outlined in the ASTM standard.

9.0246 Modeling and Experimental Validation of a Fractal Tetrahedron UAS Assembly

Kevin Garanger (Georgia Institute of Technology), Jeremy Epps , Eric Feron (Georgia Institute of Technology),

Presentation: Kevin Garanger, Thursday, March 12th, 11:25 AM, Dunraven

This paper presents the foundation of a modular robotic system comprised of several novel modules in the shape of a tetrahedron. Four single-propeller submodules are assembled to create the Tetracopter, a tetrahedron-shaped quad-rotorcraft used as the elementary module of a modular flying system. This modular flying system is built by assembling the different elementary modules in a fractal shape. The fractal tetrahedron structure of the modular flying assembly grants the vehicle more rigidity than a conventional two-dimensional modular robotic flight system while maintaining the relative efficiency of a two-dimensional modular robotic flight system. A prototype of the Tetracopter has been modeled, fabricated, and successfully flight-tested. The results of this research set the foundation for the development of Tetrahedron rotorcraft that can maintain controllable flight and assemble in flight to create a Fractal Tetrahedron Assembly.

9.03 Aircraft Systems & Avionics

Session Organizer: John Ennis (USMC), Andrew Anderson (Navair), Andrew Lynch (Naval Air Systems Command),

9.0301 Aerodynamic Effects of an Electromagnetic Wing and It's Application for LEO Transportation.

Sayantan Saha (SRM INSTITUTE OF SCIENCE AND TECHNOLOG), Mohammed Abrar Nizami (GATE PATHSHALA EDUCATIONAL SERVICES LLP.), Pratik Sarkar (SRM Institute of science and technology), Samanyu Raina (SRM IST), Vinayak Malhotra (SRM University), HENRYRAGOBEYAM NELSON (Jeppiar Engineering College),

Presentation: Sayantan Saha, Sunday, March 8th, 04:30 PM, Dunraven

Objects in LEO encounter atmospheric drag from gases in thermosphere as well as exosphere, depending on orbit height. A substantial amount of energy is lost in overcoming this drag decreasing the overall effectiveness of the vehicle. Launch vehicles on the other hand experience huge atmospheric drag after take-off and during flight in lower altitude. Various vehicle configaration and shapes are employed to overcome these conditions. The concept of an Electromagnetic wing involve wings that can auto adjust themself with respect to the flight regime and flow conditions, enabling them to operate at optimum efficiency. The idea is to conceptualize Electromagnetic wing that could be operated at low earth orbits as well as low altitudes at any flight speed ranging from low to high subsonic and supersonic speeds. The present work attempts to develop such Electromagnetic wing that are operational irrespective of the regimes. To achieve this it is necessary to understand and establish the relation between various energies associated with a wing operating at such flight conditions which are aerodynamic, electromagnetic, vibration and rotational. The understanding of these energies as a whole will lead to the idea of developing an automated wing. Experimental tests include wind tunnel experiments over a Wing while running high voltage electricity on the wing’s surface, vibrating the body, rotating and twisting the body at different chord locations, also performing coupled tests of the above experiments. It can be anticipated that the above test will have both positive and negative results but collectively these results will lead towards the method of obtaining an automated wing. The work can be extended to supersonic speeds as well. The work will also study the interaction of electro-thermal forces with aerodynamic forces. The observed data will then be compared with the data from the tests without running electricity or rotating vibrating and twisting the wing. The novelty of the work is it's simplicity and that it's results will be used for designing a structure that adjusts itself according to the flow conditions, flight conditions at Leo and below thus eliminating the need for different structures for various flight regimes and flow conditions. The idea comprehensively can be applied on space shuttles or landing capsules for inter-planetary missions. Additionally, it can be used for designing flight structures of crafts that will operate for LEO space transportation as it provides design modularity and hands off hands in approach with the present designs.

9.0302 Design of Morphing Aircraft for Aeroelastic Performance

Nikhil Nigam (Intelligent Automation, Inc.),
Presentation: Nikhil Nigam, Sunday, March 8th, 04:55 PM, Dunraven

As advanced aircraft concepts are envisioned, lighter aircraft structure construction is being explored for improvement of fuel efficiency. This can have severe repercussions on the aeroelastic performance, which need to be alleviated. We propose to use morphing mechanisms to address aeroelastic concerns. This involves careful development of the morphing mechanisms and skins, as well as, a suitable aeroservoelastic design architecture for such concepts. This presentation focuses on the latter and discusses our ongoing work on developing the design optimization architecture that is envisioned to couple aerodynamics, structures and controls within a design optimization framework.

9.0307 Electromagnetic Effects for Electrical Power Generation and Consumption Pair Systems

James Lee (Boeing Company),
Presentation: James Lee, ,

Electrical power generation and consumption pair systems on aircraft play critical roles for fundamental aviation operation. The importance of electrical power generation and consumption pair has been increasing due to extensive use of fly-by-wire in modern aircraft. In order to maintain the safe and successful flight operations, we must ensure the electrical power generation and consumption pair meets the electromagnetic interference requirements set by regulatory agencies and industrial standards. We would like to demonstrate this electromagnetic effect design and analysis processes with modern aviation power system examples. For electromagnetic effects, we consider the radio frequency emissions and lightning effects which originate in power generation subsystems. Those electromagnetic effects affect the downstream electrical power consumption subsystems. We want to analyze the electromagnetic interference at the power generation subsystem and at the power consumption subsystem. From design and certification point of view, we need to assess the typical maximum strengths of the transient level of the emission and lightning, and analyze the downstream effects at the location of the affected power consumption subsystems. This process enables design, qualification and certification of the electrical power generation and consumption pair. We describe the power generation and consumption pair fundamentals. The details of evaluating the broadband emission noise are presented. We discuss the optimum solutions that help resolve these RF and lightning issues. We conclude with a summary and present future work suggestions.

9.0308 Impact of HHO Gas on Engine Performance and Emissions

Mahmoud Sayed (Canadian International College), Mohammed Gad (Fayoum university), Tarek Mahmoud (MILITARY TECHNICAL COLLEGE),
Presentation: Tarek Mahmoud, Sunday, March 8th, 05:20 PM, Dunraven

Green transportation will play an important role in future such as: ground and air applications. Hydrogen has a wide variety of applications in spite of decreasing of natural resources. Depletion of fossil petroleum resources and continuous increase of fuel consumption led to search about fuel saving solutions. Hydroxy gas (HHO) was produced by the electrolysis process. HHO gas was used as an additive fuel. Effect of HHO on engine performance and exhaust was investigated. A constant flow rate of 0.42 liter per minute of HHO gas was introduced through the intake port of the engine. Tests were investigated at different engine loads. HHO gas was enriched with air in diesel engine, the thermal efficiency was increased by 7% and specific fuel consumption was reduced by 15% at full load compared to diesel oil. HC emission was reduced at an average of 25% with hydroxy gas. CO emission was reduced at an average of 18% in comparison to pure diesel. NOx was increased with hydroxyl gas addition at full load condition by about 8% compared to pure diesel. HHO gas was recommended as a good additive to diesel oil in performance improvement and emissions reductions.

9.0313 Computational Fluid Dynamics Study for Drag Reduction of an Airborne Surveillance Gimbal

Amani Bin Amro , Kursat Kara (Oklahoma State University), Dimitrios Kyritsis Kyritsis (Khalifa University),
Presentation: Amani Bin Amro, Sunday, March 8th, 09:00 PM, Dunraven

This article describes the drag minimization of an existing gimbal assembly mounted to an airplane, scanning a sight for surveillance purposes. This has been numerically investigated using Computational Fluid Dynamics method supported by Fluent 19.2 software, solving Reynolds-Averaged Navier Stokes. For the existing surveillance system, the given flight operational conditions were analyzed based on International Standard Atmosphere where the flow obtained is incompressible turbulent flow. To start the simulations, study on simple 3D sphere simulation was conducted at two Reynolds numbers of 1×106 and 1.5644×106 using two different turbulence models, the SST k-ω and the realizable k-ε. Drag, lift and separation angle data were computed and compared. Based on the flow simulation setup of the sphere, the existing gimbal was simulated for Reynolds number of 1.5644×106 comparing both turbulence models. Large zone of vorticity, low-pressure wake, separation and vortex shedding were clearly observed introducing huge drag. Two solutions were suggested which are changing the gimbal orientation and optimizing the gimbal geometry. The simulation results described in this study have illustrated the capability of both turbulence models. The results obtained agreed really well when compared computationally and experimentally. Improvements of almost 60% were obtained by the two suggested solutions where the optimized gimbal shows higher improvement percentage.

9.0314 Study on Thermal Shock Simulation of Superalloy Using Fully Coupling Method

Peng Guan (Northwestern Polytechnical University),
Presentation: Peng Guan, Sunday, March 8th, 09:25 PM, Dunraven

Most of the nozzle guide vanes (NGV) are failed due to thermal shock during non-cruising operation. A numerical method was developed to simulate the thermal shock processes by fully coupling method (FCM). In order to study advantages of FCM, the heat conduction equation of one-dimensional infinite plate affected by strong heat transfer environment was deduced and solved. The results were compared with FCM and decoupling method (DCM) in same conditions. The influences of ambient temperature

and heat transfer coefficient (HTC) on transient temperature and thermal stresses at different thickness were analyzed. It's shown that with the increase of ambient temperature, the temperature errors between numerical solution and analytic solution solved by FCM are reduced by 5%-50% compared with DCM. With the increase of HTC, the thermal stress calculation accuracy of FCM is improved. Under the condition of higher ambient temperature, the application of FCM is more necessary.

9.04 Air Vehicle Flight Controls

Session Organizer: Tom Mc Ateer (NAVAIR), Olivier Toupet (JPL), Christopher Elliott (Lockheed Martin Aeronautics Company and University of Texas at Arlington),

9.0403 Output Stabilization of Military UAV in the Unobservable Case

Alain Ajami (LSIS (Laboratoire des Sciences de l'Information et des systèmes) - UMR CNRS 6168),
Presentation: Jean Paul Gauthier, Friday, March 13th, 08:30 AM, Lamar/Gibbon

I shall present a solution to a problem of dynamic output stabilization of a non observable nonlinear system. This system is just an academic kinematic model of a HALE drone. Although the system looks very simple, the theoretical developments are not trivial at all. In fact, this study lies in the context of a very general project, "dynamic output stabilization of systems with bad observability properties". In particular, a challenging (open) problem is the question of the coupling of a stabilzing feedback control law with a Kalman filter, or an extended kalman filter. Here, the strategy we apply is quite different, but the problems that appear are very similar.

9.0405 Predictive Human-Machine Interface for Teleoperation of Air and Space Vehicles over Time Delay

Markus Wilde (Florida Institute of Technology), May Chan (Florida Institute of Technology), Brian Kish (Florida Institute of Technology),
Presentation: Markus Wilde, Wednesday, March 11th, 04:30 PM, Amphitheatre

Current plans for the exploration of Moon and Mars envision the use of telerobotic systems controlled from orbiting laboratories. The advantage of telerobotics is that it combines the resilience, endurance and precision of robots with the inherent flexibility, anticipation and decision making capabilities of humans. The primary disadvantage of telerobotics is the communication time delay in the human-robot control loop. The delay can lead to a loss of situation awareness, an increase in operator work load, and an overall decrease in effectiveness and efficiency of the human-robot system. Most of the effects of the delay can be mitigated by the use of predictive displays, presenting the operator with a simulated system state. This paper presents current work on such a predictive display designed to support an operator in remote flight and landing of space robots and unmanned aerial vehicles. The Adaptable Human-Machine Interface was developed for hardware-in-the-loop laboratory experiments with a Parrot A.R. Drone 2.0 quadcopter as test case. Based on live video from two on-board cameras, attitude and velocity telemetry, and control inceptor deflection, the interface calculates a predicted flight path and attitude and presents it in a “tunnel in the sky” display. The graphical display itself was developed in the Unity3D game engine. The paper describes the implementation of the interface between Unity3D and the A.R. Drone, the dynamic model of the quadcopter, and the prediction algorithm. The paper also discusses the results of flight tests involving a number of test subjects and projects the path forward in the development of this technology.

9.0406 Development of an Actuator for an Airdropped Platform Landing System

Victor Caldeira Barbosa (Universidade de Brasília), Renato Borges (Universidade de Brasilia), Manuel Barcelos Júnior , Simone Battistini (Sheffield Hallam University), Chantal Cappelletti (Universidade de

Brasília),
Presentation: Victor Caldeira Barbosa, ,

This work presents an actuation system that aims at improving the maneuvering capability during the landing phase of the LAICAnSat platform. The LAICAnSat is a lowcost, modular platform for high altitude applications, such as remote sensing, telecommunications, research, development and innovation within the aerospace field. The landing system uses a ram-air parachute that is actuated by servo motors located on a pseudo 2U CubeSat platform. This platform differs from the actual CubeSat standard due to the actuation mechanisms on the outside of a 2U standard module. A brake lines actuator is responsible for the directional, speed and glide ratio control. The paper provides details of the design, realization and testing of the actuation system, which represent a first attempt in the development of an autonomous landing system for the LAICAnSat.

9.0407 Decoupling Numeric and Analytic Linear Analysis for Modular Flight Control Law Synthesis

Christopher Elliott (Lockheed Martin Aeronautics Company and University of Texas at Arlington),
Presentation: Christopher Elliott, Friday, March 13th, 08:55 AM, Lamar/Gibbon

Traditional flight control synthesis techniques rely on full-model numerical perturbation to compute a linear model via point and slope differentiation, valid in a small neighborhood around an operating condition of interest. While this approach is valid, insight into the sensitivities of a linear model may be nebulous, and computational efficiency can be gained, as well as reuse of an analytical linear model, by decomposing common analytic terms and platform specific numerical models. In this work, a general set of nonlinear equations of motion are extended for a VTOL (Vertical Take Off and Landing) vehicle with a non-traditional suite of effectors and a heavy rotating duct. The nonlinear equations, presented in both matrix and scalar form, are then decomposed and linearized to promote reuse with modularity by decoupling platform specific data (aerodynamics and control power) with common six degree of freedom inertia and mass properties effects. A sub-optimal infinite horizon state feedback control law, referred to as a servomechanism, is synthesized and simulation results are presented. Finally, the paper concludes with a summary and path forward for future work.

9.0410 Dynamic Waypoint Navigation and Control of Light Weight Powered Paraglider

Prashant Kumar (Indian Institute of Technology, Kanpur), Sarvesh Sonkar (iit kanpur), Ajoy Ghosh , Deepu Philip (Indian Institute of Technology, Kanpur),
Presentation: Prashant Kumar, ,

A Powered Paraglider, also known as Paramotor, has a ram-air inflated canopy in the shape of an aerofoil from which a payload, commonly called as Gondola, housing both propulsion system and control mechanism is suspended. It can lift heavy loads, is quick to setup for rapid launch, and is compact and light-weight, thereby making it ideal for military operations like tactical surveillance and cargo deployment. Paramotors are suitable for scenarios where stable and low speed flying capabilities are necessary. This paper presents a software architecture for guidance and control of light weight small scale Paramotors. For heading and altitude tracking, the system uses feedback compensated control laws. First, linear models are derived that describe both the Paramotor's longitudinal and lateral dynamics. Then, a six degree-of-freedom model is used to describe dynamics, weight, aerodynamic forces on payload and parafoil, aerodynamic moments, effect of apparent forces and moments, moments generated on the centre of mass by the forces exerted at the payload and parafoil. Then system identification based on simplified linear lateral and longitudinal models is used. These simplified linear models are used for designing control laws using classical frequency domain techniques. MATLAB/Simulink was used to simulate the performance of the proposed

Paramotor controllers. It was found that the described approach is robust enough for designing control strategies to maintain stability in event of disturbances.

9.0412 A New Recursive Framework for Trajectory Generation of UAVs

Nunzio Letizia (University of Klagenfurt), Babak Salamat (Alpen-Adria-Universität), Andrea Tonello (University of Klagenfurt),
Presentation: Nunzio Letizia, ,

In this presentation we propose the Recursive Smooth Trajectory generation algorithm (RST) that allows for finding a smooth polynomial path, and thus a close form trajectory satisfying any arbitrary dynamic limitations translated into kinematic constraints (e.g. position, velocity, acceleration, etc). Each kinematic constraint is recursively fulfilled, leading to a fast online implementation for the E-FMS. Unmanned aerial vehicles (UAVs) have recently gained increasing attention. Self-positioning and integrated navigation are main aspects during a flight mission and rely on predefined trajectories. Current guidance and control systems provide real-time control laws to track desired trajectories given by the Embedded Flight Management System (E-FMS). Since some UAVs are highly non-linear systems with under-actuation properties from the control point of view, discontinuities in control inputs (coming from trajectories generated by E-FMS) can produce undesired vibrations causing aging and damages in the structure. The RST algorithm tackles this problem. Its effectiveness and suitability over a minimum-snap piecewise polynomial approach for highly nonlinear UAV flight is discussed.

9.0413 Robust Energy-Based Control of a Swash Mass Helicopter Subject to Matched Disturbances

Babak Salamat (Alpen-Adria-Universität), Andrea Tonello (University of Klagenfurt),
Presentation: Babak Salamat, ,

We present a helicopter structure that comprises a double blade coaxial shaft rotor and swash masses to control the orientation and therefore maneuvering the vehicle. It is referred to as a swash mass helicopter (SMH). The SMH is subject to disturbances so that the problem addressed in this paper is the robust control under the presence of matched and unknown disturbances. We first present the dynamical system of the SMH. Then, under the presence of highly-coupled inputs, an interconnection and damping assignment passivity-based Control (IDA-PBC) approach is derived. The problem of increasing robustness in the presence of disturbances is addressed. Finally, several numerical results are reported to show the performance of the proposed control design.

9.0414 Error Dynamics Based Finite-time Sliding Mode Control of Missile Latex with Autopilot Dynamics

Abhinav Kumar (Indian Institute of Technology Kanpur), Salahudden Qazi (Indian Institute of Technology Kanpur), Dipak Giri ,
Presentation: Abhinav Kumar, Thursday, March 12th, 09:25 PM, Lamar/Gibbon

Tracking error in missile guidance laws can be defined by the difference between the heading angle and Line of sight or Zero effort miss or even LOS rate depending on the constraints and the requirements of the mission. In this paper, efforts have been made to propose control based on variable error dynamics. The control is obtained with the sliding mode approach and is verified for stability by the Lyapunov theory. Also, in practical applications, the autopilot lag of missile influences the guidance laws derived unfavorably. Hence, to deal with the problem, autopilot dynamics has been considered and augmented in the guidance law designed. Since the inclusion of autopilot dynamics involves a first order derivative of LOS angular rate, a low pass filter is implemented to solve the problem. The error dynamics has been derived non-ideally from Schwartz's inequality and a first order autopilot dynamics has been considered for the auto-pilot lag which has also been validated by the sliding manifold with the help of Lyapunov Stability criterion. The key point in the whole process is that time-varying gain has been considered for the error dynamics instead of choosing it as a constant and is decided by the specific missile problem. The simulation has been done with the objective of nullifying the Zero effort miss for the case of homing air target and the results of the proposed control have been compared with the well-established proportional navigation guidance law.

9.0415 Robust Controller Design for Bank to Turn Asymmetric High-Speed Projectile

Salahudden Qazi (Indian Institute of Technology Kanpur), Dipak Giri , Abhinav Kumar (Indian Institute of Technology Kanpur), Vijay Shankar Dwivedi (IIT Kanpur), Ajoy Ghosh ,
Presentation: Salahudden Qazi, ,

This paper presents a design of a robust linear-quadratic regulator (LQR) and dynamic inversion (DI) controller for a generic high-speed projectile operating in the bank to turn (BTT) mode. The LQR controller has been designed using the nonlinear optimization technique and RK4 method with a step size of 0.01s. In the optimization algorithm, it guesses values of diagonal Q and R matrices (based on random numbers of appropriate magnitude). A detailed dynamical model of the projectile has been derived. The standard RK4 method has been adopted for numerical simulation. From the available state parameters, the sideslip angle parameter is selected as a commanded variable because this variable is the interest of the present study. The controllers are also tested with variation in aerodynamic parameters. The test is performed at different initial side slip angles varying from 1° to 23°.

9.0418 Automated Flight Planning Method to Facilitate the Route Planning Process in Predicted Conditions

Grzegorz Drupka (Rzeszow University of Technology),
Presentation: Grzegorz Drupka, Friday, March 13th, 09:20 AM, Lamar/Gibbon

The primary purpose of this study was to elaborate a method that facilitates aircraft operation at the flight planning stage by automating the flight planning process. This paper describes the impact that external factors, such as airspace structure or weather conditions, have on flight efficiency. The proposed method was based on the discrete airspace model and a specifically designed manner of data processing in respect to the conditions data set in this model. The entire process makes it possible to interpret store data to seek and suggest the path according to user preferences. By specifying the departure and arrival aerodromes, the user obtains data about distance, flight duration, fuel consumption, route charges, overall cost of the en-route phase, and the impact of turbulences. The solution was developed using the C++ programming language. The Floyd–Warshall algorithm was applied to find the shortest ("lowest cost") path. However, before the path seeking algorithm was employed, several methods had been used to evaluate the data inserted into the model with regard to aircraft performance and the predicted position. The predicted position within the location on the model was established using graph theory and applying a Voronoi diagram. The obtained result demonstrated that the elaborated method can be used to obtain information about benefits from individual path variants. After entering the aerodrome of departure and aerodrome of arrival requests, the user obtains a flight path according to the criteria provided in the request. As proven in the discrete airspace model, even more advantageous paths can be found than the one based on the shortest route. The elaborated method can bring benefits in a variety of transportation problems. It involves a useful solution that allows the application of the Floyd-Warshall algorithm in seeking a "low-costs" route based on more than one criterion. It may be useful in planning autonomous missions for remotely piloted aircraft systems. In aviation, the adoption of this method could even contribute

to reducing the discrepancy between the planned flights submitted to the processing system and the actual network situation. That, as a result may decrease time-related deviations, and reduce the workload of Air Traffic Control Officers.

9.0419 Analysis of State Estimation Drift on a MAV Using PX4 Autopilot and MEMS IMU during Dead-reckoning

Jong Tai Jang (Korea Aerospace Research Institute), Angel Santamaria Navarro , Brett Lopez , Ali Agha ,
Presentation: Jong Tai Jang, Thursday, March 12th, 09:50 PM, Lamar/Gibbon

In perceptually degraded situations, state estimation drift is a major source of failure for autonomous operations of Micro Aerial Vehicles (MAV). This paper serves as a guide for understanding and characterizing estimation drift during dead-reckoning navigation with systems using onboard MEMS inertial measurement units. The analysis is conducted with the commercial-off-the-shelf Pixhawk flight controller, running the commonly-used PX4 autopilot. The performance of the Extended Kalman Filter (EKF2) and Local Position Estimator (LPE) were characterized through a two-step experiment. First, the onboard IMU is manually excited while the estimators receive state updates from a motion capture systems. In the second step, a dead-reckoning scenario is created by no longer providing a state update to each estimator. Heat control was also added to analyze temperature effects on the IMU biases and hence estimation drift. Our analysis shows how the estimation drift depends on the quality of the IMU, excitation of the IMU, the estimation algorithm, and temperature control.

TRACK 10: SOFTWARE AND COMPUTING

Track Organizers: Kristin Wortman (Johns Hopkins University Applied Physics Laboratory), Sanda Mandutianu (Jet Propulsion Laboratory),

10.01 Computational Modeling

Session Organizer: Virgil Adumitroaie (Jet Propulsion Laboratory), Darrell Terry (The Mitre Corporation),

10.0101 Trajectory Reduced-Order Modeling Using Indirect Methods

Michael Sparapany (Purdue University),
Presentation: Michael Sparapany, Tuesday, March 10th, 08:30 AM, Dunraven

Aerospace vehicles, especially hypersonic vehicles, operate in a wide range of environments ranging from low energy exoatmospheric skips to high energy reentry. The lack of test facilities available that can replicate these environments, particularly the high energy environments, has led to the proliferation of computational tools. Due to the high computational cost involved with high-fidelity models, recent research has turned to so-called Reduced-Order Models (ROMs) in order to capture results from the high-fidelity simulations. Though these techniques have unique challenges, they have generally been applied with tremendous success. ROMs are primarily desirable due to their small side-on-disk and rapid evaluation time. In most modern examples, trajectory considerations have largely been either simplified or ignored. Presently, performing full trajectory optimization in-the-loop with some of these analyses is prohibitively expensive. General purpose trajectory optimization routines fall under one of two categories: direct and indirect methods. Direct methods are widespread due to the availability of high performance non-linear programming routines such as IPOPT and SNOPT. One major issue in optimal control is the possibility of so-called control chattering caused by high-order singular arcs. This is the phenomena where a control switches an infinite number of times in a finite time interval. Although control chatter is often times similar to bang-bang control in appearance, it is not a feature of optimal motion. In scenarios where a single trajectory is being generated, this may not be an issue. Control chatter may be removed in post-processing "by-hand" or can even be ignored if the chatter occurs in a region where the system does not have much control authority to begin with. To build a high-quality ROM, large representative data sets are required to the tune of tens, or even hundreds of thousands of trajectories. Control chattering and other artifacts may invalidate a data set. In indirect methods, trigonomerization of constraints may be used to resolve high-quality continuous trajectories. Singular arcs are a common and unavoidable occurrence, however if two infinitesimally close missions are selected and the resulting two optimal trajectories are also infinitesimally close and continuous, it is expected that a high-quality ROM may be generated from this data. Advances in modern trajectory optimization software using indirect methods have enabled the generation of the large sets of data required for creating ROMs. The primary goal of this paper is to establish the process for defining and solving the optimal control problem associated with trajectories of interest. These optimal control problems are then solved in a continuation process to generate a large amount of data. ROMs and then trained on the resulting data set from the continuation process. The resulting ROMs have a rapid evaluation time and may be used in analysis to increase the fidelity of analysis all while not increasing computational complexity too much.

10.0102 High Speed Modeling for Grid Fins Using a DNN Approach

Roy Hartfield (Auburn University),
Presentation: Mark Carpenter, Tuesday, March 10th, 08:55 AM, Dunraven

For flight dynamics modeling of a missile system to predict trajectories, very efficient aerodynamic models with at least conceptual design level fidelity are required because of the extreme diversity in flight conditions encountered. This paper presents a Deep Learning Neural Network (DNN) based approach for predicting 5 missile aerodynamic coefficients (dependent variables). This approach has been implemented for a diversity of grid fin equipped missile configurations. For this paper, no canards are incorporated in the training data sets. For this demonstration effort, a lower order physics model for the aerodynamics has been used to generate training and validation data. A single center body geometry has been considered in this analysis with a full range of grid fin semi spans, cell sizes, Mach numbers, incident angles, and angles of attack have been considered (a total of 8 predictor variables). In this investigation, techniques were developed for selecting an appropriately small subset of the data for training DNNs and using the larger remainder of the data for testing. Results presented in this work point the way toward modeling aerodynamics of grid fin equipped missile systems with high fidelity using a very limited set of high resolutions computational fluid dynamics solutions.

10.0103 Vorticity Approaches for Morphing Wings

Roy Hartfield (Auburn University),
Presentation: Shivaranjani Sathe, Tuesday, March 10th, 09:20 AM, Dunraven

This paper describes the implementation of a vorticity-based solution for the design of morphing wings. The vorticity-based solver known as FlightStream® has been validated and used for wing geometries tested by NASA Engineers in the University of Washington Wind Tunnel Facilities. Loads, moments and pressure distributions on morphed wings is presented in the validation section and comparisons with lift and drag data are compelling. No wind tunnel pressure data is available; however, the pressure distributions are presented to inform the load data. In addition to the validation data, an analysis of morphed wings in two configurations is presented. The geometry for the configurations presented in this paper were created using Open Vehicle Sketch Pad (OpenVSP). The wing geometry from the literature, and used for the validation, is described. The work presented in this paper establishes the practicality of using vorticity methods to drive trade studies and optimization-based design activities for morphing wings. The work presented in this paper is validated for the quasi-steady flow conditions associated with the available wind tunnel data.

10.0104 Numerical Study of Deflagration to Detonation Transition Using Obstacle Combinations in OpenFOAM

Vinayak Bassi (United Airlines Business Services Pvt. Ltd.), Udit Vohra , Rajpreet Singh , Tejinder Jindal (Punjab Engineering College Chandigarh),

Presentation: Vinayak Bassi, Tuesday, March 10th, 09:45 AM, Dunraven

Deflagration and detonation are the modes of combustion at subsonic and supersonic speed respectively. Detonation is marked by sudden rise in pressure in the flow. In this study, Deflagration to Detonation transition (ddt) is numerically investigated in a homogeneous Hydrogen-air stoichiometric mixture inside a tube of 1m length and 50 mm diameter with obstacles. The two-dimensional compressible Reynolds Averaged Navier Stokes equation is solved using open source deflagration to detonation solver ‘ddtFoam’ at OpenFoam platform. The obstacles here are the obstructions in the flow for turbulence enhancement which results in earlier transition of ddt. Seven different combinations of obstacles (ddt enhancement devices) are used in the study, which are various combinations of orifice plate (rectangular obstacle) and Shchelkin spiral (round obstacle). By assigning appropriate initial and boundary conditions, 2D numerical simulations are performed and compared. Deflagration to detonation transition is observed in the tube at various time and locations depending on obstacle configuration. Pressure, temperature and flame tip location vs. time plots are plotted and it has been observed that ddt transition occurred in all the cases except for empty tube and case with two orifice plates. The detonation velocity is close to the CJ velocity value. Faster transition in ddt was observed in the cases with combination of both the obstacles followed by the cases with single type of obstacle. Therefore, earlier ddt transition results in shorter run-up length which greatly affects the tube length which in turn is an integral part of Pulse Detonation Engine operation. Keywords – Deflagration, detonation, ddt (deflagration to detonation transition), hydrogen-air, ddtFoam, ddt enhancement devices, orifice plate, Shchelkin spiral, CJ velocity

10.0105 Computational Framework for the Study of Infectious Disease Spread through Commercial Air-Travel

Sirish Namilae (Embry-Riddle Aeronautical University),

Presentation: Sirish Namilae, Tuesday, March 10th, 10:10 AM, Dunraven

This paper presents an integrated computational modelling framework combining pedestrian dynamics and infection spread models, to analyse the infectious disease spread during the different stages of air-travel. While, commercial air travel is central to the global mobility of goods and people, it has also been identified as a leading factor in the spread of several epidemic diseases including influenza, SARS and Ebola. The mixing of susceptible and infectious individuals in these high people density locations like airports involves pedestrian movement which needs to be taken into account in the modelling studies of disease dynamics. We develop a Molecular Dynamics based social force modeling approach for pedestrian dynamics and combine it with a stochastic infection dynamics model to evaluate the spread of viral infectious diseases in airplanes and airports. We apply the multiscale model for various key components of air travel and suggest strategies to reduce the number of contacts and the spread of infectious diseases. We simulate pedestrian movement during boarding and deplaning of some typical commercial airplane models and movement of people through security check areas. We found specific boarding strategies that reduce the number of contacts. Further,

we find that smaller airplanes are more effective in reducing the number of contacts compared to larger airplanes. We propose certain queue configuration that reduces contacts between people and mitigate disease spread.

10.0112 CFD Simulation of Darrieus Type Straight Single-bladed VAWT Using OpenFOAM

Asmelash Amaha (IIT B),
Presentation: Asmelash Amaha, Tuesday, March 10th, 10:35 AM, Dunraven

Vertical Axis Wind Turbines (VAWTs) employ one or more, straight or curved blades which rotate parallel to the axis of rotation. Several authors have pointed out that VAWTs have shown renewed interests and are becoming more popular due to improvements in research and advantages they provide in wind power generation. The arrangement of blades creates complex aerodynamics followed by unsteadiness and turbulence in the flow domain. The objective of this study is to demonstrate a CFD model for simulating single-bladed VAWT traversing circular orbit and describe the unsteady aerodynamics data. The model geometric configuration consists of rotor-core and turbine diameters as 1.5m and 1.22m respectively for NACA0015 airfoil blade profile. The chord length and heigh/span ratio are 0.1542m and 1.0m respectively. Inlet velocity of water 0.091m/s yields a blade Reynolds number of 67000 for a tip speed ratio equal to 5. The results were computed using snappyHexMesh and OpenFOAM. Mesh independent test studied showed about 200k cells were enough to achieve at good mesh statistics quality parameters, taking into consideration the availability of computational resources and a compromising between accuracy, stability, and cost. The pimpleDyMFoam (compatible with moving meshes) is a suitable pressure-based solver for the unsteady 2-dimensional simulation with second-order accuracy in space and time is. The simulations show that results do not vary after 11 turbine revolutions. Non dimensionalized normal and tangential components of forces were computed using the numerical model and theory respectively and, compared with the experimental work of Oler JW. et al. (1983); the results are in good agreement. The methodology presented here can be used as a guideline for design, simulations, and analysis of single to multi-bladed VAWTs using OpenFOAM CFD with a lesser number of cells.

10.0113 Bayesian Modeling of Spacecraft Safe Mode Events

Melissa Hooke (Jet Propulsion Laboratory), Travis Imken (Jet Propulsion Laboratory),
Presentation: Melissa Hooke, Tuesday, March 10th, 11:00 AM, Dunraven

When a spacecraft experiences an unexpected anomaly that could cause permanent damage to the vehicle, the spacecraft enters a pre-specified minimally operating state called safe mode in order to protect itself from further harm. Based on data collected by the Jet Propulsion Laboratory (JPL) which spans beyond-Earth missions from the past 30 years, previous analyses have modeled the occurrence of safe mode events and the duration of their recoveries. These analyses model failure and recovery rates according to Weibull probability distributions which assume independent identically distributed (iid) data across all missions and mission timelines. Applications of these analyses have reached model-based risk assessment teams at JPL and feed into the mission design process, especially for trajectory planning on future missions. In the present analysis, we argue that the iid assumption does not hold across missions. Instead, recovery times and times between safing events should be grouped and analyzed by destination rather than treated as one population. Here, this grouping is achieved through a hierarchical Bayesian architecture which prioritizes the sharing of mission data (failure and recovery times) across missions with the same destination. The hierarchical nature of the model allows for prediction of new mission safing rates without making an iid assumption. The Bayesian model is implemented using the Gibbs Sampler, a Markov Chain Monte Carlo

(MCMC) technique which allows for flexible specification of distributions. An exploration of non-constant failure rates over the timeline of individual missions is also included.

10.02 Innovative Software Engineering and Management Techniques and Practices

Session Organizer: Ronnie Killough (Southwest Research Institute), Kristin Wortman (Johns Hopkins University Applied Physics Laboratory),

10.0201 A Case Study Using CBR Insight to Visualize Source Code Quality

Jeremy Ludwig (Stottler Henke), Devin Cline (Stottler Henke Associates, Inc (SHAI)), Aaron Novstrup (Stottler Henke Associates, Inc.),

Presentation: Jeremy Ludwig, Thursday, March 12th, 08:30 AM, Lamar/Gibbon

Creating and maintaining high-quality source code is especially important for critical systems such as those made for NASA and the DoD, and for software product lines where long- lived, reusable modules are intended to be shared by multiple systems. CBR-Insight is an automated code assessment tool developed for the US Air Force, and released as open source on GitHub, to provide an objective and understandable measure of software quality. CBRI-Insight supports the ability of technical and non-technical decision makers to verify that a project's software implementation follows through on promises around developing and sustaining reliable and maintainable software while managing technical debt.

10.0204 Discovering Relationships among Software Artifacts

Job Champagne , Doris Carver (Louisiana State University),

Presentation: Job Champagne, Thursday, March 12th, 08:55 AM, Lamar/Gibbon

Software systems have become ubiquitous in today's world. Most software will evolve after initial deployment. Software changes that are a part of that evolution often are documented in a requirements change document. One of the challenges when changing software is understanding the portions of the existing requirements and the existing code that could be affected by the change in order to avoid or minimize unexpected side effects from the changes. Researchers have addressed the problem of minimizing the effect of changes by using differ- ent methods, including text mining and clustering. Some approaches to determine change impact are based on information retrieval (IR) techniques using both term frequency—inverse document frequency (TF—IDF) and latent semantic indexing (LSI) methods. Other approaches are based on visualization techniques using degree and betweenness centrality measures. In this research, we approach the problem by applying IR techniques along with data mining. We apply TF—IDF and LSI to investigate which changes have a high potential of modifying existing requirements. We also analyze similarities between changes that do not map to existing requirements. In both cases, our threshold for identifying similarity is 80%. We designed our approach to identify, for a given change, one or more requirements that have a high potential of being associated with the change as well as identifying intra-document requirements or changes that have a high potential for consolidation. We were able to identify requirements that had a similarity of at least 80% to a change request using TF—IDF and LSI. We were also able to isolate changes that did not show a high similarity to any requirement, thus indicating that the change request was likely a request for a new requirement. The results are encouraging for assessing the impact of software change requests on requirements of an existing system.

10.0205 Scientific Software Engineering: Mining Repositories to Gain Insights into BACARDI

Lynn Von Kurnatowski (German Aerospace Center - DLR), Martin Stoffers (German Aerospace Center - DLR), Martin Weigel , Michael Meinel (German Aerospace Center (DLR)), Yi Wasser , Kathrin Rack ,

Hauke Fiedler (German Aerospace Center - DLR),
Presentation: Lynn Von Kurnatowski, Thursday, March 12th, 09:20 AM, Lamar/Gibbon

For Space Situational Awareness, the German Aerospace Center (DLR) develops the software system “Backbone Catalogue of Relational Debris Information” (BACARDI), which allows for keeping track of resident space objects. BACARDI’s key features are automated processing services which produce orbit information and products like collision warnings. We present how we applied new methods of software analytics to the BACARDI project. BACARDI is an example of a complex software system with large development effort carried out by a team of various specialists. Our goal is to design and implement an efficient software development process, balancing the explorative character of a research project and operational requirements (i.e. tailored from official standards in the aerospace domain). Therefore, we established a software development process for the project where we focus on software quality. We applied methods to structure, communicate, and utilize the diverse skills, knowledge, and experience in the team concisely and precisely. After one year of practical utilization, we analyzed the process based on the repository data. By analyzing these data, we assess and prove the effects of the introduced process on the development of a software, which is used in the aerospace domain.

10.0208 Julia Programming Language Benchmark Using a Flight Simulation

Ray Sells (DESE Research, Inc.),
Presentation: Ray Sells, Thursday, March 12th, 09:45 AM, Lamar/Gibbon

The runtime speed of the relatively new Julia programming language is assessed against other commonly used languages including Python, Java, and C++. An industry-standard missile and rocket simulation, coded in multiple languages, was used as a test bench for runtime speed.

10.03 Software Architecture and Design

Session Organizer: Martin Stelzer (German Aerospace Center (DLR)), Sanda Mandutianu (Jet Propulsion Laboratory),

10.0301 An Integrated Blockchain Approach for Provenance of Rotorcraft Maintenance Data

Maria Seale (USACE Engineer Research and Development Center), Javier Ramirez Zayas (USACE Engineer Research and Development Center), Alicia Ruvinsky (US Army ERDC), Eduardo O'Neill (USACE Engineer Research and Development Center), Owen Eslinger (US Army ERDC),
Presentation: Maria Seale, Thursday, March 12th, 04:30 PM, Lamar/Gibbon

The US Army Engineer Research and Development Center has created a Data Lake Ecosystem to support efficient storage, querying and analysis of terabyte-scale rotorcraft maintenance data sets within a high performance computing environment. The goal of a Data Lake Ecosystem is to provide a scalable multi-purpose repository for integrating, manipulating and analyzing large-scale, heterogeneous data such as the rotorcraft maintenance data. The ecosystem must support the ability to perform holistic analysis across datasets and must ensure data integrity and security. For the latter, it is essential to keep a record of the creation and operations performed on a Data Lake object – a process known as data provenance. Similar to financial accounting systems, data provenance provides an accurate historical audit trail of transactions on a dataset that can be used to ensure a verified and valid state of the data. Data provenance must enforce immutability and chronology to ensure data integrity. Blockchain technology facilitates the recording and tracking of assets in a transactional network. Treating data as the relevant asset in a blockchain network presents an opportunity to leverage this technology to reduce risk and ensure data fidelity. In this presentation, we discuss a trusted data provenance application for rotorcraft maintenance data based on blockchain technology. We designed and implemented a proof-of-concept application to collect and verify Data Lake provenance by embedding the data provenance on a private blockchain platform. This application allows the replication of data provenance on every node of a trusted closed network, ensuring high availability and fault tolerance. With the proposed blockchain model, data provenance for unique Data Lake objects can be stored securely and efficiently verified. Results from evaluations demonstrate that blockchain technology provides secure, immutable, and reliable data provenance that is essential for maintaining the integrity of information in a Data Lake environment.

10.04 Software Quality, Reliability and Safety Engineering

Session Organizer: Paul Wood (Southwest Research Institute), Kristin Wortman (Johns Hopkins University Applied Physics Laboratory),

10.0401 Formal Verification of Astronaut-Rover Teams for Planetary Surface Operations

Matt Webster (University of Liverpool),

Presentation: Matt Webster, Thursday, March 12th, 04:30 PM, Amphitheatre

This presentation describes an approach to assuring the reliability of autonomous systems for Astronaut-Rover (ASRO) teams using the formal verification of models in the Brahms multi-agent modelling language. Planetary surface rovers have proven essential to several manned and unmanned missions to the moon and Mars. The first rovers were tele- or manually-operated, but autonomous systems are increasingly being used to increase the effectiveness and range of rover operations on missions such as the NASA Mars Science Laboratory. It is anticipated that future manned missions to the moon and Mars will use autonomous rovers to assist astronauts during extra-vehicular activity (EVA), including science, technical and construction operations. These ASRO teams have the potential to significantly increase the safety and efficiency of surface operations. We describe a new Brahms model in which an autonomous rover may perform several different activities including assisting an astronaut during EVA. These activities compete for the autonomous rover's "attention" and therefore the rover must decide which activity is currently the most important and engage in that activity. The Brahms model also includes an astronaut agent, which models an astronaut's predicted behaviour during an EVA. The rover must also respond to the astronaut’s activities. We show how this Brahms model can be simulated using the Brahms integrated development environment. The model can then also be formally verified with respect to system requirements using the SPIN model checker, through automatic translation from Brahms to PROMELA (the input language for SPIN). We show that such formal verification can be used to determine that mission- and safety-critical operations are conducted correctly, and therefore increase the reliability of autonomous systems for planetary rovers in ASRO teams.

10.0402 Are Onboard Errors/Events a Useful Proxy for Software Reliability?

Paul Wood (Southwest Research Institute), Joel Allardyce (Southwest Research Institute),

Presentation: Paul Wood, Thursday, March 12th, 04:55 PM, Amphitheatre

Computerized elements of spacecraft (S/C) typically produce error and event indications as they perform their processing. Some indications are related to routine activities or less common events, while others indicate off-nominal conditions detected onboard such as single event upsets. Finally, some errors or events are produced due to software defects. These are the topic of this paper, and we analyze the nature and frequency of reported errors/events to investigate the question of whether such reports can be used as a proxy for detecting software errors. While some indications are intended to point to internal errors detectable by the software itself, many of the indications of software defects are not explicitly intended to serve that purpose. Further analysis is required to determine that an indication is as the result of a software defect rather than some other cause. Our analysis is based on error and event data from Magnetospheric Multiscale (MMS) Central Instrument Data Processor (CIDP). The CIDP coordinates activities for the payload deck on each MMS observatory and is the interface between the spacecraft (S/C) processor and the payload deck for instrument commanding and instrument telemetry reporting. Of particular interest, the CIDP stores science data files in a specialized recorder separate from the primary S/C recorder and manages science data playback including freeing of science files for reuse. Many CIDP indications are generated in processing the science files. MMS has been operating for more than four years including commissioning, the primary mission, and the extended mission. Given the number of instruments/controllers in the payload, four observatories, and more than four years of operation, a large volume of recorded errors and events reported by the CIDP are available for analysis. These were examined to determine the relationship between the reports and software reliability. Many reports do not indicate software defects; however, some point to defects. This paper evaluates the potential for using such reports as a proxy for determining software reliability of onboard flight software.

10.0403 IV&V Assurance Case Design for Artemis II

Gerek Whitman (SAIC), Paul Amoroso (TMC technologies), Gregory Black (SAIC Inc), Deneen Granger (SAIC), Justin Smith (NASA Independent Verification & Validation), John Bradbury (Engility Corporation), Wesley Deadrick (NASA - Goddard Space Flight Center),

Presentation: Gerek Whitman, Thursday, March 12th, 05:20 PM, Amphitheatre

As human-rated missions like those in NASA's Artemis program continue to grow in both size and complexity, and the role of software in achieving mission objectives expands dramatically, NASA's Independent Verification and Validation (IV&V) Teams face evolving challenges in assuring the safety and performance of the safety- and mission-critical embedded software that is essential to landing astronauts on the surface of the Moon by 2024. Key among these challenges is IV&V's desire to present a cohesive, integrated assurance statement to its stakeholders that encapsulates and summarizes our assurance positions across the integrated Artemis systems and their combined role in support of a safe and successful flight. In order to meet this challenge, the IV&V Teams have begun a transition to using formal assurance case concepts and documentation in the Goal Structuring Notation (GSN) to build an argument in support of software assurance. IV&V recognizes significant benefits to the logical argumentation structure provided by assurance cases and GSN over our current practices for documenting and managing assurance claims. In order to reap these benefits, IV&V is integrating the use of assurance case concepts with our paradigm of follow-the-risk capability based assurance. Because of this, assurance cases created and used by IV&V are distinct from the sort of assurance case created by a development project or embedded software assurance organization. IV&V's assurance cases depend much less upon standards and regulations, and more on evidence captured by IV&V regarding the environment, requirements, design, and implementation. IV&V constructs an independent network of claims based on an independent decomposition of arguments. Based upon the risk posture of these claims and their associated software and software artifacts, IV&V then develops and executes engineering analyses and testing, which provide evidence to either support or refute the claim. This emerging risk-informed assurance case methodology is being put into practice as IV&V plans for support of the Artemis II mission, the first flight of the Orion capsule and Space Launch System with astronauts on board.

10.0406 Identifying Attack Surfaces in the Evolving Space Industry

Hu Yuan (University of Warwick), Carsten Maple (University of Warwick),

Presentation: Hu Yuan, Thursday, March 12th, 09:00 PM, Amphitheatre

Identifying Attack Surfaces in the Evolving Space Industry The space industry is currently undergoing substantial change. This evolution of space has seen new entrants enter the market and its associated supply chain. These organisations have entered the industry as technology develops and barriers to entry have fallen, thus expanding the industry beyond the traditional large players and loosening their control. This change to the environment that has seen commercial space take a more prominent role has recently been described as NewSpace by NASA researchers; others talk of alt.space or entrepreneurial space. Each of the terms signifies the revolution in the landscape we are witnessing. We are seeing many new entities are deploying devices in space. This change is complicated by technological developments such as implementing machine learning-based autonomous space systems and the Internet of Space Things (IoST). Key advances are centred around CubeSats and the IoST is providing connectivity at low cost. The IoST systems are likely to rely on satellite-to-x communication and interactions with broader aspects of the ground segment to a higher degree than existing space systems. Further, these IoST systems feature a myriad of components, developed by a range of companies from a number of countries; satellite systems are launched to carry multiple payloads. These developments are leading to a change in the cybersecurity threat landscape of space systems. Consequently, there will be a significantly greater number of attack vectors for adversaries to exploit, and new, previously infeasible, threats will need to be managed. In this paper, the development of NewSpace and the Internet of Space Things are presented and discussed. We develop the outline of a reference architecture (RA) that can be used to provide a better understanding of changes of the new system and abstractly model in situ applications of this new landscape. The RA will specify high-level system components and their interactions, and build upon similar approaches used to understand changes to transport systems and building systems. We instantiate the RA with concrete components so that a threat analysis can be performed. We develop and consider use cases, and then identify threat actors and their goals for subverting the system. There are existing analyses of threats to space systems, and so to avoid repeating existing analyses, we focus on the changes in threat actors, goals and methods that arise due to the changing space environment. The RAs of satellite system and space robots are specifically addressed in this paper. By using these abstract RAs, we can analyse the potential attacks against individual components. Threat modelling approaches can then be performed to analyse the threats. We examine our example use cases by developing attack trees for these specific scenarios. Our two specific use cases are animal tracking (the subject of a future Cubesat launch) and autonomous debris collection. Through the use of these instantiations, the methodology for identifying new threats is explained.

10.05 Model-based Systems and Software Engineering

Session Organizer: Oleg Sindiy (Jet Propulsion Laboratory), Alexander Murray (Jet Propulsion Laboratory),

10.0501 Towards an H/W-S/W Interface Description for a Comprehensive Space Systems Simulation Environment

Emanuel Kopp (German Aerospace Center - DLR), Sascha Müller (German Aerospace Center - DLR), Fabian Greif (Deutsches Zentrum für Luft- und Raumfahrt), Anko Boerner (German Aerospace Center - DLR),

Presentation: Emanuel Kopp, Wednesday, March 11th, 08:30 AM, Cheyenne

In the development of space instruments it is common practice to analyze the software, developed in the course of the project, for errors by extensive tests as well as to simulate the different application scenarios to verify the behavior of the software. The hardware is often only modeled as a black box to the software and is usually not an active part of the simulation. In general, the interface between hardware and software is described and analyzed by a Hardware/Software Interaction Analysis (HSIA) at a late stage of the project, when the development of the hardware has generally been completed. In order to be able to integrate the hardware into a representative simulation of the system, especially with regard to Fault Detection Isolation and Recovery (FDIR), it is necessary to develop an interface that contains all important information about the structure of the hardware and its behavior. Thus the current state of the hardware can be described at any stage of the project and can be taken into account for software development. This paper introduces a hardware/software-interface description using HSIA, Failure modes, effects and criticality analysis (FMECA) and Fault Tree Analysis (FTA) as a baseline. Based on these three methods the hardware is analyzed and grouped in sub-systems in order to avoid unnecessary complexities in the description without losing important information. The overall goal is to model the interaction of hardware and software as accurately as possible to identify errors both in the software and in the hardware design. The description can also be used at a later stage to implement it into a Model-Based Systems Engineering framework like the Virtual Satellite (VirSat), developed by the German Aerospace Center (DLR). Concept and implementation of the hardware/software- interface with special focus on fault cases, detectability and fault mitigation will be described. The benefits of an interface description in an early stage of the hardware design are discussed. On the basis of an actual project, a hardware analysis is performed and the interface is described with the developed approach in order to evaluate its suitability. Finally, the feasibility and limits of this approach are assessed.

10.0502 CAESAR Model-Based Approach to Harness Design

David Wagner (California Institute of Technology), So Young Kim , J. Jenkins (Jet Propulsion Laboratory), Nicolas Rouquette (JPL),

Presentation: David Wagner, Wednesday, March 11th, 08:55 AM, Cheyenne

Spacecraft are essentially electromechanical systems designed as an integrated set of interacting assemblies designed and implemented by many different subsystem organizations. And thus, a key system engineering process is to specify and design the electrical connections between the subsystems and assemblies that enable them to interact. The physical product of this effort is a set of electrical harnesses that need to be delivered to the assembly facility when the assemblies arrive to be integrated and tested. Spacecraft integration schedules leave little room for mistakes in harness designs that may bundle hundreds of individual conductors to complete thousands of connections. In recent history at the Jet Propulsion Laboratory (JPL), this design and development process has been transformed from a somewhat ad-hoc sequence of interactions into a repeatable methodology with clearly defined intermediate design products through the use of a model-based approaches. JPL established the IMCE (Integrated Model Centric Engineering) project to develop an integrated suite of COTS and custom systems engineering tools/applications and associated methodology , named CAESAR (Computer Aided Engineering for Spacecraft System Architectures) to promote better process. CAESAR's first systems engineering discipline focus was the integrated electrical systems engineering and harness design process. Beginning in 2018, partnering with Europa Clipper, the CAESAR team worked with the system engineering and subsystem implementation organizations involved in this entire supply chain to develop model-based methods, new tooling, and interface design, reporting, V&V and analysis products resulting in a reusable generative flow process. The process integrates commercial design tools with a new model-based specification tool, and information integration using an ontology-based architecture. The CAESAR team has been working closely with the Europa Clipper project to roll out new tooling and methodology as the project is trying to use it to produce their design products. We will report on improvements to existing methodology that have already been delivered, and the benefits accrued, as well as future work to integrate many more planned electrical-harness design improvements that would have been too disruptive to introduce in the project's critical path, but will make the process much more efficient for future flight projects.

10.0503 Enabling Space Exploration Medical System Development Using a Tool Ecosystem

Jennifer Amador (NASA - Glenn Research Center), Jennifer Mindock (KBRwyle),
Presentation: Jennifer Amador, Wednesday, March 11th, 09:20 AM, Cheyenne

The NASA Human Research Program's (HRP) Exploration Medical Capability (ExMC) Element is utilizing a Model Based Systems Engineering (MBSE) approach to enhance the development of systems engineering products that will be used to advance medical system designs for exploration missions beyond Low Earth Orbit. In support of future missions, the team is capturing content such as system behaviors, functional decomposition, architecture, system requirements and interfaces, and recommendations for clinical capabilities and resources in Systems Modeling Language (SysML) models. As these products mature, SysML models provide a way for ExMC to capture relationships among the various products, which includes supporting more integrated and multifaceted views of future medical systems. In addition to using SysML models, HRP and ExMC are developing supplementary tools to support two key functions: 1) prioritizing current and future research activities for exploration missions in an objective manner; and 2) enabling risk-informed and evidence-based trade space analysis for future space vehicles, missions, and systems. This presentation will discuss the long-term HRP and ExMC vision for the larger ecosystem of tools, which include dynamic Probabilistic Risk Assessment (PRA) capabilities, additional SysML models, a database of system component options, and data visualizations. It also includes a review of an initial Pilot Project focused on enabling medical system trade studies utilizing data that is coordinated across tools for consistent outputs (e.g., mission risk metrics that are associated with medical system mass values and medical conditions addressed). This first Pilot Project demonstrated successful operating procedures and integration across tools. Finally, the presentation will also cover a second Pilot Project that utilizes tool enhancements such as medical system optimization capabilities, post-processing, and visualization of generated data for subject matter expert review, and increased integration amongst the tools themselves.

10.0505 There's No 'I' in SEAM – an Interim Report on the 'Spacecraft Early Analysis Model'

Joe Gregory (University of Bristol), Lucy Berthoud (University of Bristol), Theo Tryfonas (University of Bristol), Ludovic Faure (Airbus Defence & Space),
Presentation: Joe Gregory, Wednesday, March 11th, 09:45 AM, Cheyenne

Model-Based Systems Engineering (MBSE) represents a move away from the traditional approach of Document-Based Systems Engineering (DBSE), and is used to promote consistency, communication, clarity and maintainability within systems engineering projects. In previous work, industry focus groups have indicated that one way this can be achieved is by performing early functional validation of elements of the spacecraft avionics. This paper presents an extended approach, introduced in a case study previously published by the authors, to enable early functional analysis of a spacecraft. The approach uses the 'Spacecraft Early Analysis Model' (SEAM), a SysML-based model framework for the definition, development and analysis of a space-based mission and corresponding space system. This formal model-based representation of the system enables the high-level simulation of the design during Phase B of the spacecraft system lifecycle. The SEAM pulls together different, traditionally disparate, analysis tools and enables them to work together, producing an integrated system model spanning multiple tools. It facilitates the simulation of the mission using dedicated orbit modelling software, analysis of the completeness and accuracy of the system behaviour, and provides an indication of the appropriate logical architecture. The SEAM has been developed iteratively by applying it to Earth-observation case studies from the Biomass mission, refining the capabilities of the template accordingly, and subsequently generalising the model. The resulting interim version of the Spacecraft Early Analysis Model contains a series of MBSE patterns that will ultimately provide users with a comprehensive and consistent SysML-based structure that enables early functional definition and analysis of spacecraft. Next steps in the development of the SEAM include its application to a wider variety of use cases to develop and demonstrate its versatility, and the development of metrics to measure its perceived value among practitioners.

10.0506 Addressing Deep Uncertainty in Space System Development through Model-based Adaptive Design

Mark Chodas (NASA Jet Propulsion Lab), Rebecca Masterson , Olivier De Weck (Space Systems Laboratory),

Presentation: Mark Chodas, Wednesday, March 11th, 10:10 AM, Cheyenne

When developing a space system, many properties of the design space are initially unknown and are discovered during the development process. Therefore, the problem exhibits deep uncertainty. Deep uncertainty refers to the condition where the full range of outcomes of a decision is not knowable. A key strategy to mitigate deep uncertainty is to update decisions when new information is learned. In this paper, the spacecraft development problem is modeled as a dynamic, chance-constrained, stochastic optimization problem. The Model-based Adaptive Design under Uncertainty (MADU) framework is presented, in which conflict-directed search is combined with reuse of information to solve the development problem efficiently in the presence of deep uncertainty. The framework is built within a Model-based Systems Engineering (MBSE) paradigm in which a SysML model contains the design, the design space, and information learned during search. The development problem is composed of a series of optimizations, each different than the previous. Changes between optimizations can be the addition or removal of a design variable, expansion or contraction of the domain of a design variable, addition or removal of constraints, or changes to the objective function. These changes are processed to determine which search decisions can be preserved from the previous optimization. The framework is illustrated on a case study drawn from the thermal design of the REgolith X-ray Imaging Spectrometer (REXIS) instrument. This case study demonstrates the advantages of the MADU framework with the solution found 30% faster than an algorithm that doesn't reuse information. With this framework, designers can more efficiently explore the design space and perform updates to a design when new information is learned. Future work includes extending the framework to multiple objective functions and continuous design variables.

10.0507 Vision for Cross-Center MBSE Collaboration on the Gateway Program

Jeremiah Crane (Booz Allen Hamilton), Robert Morgenstern (NASA - Goddard Space Flight Center), Edith Parrott (NASA Glenn Research Center),

Presentation: Jeremiah Crane, Wednesday, March 11th, 10:35 AM, Cheyenne

Descriptive models used for Model-based System Engineering (MBSE) purposes often times become just as complex as the systems they abstract. Large number of elements, various functions of different tools, and incomplete standards or requirements apply to both systems and MBSE models. Modeling can be challenging when there is only one model and a single team and the additions of multiple teams and models compounds those challenges. These issues can be ameliorated by recognizing the mode model is a system itself, and treat it as such. Being upfront and defining the model’s goals, requirements, standards and interfaces can go a long way in ameliorating the complexities that

inevitably arise as models grow in size and scope. The goal of this paper is to share the cross-center vision for model collaboration, and lessons learned on Gateway in developing and implementing that vision for the various system engineering products used for SDR and beyond. This mindset about systems models is particularly useful when the circumstances project necessitates having multiple models managed by different organizations. Such as the case for the NASA's Deep Space Lunar Gateway, which will be the focus of this paper. The program aims to establish a cis-lunar habitat built up over several launches similar to the International Space Station. Acquisition of these modules is spread across multiple centers, with Glenn Research Center (GRC), Marshall Space Flight Centers, Kennedy Space Center, and the program office at Johnson Space Center. On top of those centers, there is also integration with international partners (IP), industry and cross-program considerations with Orion and the Human Lander System. IP's and industry in particular cause us to have to address how to handle export control and proprietary data by potentially black boxing parts of the models. All of these factors lead to a challenging collaboration environment for systems models. This paper will cover the Gateway's MBSE teams' cross-center approach to the integration and coordination of MBSE models which includes : defining the interfaces between models, establishment of tool environments, the models standards and ontology, configuration management processes, a MBSE Management Plan (MBSEMP) and establishment of various working groups to refine (and maintain) the modeling processes. With these integrated models , the various teams hope to use them to create products in support of the Gateway System Design Review (SDR) by providing Functional Allocations (FA), Concepts of Operations (ConOps), Architecture Description Documents (ADD), Interfaces Requirements Documents (IRD), Interface Control Diagrams (ICD) and various Technical Performance Measures such as Mass and Power rollu ps of the modules. In order to produce these products and since the data is stored in different models, agreements on what types of data, to what level, and the modeling standards on how to capture that data are needed to define the model interfaces. This develops the digital thread throughout the environment for functions, requirements and verification artifacts which can then be used to help improve the system integration efforts.

10.0508 Integrating Safety & Mission Assurance into MBSE

Nicholas Waldram (Jet Propulsion Laboratory), Steven Cornford (Jet Propulsion Laboratory),
Presentation: Nicholas Waldram, Wednesday, March 11th, 11:00 AM, Cheyenne

The Model-Based Mission Assurance (MBMA) Program, led by John Evans within the Office of Safety and Mission Assurance (OSMA) at NASA is leading the charge in terms of integrating mission assurance into MBSE for flight projects. While OSMA operates with a charter at the agency level, the JPL contingency of support, including Steve Cornford and Nicholas Waldram, has a unique role in tying MBSE into the S&MA discipline. Through our work as part of the Cross Lifecycle Modeling (CLM) team we have been able to prototype and develop technologies and modeling patterns, and apply them to use-cases for the NASA Sounding Rocket Program Office (SRPO) under the Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) mission. The feedback from SRPO helped us mature our strategies towards lowering the barrier to entry to model data for a variety of stakeholders.

10.0509 FACE™ Ecosystem Model-based Tools Designed for the FACE Technical Standard v3.0 & v2.1

Stephen Simi (Tucson Embedded Systems, Inc.),
Presentation: Stephen Simi, Wednesday, March 11th, 11:25 AM, Cheyenne

FACE Ecosystem - Model-based Tools designed for the FACE Technical Standard Presentation Outline Significance of Model-Based tooling to the FACE Eco-system

Three Use Cases of FACE Data Model Conversion with Level of Effort (LOE) Savings Projections Lessons Learned using the FACE Eco-system (hybrid) tools and experiences within a cross-organizational integrated product team (IPT) environment Summarize the role of Model-Based tooling applied to the FACE Eco-system

10.0510 Demonstrating Assurance of Model-Based Fault Diagnosis Systems on an Operational Mission

Allen Nikora (Jet Propulsion Laboratory, California Institute of Technology), Mishaal Aleem (NASA Jet Propulsion Lab), Ryan Mackey (Jet Propulsion Laboratory), Lorraine Fesq (Jet Propulsion Laboratory), Seung Chung (Jet Propulsion Laboratory), Ksenia Kolcio Prather (Okean Solutions, Inc), Maurice Prather (Okean Solutions, Inc.), Matthew Litke (Okean Solutions),

Presentation: Allen Nikora, Wednesday, March 11th, 11:50 AM, Cheyenne

Developers of robotic scientific and commercial spacecraft are trending towards use of onboard autonomous capabilities for responding quickly to dynamic environments and rapidly changing situations. These capabilities need to know the state of the spacecraft's health. Model-based fault diagnosis (MBFD) is an approach to estimating health by continuously verifying accurate behavior and diagnosing off-nominal behavior. Proper functioning of MBFD depends on 1) the quality of the diagnostic system model that is analyzed and compared to commands and onboard measurements to estimate a system's health state, and 2) the correct functionality of the diagnosis engine interrogating the model and comparing its analyses to observed system behavior. Our goal is to develop Verification and Validation (V&V) techniques for MBFD to provide future missions sufficient confidence in its functionality and performance to deploy it on the systems they develop. Our work has been focused on infusing the techniques we developed earlier to an operational mission. First, we are constructing diagnostic models of a spacecraft attitude control system and updating our diagnostic engine so they can be demonstrated aboard the Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) mission, an operational spacecraft for which experiments in autonomy are being planned and executed, using the V&V techniques we have previously developed to assure they are both correct and complete. Since it is nearing the end of its life, ASTERIA provides a unique opportunity to demonstrate MBFD since the monitored components are expected to fail. Our demonstration will give system developers additional confidence to make timely, informed MBFD deployment decisions. Second, we will be completing performance assessments of the diagnostic engine/diagnostic model ensemble both on the flight system and ground-based testbeds to gain confidence in MBFD's ability to run successfully in a spacecraft's resource-constrained environment without adversely affecting other on-board activities. Finally, we are capturing our experience in preparing this demonstration in a set of checklists and guidance documents. Current practice includes high-level institutional guidance documents and standards, but at a high level of abstraction that does not necessarily address specific MBFD concerns. The purpose of the new checklists is to provide future mission developers clear, unambiguous, procedure-oriented guidance on assuring MBFD. This paper describes our work in these areas. For the first area, we describe the diagnostic models and updated diagnostic engine that will be used for the on-board demonstration. We describe how the V&V techniques we developed earlier are used to assure model and engine correctness and completeness. For the second area, we identify the performance measurement and assessment techniques used to characterize the diagnostic engine and diagnostic models, and discuss the effect of measured performance on overall mission operation. Finally, we present the checklist and guidance documents and describe how they meet the goals of providing system developers with clear, unambiguous, procedure-oriented guidance on MBFD assurance. We show how the techniques we have developed map into those artifacts.

10.0511 Bidirectional Text-to-Model Element Requirement Transformation

Marlin Ballard (Georgia Institute of Technology), Russell Peak (Georgia Tech), Selcuk CIMTALAY (GA Tech), Dimitri Mavris (Georgia Institute of Technology),

Presentation: Marlin Ballard, Wednesday, March 11th, 04:30 PM, Cheyenne

Elicitation, representation, and analysis of requirements are important tasks performed early in the systems engineering process. This remains true with the adoption of Model-Based Systems Engineering (MBSE) methodologies. Existing SysML-based methodologies often choose between (i) using external requirements documents and/or databases as the authoritative source for requirements truth versus (ii) generating requirements directly, as elements in the system model. In either case, there is often need for the systems engineer to manually develop a model-based requirements representation, as this faculty is not automatic in the commonly-used SysML feature set. Additionally, once the system model has been completed, systems engineers typically must prepare traditional “shall-statement” requirements for external review purposes, as not all stakeholders can be expected to be trained in system model interpretation. This paper details a novel effort to address both problems, by automatically transforming text-based requirements (TBR) into SysML model-based requirement (MBR) representations, and vice versa. The text-to-model based transformation direction uses requirement templates and natural language processing techniques, expanding on work from the field of requirements engineering. This paper also presents an aerospace-domain case study application of the developed tool. In the case study, a selected set of requirements were analyzed, and a system model was constructed. Then, the intermediate output system model was updated with additional elements, to represent the progression of the project’s systems engineering process. The modified system model was then analyzed, constructing text-based requirements from the structure. The resulting text-based requirements were compared to the initial set of input requirements to assess consistency in both directions of analysis. The methodology developed in this paper improves the systems engineering process by saving the systems engineer time constructing potentially repetitive model elements, and by enabling model-based requirement analyses to methodologies previously only capable of processing text-based requirements. Further, the methodology eases the responsibility of the systems engineer to maintain a copy of the model-based requirements in text-based format.

10.0512 Facilitating the Transition to Model-Based Acquisition

Marlin Ballard (Georgia Institute of Technology), Adam Baker (Georgia Tech Research Institute), Russell Peak (Georgia Tech), Selcuk CIMTALAY (GA Tech), Mark Blackburn (Stevens Institute of Technology), Dimitri Mavris (Georgia Institute of Technology),

Presentation: Marlin Ballard, Wednesday, March 11th, 04:55 PM, Cheyenne

One major benefit offered by MBSE is the ability to formalize interactions between subsystems in the design process. This formalization eases the transfer of information between parties. The process of government acquisition is likewise characterized by information transfer: diverse requirements must be altered and tracked between the requesting, responding, and evaluating parties. Thus, it is a natural extension of MBSE is to apply it to the acquisition process. This paper demonstrates a set of tools and patterns developed during a surrogate simulation of an MBSE-enabled Request for Proposal between NAVAIR and a responding contractor. In particular, the tools presented were developed from the NAVAIR Systems Model viewpoint. This paper covers four tools developed in this surrogate pilot. The first analyzes the problem of requirement generation. While standards such as the OMG SysML are being adopted by MBSE practitioners, the model literacy of all stakeholders is unlikely and may never be fully guaranteed. Document generation tools, such as OpenMBEE have been developed for SysML software, which enable presentation of descriptive information about the model.

This paper demonstrates modeling patterns and a tool that translates information from native-model form into a text-based format. The second and third tools presented assist in the acquirer's source selection process. Making use of the patterns which generate the text requirements above, Evaluation and Estimation Models are presented, which can act directly on contractors' responses. The Evaluation Model assists the verification process by ensuring numerical requirements are satisfied. The Estimation Model compares the contractors' claimed values with historically expected values, to assist directing the source selection experts' focus of examination. The fourth tool presented offers a method of extracting historical traceability for model elements. This aids the acquisition process by enabling digital signoff at any stage of the acquisition process. These four tools were applied in the surrogate acquisition process for a notional UAV, and a description of this case study is presented.

10.0513 Adapting Progressive MBSE Development to Document Based Contracts

Richard Ferguson (BAE Systems), Joseph Marshall (BAE Systems),

Presentation: Richard Ferguson, Wednesday, March 11th, 05:20 PM, Cheyenne

Every new program executed by BAE Systems Space Systems continues to increase and mature the Model Based Systems Engineering (MBSE) development position. While the benefits of MBSE are realized internally, each program is forced to regress to a legacy document- based structure for customer interaction and contract deliverables. Until there is a paradigm shift in how contracts are fulfilled, there will be a need to adapt the model to traditional document deliverables. This paper discusses the challenges of adapting Model Based System Engineering models and development processes with legacy document- based contracts through document representation within the model combined with document exportation.

10.0515 Object-Process Model-Based Operational Viewpoint Specification for Aerospace Architectures

Yaniv Mordecai (Massachusetts Institute of Technology), Edward Crawley (Massachusetts Institute of Technology),

Presentation: Yaniv Mordecai, Wednesday, March 11th, 09:00 PM, Cheyenne

Remote-controlled or autonomous multi-rotor air vehicles, or drones, have become common and commercially available even to individual consumers, mostly for imaging purposes. Drones appeal to mission architects looking to extend the toolbox provided to operators performing challenging missions such as public safety operations. However, careful analysis of the operational context and concept of operations must take place before major acquisitions. The purpose of this paper is to propose a model-based operational architecture definition framework, which is based on the Department of Defense Architecture Framework (DoDAF) ontology and uses Object Process Methodology (OPM) as its underlying modeling language. Through careful mapping of DoDAF Operational Viewpoint (OV) ontology to OPM ontology, we were able to show that the entire OV ontology can be covered by a small set of objects, processes, relations among them, and constructs comprising them. We then show how to instantiate the ontology to create a model of an actual architecture of interest while maintaining strong typing of the model elements to ensure validity, integrity, consistency, and continuous compliance with the OV. We demonstrate our approach on the case of using drones in public safety enterprises for the purpose of crowd management in massively attended events and locations. The proposed framework allows for capturing ConOps and OpsCon in a lightweight, yet robust and consistent manner, and improve communication and concept validation between operational stakeholders and enterprise architects.

10.06 Implementing Artificial Intelligence for Aerospace

Session Organizer: Christopher Bridges (Surrey Space Centre), Jeremy Straub (North Dakota State University),

10.0607 Artificial Intelligence Algorithms for Power Allocation in High Throughput Satellites: A Comparison

Juan Jose Garau Luis (Massachusetts Institute of Technology), Nils Pachler (Massachusetts Institute of Technology), Markus Guerster (Massachusetts Institute of Technology), Inigo Del Portillo (Massachusetts Institute of Technology), Bruce Cameron (Massachusetts Institute of Technology), Edward Crawley (Massachusetts Institute of Technology),

Presentation: Juan Jose Garau Luis, Thursday, March 12th, 04:55 PM, Lamar/Gibbon

Automating resource management strategies is a key priority in the satellite communications industry. The future landscape of the market will be changed by a substantial increase of data demand and the introduction of highly flexible communications payloads able to operate and reconfigure hundreds or even thousands of beams in orbit. This increase in dimensionality and complexity puts the spotlight on Artificial Intelligence-based dynamic algorithms to optimally make resource allocation decisions, as opposed to previous fixed policies. Although multiple approaches have been proposed in the recent years, most of the analyses have been conducted under assumptions that do not entirely reflect operation scenarios. Furthermore, little work has been done in thoroughly comparing the performance of different algorithms. In this paper we compare some of the recently proposed dynamic resource allocation algorithms under realistic operational assumptions, addressing a specific problem in which power needs to be assigned to each beam in a multibeam High Throughput Satellite (HTS). We focus on Genetic Algorithms, Simulated Annealing, Particle Swarm Optimization, Deep Reinforcement Learning, and hybrid approaches. Our multibeam operation scenario uses demand data provided by a satellite operator, a full radio-frequency chain model, and a set of hardware and time constraints present during the operation of a HTS. We compare these algorithms focusing on the following characteristics: time convergence, continuous operability, scalability, and robustness. We evaluate the performance of the algorithms against different test cases and make recommendations on the approaches that are likely to work better in each context.

10.0608 Toward an Autonomous Aerial Survey and Planning System for Humanitarian Aid and Disaster Response

Ross Allen (MIT Lincoln Laboratory), Mark Mazumder (Massachusetts Institute of Technology),

Presentation: Ross Allen, Thursday, March 12th, 05:20 PM, Lamar/Gibbon

In this paper we propose an integrated system concept for autonomously surveying and planning emergency response for areas impacted by natural disasters. Referred to as AASAPS-HADR, this system is composed of a network of ground stations and autonomous aerial vehicles interconnected by an ad hoc emergency communication network. The system objectives are three-fold: 1. provide situational awareness of the evolving disaster event, 2. generate dispatch and routing plans for emergency vehicles, and 3. provide continuous communication networks to augment pre-existing communication infrastructure that may have been damaged or destroyed. Lacking development in previous literature, we give particular emphasis to the situational awareness objective of disaster response by proposing an autonomous aerial survey that is tasked with assessing damage to existing road networks, detecting and locating human victims, and providing a cursory assessment of casualty types that can be used to inform medical response priorities. In this paper we provide a high-level system design concept, identify existing AI perception and planning algorithms that most closely suit our purposes as

well as technology gaps within those algorithms, and provide initial experimental results for non-contact health monitoring using real-time pose recognition algorithms running on a Nvidia Jetson TX2 mounted on board a quadrotor UAV. Finally we provide technology development recommendations for future phases of the AASAPS-HADR system.

10.0609 Application of Sparse Identification of Nonlinear Dynamics for Physics-informed Learning

Matteo Corbetta (NASA - Ames Research Center),
Presentation: Matteo Corbetta, Thursday, March 12th, 09:00 PM, Lamar/Gibbon

Advances in machine learning and deep neural networks has enabled complex engineering tasks like image recognition, anomaly detection, regression, and multi-objective optimization, to name but a few. The complexity of the algorithm architecture, e.g., the number of hidden layers in a deep neural network, typically grows with the complexity of the problems they are required to solve, leaving little room for interpreting (or explaining) the path that results in a specific solution. This drawback is particularly relevant for autonomous aerospace and aviation systems, where algorithm failures may have serious safety and monetary consequences. Including physics knowledge in such data-driven tools may improve the interpretability of the algorithms, thus enhancing model validations against events with very low probability. Such events include, for example, spacecraft or aircraft system failures, for which data may not be available in the training phase. This paper investigates a recent physics-informed learning algorithm for identification of system dynamics, and shows how the governing equations of a system can be extracted from data using sparse regression. The learned relationships can be utilized as a surrogate model which, unlike typical data-driven surrogate models, relies on the learned underlying dynamics of the system rather than large number of fitting parameters.

10.0610 Allocating Power and Bandwidth in Multibeam Satellite Systems Using Particle Swarm Optimization

Nils Pachler (Massachusetts Institute of Technology), Markus Guerster (Massachusetts Institute of Technology), Juan Jose Garau Luis (Massachusetts Institute of Technology), Bruce Cameron (Massachusetts Institute of Technology), Edward Crawley (Massachusetts Institute of Technology),
Presentation: Juan Jose Garau Luis, Friday, March 13th, 08:30 AM, Cheyenne

This work presents an implementation of a new metaheuristic algorithm based on Particle Swarm Optimization (PSO) to solve the joint power and bandwidth allocation problem. We formulate this problem as a multi-objective approach that considers the different constraints of a communication satellite system. The evaluation function corresponds to a full-RF link budget model that accounts for adaptive coding and modulation techniques as well as multiple types of losses. We benchmark the algorithm using a realistic traffic model provided by a satellite communications operator and under time restrictions present in an operational environment. The results show a fast convergence of the PSO algorithm, reaching an admissible solution in seconds. However, the PSO tends to get stuck in local optima and often fails to reach the global optimum. This motivates the creation of a hybrid metaheuristic combining the presented PSO with a Genetic Algorithm (GA). We show that this approach dominates the PSO-only both in terms of power consumption and service rate. Furthermore, we also show that the hybrid implementation outperforms a GA-only algorithm for low run-time executions (10-second executions). The hybrid provides up to an 85% power reduction and up to 10% better service rate in this case.

10.0612 Real-time Motion Planning in Unknown Environments for Legged Robotic Planetary Exploration

Keenan Albee (Massachusetts Institute of Technology), Alejandro Cabrales Hernandez (Massachusetts Institute of Technology), Oliver Jia-Richards (Massachusetts Institute of Technology), Antonio Teran Espinoza (Massachusetts Institute of Technology),

Presentation: Keenan Albee, Friday, March 13th, 08:55 AM, Cheyenne

Planetary surface robotic explorers currently implement limited amounts of autonomy, often relying on rigorously-developed offline plans. If deviation occurs, long communication delays often result in rover downtime and subsequent lost time for scientific exploration. Onboard robotic motion planning that is fast and accounts for obstacles and robot kinematics is one key piece of the autonomy pipeline required to bring more meaningful autonomy to planetary exploration. Current approaches normally rely on sampling-based planning methods like the rapidly exploring random tree (RRT) algorithm which has had considerable success for kinematic motion planning. However, global computation over the entire state space for high-dimensional systems in cluttered environments like legged robots on a planetary surface can be complex and too slow for practical use. What's more, complete environment information is often not available a priori. This work proposes a real-time combined global-local planner for a legged robot in a partially unobserved, cluttered environment. Large obstacles known beforehand (e.g., orbital imagery) are accounted for using a fast global planner on a low-dimensional model. Unknown small obstacles which restrict foot placements are dealt with as they are observed using a slower but real-time local planner, obeying the complex legged robot kinematics. This approach, called SweepingRRT, makes use of observed information locally as it becomes known, while providing the fast global replanning that may be necessitated by new obstacle observations. The planning algorithm is demonstrated in simulation for a standard four-legged, eight-jointed robot in some demonstrative obstacle environments consisting of large (known) and small (unknown) obstacles using a limited sensor range.

10.0613 Fuzzy Modelling of Fuel Consumptions and Emissions for Optimal Navigation of a BOEING-747 Aircraft

Olusayo Obajemu (The University of Sheffield), Mahdi Mahfouf (Universty of Sheffield), Lohithaksha Maniraj Maiyar (University of Sheffield), Jun Chen (Queen Mary University of London),

Presentation: Jun Chen, Friday, March 13th, 09:20 AM, Cheyenne

The paper investigates the use of the ICAO database for fuel and emissions estimation for a taxiing aircraft

10.0614 Recharging of Distributed Loads via Schedule Optimization with Autonomous Mobile Energy Assets

Casey Majhor (Michigan Technological University), John Naglak (Michigan Technological University), Carl Greene (Michigan Technological University), Wayne Weaver , Jeremy Bos (Michigan Technological University),

Presentation: Casey Majhor, Friday, March 13th, 09:45 AM, Cheyenne

As the development and use of multi-agent autonomous systems increases for use in applications such as planetary exploration, military reconnaissance, or microgrid systems, optimized operations needs to be considered in order to maximize the utility of resources. In autonomous mobile systems, mission plans involving path planning, scheduling, and energy management are all of immense concern and priority in operations where energy resources are limited or scarce. An optimization method with the ability to allocate tasks is a valuable tool for use in these systems. Mobile microgrids, with the ability to adapt and reconfigure to better service electrical loads, requires

this optimized mission planning. This paper proposes multiple algorithm optimization strategies of task allocation for energy assets in an autonomous mobile sub-microgrid system. The objective is to create an optimal mission plan to navigate to and recharge distributed and fixed electrical loads wirelessly, in order to extend and maximize their operational life. Data collection from sub-mission testing with a Clearpath Husky robotic unmanned ground vehicle is utilized for Monte Carlo simulations to better understand algorithm mission response to variable parameters. The novel results will show that the optimization approach and methods can be regarded as a reliable schedule optimization tool for this application of wireless recharging of loads/subsystems. The proposed approach can be extended to a multitude of applications in mission planning, involving different objectives such as recharging wireless sensor networks, unmanned aerial vehicles, or other UGVs to extend mission operation time.

10.0615 Autonomous Coverage Path Planning Using Artificial Neural Tissue for Aerospace Applications

Byong Kwon (University of Arizona), Jekan Thangavelautham (University of Arizona),
Presentation: Byong Kwon, Friday, March 13th, 10:10 AM, Cheyenne

Although many algorithms exist for robotic complete, coverage path planning (CPP), most algorithms are not practical for real-world use because they rely on perfect, prior knowledge of a static target environment, hardwired path planning or substantial human interaction, among other things. Moreover, many algorithms do not consider the real-world constraints of limited on-board power, computing, memory or communications, especially for low cost, multi-agent swarms. For aerospace applications, power-constrained CPP algorithms are critical because they can impact the effectiveness of future applications. In this paper, we apply the Artificial Neural Tissue (ANT) control algorithm to solve simulated CPP tasks, where multiple agents cooperate and completely or almost completely, cover 2-dimensional, basic geometric, open grid areas in linear or quasilinear time, where time complexity is measured by the number of robot time steps and the open grid cells to cover. In these ANT simulations, there is no central controller and the agents are constrained by limited time steps, a priori knowledge of the target environment, on-board memory and sensors. Also, the agents do not communicate among themselves. However, the ANT agents do rely on pheromones/markers to track whether a grid cell has been visited, and receive information from a central station concerning total area coverage, time and global reference directions. In these CPP tasks, the performance of ANT is comparable to the best-known, grid-based, heuristic coverage algorithm with a quasilinear upper bound cover time.

10.0616 Multi-Agent Decision Processes for Space-Based Battle Management, Command & Control Systems

Daniel Clancy (Georgia Tech Research Institute),
Presentation: Daniel Clancy, Friday, March 13th, 10:35 AM, Cheyenne

A decentralized and distributed Battle Management, Command and Control (BMC2) systems architecture for a space-based, layered defense system will be discussed from a stochastic games perspective, in particular a Multi-Stage, Markov Stochastic Game (MSMSG). The MSMSG will consist of blue agents versus red opponents with two types of optimal policy solutions being presented from a zero-sum game perspective. The first policy solution to be presented is for the Engagement Planning function of a BMC2 system. The engagement planning function is interested in determining the optimal Courses of Action (COA) for each heterogeneous platform, based on the number of different types of agent and opponent platforms. The solution to this problem is shown to be a saddle point of the minimax theorem, which means that there is a unique, pure strategy that can be employed at each stage of the MSMSG. The second policy solu-

tion is for the Action function of the BMC2 system, the effector to platform assignment problem, and is based on the number of unique effectors available on both the blue agent and the red opponent platforms. The solution to this type of problem can be either a pure strategy or a mixed strategy. Two reinforcement learning approaches, minimax-Q temporal-difference learning, QTD, and Monte Carlo Tree Search (MCTS), will be demonstrated as promising approaches for solving each of these types of optimal policy determination problems.

10.0619 Gaussian Process Regression Based Gas Turbine Performance Deck Generation

Volkan Aran , Emrah Güllü ,

Presentation: Volkan Aran, Friday, March 13th, 11:00 AM, Cheyenne

A gas turbine "performance deck" is an engine model in the form of a computer program which can simulate engine performance for varying input parameters. A performance team is usually held responsible to produce such a computer program in a gas turbine project and it is transferred to other project teams and customers for their needs. This computer program may include complicated component models and an iterative matching algorithm or it may include bunch of tables to interpolate/extrapolate data from. Although the first approach is way to go for the use of a performance specialist, the latter is better suited to transfer such a computer program outside the performance team. This is due to the fact that iterative matching algorithms can have convergence problems and produce no result. Tabulation of the performance data can be done with a grid based approach where each input parameter is divided into grids and an n-dimensional table is created, where n is the number of input parameters. Although it is quite straightforward to obtain such a table, its size increases exponentially with the number of input parameters. Considering that number of input parameters of a performance deck vary between 5-10, even with relatively coarse grids for each input parameter (5-10), number of performance points required to be solved can reach millions easily. This type of a table can take days to produce. We propose using Gaussian Process Regression (GPR) in order to tackle this problem. GPR is a non-parametric regression algorithm whose computational complexity does not depend on the number of the input dimensions. GPR is also the state of the art technique for the internal combustion engine modeling for the automotive industry. GPR can be evaluated as a gray-box modeling since the model preserves physical data and estimates distribution between them in place of total parametric abstraction. In this study, a GPR based performance deck is created for NASA T-MATS JT9D engine model and quite promising results are obtained.

10.0621 Anomaly Scoring for Prediction-Based Anomaly Detection in Time Series

Tianyu Li (Purdue University), Mary Comer (Purdue University), Edward Delp (Purdue University), Sundip Desai (Lockheed Martin Space Systems Company), James Mathieson (Lockheed Martin Space Systems Company), Richard Foster (Lockheed Martin Space Systems Company), Moses Chan ,

Presentation: Tianyu Li, Friday, March 13th, 11:25 AM, Cheyenne

Prediction-based anomaly detection methods for time series have been studied for decades and demonstrated to be useful in many applications. However, many predictors cannot accurately predict values around abrupt changes in time series, which may result in false detections or missed detections. In this paper, the problem is addressed using an anomaly scoring method for prediction-based anomaly detection. A Long Short-Term Memory (LSTM) network is used for prediction, and a dynamic thresholding method is used for anomaly extraction from prediction errors. The pattern of falsely detected anomalies, or false positive sequences (FPS), in training data is learned by a clustering algorithm. A score is assigned to each detected anomaly in test data according to its distance to the nearest FPS pattern learned from training data. The effectiveness of this method is demonstrated by testing it on a variety of public time series datasets.

10.07 Human-Systems Interaction

Session Organizer: Andreas Gerndt (German Aerospace Center (DLR)), Janki Dodiya (German Aerospace Centre),

10.0702 Designing a Fusion of Visible and Infra-red Camera Streams for Remote Tower Operations

Anne Papenfuß (German Aerospace Center - DLR), Fabian Reuschling , Joern Jakobi ,
Presentation: Anne Papenfuß, Sunday, March 8th, 04:30 PM, Madison

The research project INVIDEON evaluated requirements, technical solutions and the benefit of fusing visible (VIS) and infra-red (IR) spectrum camera streams into a single panorama video stream. In this paper, the design process for developing a usable and accepted fusion is described. As both sensors have strengthens and weaknesses, INVIDEON proposes a fused panorama optimized out of both sensors to be presented to the ATC officer (ATCO). This paper gives an overview of the project and reports results of acceptance and usability of the INVIDEON solution. The process of supporting the definition of requirements by means of rapid prototyping and taking a user-centered approach is described. Main findings of requirements for fusing VIS and IR camera data for remote tower operations are highlighted and set into context with the air traffic controller's tasks. A specific fusion approach was developed within the project and evaluated by means of recorded IR and VIS data. For evaluation, a testbed was set up at a regional airport and data representing different visibility conditions were selected out of 70 days data recordings. Five air traffic controllers participated in the final evaluation. Subjective data on perceived usability, situational awareness and trust in automation was assessed. Furthermore, qualitative data on HMI design and optimization potential from debriefings and comments was collected and clustered.

10.0704 A Conceptual Design of an Inattention Management Middleware with Adaptive Target Saliency

Max Nicosia (University of Cambridge), Per Ola Kristensson (University of Cambridge),
Presentation: Max Nicosia, ,

Safety-critical operators such as pilots, air-traffic controllers and drone operators are required to attend, understand and process multiple data points of varying complexity in order to execute tasks effectively. In such situations, a performance risk caused by operator inattention emerges. Operator inattention can arise due to many factors, such as information overload, cognitive overload, lack of training, stress, external distractions and a general failure to factor in behavioral phenomena, such as change and inattentional blindness, into the design. Our proposed solution to this problem is to actively manage operator inattention by dynamically changing the saliency of each data point to match its relevancy in relation to the task the operator is currently performing. Saliency can then be used as a means to steer the operator to attending the relevant information at the right time. To realise this solution, we present the design of a middleware that can be used to manage inattention. In this work we discuss the design of a task-agnostic multi-display middleware system that makes use of eye-tracking information and live-task performance metrics to dynamically adjust the saliency of individual dimensions of data points as a means to improve current operator performance. The presented middleware's design is based on abstracting a task into three task stages: 1) a detection stage, 2) an analysis and undestanding stage, and 3) a task execution stage. These three stages are designed to resemble a simplified version of Situation Awareness Levels. Using these task stage abstractions allows for the middleware to be configured to trigger different saliency profiles for a specific data point dimension based on its relevance to the current task, the users' performance and its task stage. This design approach allows for the middleware configuration to be decoupled from both the task and/or user optimisation profiles and the target application. The separation means that the middleware's configuration can be updated as the target application and its requirements evolve.

10.0706 Digital Twin Assessments in Virtual Reality: An Explorational Study with Aeroengines

Slawomir Tadeja (University of Cambridge), Yupu Lu , Pranay Seshadri (University of Cambridge), Per Ola Kristensson (University of Cambridge),

Presentation: Slawomir Tadeja, ,

We present an immersive environment where Virtual Reality (VR) is used to visualize the performance of a fleet of aircraft engines. Our virtual environment uses 3D geometric computer-aided design (CAD) models of the engines paired with performance maps that characterize their nominal working condition. These maps plot the pressure ratio and efficiency as a function of shaft speed and inlet flow capacity for the numerous engine sub-systems. Superimposed on these maps is the true performance of each engine, obtained through real-time sensors. In this bespoke virtual space, an engineer can rapidly analyze the health of different engine sub-systems across the fleet within seconds. One of the key elements of such a system is the selection of an appropriate interaction technique. There are many interesting solutions that can be studied here, including bimanual manipulation of data in conjunction with gaze-tracking or a controller-based interface. To this end, we explore how can we leverage interaction methods facilitated by the combination of gaze-tracking coupled with hand-tracking achieved via an additional sensor attached to the front of the VR headset, with no need for the user to hold a controller. We report on an observational study with a small number of domain-experts to identify usability problems, spot potential improvements, and gain insights into our design interaction capabilities. The study allows us to trim the design space and to guide further design efforts in this area. We also analyze qualitative feedback provided by the end-users and discuss the lessons learned during the design, implementation, verification and validation of the system.

10.0707 Kontur-3: Human Machine Interfaces for Telenavigation and Manipulation of Robots from ISS

Cornelia Riecke (German Aerospace Center - DLR), Bernhard Weber (German Aerospace Center - DLR), Maximilian Maier , Martin Stelzer (German Aerospace Center (DLR)), Ribin Balachandran (German Aerospace Center - DLR), Alexander Kondratiev (The Russian State Scientific Center for Robotics and Technical Cybernetics), Andrey Vasiliev , Aleksei Sergeev (The Russian State Scientific Center for Robotics and Technical Cybernetics), Vladimir Dubinin (Federal State Unitary Enterprise «Central Research Institute of Mechanical Engineering» / FGUP TsNIIImash), Olga Rudakova (Federal state unitary enterprise Central Reaserch Institute for machine building),

Presentation: Martin Stelzer, Sunday, March 8th, 09:25 PM, Madison

Space agencies are planning crewed lunar and Mars exploration missions to be realized within the next decade. Sending humans directly to the surface of the celestial bodies is, however, extremely dangerous and costly. Therefore, humans will teleoperate robots from an orbital spacecraft to explore the surface, acquire samples and to construct habitats. In the German-Russian Kontur-2 space project (2012-2017), the basic telerobotic scenario was realized, i.e. cosmonauts located in an orbiter (ISS) controlled robotic systems on a planet (Earth) with a force feedback joystick. This paper presents the planned experiments and Human Machine Interface (HMI) devices for the Kontur-3 space project, which is a follow-up project of Kontur-2. The paper reports the main technical achievements and human factors results of the Kontur-2 project and, the need for more effective HMI devices to be developed in Kontur-3. The preparations for the ISS experiments with the newly developed devices would bring new insights to the research community and can also become a major contribution to the planning, development and implementation of future space missions

10.0710 Headline-based Visualization to Prioritize Space Threats

John Ianni (Air Force Research Laboratory),
Presentation: John Ianni, Sunday, March 8th, 04:55 PM, Madison

Command and control systems seldom, if ever, make the big picture immediately apparent. These information systems are often a collection of specialized tools for analysts and planners but miss the opportunity to consolidate the message. Thus those who may be involved in responses may be unaware of the larger situation. This issue will likely be worse for multi-domain operations centers that must deal with a wider array of issues. This presentation will discuss software called C Portal that provides scoring methodologies and human-computer interface concepts that provide high-level situation awareness and assists in prioritizing responses. The scoring is based on the Analytic Hierarchy Process that sums up weighted criteria. For the purposes of C Portal, the highest level criteria includes threat impact, urgency and uncertainty. C Portal's visualization leverages treemapping technology and the time-proven concept of newspaper headlines to call attention to the highest priorities. The uncluttered visualization and logical navigation could be suitable for smartphone-sized displays, wall displays for large groups, or anything in between. A preliminary version of C Portal was transitioned to the National Space Defense Center as part of a Joint Emergent Operational Need and benefited from iterative operator engagements.

10.0711 Evaluation of Interaction Techniques for Early Phase Satellite Design in Immersive AR

Anna Bahnmüller , Syed M. Azeem (German Aerospace Center (DLR)), Georgia Albuquerque (German Aerospace Center - DLR), Andreas Gerndt (German Aerospace Center (DLR)),
Presentation: Anna Bahnmüller, Sunday, March 8th, 09:00 PM, Madison

In this paper, we present a new controller-based interaction technique on the Microsoft HoloLens to support communication for the early phase satellite design at the Concurrent Engineering Facility (CEF). We design a virtual satellite with virtual moveable objects utilizing two different interaction methods: the default hand gesture-based interaction method and a novel controller-based interaction method for rotation and translation of satellite components in immersive augmented reality. In order to evaluate our method, we conduct a perceptual study with 12 participants. We apply multiple performance metrics for each user on both methods. Additionally, we measure user preferences and ease of use. Our results show that our controller-based method is significantly more precise for placing objects (consisting of position and orientation). Furthermore, it is less time consuming than the hand gesture-based method and more preferred by the participants.

10.08 Image Processing and Computer Vision

Session Organizer: Amir Liaghati (Boeing),

10.0801 Aerodrome Taxiway Line Detection and Cross-Track Error Estimation Using Computer Vision Techniques

Aman Batra (University of Malta), Jason Gauci (University of Malta),
Presentation: Aman Batra, Monday, March 9th, 04:30 PM, Madison

The proposed paper describes a computer vision-based method to detect aerodrome taxiway lines and to estimate the deviation of a large passenger aircraft from the taxiway centerline using an onboard camera located on the vertical stabilizer of the aircraft. This method could be applied as part of a larger system to increase the situation awareness of pilots during taxiing and to alert them if the aircraft deviates from the centerline. The proposed method takes advantage of color and edge information in the camera images and proposes a Sliding Window (SW) method and clustering techniques to detect and process taxiways markings. First, the input image is transformed to a top-down view by applying the Homographic Transform. Then, color and edge detection techniques are applied to the top-down view to generate a binary map of pixels belonging to taxiway lines. Then, the region of the image directly in front of the aircraft is processed to determine whether the aircraft is turning or moving in a straight line. If it is determined that the aircraft is turning, the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) clustering technique is applied to the binary map; otherwise, a SW method is used to detect the taxiway centerline ahead of the aircraft and to detect any taxiway branches or junctions. Finally, the aircraft's lateral deviation from the taxiway centerline is estimated using a template matching approach. Tests on simulated video sequences show that the SW technique achieves a detection rate of 80% and a false positive rate of 3%. On the other hand, the clustering technique achieves a detection rate of 76% and a false positive rate of 4%. The aircraft's deviation from the taxiway centerline is estimated with a mean error of 0.8 pixels and a worst case error of ±3 pixels.

10.0802 Using GANs to Generate Random Surface Materials for High Fidelity Low Altitude Imaging Simulations

Sournav Sekhar Bhattacharya (Texas A&M University), Neil McHenry (Texas A&M University), Gregory Chamitoff (Texas A&M University), Zachary Summers , Aditi Panchal (Texas A&M University), Elise Koock (Texas A&M University),

Presentation: Sournav Sekhar Bhattacharya, Monday, March 9th, 04:55 PM, Madison

The various emerging technologies surrounding the use of generative machine learning allow for the automation of procedures which would normally take a large amount of human development time. This can be applied to the domain of simulations in low altitude flight imaging simulations. Low altitude imaging consists of images taken at an altitude of less than 500 feet above the surface in this context. Simulating the acquisition of such images using commercial game engines such as Unity or Unreal Engine 4 is possible. However one defect in the images thus taken is the repetition of material images on the terrain itself. This lowers the fidelity of the simulation since materials that represent certain characteristics of the ground are based on a single or small group of source images. In the past few years a set of generative neural network architectures known as generative adversarial networks (GANs) have seen much development. We propose a method using GANs in order to generate variations of similar terrain with a high degree of randomness in order to replace tiling caused by using similar images. We have been sucessful in developing textures for a variety of terrain types including sand and grass by utilizing the evaluation functions and blending algorithms we have constructed. Using these images as terrain textures will allow for a higher fidelity simulation and will provide a more accurate test bed for computer vision algorithms operating in the domain of low altitude flight.

10.0803 Low-Cost Smart Surveillance and Reconnaissance Using VTOL Fixed Wing UAV

Sarvesh Sonkar (iit kanpur), Prashant Kumar (Indian Institute of Technology, Kanpur), Deepu Philip (Indian Institute of Technology, Kanpur), Ajoy Ghosh ,

Presentation: Sarvesh Sonkar, ,

Paper title: Low-Cost Smart Surveillance and Reconnaissance Using VTOL Fixed Wing UAV Generally, surveillance refers to a single, known, and mostly static point of interest that is observed for a predetermined amount of time. Similarly, reconnaissance implies a large area to be covered thereby requiring rapid mobility and capability to observe multiple points of interest. Real-time video surveillance is a good way to realize both surveillance and reconnaissance, which involves multiple challenges and complexities;

viz., computational efficiency, latency, image quality, etc. The concept of utilizing a fixed wing VTOL Unmanned Aerial Vehicle (UAV) is more appropriate than the conventional fixed-wing UAV or multi-rotors, in terms of the quality of visual imageries, increased operational range, reduced time to target and thereby reduced mission times, minimal dependencies on infrastructure, and so on. This research studies the application of a fixed wing VTOL UAV for real-time low-latency monitoring system for reconnaissance; thereby quantifying various benefits, including the practical performance of such a video surveillance system. The simulation required for this research is realized using Robot Operating System (ROS) and the final model is validated using both hardware and software

10.0804 Recurrent Neural Network Based Prediction to Enhance Satellite Telemetry Compression

Ahmed F.shehab (Military Technical College), Mohamed Elshafey (Military Technical College), Tarek Mahmoud (MILITARY TECHNICAL COLLEGE),

Presentation: Tarek Mahmoud, Monday, March 9th, 09:00 PM, Madison

Because of the gradually increasing number of remote measured low and/or high frequency sampled parameters in space applications, aerospace mission operators have to make hard choices on which parameters at which sampling rates should be downlinked. On-board aerospace applications are characterized by limited storage and communication budgets, while lossless data compression schemes should be sufficient enough to enhance transmission efficiency and hence the whole aerospace mission. In this paper, a proposed two-stage lossless compression method for telemetry data is presented. The proposed method consists of a decorrelation stage and an entropy coding one. The Long-Short-Term Memory (LSTM) Recurrent Neural Network (RNN) is implemented as a predictor in the decorrelation stage of the proposed method, and an illustrative method of applying LSTM network for telemetry data samples prediction is presented and figured out. In experiments, different entropy coders: Rice codes, arithmetic method and Huffman algorithm are separately implemented at the second stage. The proposed method is tested by different real telemetry data sets of FUNcube satellite in frames of data words of 8-,10-,16-bits widths. Experimental results show that the proposed method improved compression efficiency based on a single stage of entropy coder: Rice codes, arithmetic code, and Huffman algorithm by a ratio up to: 98%, 21%, and 1.6%, respectively.

10.0806 Adaptively Lossy Image Compression for Onboard Processing

Justin Goodwill , David Wilson (NASA Goddard Space Flight Center), Sebastian Sabogal (University of Florida), Christopher Wilson (NSF CHREC), Alan George (University of Pittsburgh),

Presentation: Justin Goodwill, Monday, March 9th, 09:25 PM, Madison

More efficient image-compression codecs are an emerging requirement for spacecraft because increasingly complex, onboard image sensors can rapidly saturate downlink bandwidth of communication transceivers. While these codecs reduce transmitted data volume, many are compute-intensive and require rapid processing to sustain sensor data rates. Traditional spacecraft often rely upon slow, radiation-hardened processing technologies due to the harsh space environment. However, significant advancements in hardware and software dependability have enabled short-term and/or low-Earth orbit missions to instead use commercial-off-the-shelf (COTS) components, which provide substantial benefits in processing capability and power efficiency. Modern COTS technology provides several orders of magnitude increase in computational capacity, enabling compute-intensive, onboard sensor processing, such as intelligent image-compression techniques. For this research, we describe two compression algorithms for deployment on modern flight hardware: (1) end-to-end, neural-network-based, image

compression (CNN-JPEG); and (2) adaptive image compression through feature-point detection. Intelligent data-processing pipelines can help overcome limited downlink bandwidth because they can adapt to sensor data and compress it more effectively. Recent research in neural-network-based approaches for lossy image compression has shown dramatic improvements in image quality at lower data rates, in comparison to traditional codecs such as JPEG and JPEG-2000. Importantly, unlike traditional codecs, these machine-learning frameworks are not data-agnostic but adaptable to the application based upon input training data. Earth-observation satellites are an ideal use case, since satellite data is readily available and plentiful; therefore, developers can use that data for training purposes. Our first algorithm, CNN-JPEG, uses a hybrid approach combining convolutional neural networks (CNNs) and JPEG. In the encoder, the image is input into a three-layer CNN to obtain a compact image representation, which is then encoded with JPEG. In the decoder, a deeper 20-layer CNN reconstructs the original image. CNN-JPEG shows 24% higher average PSNR (Peak Signal to Noise Ratio) and 31% higher average SSIM (Structural SIMilarity index) versus standard JPEG on a dataset collected on the Space Test Program – Houston 5 mission onboard the International Space Station. We ported the encoder CNN to TensorFlow Lite and executed on Cortex-A9 cores of the Zynq 7020 processor, demonstrating an average runtime of 131 s. To reduce execution time, the algorithm was then accelerated in the FPGA fabric using the Xilinx SDSoC design flow. For our second algorithm, we developed an adaptive image-compression pipeline based upon JPEG that leverages Oriented FAST and Rotated BRIEF feature-point detection to adaptively tune compression ratio. To dynamically adjust rate-distortion based upon feature content, the JPEG quality factor is adjusted based on a linear relationship with feature-point count. This adaptive compression allows for a tradeoff between PSNR/SSIM and combined file size over a batch of images, compared to compression with a static JPEG quality factor.

10.0807 Gate Detection Using Deep Learning

Daniel Zhang , Daniel Doyle (Virginia Tech),
Presentation: Daniel Zhang, ,

First-Person View drone racing requires the ability to quickly identify and navigate through a series of gates. Human racers are easily able to identify these gates in a matter of milliseconds. Now, the challenge is for a drone with an embedded computer to do the same. Several traditional computer vision techniques and deep learning networks are evaluated for this task. The basics of deep learning, convolutional neural networks, and different deep learning based image processing capabilities are described. Implementation of Lockheed Martin's AlphaPilot AI Drone Challenge is presented, showing the training and prediction process. Further testing is also shown, and recommendations for future testing are made.

TRACK 11: DIAGNOSTICS, PROGNOSTICS AND HEALTH MANAGEMENT (PHM)

Track Organizers: Wolfgang Fink (University of Arizona), Andrew Hess (The Hess PHM Group, Inc.),

11.01 PHM for Aerospace Systems, Subsystems, Components and Structures

Session Organizer: Andrew Hess (The Hess PHM Group, Inc.),

11.0101 Combining Case-Based Reasoning and Self-Organizing Maps for System Anomaly Detection and Management

Sowmya Ramachandran (Stottler Henke Associates), Maia Rosengarten (Stottler Henke Associates, Inc (SHAI)),

Presentation: Sowmya Ramachandran, Thursday, March 12th, 04:30 PM, Lake/Canyon

This paper describes Anomaly Detection via Topological-feature Map (ADTM), a data-driven approach to Integrated System Health Management (ISHM) for monitoring the health of spacecraft and space habitats. Developed for NASA Ames Research Center, ADTM leverages proven artificial intelligence techniques for rapidly detecting and diagnosing anomalies in near real-time. ADTM combines Self-Organizing Maps (SOMs) as the basis for modeling system behavior with supervised machine learning techniques for localizing detected anomalies. A SOM is a two-layer artificial neural network (ANN) that produces a low-dimensional representation of the training samples. Once trained on normal system behavior, SOMs are adept at detecting behavior previously not encountered in the training data. Upon detecting anomalous behavior, ADTM uses a supervised classification approach to determine a subset of measurands that characterize the anomaly. This allows it to localize faults and thereby provide extra insight. We demonstrate the effectiveness of our approach on telemetry data collected from a lab-stationed CubeSat (the “LabSat”) connected to software that gave us the ability to trigger several real hardware faults. We include an analysis and discussion of ADTM’s performance on several of these fault cases. We conclude with a brief discussion of future work, which contains investigation of a hierarchical SOM-architecture as well as a Case-Based Reasoning module for further assisting astronauts in diagnosis and remediation activities.

11.0102 Leveraging PHM in Conjunction with Intelligent Scheduling to Improve Manufacturing Resilience

Robert Richards (Stottler Henke Associates, Inc. (SHAI)),

Presentation: Robert Richards, Thursday, March 12th, 04:55 PM, Lake/Canyon

The scheduling of a manufacturing facility is a complex endeavor even when the equipment resources are always considered available. However, under real-world conditions, the added complexity of unplanned downtime can significantly increase the difficulty of meeting deadlines. More reliable and efficient operations can be achieved by predicting problems and then rescheduling operations to minimize or avoid the problems’ adverse effects. This presentation will provide lessons learned from the real-world application of these ideas working with the US Air Force on best practices for leveraging diagnostics, prognostics, and health management in conjunction with intelligent scheduling to improve manufacturing system resilience. The goal is for diagnostic systems to identify impending faults quickly and automatically, providing the information needed to the intelligent scheduling system in order for the intelligent scheduling to determine how to minimize or completely mitigate the issues. Prognostic systems can estimate impending failures or rates of performance degradation; the intelligent scheduling system uses these diagnoses and predictions, along with the manufacturing deadlines and priorities, to develop mitigation strategies to minimize or avoid disruptions.

11.0103 Accelerating Uncertainty Propagation in Power Laws for Prognostics and Health Management

Matteo Corbetta (NASA - Ames Research Center),

Presentation: Matteo Corbetta, Thursday, March 12th, 05:20 PM, Lake/Canyon

This paper proposes a sampling-based approach for uncertainty propagation in scalar power laws. The methodology takes advantage of the properties of stochastic calculus, and outperforms the standard Monte Carlo integration in terms of speed of computation.

Three sources of uncertainty are considered; (i) modeling error arising from regressions on historical data, (ii) uncertainty or ignorance on the power law parameters, i.e., constant and exponent, and (iii) initial condition defined through probability density functions. The method is applied to an existing scenario extracted from literature in the area of prognostics and health management, and is then compared against state-of-the-art Monte Carlo integration based on Euler's forward method. The results show that the accuracy of the proposed uncertainty propagation method is virtually identical to Euler's integration. However, the presented approach is orders of magnitude faster than the integration via Euler's forward method when computing the first hitting time of a threshold. This translates into faster computation of the first hitting time distribution, which is one of the key elements of prognostics and health management.

11.0109 Data-Driven Source Localization of Impact on Aircraft Control Surfaces

Li Ai (University of South Carolina), Vafa Soltangharaei (University of South Carolina), Rafal Anay (USC), Michael Van Tooren (University of South Carolina), Paul Ziehl (University of South Carolina),

Presentation: Li Ai, Thursday, March 12th, 09:00 PM, Lake/Canyon

The Aircraft are potentially subjected to damaging events during their service life. How to cope with impact events and impact related damage is a priority in the development of aircraft composite structures. In the presentation, I will introduce the Acoustic emission (AE) method and the impact monitoring method in this paper which utilizes acoustic emission (AE) based data to classify and thereby localize impact events. The method is implemented and tested on a full-scale aircraft elevator. The innovative aspect of the new method lies in the use of a deep learning algorithm to achieve zonal localization of impact events. For this study, stacked autoencoder (SAE) algorithms were applied. To train and test the performance of the new model, the aircraft elevator impact test setup from prior work was used. In the presentation, the introduction of SAE, the details of the test setup and the test results will be presented.

11.0110 Tensor Train Decomposition for Data-Driven Prognosis of Fracture Dynamics in Composite Materials

NAGARAJAN RAGHAVAN (Singapore University of Technology and Design), Duong Pham (Singapore University of Technology and Design), Shaista Hussain , Mark Jhon (Institute of High Performance Computing, A*STAR),

Presentation: Duong Pham, Thursday, March 12th, 09:25 PM, Lake/Canyon

The paper will be presented by the first author, Dr. PHAM LUU TRUNG DUONG. He has already registered for the conference. Kindly take note.

11.0111 Predicting Failures in 747-8 Aircraft Hydraulic Pump Systems

Maximilian Müller (econda GmbH), Eric Falk (NIUGroup Sàrl-S), Jorge Meira (University of Luxembourg), Redouane Sassioui , Radu State (University of Luxembourg),

Presentation: Jorge Meira, Thursday, March 12th, 09:50 PM, Lake/Canyon

Abstract—Civil aviation, be it for passengers or cargo, is a highly competitive market, airlines are therefore strongly driven to increase earnings and reduce costs. The maintenance of the aircraft fleet is one pivotal aspect of this. In the industry two types of events occur, scheduled and unscheduled maintenance. While normal scheduled maintenance is already expensive, unscheduled maintenance events are even more so. The potential for savings is paramount when unscheduled events can be reduced to a minimum. Additionally, the safety of the customers is a huge concern, which is why possible failures ought to be detected as soon as possible. Over the last years, the large amounts of data that became available over the last decade open then door to a new range of applications. It got possible to learn from the past to predict future events, detect abnormal changes or behaviors, based on newly generated data. In this work we describe the ap-

plication of anomaly detection on aircraft data. The goal is to predict upcoming failures of the turbine's hydraulic pumps, having severe financial implications should they be replaced in a context of unscheduled maintenance. In this context, we describe how we addressed this challenging task, and how crucial expert knowledge is when approaching such difficult undertakings. With our dataset we studied multiple outlier detection methods, ST-DBSCAN has proven to be the best suited method for this use case. We show how we identified the correct data frames to apply the methodology, and evaluate its prediction performance on a real-world dataset from several aircrafts.

11.02 PHM for Autonomous and Control Systems Applications

Session Organizer: Derek De Vries (Nothrop Grumman Innovation Systems),

11.0202 In-Time UAV Flight-Trajectory Estimation and Tracking Using Bayesian Filters

Portia Banerjee (SGT/NASA Ames Research Center), Matteo Corbetta (NASA - Ames Research Center),
Presentation: Portia Banerjee, Wednesday, March 11th, 11:50 AM, Lake/Canyon

Rapid increase of UAV operation in the next decade in areas of on-demand delivery, medical transportation services, law enforcement, traffic surveillance and several others pose potential risks to the low altitude airspace above densely populated areas. Safety assessment of airspace demands the need for novel UAV traffic management frameworks for regulation and tracking of vehicles. Particularly for low-altitude UAV operations, quality of GPS measurements feeding into the UAV is often compromised by loss of communication link caused by presence of trees or tall buildings in proximity to the UAV flight path. Inaccurate GPS locations may yield to unreliable monitoring and inaccurate prognosis of remaining battery life and other safety metrics which rely on future expected trajectory of the UAV. This work therefore proposes a generalized trajectory monitoring and prediction methodology for autonomous UAVs using in-time GPS measurements. Firstly, a 4D smooth trajectory generation technique from a series of waypoint locations with associated expected times-of-arrival based on B-spline curves is presented. Initial uncertainty in the vehicle's expected cruise velocity is propagated through the trajectory to compute confidence intervals along the entire flight trajectory using error interval propagation approach. Further, the generated planned trajectory is considered as the prior knowledge which is updated during its flight with incoming GPS measurements in order to estimate its current location and corresponding kinematic profiles. The estimation of the vehicle position is defined in a state-space representation such that the position at a future time step is derived from position and velocity at current time step and expected velocity at the future time step. A linear Bayesian filtering algorithm is employed to efficiently refine position estimation from noisy GPS measurements and update the confidence intervals. Further, a dynamic re-planning strategy is implemented to incorporate unexpected detour or delay scenarios. Finally, critical challenges related to uncertainty quantification in trajectory prognosis for autonomous vehicles are identified, and potential solutions are discussed at the end of the paper. The entire monitoring framework is demonstrated on real UAV flight experiments conducted at the NASA Langley Research Center.

11.03 PHM System Design Attributes and Architectures

Session Organizer: Andrew Hess (The Hess PHM Group, Inc.), Derek De Vries (Nothrop Grumman Innovation Systems),

11.0302 Application of a Physics-of-Failure Mentality for Aerospace Health Management Systems

Homer Dewey (Northrop Grumman Corporation), Derek De Vries (Nothrop Grumman Innovation Systems),

Presentation: Homer Dewey, Thursday, March 12th, 11:50 AM, Lamar/Gibbon

In today's environment of customers demanding more efficient and affordable designs, with higher performance and lower overall cost of ownership, it is imperative that improvements and standardizations are applied to the technical assessment approaches within aerospace systems. Historically, aerospace system and component analysts have evaluated design integrity based on safety factor or margin-of-safety design criteria. This approach obtains capability or failure limits through material testing to failure and applying fixed multipliers to the results in order to ensure conservative answers. The induced loads are typically calculated using numerical methods using empirical characterization data obtained from laboratory testing. With a system composed of multiple components, this repeated application of conservativism has resulted in a large bias that pushes the results to be overly conservative, resulting in increased cost and decreased performance of the system compared to an optimal solution. Often this also leads to increased margins for materials and components resulting in increased mass and cost. This method is a “good enough” approach that has been universally accepted and proven successful, however it does not enable quantification of uncertainties or understanding of the probability of failure. The desire to become more optimized, efficient, and affordable is driving more rigorous and accurate assessments of designs, and a transition to a physics-of-failure mentality will allow for optimal designs to be created with known uncertainties in their capability. This approach does not sacrifice safety or performance margins, rather it quantifies the relationship between product performance and confidence in the design solution. This presentation describes the application of a physics-of-failure mentality for aerospace health management systems. Discussion begins with a historical perspective and then describes the importance of assessing and understanding the capabilities of an aerospace system’s components, modeling those capabilities, and utilizing those models to generate critical parameters to monitor and accurately assess the system performance. Uncertainty in models is discussed. Finally, best practices for ensuring the quality of those models through anchoring, validation, and parameter sensitivity studies are offered.

11.04 Sensor Technologies for PHM Applications

Session Organizer: Morteza Safai (Boeing Company),

11.0401 Assessing Structural Health in Extreme Environments with Distributed Fiber Sensing

Alex Tongue (Sensuron),

Presentation: Alex Tongue, Wednesday, March 11th, 04:55 PM, Lake/Canyon

Fiber optic sensing offers a variety of unique advantages over traditional solutions for measuring strain, temperature, load, and displacement, and is often the only solution for a variety of extreme environments. Fiber optics is seeing a growing pace of adoption as it makes its way from R&D organizations to commercial structural testing facilities, and further to being deployed on a variety of aircraft and ground vehicles. This presentation will provide an overview of distributed fiber sensing technology based on Optical Frequency Domain Reflectometry. The fundamentals of fiber and fiber sensing will be discussed, its applicability to extreme environments, as well as comparisons to traditional electrical solutions. The discussion will also include a brief overview of the technology's history from its NASA roots to commercial development and deployment. Lastly, the presentation will illustrate recent and ongoing applications with a focus on the aerospace industry. Its applicability to extreme environments will be demonstrated through its use for in-flight measurements on a variety of aircraft platforms.

11.0402 Stochastic Percolation Network Model for Hybrid Nanocomposites

Sirish Namilae (Embry-Riddle Aeronautical University),
Presentation: Sirish Namilae, Wednesday, March 11th, 05:20 PM, Lake/Canyon

Agglomeration is a common occurrence in polymer nanocomposites with carbon nanotubes (CNT) and graphene nanoplatelets (GNP) as fillers and usually leads to a reduction of electrical and mechanical properties of the composites. While the conductive nanocomposites exhibit remarkable electromechanical properties and have potential applications in sensing and actuation, their performance mainly depends on the polymer matrix and the dispersed nanofillers. In this paper, we use a two-dimensional Monte Carlo percolation model for monofiller and hybrid nanocomposites to examine the effect of CNT agglomeration, GNP geometry, CNT-to-GNP volume ratio and polymer matrix properties on the strain sensing behavior of the nanocomposites. We generate microstructures of tunneling network with different size, aspect ratio, alignment and content of GNP fillers. Agglomeration parameters such as agglomerate content, morphology (equiaxed to rope-like), and agglomerate filler density are also modelled to generate realistic microstructure. The Poisson's ratio and the tunneling barrier height of the polymer matrix are also parametrized. Our results indicate that high level of agglomeration leads to a systematic decrease of piezoresistivity, while low agglomeration level with low filler density within agglomerates improves the electromechanical behavior. The addition of GNP as second filler to the CNT composites leads to a better piezoresistive behavior of the nanocomposites. Increasing the content, aspect ratio and size of the GNP also leads to an improvement of the piezoresistivity. GNPs uniformly aligned in the direction of electrical conductivity measurements lead to a significantly higher piezoresistive behavior, up to 6 times greater than that of nanocomposites based on only CNT. Higher values of the polymer matrix Poisson's ratio lead to an improved piezoresistivity.

11.0403 Direct-write Ultrasonic Sensors for the Application of Aircraft Diagnostics and Health Management

Shuting Chen (Institute of Materials Research and Engineering (IMRE), A*STAR),
Presentation: Shuting Chen, Wednesday, March 11th, 04:30 PM, Lake/Canyon

Ultrasonic sensors are one of the important technologies for structural monitoring and assessing the structural integrity for aircraft diagnostics and health management. Discrete ultrasonic sensors based on piezoelectric ceramics manually installed on structures have been evaluated for aircraft diagnostics and health management. However, it is challenging and time-consuming to install a large number of bulky and heavy discrete ultrasonic sensors in aircraft. In addition, positioning inaccuracy and bonding quality from the manual sensor installation may result in inconsistency. Direct-write ultrasonic sensors are batch fabricated on the structures using scalable processing method. The sensors have low profile and light weight as they are made of thin layer of coatings (typical total thickness < 100 μm). By eliminating the adhesive layers required for installing discrete sensors, the direct-write sensors offer excellent acoustic coupling with the structure, and thus enable improved reliability and consistency. In this work, two case studies of using direct-write sensors made of piezoelectric polymer coating to detect cracks near fastener holes in aluminum structures are reported. Notches cut from the holes simulated fatigue cracks in Case Study I, and fatigue cracks extended from the notches were involved in Case Study II. The presence of these defects around the fastener holes resulted in reduced signal amplitude of different modes of ultrasonic waves. A computer-controlled testing system was developed to collect time-domain signals at various frequencies and to plot the data into 2D graphs, which can be potentially used

as an “ultrasonic signature” of the structure. In addition, damage indexes based on the residual ultrasonic energy were calculated, and could be used as an indicator of severity of damage of the structure

11.06 PHM for Non-Aerospace Applications

Session Organizer: Joseph Thorp (Aramco), Andrew Hess (The Hess PHM Group, Inc.),

11.0601 An Evaluation of Safe and Cost-effective Solutions for UAS-enabled Bridge Inspection Practices

Ali Karimoddini ,
Presentation: Ali Karimoddini, ,

Unmanned Aerial System (UAS)-enabled bridge inspection technique, as a promising alternative to conventional practices, has drawn more interest in recent years. However, UAS performance metrics requirements imposed by bridge structure (e.g., turbulent flow characteristics around the bridge) and terrain characteristics (e.g., surface roughness, temperature, humidity), have made the selection of the suitable UAS platform a challenging problem. Currently, there is no verified and comprehensive methodology for UAS-enabled bridge inspection practices; existing case-dependent solutions rely on general-purpose commercially available UAS platforms. There is no study to quantify the gap between the performance metrics of the commercially available UAS platforms to those required for the bridge inspection. This presentation provides a framework to systematically select a commercially available UAS that is the most appropriate choice for bridge inspection. An Analytic Hierarchy Process (AHP) methodology will be adopted for the multiple-criteria decision making (MCDM) and comparing the capabilities of multiple UAS platforms. The AHP methodology will be applied to 32 criteria defined under Four major categories including flight performance, situational awareness, payload and sensor capabilities, and communication quality. The developed method will be illustrated and applied to a set of UAS platforms. A pairwise comparison approach will be conducted in a hierarchical manner at the category level, criterion level, and candidate platform level. The results from comparison tables that meet the required AHP consistency ratio threshold, will enable the selection of the most suitable UAS for bridge inspection in the defined scenario.

11.0603 A General Approach to Assessing the Trustworthiness of System Condition Prognostication

Volodymyr Ulanskyi (Mathematical Modelling & Research Holding Limited), Ahmed Raza (PDP - UAE MAINTENANCE GROUP),
Presentation: Volodymyr Ulanskyi, Wednesday, March 11th, 09:25 PM, Lake/Canyon

For systems that perform crucial functions, it is vital to prognosticate the condition for a future time slot of operation. Prognostication allows accomplishing the tasks of managing the health of complex systems by timely switching to backup equipment, using other modes of operation, planning maintenance work, etc. As examples, we can specify vehicle systems, equipment of technological processes, equipment of nuclear power plants, and much more. For such systems, it is essential to establish not only that they are operable at the time of inspection but also that they will not fail in the upcoming operation interval. Prognostication is associated with the prediction of future system conditions. Therefore, anyone should recognize that the future is always overshadowed by uncertainty. The sources of uncertainty in respect to the prognostication results are methodological errors, instrument errors, noise, and errors due to changing the ambient environment. This paper proposes a mathematical model for assessing the trustworthiness of the system condition prognosis. The set of mutually exclusive events at the time of predictive checking are analyzed. Correct and incorrect decisions correspond to events such as true-positive, false-positive, true-negative, and false-negative. We propose general expressions to calculate the probabilities of possible decisions when predicting the system condition at discrete times. We also show that for computing these probabilities is necessary to determine the conditional probability density function of a random error in evaluating the time to failure. The effectiveness indicators for predictive maintenance are considered in the form of average operating costs, total error probability, and a posteriori probability of failure-free operation in the upcoming interval. We illustrate the proposed approach by calculating the probabilities of correct and incorrect decisions for a specific stochastic deterioration process, for which we demonstrate that the trustworthiness indicators are very much dependent on the standard deviation of the measurement error of the system state parameter.

11.07 PHM for Human Health and Performance

Session Organizer: Wolfgang Fink (University of Arizona), Alexandre Popov (AIAA SETC),

11.0701 Inventory of Vital Sign Changes as Indicators of Environmental Changes aboard Space Habitats

Wolfgang Fink (University of Arizona), Shaun Brown (University of Arizona), Akanksha Prasad (RML and PGIMER),

Presentation: Andrew Hess, Thursday, March 12th, 09:20 AM, Lake/Canyon

The purpose of this paper is to explore the possibility of using crew member vital sign changes as an indicator of changes in the environment and breathable atmosphere within space habitats. As such, we have compiled a list of findings describing how different environmental conditions aboard isolated orbiting or landed space habitats can be assessed through monitoring changes in crew member vital signs via noninvasive techniques, such as electrocardiogram (ECG) readings, blood oxygenation measurements, ocular structure observation, and visual performance assessment. Akin to the "canary in the coal mine" principle, the crew members act as biosensors that, when integrated into other subsystems, help monitor space habitat health as a whole as part of an overarching Prognostics and Health Management (PHM) approach. The availability and compactness of ECG, blood oxygenation, ocular structure, and vision performance monitoring equipment – ranging from devices having a form-factor of a wristwatch to smartphone-based examination equipment – lend themselves to be ideal in environments where self-diagnostics and payload considerations are vital to mission success. We provide a list of results on how carbon monoxide (CO), carbon dioxide (CO2), oxygen (O2), and radiation exposure impact ECG measurements, blood oxygenation, ocular structure, and vision performance to quantify the health of the space habitat environment. The findings reported in this paper may lay the foundation for subsequent, e.g., deep learning based, anomaly detection frameworks that, in conjunction with other subsystems, may help determine more accurately cross correlations between different environmental factors aboard space habitats and corresponding vital sign changes of crew members.

11.0701 Inventory of Vital Sign Changes as Indicators of Environmental Changes aboard Space Habitats

Wolfgang Fink (University of Arizona), Shaun Brown (University of Arizona), Akanksha Prasad (RML and PGIMER),

Presentation: Andrew Hess, Thursday, March 12th, 09:20 AM, Lake/Canyon

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11.0702 CELL Ultracomputing Platform for Metabolic and Cardiovascular Health Monitoring Using Wearables

Sandeep Gulati (Zyomed Corp), Dan Mandutianu (Zyomed),
Presentation: Sandeep Gulati, Thursday, March 12th, 09:45 AM, Lake/Canyon

CELL Ultracomputing Platform for Metabolic and Cardiovascular Health Monitoring using Wearables Dan Mandutianu, Sandeep Gulati, John Hopple, Vijay Daggumati, Tim Ruchti , Bill Van Antwerp Zyomed, Pasadena, CA Current processing systems are limited in their ability to provide holistic view of personalized health from wrist wearables and smart clothing, embedded with a mix of low and high fidelity - optical, MEMS, RF and other electronic biosensors. The mathematics of combining data from disparate sensors with asynchronous arrival events, episodic and continuous sampling and varying performance due to confounders and physiological variability injects unique challenges in building predictive models and providing actionable, engaging information over long duration to the users. As wearables become more sophisticated, with new analytics added on a regular basis, the information processing challenge becomes harder. Our ultra-scalable CELL analytical platform is inspired by the scale of cellular networks found in nature – distributed information pathways and triggers in living organisms and creatures. CELL is a virtual machine implementing the data-flow architecture where “the network is the computer”. It integrates the communication and processing resources into a coherent model where computing is generally distributed between the wearable, smart phone and cloud. Within CELL’s data driven framework there is no control point moving from step to step. Instead it is the data drilling through the processing nodes. The CELL “program” is in fact a directed graph where the nodes are “instructions” and the arcs are the channels through which data are flowing. The execution is truly opportunistic. When data become available the nodes perform the processing. The parallelism and distribution are inherent to the architecture. There can be any number of nodes in the graph performing identical or different actions. No central processing unit (CPU) is present. Accordingly, the termination of a program does not have a clear definition and only the resulting health performance analytics being produced give a measure of the progress. The paper will describe our CELL architecture in detail and discuss departures from traditional and emerging processing containers (such as Confluent, Kubernetes etc.) applied to analyzing health data from wearables. Our implementation and results using the CELL will be presented from multi-sensor devices with metabolic, cardiovascular and impedance biosensor examples for wellness and clinically relevant metrics; including implications for scalability and real-time fused analytics that combine data from multiple sensors.

11.0702 CELL Ultracomputing Platform for Metabolic and Cardiovascular Health Monitoring Using Wearables

Sandeep Gulati (Zyomed Corp), Dan Mandutianu (Zyomed),
Presentation: Sandeep Gulati, Thursday, March 12th, 09:45 AM, Lake/Canyon

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11.0703 Submitting Formal Proposals to NASA on the “PHM for Astronauts” Project to Run on the ISS.

Alexandre Popov (AIAA SETC),
Presentation: Alexandre Popov, Thursday, March 12th, 10:10 AM, Lake/Canyon

The paper and presentation discusses an unsolicited proposal to NASA to implement the “Prognostics and Health Management (PHM) for Astronauts” project, the first international collaborative project to run on the International Space Station (ISS). The collaborative project is to validate the “PHM for Human Health and Performance (HH&P)” concept that the author introduced in his “System Health Management and Space Medicine Predictive Diagnostics. Common Concepts and Approaches.” paper in 2012. Since then the concept has been elaborated, refined, and further evolved in a dozen papers published by the author and his coauthors from the PHM Society and universities of United States and Canada. Following the NASA language for unsolicited proposals and discussing the project on validation of the advanced concept and corresponding technology candidates with predictive screening capability the paper articulates both the novelty of and need in implementing the to-be-validated concept on crew health maintenance in terms of recommendations by experienced astronauts and healthcare professionals on crewed space programs. The proposal particularly suggests NASA to employ PHM-based solutions with predictive screening capability, providing early and actionable real-time warnings of impending health issues that otherwise would have gone undetected unless a symptom is manifested or a sign is detected at a relatively late stage. The purpose of the discussion is to get a feedback from the international space community on the collaborative project. The presentation is to emphasize why a true collaboration on the ISS is paramount and why the breakthrough research project is the one to benefit not only space explorers but also terrestrial applications related to healthcare delivery.

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11.0704 Long Term Monitoring of Respiration and CO2 Using Flexible Printed Sensors

Emil Jovanov (University of Alabama, Huntsville), Ian Small (NASA- Marshall Space Flight Center), Terry Rolin , Harsha Ganegoda (The University of Alabama in Huntsville), Curtis Hill (NASA MSFC),
Presentation: Emil Jovanov, Thursday, March 12th, 08:55 AM, Lake/Canyon

Long term unobtrusive monitoring of respiration and environmental conditions is critical for tracking the health and psychophysiological state of astronauts. Wearable, flexible sensors provide increased comfort and improved human factors. Recent advances in additive manufacturing, such as printed electronics, allow miniaturization of sensors and implementation onto flexible, unobtrusive substrates. We developed a low power, flexible, sensor platform with wireless Bluetooth Low Energy (BLE) interface. The platform integrates 9 Degrees of Freedom (DOF) inertial sensor, ambient sensor (temperature, humidity, and Carbon Dioxide/Volatile Organic Compounds - CO_2/VOC sensor), and prototyping area for printed sensors. In this paper we present an implementation of a printed co-doped barium titanate capacitive sensor that is highly sensitive to water vapor as an unobtrusive breathing sensor. The 2x4mm sensor is highly sensitive to changes during breathing, even at distances of more than 20cm. Synergy of information from on-platform and printed sensors allows long term user monitoring both as wearable and ambient sensor. We demonstrate the results of sensor validation using 9 subjects. Average change of capacitance of the sensor during breathing at the distance of 7.5 cm was 6.2±3.5 pF. Our sensors represent very good option low-power, wearable, and unobtrusive monitoring.

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11.08 PHM for Commercial Space Applications

Session Organizer: Wolfgang Fink (University of Arizona), Andrew Hess (The Hess PHM Group, Inc.),

11.0801 Spaceborne SAR Interferometry Exploitation for Longitudinal Ground Deformation Monitoring

Sandeep Gulati (Zyomed Corp),

Presentation: Sandeep Gulati, Wednesday, March 11th, 09:00 PM, Lake/Canyon

Multi-temporal Interferometric SAR (InSAR) is a promising modality for spaceborne analysis of ground and structure deformations for predictive alerting. With increasing deployments of highly-capable commercial satellites offering high spectral and spatial resolution, global coverage and site revisit rates, predictive structural instability/integrity assessment is becoming accessible at a fraction of cost of aerial and ground based solutions. This paper presents an overview of the opportunities and challenges in affordably monitoring new and longstanding large buildings, monuments and ground infrastructure. This is necessitated by increasingly intense exploitation of environmental resources, hydrogeological instabilities and risk of natural disasters in environments perturbed by human activities that has created new risks. Planetek’s Rheticus® Displacement (RD) solution provides actionable, accurate assessment of land subsidence and slow changes. The underlying SPINUA (Stable Point Interferometry even Over Un-urbanized Areas) technique has already been shown to be robust in non- and scarcely urbanized areas. The talk will provide an overview of InSAR usage and multi-temporal analysis processing chain to estimate ground displacement and velocity, including results from well-characterized distributed scatterers. New results are presented that combine Quantum Resonance Interferometry (QRI) signal-to-noise ratio (SNR) and signal-to-clutter ratio (SCR) enhancement processing within RD computational pipeline for extending the reliability of displacement computations to complex, vegetated ground topography and reducing the number of ground fiducials. New results are presented on dataset acquired using European Space Agency (ESA) Sentinel-1 C-band InSAR instrument (with revisit time of 6 days) with high swath-width over the Lesina Marina site in Southern Italy. Comparisons with prior results from ESA European Remote Sensing (ERS) and Environmental Satellite (ENVISAT) and other mission data-sets (covering more than 20 years) will be provided. QRI-enhanced displacement maps, compared in terms of the density of measured coherent targets and the precision of the estimated velocity, will be provided. The paper will discuss the utility of improved InSAR processing in all-weather, early warning land hazard monitoring satellite system.

PANEL 11.10: PHM from a Practitioner's Perspective - a Potpourri of Capabilities, Experiences, Issues, and Lessons Learned

Session Organizer: Michael Houck (NAVAIR 4.4.2, Propulsion & Power), Andrew Hess (The Hess PHM Group, Inc.),

TRACK 12: GROUND AND SPACE OPERATIONS

Track Organizers: David La Vallee (Johns Hopkins University APL), Mona Witkowski (Jet Propulsion Laboratory),

12.01 Spacecraft Fight Operations: Innovative Mission Operations Approaches

Session Organizer: Allan Cheuvront (General Dynamics C4 Systems), Mona Witkowski (Jet Propulsion Laboratory),

12.0101 Launching a Spacecraft to the Sun: Development and Execution of the PSP Launch Countdown Procedure

Justin Hahn (JHU-APL),

Presentation: Justin Hahn, Thursday, March 12th, 10:10 AM, Lamar/Gibbon

NASA's Parker Solar Probe (PSP) mission will revolutionize our understanding of the Sun by traveling through the Sun’s atmosphere, closer to the surface than any spacecraft before it, to provide humanity with the closest-ever observations of a star. The PSP spacecraft was designed, built, and operated by the Johns Hopkins Applied Physics Laboratory (APL). A successful launch of the spacecraft occurred on August 12, 2018 from Cape Canaveral, Florida on a Delta IV Heavy launch vehicle using an additional upper stage. This paper describes the development and execution of the launch countdown procedure that was used by the APL spacecraft Integration and Test (I&T) team to prepare the spacecraft for launch. Specific aspects of the complex spacecraft design are introduced where these led to unique driving requirements for the countdown process. The nominal countdown activity timeline is reviewed, and spacecraft contingency procedures are presented that were developed for use in the event of a hold, recovery, recycle, or scrub. Associated test scripts and telemetry display pages specific to the spacecraft countdown are also discussed, as well as pre-launch testing and launch rehearsals. Finally, an overview is provided of spacecraft countdown operations during two launch attempts on back-to-back days. This sequence challenged the spacecraft team to exercise a range of countdown contingency procedures, both to resolve technical issues with the spacecraft ground systems and to support launch vehicle scrubs and recycles. All spacecraft countdown operations were ultimately completed successfully, culminating in the successful launch of PSP.

12.0102 Parker Solar Probe: Mission Operations Challenges during Commissioning and Beyond

Nickalaus Pinkine (JHU/APL), Kimberly Ord (Johns Hopkins Applied Physics Lab),
Presentation: Nickalaus Pinkine, Thursday, March 12th, 10:35 AM, Lamar/Gibbon

NASA's Parker Solar Probe (PSP) will be the first mission to "touch" the Sun. PSP will travel directly into the Sun's atmosphere about 4 million miles from the surface, much closer than any other spacecraft. About the size of a small car, the spacecraft will complete its scientific objectives by exploring the inner region of the heliosphere, performing in-situ and remote sensing observations of the magnetic field, plasma, and accelerated particles. Parker Solar Probe is designed to complete 24 solar encounters over its seven-year mission, using seven Venus gravity assists that reduce the size of its heliocentric orbit, enabling the spacecraft to get progressively closer to the Sun. The mission trajectory coupled with the extreme solar environment and resulting spacecraft complexity pose some unique challenges for mission operations. This paper describes the operational challenges associated with commissioning Parker Solar Probe, executing its first Venus Flyby and completing its first solar encounter in less than only three months' time after launch. Anomalies that occurred during commissioning, subsequent recovery operations and operational lessons learned are also discussed. Finally, the operational processes and software tools used to manage the mission's unique operational constraints to support orbit planning, command sequencing and real-time operations are discussed.

12.0103 CloudSat – Design of Hip-Hop to Increase Mission Longevity

Heidi Hallowell (Ball Aerospace), Ian Gravseth (Ball Aerospace and Technologies Corp),
Presentation: Heidi Hallowell, Thursday, March 12th, 11:00 AM, Lamar/Gibbon

CloudSat, now in its 13th year on orbit, has employed various strategies over its lifetime to compensate for a weakened battery and the loss of a reaction wheel. The creative efforts required to keep the mission going have been documented in a number of earlier papers [1-4]. This paper focuses on a prospective change in on-orbit operations which will help maintain or reduce the current loads on the battery in eclipse and enhance mission longevity. Keeping the battery healthy drives many of the operational modes on the SC (spacecraft) and seasonal operational adjustments have often been required in the past. In the normal mode of operation, called DO-Op (Daylight only Operations), science data is collected only during the daylight portion of the orbit and then the spacecraft goes into a spin stabilized, low power, hibernate mode in eclipse. To implement DO-Op, the spacecraft exits umbra spinning with the +X axis pointed at the sun. Then, after capturing attitude control, the spacecraft performs an approximately 180 deg yaw around the boresight of the CPR (Cloud Profiling Radar) so that at umbra entry the +X axis is again pointed at the sun. The spin rate in eclipse is high enough to maintain the orientation of the +X axis but low enough and properly timed to simplify capture at umbra exit. The largest load in umbra is the thermostatically controlled CPR Stability Heater. As the vehicle has aged, there has been a yearly trend towards increased CPR stability heater on-time which has reduced already critical power margin. The on-time of the CPR stability heater varies during the year and in the summer season the heater, which is not manually controllable, turns on longer resulting in the minimum power margin. The concern was that, if this trend continued, coupled with loss of capacity as the battery ages, it would be necessary to suspend science data collection for longer and longer periods in the summer. Reducing loads in eclipse would, of course, maintain the science collection and ultimately increase the mission's lifetime. A new operational mode called Hip-Hop (Hi Power Amplifier Heater Operation) has been developed which accomplishes this goal. In Hip-Hop a carefully timed sequence of SC attitudes exposes the CPR -X radiator to the Sun while simultaneously maintaining uninterrupted science operation. On-orbit tests have confirmed that this mode significantly reduces the heater on time. This paper will discuss the design of Hip-Hop, illustrating the ADCS impacts, and the predicted thermal and power usage improvements. Detailed software test bench runs will be discussed, as will results from on-orbit testing.

12.0104 MER Opportunity Dust Storm Recovery Operations and Implications for Future Mars Surface Missions

Michael Staab (NASA Jet Propulsion Lab), Jennifer Herman (Jet Propulsion Laboratory), Kevin Reich (NASA Jet Propulsion Laboratory), Vishnu Sridhar (NASA Jet Propulsion Lab), Robert Nelson (The Jet Propulsion Laboratory),

Presentation: Robert Nelson, Thursday, March 12th, 11:25 AM, Lamar/Gibbon

In June 2018, NASA's Mars Exploration Rover Opportunity became engulfed in the most intense global dust storm observed in its 14-year mission and in Mars' recorded history. Sapped of life-giving solar energy, Opportunity fell silent to ground operators on June 11, in what would be its final call home. Over the course of the next eight months, the MER team employed numerous recovery efforts and radiated over one thousand commands to wake the silent rover. Although unsuccessful, MER's dust-storm recovery team changed the paradigm of dust-storm operations from Opportunity's survival of a previous global dust storm in 2007. In this paper, the authors offer a glimpse into MER's recovery efforts and lessons learned from Opportunity dust-storm operations for future solar-powered Mars surface missions. First, the authors discuss the indicators of the approaching dust storm and the actions the team employed to reduce Opportunity's power consumption and preserve available battery charge prior to loss of contact. Second, the authors discuss the team's recovery efforts until Opportunity's declared End-of-Mission, the steps the team took to re-establish contact with Opportunity, the assumptions made during each step of the recovery process, and the commanding actions employed. Finally, the authors discuss the operational impacts of global dust storms on the safe and successful operation of solar-powered spacecraft on the Martian surface, and offer design recommendations for future solar-powered missions from the lessons learned during Opportunity's 14-year mission and experience through two global dust storms.

12.02 Flight/Ground Systems, Mission Planning and Operations

Session Organizer: Judith Furman (Southwest Research Institute), Nancy Vandermey (Cal Tech JPL), Priyanka Sharma (Jet Propulsion Laboratory),

12.0203 Blackbird: Object-Oriented Planning, Simulation, and Sequencing Framework Used by Multiple Missions

Christopher Lawler (NASA Jet Propulsion Lab), Forrest Ridenhour (JPL), Shaheer Khan (JPL), Nicholas Rossomando (Jet Propulsion Laboratory), Ansel Rothstein-Dowden (Jet Propulsion Laboratory),

Presentation: Christopher Lawler, Sunday, March 8th, 05:20 PM, Lamar/Gibbon

Every JPL flight mission relies on activity planning and sequence generation software to perform operations. Most such tools in use at JPL and elsewhere use attribute-based schemas or domain-specific languages (DSLs) to define activities. This reliance poses user training, software maintenance, performance, and other challenges. To solve this problem for future missions, a new software called Blackbird was developed which allows engineers to specify behavior in standard Java. The new code base has over an order of magnitude fewer lines of code than other JPL planning software, since no DSL or schema interpreter is needed. The use of Java for defining activities also allows mission adapters to debug their code in an integrated development environment, seamlessly call external libraries, and set up truly multi-mission models. These efficiency gains have significantly reduced the amount of development effort required to support the software. This paper discusses Blackbird's design, principles, and use cases. Within a year of its completion, six projects have begun using Blackbird. The Mars 2020 mission is using Blackbird to generate command sequences for cruise and Mars approach. By using multi-mission models, the Mars 2020 cruise adaptation was created in fewer than three months by three engineers at less than half time each. Work has begun to use Blackbird for communications planning during Mars 2020 surface operations. The Psyche mission uses Blackbird to generate its reference mission plans in development. Full simulations with 123,000 activities and 4.7 million resource value changes complete in about one minute. Psyche is also working towards using Blackbird in operations to support integrated activity planning and generate sequences. The InSight project is using Blackbird for mission planning in operations, replacing error-prone manual processes. For the NISAR mission, Blackbird evaluates threats to the commissioning phase timeline. The Europa Lander pre-project used Blackbird to perform a trade study. The ASTERIA mission is automating sequence generation in Blackbird. Going forward, more interested projects are likely to begin using Blackbird, and the capabilities of the core and multi-mission models will keep growing.

12.0204 Neighbors on the Red Planet: Mars Science Laboratory Relay Planning Post-InSight Arrival

Nancy Vandermey (Cal Tech JPL), Pegah Pashai (Jet Propulsion Laboratory), Aseel Anabtawi (NASA Jet Propulsion Lab), Jackson Quade ,

Presentation: Nancy Vandermey, Sunday, March 8th, 09:00 PM, Lamar/Gibbon

The Mars Science Laboratory (MSL) strategic communications planning toolset selects orbiter relay opportunities that the rover will use for transmitting data back to Earth. The toolset was extensively reworked in preparation for the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport's (InSight) arrival at Mars in November 2018 and the regular use of Mars Atmosphere and Volatile Evolution (MAVEN) and Trace Gas Orbiter (TGO) orbiters as relay assets in addition to Mars Reconnaissance Orbiter (MRO) and 2001 Mars Odyssey (ODY). Overflight selection criteria was automated in the new toolset to take into account overflight deconfliction and down-selection as well as tactical timeline planning impacts and total data return. This was done while remaining flexible and configurable for changing mission priorities. As the Curiosity rover ages, the MSL planning team must overcome issues such as reduced budgets, memory bank anomalies, and reduced power availability. These are some examples of factors that affect the strategic communications planning toolset. These topics will all be presented and discussed.

12.0205 Operations Concept for Responding to Urgent Requests for NASA-ISRO Synthetic Aperture Radar (NISAR)

Priyanka Sharma (Jet Propulsion Laboratory),

Presentation: Priyanka Sharma, Sunday, March 8th, 09:25 PM, Lamar/Gibbon

The NASA-ISRO Synthetic Aperture Radar, or NISAR, mission is an Earth-mapping radar observatory to be launched from Sriharikota (India) in 2022. This mission is a collaboration between the National Aeronautics and Space Administration (NASA) and the Indian Space Research Organization (ISRO). This spacecraft will carry two instruments that will operate at radar wavelengths (L and S-band) and will provide data for understanding changes in the Earth's land surface. The scientific data from this mission will revolutionize our understanding of the causes and consequences of land surface changes on Earth, ranging from Solid Earth Deformation in the form of natural hazards like earthquakes, volcanic eruptions and landslides, to ecosystem disturbances, to changes in the cryosphere (measurements of polar ice caps, ice sheets and sea ice). A nominal Reference Observation Plan, that repeats roughly every 12-24 days, developed prior to launch by the NISAR Mission Planning team, in consultation with the Science Team, will form the basis of science data collection by the payload instruments onboard the NISAR observatory after launch. Scheduling of science observations for the mission requires accounting for limited spacecraft resources like onboard data storage, downlink capacity, energy/power, thermal limits and instrument duty cycles. In addition to nominal science data collection, the project has a Level 1 requirement to respond to requests for urgent data acquisition over disaster sites (natural or anthropogenic) by scheduling new acquisitions within 24 hrs of notification and delivering science data within 5 hours of data acquisition. This capability is to be exercised on a 'best-efforts basis'. While the definition of what constitutes an 'urgent request', and how such requests would be submitted to the project, is within the domain of the Science Team, the Mission System team is responsible for developing the baseline operations concept and implementation approach for responding to such requests. Given the 'best-efforts' nature of this requirement, a few high-level guidelines have been developed to help guide the formulation of the operations concept, and are presented in this paper. Requests for urgent response data will be accommodated following the guiding principle of minimal to no impact on nominal science and planned engineering activities. No change in satellite orbit or attitude will be made for urgent response. Restricting response approaches to only changing the downlink and/or ground processing priority for existing observations, and adding new observations only in areas where NISAR will not be nominally imaging, allows for minimal impact on the Reference science Observation Plan. No instrument mode changes will be allowed for urgent response (except for high-priority requests), and no new observations that impact either planned science or engineering activities will be scheduled. Additionally, data requests must fit within the available project resource margins (both spacecraft and ground resources are to be evaluated). Both JPL and ISRO will be involved at various steps of the implementation, irrespective of whether the urgent request is for L-SAR (NASA instrument) or S-SAR (ISRO instrument) or a joint dataset.

12.0206 Detecting Juno's 'Heartbeat': Communications Support during Critical Events of the Juno Mission

Dustin Buccino (Jet Propulsion Laboratory), Daniel Kahan , Melissa Soriano (Jet Propulsion Laboratory), Susan Finley , Andre Jongeling (Jet Propulsion Laboratory), Yu Ming Yang (NASA Jet Propulsion Lab), Kamal Oudrhiri (Jet Propulsion Laboratory),

Presentation: Dustin Buccino, Sunday, March 8th, 09:50 PM, Lamar/Gibbon

Since launch, radio science has provided critical telecommunications support to the Juno mission. Utilizing high-sensitivity open-loop receivers and real-time signal processing, radio science is able to detect the 'heartbeat' of the Juno spacecraft and determine the current state of the spacecraft. Radio science has provided communications monitoring support for the spacecraft launch in 2011, spacecraft main engine firings (including Deep Space Maneuvers in 2012 and Jupiter Orbit Insertion in 2016), the Earth gravity assist flyby in 2013, and times when the spacecraft was off-Earth point during Jupiter closest approach with a weak signal level. Multiple frequency shift keying (MFSK) 'tones' were utilized during main engine firings on Juno, including Jupiter Orbit

Insertion (JOI). Tones are decoded in near real-time for delivery to the project. Robust implementation of hardware, software, and operations planning has ensured successful data collection and real-time status reporting of spacecraft state to the Juno mission. Lessons learned from communicating with Juno in this way while in the harsh environment of Jupiter are documented and discussed in the context of upcoming missions to Jupiter.

12.0210 The JWST Flight Dynamics Operations Concept and Flight Dynamics Ground System

Joshua Levi (a.i. solutions, Inc.), Ann Nicholson (a.i. Solutions Inc.), Jon Landis (a.i. solutions), Karen Richon (NASA - Goddard Space Flight Center),

Presentation: Joshua Levi, Monday, March 9th, 04:30 PM, Dunraven

The James Webb Space Telescope (JWST) Flight Dynamics Team (FDT), operating from the NASA Goddard Space Flight Center Flight Dynamics Facility (FDF), is responsible for performing orbit determination, propagating the spacecraft trajectory, predicting view periods, and planning, monitoring, reconstructing, and calibrating maneuvers. The FDT also performs launch window analyses to determine launch dates, times, and durations for the multiple mid-course correction maneuvers that will enable JWST to reach its operational trajectory. To provide these capabilities throughout the lifetime of JWST mission operations the FDT designed, developed, and tested the JWST Flight Dynamics Ground System (FDGS). The FDGS provides innovative approaches that address challenging aspects of JWST operations such as the timing of the initial mid-course correction maneuver and the large spacecraft area and resulting solar radiation pressure forces. Design of the FDGS began with requirements definition, trade studies, and prototyping to inform FDGS development. An assessment was also performed to determine where the FDGS would reside revealing that existing FDF operational infrastructure would provide efficiencies for development and operations. Selected development tools allowed the FDT to properly document development activities and track progress even as the FDGS development process evolved to better meet the needs of the mission. Further efficiencies were implemented through continuous integration and automated testing that rapidly provided tested builds of the FDGS software for use in frequent launch and operations simulations.

12.0211 NISAR’s Unique Challenges and Approach to Developing Robust JPL/ISRO Joint Operations

David Mohr (JPL),

Presentation: David Mohr, Monday, March 9th, 04:55 PM, Dunraven

With the goal of minimizing the complexity of operational interfaces, NISAR must still perform - integrated long and short-term science planning, - coordinated commanding necessary to execute joint SAR observations, - coordinated commanding necessary to carry out all of the Ka-band downlinks, and - anomaly response and recovery. The presentation describes NISAR’s approach to addressing each of these challenges to joint operation of the Observatory.

12.0214 Conducting Efficient Remote Science and Planning Operations for Ocean Exploration Using xGDS

David Lees (NASA Ames Research Center/CMU), Tamar Cohen (SGT, Inc), Matthew Deans , Darlene Lim (Bay Area Environmental Research Institute/NASA ARC),

Presentation: David Lees, Monday, March 9th, 05:20 PM, Dunraven

NASA Ames’ Exploration Ground Data Systems (xGDS) supports rapid scientific decision making by synchronizing information in time and space, including video and still images, scientific instrument data, and science and operations notes in geographic and temporal context. We have deployed xGDS at multiple NASA field analog missions

over the past decade. In the last two years, we have participated in SUBSEA, a multi-institution collaborative project*. SUBSEA used the research ship E/V Nautilus along with its two ROVs, Hercules and Argus, to remotely explore deep ocean volcanic vents as an analog for ocean worlds (e.g. Enceladus). This work allowed us to compare the existing oceanographic operations methods and technologies used for ocean exploration with corresponding tools and approaches developed and used at NASA. In the first year of SUBSEA we observed existing remote science operations from the Inner Space Center (ISC)**. In the second year, we deployed xGDS at ISC to complement existing capabilities with xGDS tools designed to support remote Nautilus science operations from the ISC. During operations, video, ROV and instrument telemetry were streamed from the ship to the ISC. As the science team watched dive operations, they could annotate the data with observations that were relevant to their work domain. Later, the team members could review the data at their own pace to collaboratively develop a dive plan for the next day, which had to be delivered on a fixed daily schedule. The opportunity to compare operations under different conditions enabled us to make several key observations about conducting remote science and planning operations efficiently: (i) Reviewing data collaboratively and interactively with temporal and spatial context was critical for the remote science team's ability to plan dive operations on the Nautilus. (ii) Science team members were actively engaged with the remote dive operations because they could interact with the collected data and visualize it as they desired. (iii) Being able to replay past events at accelerated speeds, and jump to points in time and spaced based on search results, provided efficient access to critical points of interest in a massive volume of data, so the remote science team could deliver plans on time. * SUBSEA (Systematic Underwater Biogeochemical Science and Exploration Analog) is a multi-institution collaboration supported by NASA, NOAA's Office of Exploration Research (OER), the Ocean Exploration Trust (OET) and the University of Rhode Island's Graduate School of Oceanography (GSO). **ISC is GSO's remote operations facility.

12.0216 The Reference Activity Plan: Collaborative, Agile Planning for NASA's Europa Clipper Mission

Kaley Pinover (NASA Jet Propulsion Laboratory), Eric Ferguson (Jet Propulsion Laboratory), Duane Bindschadler (Jet Propulsion Laboratory), Kathryn Schimmels (NASA Jet Propulsion Lab),

Presentation: Kaley Pinover, Monday, March 9th, 09:00 PM, Dunraven

Activity planning efforts on planetary exploration missions must effectively translate high-level scientific objectives into command products that execute onboard the spacecraft. In prior flagship-class orbiter missions, this process has been implemented using two approaches: activity plans are either systematically created from scratch for each orbit via a linear planning process, or future orbit plans are developed far in advance and carefully iterated upon to ensure maximum science return. These approaches have been effective, particularly for projects whose science observation strategies vary over the course of the mission, but require a number of operational constraints. Large team sizes, difficulty in relating detailed plans to qualitative science objectives, and the fragile nature of pre-planned activity sets allow limited opportunity for flexibility and optimization of plans during development. The baseline trajectory design for the Europa Clipper mission uses a suite of 45 low-altitude, short-period flybys of Europa at varying geometries to globally map the surface of the moon. In order to effectively integrate the activities of the spacecraft and its ten science instruments into a valid plan on the cadence necessitated by the trajectory design, mission operations engineers have developed a collaborative, agile uplink planning architecture. The foundational product of this planning architecture is the Reference Activity Plan (RAP), a full-mission activity plan that leverages the project's largely repeatable science observation patterns to create a template for planning at both strategic and tactical levels. Activities in the RAP are codified using a common schema and can be placed in the plan using constraint-based scheduling software that is driven by objective and quantifiable science measurement requirements. This approach enables dynamic modification of the whole mission plan in large or small segments, which allows planners to react to new science information or incorporate flight system performance characteristics into future orbit activities. The RAP also allows planners to understand the impact of their activity changes on the rest of the plan; since each subject matter expert has visibility into the entire set of planned activities, and the impact of their proposed changes upon the full plan is simulated, they can more effectively collaborate with the rest of the operations team to develop a conflict-free plan with less iteration. This presentation examines unique operations considerations that drove the design of the Reference Activity Plan, the composition and proposed implementation of the RAP, and how the use of a single authoritative activity plan allows collaborative, flexible planning during uplink plan development.

12.0218 Operational Techniques for Dealing with Long Eclipses during the MMS Extended Mission

Trevor Williams (NASA Goddard Space Flight Center), Seth Shulman (KBRwyle), Neil Ottenstein (ai solutions), Eric Palmer (a.i. solutions, Inc.), Christopher Riley , Sean Letourneau , Jacob Hollister (a.i. solutions), Yohannes Tedla (KBRwyle), Dominic Godine (a.i. solutions, Inc.),

Presentation: Eric Palmer, Monday, March 9th, 09:25 PM, Dunraven

Launch window design for the Magnetospheric Multiscale (MMS) mission ensured that no excessive eclipses would be encountered during the prime mission. However, no orbit solutions exist that satisfy the eclipse constraints indefinitely: most extended mission years contain 1-3 eclipses long enough to potentially damage either the spacecraft or its scientific instruments. Two steps were taken to improve the situation. Firstly, raising apogee radius from 25 to 29.34 Earth radii altered the Sun-Earth-MMS phasing, so efficiently achieving reductions in the long eclipse durations. These maneuvers were performed in February 2019, in preparation for the first pair of long eclipses during the subsequent August. Secondly, a set of operational steps were taken around the time of the eclipses to help maintain spacecraft and instrument temperatures while preventing power load shedding. These steps included raising key onboard temperatures through adjusting the spacecraft attitude to tilt the instrument deck towards the Sun, and engaging select heaters prior to going into eclipses. In addition, all scientific instruments were turned off, as well as high-power, non-critical spacecraft systems, to conserve energy. These steps each came with trade-offs which will be discussed in the paper. Finally, the results that were obtained when the spacecraft experienced the first set of extremely long eclipses will be discussed, as will lessons learned for future long eclipses.

12.04 Payload and Instrument Operations and Planning

Session Organizer: Radu Popescu (AptPace. Ltd.), Nancy Vandermey (Cal Tech JPL), Amy Hale (Jet Propulsion Laboratory),

12.0401 The InSight APSS Data Return Anomaly: Development of an Automated Detection and Response Method

Emily Manor Chapman (Jet Propulsion Laboratory), Elizabeth Barrett (JPL), Farah Alibay (Jet Propulsion Laboratory), Kyle Cloutier (NASA Jet Propulsion Lab), Jonathan Grinblat (NASA Jet Propulsion Lab), Jesse Mendoza (NASA Jet Propulsion Lab), Nimisha Mittal ,

Presentation: Emily Manor Chapman, Friday, March 13th, 11:25 AM, Amphitheatre

The Auxiliary Payload Sensor Suite (APSS), a collection of environmental sensors carried by the Interior exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) lander, is capable of measuring Martian air temperature, wind speed, atmospheric pressure, and local magnetic fields. After beginning Mars surface operations, the instrument experienced an anomaly that prevented it from returning science data. The anomaly affected not only the instrument, but also had impacts at the system level. APSS returned to normal operations, however the anomaly occurred again just several weeks later. This proved the need for a streamlined recovery response that would be adaptable to the operations planning cycle and workforce, that would limit the system-level impacts of the anomaly, and that would minimize the instrument downtime. The recovery response evolved from a ground-in-the-loop response to an onboard method for detecting occurrences of the anomaly and automatically recovering the instrument. Ultimately, the automated detection and response method reduced instrument downtime from days to hours and significantly minimized science data loss.

12.06 Automation and Machine Learning Applications in Spacecraft Operations

Session Organizer: Zaid Towfic (Jet Propulsion Laboratory), Mazen Shihabi (Jet Propulsion Laboratory),

12.0601 Impact of Electro-Optical Visual Hindrances in Satellite Imagery

Seif Azghandi ,

Presentation: Seif Azghandi, Friday, March 13th, 08:30 AM, Amphitheatre

Impact of atmospheric noise on satellite imagery. It includes previous work which did not contain noise followed by adding noise and atmospheric quality hindrances followed by statistical measuring and reporting.

12.0602 A Reinforcement Learning Framework for Space Missions in Unknown Environments

Peyman Tavallali (Jet Propulsion Laboratory), Sisir Karumanchi (NASA Jet Propulsion Lab), William Reid , Joseph Bowkett (Jet Propulsion Laboratory), Brett Kennedy (Jet Propulsion Laboratory),

Presentation: Peyman Tavallali, Friday, March 13th, 08:55 AM, Amphitheatre

A land-and-traverse mission to icy worlds such as Europa and Enceladus is challenging due to lack of prior knowledge regarding the terrain conditions. Previous work showed that rovers with high degrees of freedom (DoF) can achieve robust traversal by leveraging redundant modes for mobility to counter terrain uncertainty (e.g. walking, driving, or inch-worming). This paper presents a generic and scalable reinforcement learning scheme for enabling on-board decision making on rovers to automatically switch between modes of traversal based on online performance feedback. The objective is to maximize energy efficiency, minimize operator input and successfully negotiate unstructured terrain conditions without relying on exhaustive prior knowledge. The proposed methodology is well grounded in the literature on reinforcement learning and has been adapted to address conformance to validation and verification requirements and JPL flight operations history of using per-sol prescribed sequences for a space mission.

12.0603 Battery Health Quantification for TDRS Spacecraft by Using Signature Discriminability Measurement

Kenneth Ma (Peraton. Corp), Harry Shaw (NASA - Goddard Space Flight Center), Haleh Safavi (NASA - Goddard Space Flight Center), Thomas Williams (SGT Inc), Katherine Schauer (NASA - Goddard Space Flight Center),

Presentation: Kenneth Ma, Friday, March 13th, 09:20 AM, Amphitheatre

The NASA/GSFC Space Network Project Office (SN) currently operates a constellation of ten geosynchronous TDRS spacecraft launched over the past 30 years. The SN project collects up to 16.5 Gigabytes of telemetry every month. Generally, the spacecraft health and functionality are obtained by the use of real-time telemetry data for the multiple spacecraft subsystems, which are transmitted to the main ground station at the White Sands Complex in Las Cruces, NM. Recently, the SN has instituted a program of

Big Data to analyze the large amounts of data using a variety of tools including Machine Learning, Artificial Intelligence, development of training sets, and a variety of mathematical modeling tools. The goal is to improve spacecraft management and obtain a more accurate prediction of the spacecraft end of life. The combination of these efforts with those of the Aerospace Corporation, which has a contract with the SN to produce yearly reliability estimates for the TDRS fleet, will be performed. This paper presents a new concept called telemetry quality quantification (TQQ) and discusses the progress that has been made in battery performance estimation for the second-generation TDRS spacecraft using a signature discriminability measures (SDM) algorithm combined with the Aerospace Corp. battery life estimation models. This activity is important because many of the TDRS fleet of spacecraft have exceeded their on-orbit design lifetime and, therefore, NASA must carefully manage the spacecraft to continue operations while avoiding an end-of-mission scenario that leaves a non-functioning spacecraft in geosynchronous orbit.

12.0606 Machine Learning for Automated Anomaly Detection on the Mars Science Laboratory Mission

Ryan Mukai (Jet Propulsion Laboratory),

Presentation: Ryan Mukai, Friday, March 13th, 09:45 AM, Amphitheatre

The Mars Science Laboratory (MSL) Telecom Operations Team at the Jet Propulsion Laboratory (JPL) has implemented a machine learning system to in order to automate the anomaly detection process as a part of daily operations. Automated machine learning enables reliable detection of anomalies in Telecom-related telemetry and automated reporting of Telecom subsystem status, resulting in an 80% reduction in team workload and improve anomaly detection reliability. At present, machine learning methods are used to detect: 1. Anomalous long-term trends in telemetry data 2. Anomalous time-domain evolution of telemetry quantities Each of the above problems poses its own unique challenges and is addressed in different ways. In the first case, long term trending of daily minima, maximum, and mean data in temperatures, currents, voltages, and radio frequency (RF) power levels is used in addition to hard threshold safety checks to look for changes in long-term equipment health and performance. Long-term trending methods allow for ordinary seasonal variations in these quantities caused by temperature changes over the course of the Martian year while allowing operators to determine whether current performance remains in line with historical performance from previous years. Changes in long-term trends can provide important insights into the health and status of the rover’s on-board systems as well as valuable early warning if subtle degradation begins to take hold. But while trending of daily statistics is valuable, it does not detect anomalies in the short-term time evolution of engineering housekeeping and accountability (EH&A) telemetry over the course of minutes or hours during a day, and this task is handled with short-term shape analysis. Principal components analysis (PCA) has been found to provide robust detection of these anomalies, and several examples of the use of PCA to detect actual anomalous events will be provided here. In using PCA, we use both the percentage of explained variance and also a log likelihood test on the PCA expansion coefficients in the anomaly detection process to flag telemetry data for human review.

12.0607 Using Machine Learning to Automatically Detect Anomalous Spacecraft Behavior from Telemetry Data

Kedar Naik , Andrew Holmgren (Ball Aerospace), John Kenworthy (Ball Aerospace and Technologies Corp),

Presentation: Kedar Naik, Friday, March 13th, 10:10 AM, Amphitheatre

This presentation covers recent work done at Ball Aerospace on the application of machine learning to problems in analyzing spacecraft telemetry streams. Both supervised and semi-supervised methods are shown to successfully detect anomalous behavior in an instrument on the NPP weather satellite. Separately, unsupervised machine-learning methods have been used to (a) detect abnormal behavior and (b) anticipate failure in the reactions wheels aboard the Kepler space telescope. In order to automatically warn of impending failures, an unsupervised method that clusters anomalous points in time has been applied. The presentation will provide a detailed explanation of the approaches used and proffer directions of future research in the area of machine-learning-based telemetry analysis.

12.0611 Markov Decision Processes for Multi-Objective Satellite Task Planning

Duncan Eddy (Stanford University), Mykel Kochenderfer (Stanford University),
Presentation: Duncan Eddy, Friday, March 13th, 10:35 AM, Amphitheatre

This paper presents a Markov Decision Process (MDP) formulation of the satellite task scheduling problem. This formulation can be optimized for multiple operational objectives simultaneously and plan transitions between distinct functional modes. We consider the problem of scheduling image collections, ground contacts, sun-pointed periods for battery recharging, and data recorder management for an agile, resource-constrained Earth-observing spacecraft. By considering multiple mission objectives simultaneously, the algorithm is able to find an optimal task schedule that satisfies all operational constraints in a single planning step, thus reducing the operational complexity and number of steps involved in mission planning. This approach is in contrast with conventional approaches where each mission objective is treated as a separate optimization problem. We cast the space mission planning problem in the canonical MDP framework of state, action, transition, and reward. This formulation enables the direct application of standard solution techniques to the problem. The size of the action space grows exponentially in the number of image collection opportunities, making finding an exact solution for even small problem sizes impractical. Therefore, we apply the approximate solution methods of depth-first forward search and Monte-Carlo tree search to solve the problem. By adjusting the reward function, it becomes possible to select the relative value of different operational modes and tune the solution to present different behavior. By modifying the action space or reward function the algorithm can be extended to include additional orbital, attitude, or operational constraints. Both solution techniques have tunable hyper-parameters that allow users to trade between solver speed and solution quality depending on the application. Graph search and Mixed-Integer Linear Programing (MILP) formulations of image-collection planning are used to verify the optimality of the Markov decision process solution. The proposed approximate solution techniques are shown to out perform the graph search formulation solved with dynamic programming. The MDP formulation achieves 99.7% of the optimal solution found through mixed-integer programming, while executing up to 35 times faster than other approaches when only considering a single objective. When considering multi-objective optimization Monte-Carlo tree search is found to outperform forward search by up to 157%, at a cost of 1.6 times longer runtime.

12.0612 New Tools to Automatically Generate Derived Products upon Downlink Passes for MSL Operations

Katherine Donahoe (Cornell University), Jacqueline Ryan (Jet Propulsion Laboratory), Stephanie Oij (Jet Propulsion Laboratory),
Presentation: Katherine Donahoe, Friday, March 13th, 11:00 AM, Amphitheatre

As the Mars Science Laboratory (MSL) mission continues into its third extended mission, the value of automating operational procedures grows increasingly important. The

Operational Product Generation Subsystem (OPGS) of MSL is responsible for generating Level 0 products for all rover instruments (including non-imaging) and downstream Level 1 products for the engineering cameras. Mosaic imagery generated by the OPGS team on downlink assessment is comprised of data from the Navcam and Mastcam camera instruments. OPGS downlink analysts are responsible for generating key mosaics from the automatically generated single frame products for tactical and strategic operations. On Mars landed missions, data is transmitted to Earth in discrete passes that correspond to orbiter overflights, which are then assessed by representatives from each subsystem when there is a downlink assessment for the rover. Product generation at downlink assessment nominally takes 1 hour and 15 minutes to complete, and each data production process follows a specific procedure. Automating these processes reduces the time required to generate products from 1 hour and 15 minutes of intensive activity to a 10-minute validation process. Additionally, the current downlink analyst role requires up to two months training; with this automation effort, the need for learning complex procedures is greatly reduced. Beyond saving time for the analyst, automating the pilot position decreases the delay between downlink and delivering mosaics to the science users and uplink team. Giving researchers quicker access to the data is highly desirable especially as the science team is spread out across many geographic locations and time zones. It also automates and deterministically adheres to a rigid process, which allows for uniformity in all mosaic creation. In addition, it allows robustness to modifying the process as future requirements change, without the overhead of thorough user training.

TRACK 13: MANAGEMENT, SYSTEMS ENGINEERING AND COST

Track Organizers: Torrey Radcliffe (Aerospace Corporation), Jeffery Webster (Jet Propulsion Laboratory),

13.01 Systems Architecture, Engineering and System of Systems

Session Organizer: Lisa May (Murphian Consulting LLC), Daniel Selva (Texas A&M University), Dean Bucher (The Aerospace Corporation),

13.0101 Assessing the Science Benefits of Space Mission Concepts in the Formulation Phase

Marie Ivanco (NASA), Christopher Jones (NASA - Langley Research Center),
Presentation: Marie Ivanco, Sunday, March 8th, 04:30 PM, Lake/Canyon

The formulation of science-driven space mission concepts is challenging – possibly even more so than the development and production of the space systems themselves. The formulation of these missions involves defining science objectives, surveying the state of the art of instrument capabilities, documenting the Program of Record and forecasting satellite lifetimes, defining feasible alternatives for spacecraft platforms and access to space, and identifying potentially enabled applications to cite only some of the tasks faced by mission design teams. The trade space is vast, especially in an era of novel platform concepts where constellations of SmallSats are changing the current paradigm of spaceborne observations. A crucial component of the formulation of science mission concepts is the assessment of the alternatives defined in this trade space. The assessment of the concepts is so complex that a heuristic approach does not sufficiently articulates the benefits of the alternatives under consideration. This complexity can be attributed to several factors. Science missions have to satisfy multiple science goals and their associated science objectives, therefore entering the realm of multi-criteria decision problems. In addition, multiple instruments, platforms, launchers, and ground system options are combined to define the architectures. The alternatives under assessment in these multi-criteria decision problems are numerous, as are the possible components of the segments that make up the architectures. Finally, stakeholders involved in the design and assessment of these science mission concepts have varying value systems: priorities relevant to stakeholders vary from group to group based on interests, objectives, and experiences. The complexity is such that the assessment requires a deliberate and structured approach to provide a comprehensive assessment of the mission concepts. This paper presents an approach that enables the assessment of the science benefits achieved by a space mission concept in the formulation phase. The approach combines Utility and Quality assessments provided by Subject Matter Experts to produce a Science Benefit score for each identified science objective. The paper discusses how this approach was tailored for the assessment of Observing Systems in the Aerosols, Cloud, Convection, and Precipitation (ACCP) study. In this Earth Science application, Utility quantifies how important a given geophysical variable is to addressing an identified science objective, while Quality quantifies how well an architecture obtains a geophysical variable with respect to Minimum levels listed in the Science Traceability Matrix. The resulting Benefit score articulates the science capability of a given architecture to address a given objective. This paper also presents the processes implemented to obtain the assessments from Subject Matter Experts in the ACCP study.

13.0104 Optimizing Spacecraft Component Selection with Mixed-Integer Nonlinear Programming

Johannes Norheim (Massachusetts Institute of Technology),
Presentation: Johannes Norheim, Sunday, March 8th, 04:55 PM, Lake/Canyon

Spacecraft conceptual design tends to be a laborious and manual procedure, where engineers iterate on evaluating performance while having a consistent design, i.e., satisfying budgets at the system level: mass, power, link budget, etc. One interesting part of the problem is that although one could start from scratch to custom design all parts of the spacecraft, development efforts can be saved by picking existing components that satisfy the needed functionality. As a matter of fact this is generally the industry practice as it is cost prohibitive to design everything from scratch. Building a spacecraft almost exclusively out of catalog components - available commercially off-the-shelf - is especially attractive within the paradigm of CubeSats. Restricting the design to components, however, poses its own set of challenges: iterating through combinations of components that satisfy all budgets can be time consuming as one component might balance the mass budget while unbalancing the power budget. Additionally, as component catalogs keep growing, it becomes impossible to enumerate and consider all combinations, and there is a good chance to miss designs that could come at a lower cost, or a higher performance. Here a novel approach is presented applying mixed-integer nonlinear programming(MINLP), a family formulation for component selection. The research applies novel transformations methods of the nonlinear equations commonly encountered in spacecraft mission analysis and design, in combination with state of the art solvers that can use these transformations to very efficiently solve the problem. The optimization is very fast: less than a minute for the case studied, and the catalog can be expanded without an exponential growth in the solver run time. This in turn makes it very cheap to change the assumptions behind the mission and quickly enumerate optimal designs for different mission constraints. The paper presents a simple model for an Earth Observation satellite, with early conceptual design models for the communications and power system, orbital dynamics, momentum management and satellite lifetime. It then presents the general MINLP component selection formulation and transformations that were applied to the nonlinear models for each different discipline. A small catalog of real and imagined hardware options is presented for four components needed: observation payload, battery, solar cell and antenna. Four different missions are evaluated and compared where the resolution is changed from low to mid to high, and the lifetime of the satellite is changed between 3 and 5 years, showcasing the versatility of this novel method.

13.0106 Development of a Flight-Program-Ready Model-Based Assurance Platform

Arthur Witulski (Vanderbilt Univeristy), Rebekah Austin (Vanderbilt University), Nagabhushan Mahadevan , Gabor Karsai (Vanderbilt University), Ronald Schrimpf (Vanderbilt University), Robert Reed (Vanderbilt University), John Evans (NASA - Goddard Space Flight Center), Jonathan Pellish (NASA - Goddard Space Flight Center), Peter Majewicz (NASA LaRC [SSAI]),

Presentation: Arthur Witulski, Sunday, March 8th, 05:20 PM, Lake/Canyon

For the past four years, Vanderbilt and NASA have been working to create a model-based platform for evaluating the readiness of systems with significant commercial-off-the-shelf (COTS) component content to operate in a radiation environment. This approach has evolved in response to the “New Space” development challenge where COTS parts are flown ubiquitously without being vetted by conventional radiation hardness assurance techniques such as heavy-ion beam testing or physics-based simulation of radiation impact at device- or circuit level. The platform is designed to systematically assess potential radiation vulnerabilities in a spacecraft and to document how designers have evaluated the risk or chosen to mitigate that risk. The platform is named Systems Engineering and Assurance Modeling (SEAM) and implemented as a web-based, collaborative environment. The platform has two modeling aspects: systems modeling language (SysML), and goal structuring notation (GSN), from which it can produce two reliability artifacts for evaluating the mission reliability of the spacecraft: Bayesian Nets (BN) and Fault Trees (FT). On the SysML side, the system is modeled via functional decomposition diagrams (an extension to SysML), architectural diagrams via block diagram models, and fault propagation diagrams (another extension to SysML), which constitute a complete description of a spacecraft (or subsystem) with multiple functions. The GSN aspect is used to create a visual argument structure which highlights goals and strategies that can achieve the required top-level function in the given space environment for the life of the mission. These goals and strategies are supported by evidence, called ‘solutions’ typically radiation testing, mitigation strategies, or prior use that support the claims of the argument. Information in the model structures is sufficient to create topologies of Bayes nets and fault trees. Obstacles encountered while making the SEAM platform scalable include the complexity of the model, and the ability to check the SysML description with the GSN assurance argument as the system increases in capability. We designed and implemented tools to check every component and fault path to report whether it is linked with system functions of the spacecraft and the GSN assurance argument. A second issue is that spacecraft are in reality developed and evaluated on the basis of requirements, so we added the ability to create requirements diagrams in SysML and link requirements into the accountability checking previously mentioned. In the paper we will describe the capabilities added to the SEAM platform to make it capable of handling the complexity of real spacecraft development projects.

13.0107 Increasing Knowledge Capture of Space Instrumentation Using Systems Engineering Model Architecture

Bradley Drake (Los Alamos National Lab),

Presentation: Bradley Drake, Sunday, March 8th, 09:00 PM, Lake/Canyon

The iterative product development in Los Alamos National Laboratory’s (LANL) space instrumentation group requires knowledge of past, present, and expected versions of United States Nuclear Detonation Detection System (USNDS) projects. As experienced personnel leave and new personnel are introduced, a lack of sufficient knowledge retention introduces inefficiency in project development. This paper focuses on the issues of corporate knowledge loss due to personnel turnover and introduces a project architecture to be used both as a tool for increased knowledge retention and as an organizational method for new and existing researchers. Using detailed model-based systems engineering architecture and a V-Model life-cycle, we capture data developed during the project's decision-making process including major designs, costs, and risks.

13.0108 Evolutionary Formulations for Design of Heterogeneous Earth Observing Constellations

Pau Garcia Buzzi (Texas A&M University), Daniel Selva (Texas A&M University),
Presentation: Pau Garcia Buzzi, Sunday, March 8th, 09:25 PM, Lake/Canyon

The constellation and orbit design problem for Distributed Spacecraft Missions is challenging due to the extremely large space of alternatives, the presence of multiple conflicting objectives, and the expensive evaluation functions required to assess these objectives. Prior work in the literature has typically constrained this problem to simple constellation patterns that generally provide good coverage performance, such as the homogeneous Walker Delta pattern. However, this ignores potentially good architectures formed by heterogeneous constellations mixing satellites at different altitudes and inclinations. Thus, this paper studies methods to explore this part of the constellation design space which is understudied and has potential to be a cost-efficient way of satisfying coverage requirements. We adopt a framework based on multi-objective evolutionary algorithms, which have been used extensively in the literature to solve similar problems due to their ability to deal with mixed-integer problems with highly nonlinear and non-convex objective functions such as the numerical simulations required to compute coverage performance for multi-satellite systems. Moreover, we focus on formulations (i.e., chromosomes, constraints, operators) rather than algorithmic details, since it is well known that formulations are at least as critical in driving performance as the details of the optimization algorithm used itself. Specifically, we explore two new formulations for heterogeneous constellation design: (1) A fixed-length chromosome containing m 5-tuples, which encode a hybrid architecture with a fixed number of m Walker constellations at different altitudes and inclinations, where each constellation is defined by a 5-tuple consisting of altitude, inclination, number of satellites, number of planes and relative spacing parameter. In this formulation, the number of satellites in each constellation can be set to 0 to effectively reduce the number of constellations. (2) A variable-length chromosome, which encodes a heterogeneous constellation defined by the total number of satellites n_s and m 2-tuples, where each plane is defined by a 2-tuple consisting of its altitude and inclination and includes n_s/m satellites. All planes are assumed to be equally spaced in RAAN and satellites within a plane are equally spaced in mean anomaly. These two formulations are compared to a third formulation proposed earlier in the literature, which consists of a variable-length chromosome containing n_s 4-tuples to encode a constellation of n_s satellites, where each satellite is defined by a 4-tuple with its altitude, inclination, RAAN, and mean anomaly. The performance of these formulations is compared by solving different constellation design problems where the objectives are to optimize coverage and lifecycle cost. Search performance is assessed by looking at the evolution of hypervolume with the number of function evaluations. The formulations discussed in this paper were developed in the context of a NASA-funded project to develop a tool called Tradespace Analysis Tool for Constellations using Machine Learning (TAT-C ML). This tool is intended to be used during early stages of the design of Earth observation missions, and it is planned to be released open source within the next year.

13.0109 Towards Intelligent Architecting of Aerospace System-of-Systems: Part II

Cesare Guariniello (Purdue University), Linas Mockus , Ali Raz (Purdue University), Daniel De Laurentis ,
Presentation: Cesare Guariniello, Sunday, March 8th, 09:50 PM, Lake/Canyon

System-of-Systems (SoS) are composed of large scale independent and complex heterogeneous systems which collaborate to create capabilities not achievable by a single system, for example air transportation system, satellite constellations, and space exploration architectures. INCOSE SoS Primer states: “The scale, diversity and independence in a SoS makes it difficult to produce models that can accurately predict SoS-level performance”. SoS Uncertainty Quantification and Modelling and Simulation are identified as key research areas. In this work we present a methodology to accurately predict different aspects of performance for design/operation and SoS architecting, expanding previous work on intelligent architecting of aerospace SoS (Towards intelligent architecting of aerospace SoS, IEEE Aerospace 2019), by adding rigorous Uncertainty Quantification via Bayesian Neural Networks, thus addressing the research challenge posed by INCOSE. A Bayesian Neural Network is a neural network with a priori distribution on its weights. In addition to solving the overfit problem, which is common to traditional deep neural networks, Bayesian Neural Networks provide automated model pruning (or reduction of feature design space), that addresses a well-known dimensionality curse in the SoS domain. We enable SoS design/operation by using modeling and simulation, quantifying the uncertainty inherently present in SoS, and utilizing Artificial Intelligence and optimization techniques to design and operate the system so that its expected performance or behavior when the unexpected occurs (for example, a failure) still satisfies user requirements. Much of the research effort in the field of SoS has focused on the analysis of these complex entities, while there are still gaps in developing tools for automated synthesis and engineering of SoS that consider all the various aspects in this problem domain. In this expansion of the use of Artificial Intelligence towards automated design, these techniques are used not only to discover and employ features of interest in a complex design space, but also to assess how uncertainty can affect performance. This capability supports the automated design of robust architectures, that can effectively meet the user needs even in presence of uncertainty. The SoS design and evaluation methodology presented in this paper and demonstrated on a synthetic modular satellites problem has the following major parts: • Modeling and Simulation to simulate scenarios in silico, • Design of Experiments to explore the design space, • Deep Learning to develop a model which relates SoS architectural features (for example, satellites can be powered by solar arrays or fuel cells; monolithic satellite vs. fractionated into independent modules) with performance metrics such as cost or resilience by using in silico and/or field data, • Uncertainty quantification to assess the performance metrics for different architectures by employing the Deep Learning model, • Determination of the most critical architectural features that affect the SoS performance and reduction of the design space to increase the effectiveness of stochastic optimization, • Stochastic optimization of SoS to determine Pareto optimal features (choice of number of modules; power; actuator subsystems), and • Determining if any additional design/operation measures (for example, redundancy) need to be explored to further maximize the SoS performance.

13.0110 Artificial Intelligence Agents to Support Data Mining for Early Stage of Space Systems Design

Cesare Guariniello (Purdue University), Thomas Marsh (ai-one inc.), Ron Porter (Von Braun Center for Science and Innovation), Chris Crumbly (VCSI), Daniel De Laurentis ,
Presentation: Cesare Guariniello, Monday, March 9th, 04:30 PM, Lamar/Gibbon

The complex and multidisciplinary nature of space systems and mission architectures is especially evident in early stage of design and architecting, where systems stakeholders

have to keep into account all the aspects of a project, including alternatives, cost, risk, and schedule and evaluate various potentially conflicting metrics with a high level of uncertainty. Though aerospace engineering is a relatively young discipline, stakeholders in the field can rely on a vast body of knowledge and good practices for space systems design and architecting of space missions. These guidelines have been identified and refined over the years. However, the increase in size and complexity of applications in the aerospace discipline highlighted some gaps in this approach: first, the amount of available information is now very large and originates from multiple sources, often with diverse representations, and useful data for trade space analysis or analysis of all potential alternatives can be easily overlooked; second, the variety and complexity of the systems involved and of the different domains to be kept into account can generate unexpected interactions that cannot be easily identified; third, continuous advancements in the field of aerospace resulted in the development of new approaches and methodologies, for which a common knowledge database is not existing yet, thus requiring substantial effort upfront. To address these gaps and support both decision making in early stage of space systems design and increased automation in extraction of necessary data to feed working groups and analytical methodologies, we propose the training and use of Artificial Intelligence agents. These agents can be trained to recognize not only information coming from standardized representations, for example Model Based Systems Engineering diagrams, but also descriptions of systems and functionalities in plain English. This capability allows each agent to quantify the relevance of publications and documents to the query for which it is trained. At the same time, each agent can recognize potentially useful information in documents which are only loosely connected to the systems or functionalities on which the agent has been trained, and which would possibly be overlooked in a traditional literature review. The search for pertinent sources can be further refined using keywords, that let the user specify more details about the systems or functionality of interest, based on the intended use of the data. In this work we illustrate the use of Artificial Intelligent agents to sort space habitat subsystems into NASA Technology Roadmaps categories and to identify relevant sources of data for these subsystems. We demonstrate how the agents can support the retrieval of complex information required to feed existing System-of-Systems analytic tools and discuss challenges of this approach and future steps.

13.0114 Model-Based Systems Architecting with Decision Quantification for Cybersecurity, Cost, Performance

Michael LaSorda (United States Air Force, Space and Missile Systems Ctr), Ronald Sega (Colorado State University),
Presentation: Michael LaSorda, ,

The architecture selection process early in a major system acquisition is a critical step in determining the success of a program. There are recognized deficiencies that frequently occur in this step such as poor transparency into the final selection decision and excessive focus on lowest cost, which does not necessarily result in best value. This research investigates improvements to this process by integrating Model-Based Systems Engineering (MBSE) techniques; enforcing rigorous, quantitative evaluation metrics with a corresponding understanding of uncertainties; and eliciting stakeholder feedback in order to generate an architecture that is better optimized and trusted to provide improved value for the stakeholders. The proposed methodology presents a decision authority with an integrated assessment of architecture alternatives, to include expected performance evaluated against desired parameters with corresponding uncertainty distributions, and traceable to the concerns of the system's stakeholders. This thus enables a more informed and objective selection of the preferred alternative. We present a case study that analyzes the evaluation of a service-oriented architecture (SOA) providing

satellite command and control with cyber security protections. This serves to define and demonstrate a new, more transparent and trusted architecture selection process, and the results show that it consistently achieves the desired improvements. Several excursions are also presented to show how rigorously capturing uncertainty could potentially lead to greater insights in architecture evaluation, which is a robust area for further investigation. The primary contribution of this research then is improved decision support to an architecture selection in the early phases of a system acquisition program.

13.0115 Evolution of the Preliminary Fault Management Architecture and Design for the Psyche Mission

Danielle Marsh (NASA Jet Propulsion Laboratory),
Presentation: Danielle Marsh, Monday, March 9th, 04:55 PM, Lamar/Gibbon

The Psyche Mission presents the first opportunity to explore the largest metal asteroid in the solar system, (16) Psyche, which is believed to be the exposed core of a larger planetesimal that was stripped of its rocky mantle through multiple collisions during early solar system formation. The mission was selected in January 2017 for a 2022 launch as part of NASA's Discovery Program and is uniquely enabled by the integration of a Solar Electric Propulsion (SEP) Chassis delivered by SSL with JPL's core deep space avionics, flight software, and fault management architectures. One of the key design tasks is the development of a fault management system capable of being responsive to the unique elements of the combined JPL and SSL spacecraft architecture. This new design leverages the strengths of each organization, with SSL delivering its well-proven high voltage power bus and low-thrust electric propulsion subsystem from its GEO communications satellite product line, and JPL delivering its deep space mission expertise and the hardware and software most critical to deep space mission design. The development of a robust low-thrust mission and the integration of design philosophies and hardware from two organizations is not without its challenges though. A key challenge in the development of the Psyche fault management architecture and design is in the integration of design philosophies and hardware from JPL and SSL. At the architecture level, SSL GEO communications satellites are developed under the premise of highly responsive ground in the loop for the resolution of anomalies, and the implementation takes a fail-operational approach to minimize down time for its customers. In contrast, a deep space mission must be able to maintain safety with long periods of ground communication outage. Additionally, with no time-critical events after launch, the Psyche spacecraft will generally fail-safe in the presence of anomalous conditions; special consideration is being given to this approach, however, to minimize the loss of electric propulsion thrust time, which is critical to low-thrust missions. At the hardware level, the detailed definition of interfaces between JPL and SSL hardware presents a unique challenge in the development and flowdown of fault management requirements, the development and implementation of fault monitors and responses, and the development and verification of fault containment boundaries. This paper describes the evolution of the Psyche fault management architecture and design from the concept study into the preliminary design phase, with a focus on the unique challenges associated with flying GEO communications satellite hardware in deep space, implementing a robust low-thrust mission, and the integration of design philosophies and hardware from JPL and SSL. Details regarding how these challenges are addressed in the fault management design in order to maximize heritage, leverage the strengths of each organization, and minimize risk across the design are also discussed.

13.0116 A Margin Management Strategy for Low Thrust Trajectories on the Psyche Project

William Hart (NASA Jet Propulsion Laboratory),
Presentation: William Hart, Monday, March 9th, 05:20 PM, Lamar/Gibbon

In January 2017, the mission concept Psyche: Journey to a Metal World was one of two concepts selected by NASA for implementation as part of the 14th Discovery mission competition. Psyche is a deep space mission utilizing solar electric propulsion (SEP), consisting of SPT-140 Hall thrusters which have been successfully employed on multiple commercial spacecraft. The use of solar electric propulsion in deep space has resulted in challenges unique to other missions. Spacecraft designs typically balance margins across two main elements – mass and power – that are independent of one another. Utilizing a low thrust trajectory through the application of electric propulsion introduces more elements - namely flight time, missed thrust percentage and thruster duty cycle. Moreover, these elements become connected, presenting additional relationships that must be considered. This paper will present an overview of the margin management process for Psyche, and how it has evolved from the early proposal stage to its current state. It will discuss the elements that are margined, their relationship with one another, and key uncertainties that must be addressed. It discusses challenges and mitigations obtained during the refinement of the Psyche project, culminating in a new margin strategy that enables optimization across many of the system elements, and will serve as a template for future deep space SEP missions.

13.0117 Tradespace Exploration of Space Settlement Architectures Using Long-term Cost and Benefit Metrics

George Lordos (Massachusetts Institute of Technology), Markus Guerster (Massachusetts Institute of Technology), Bruce Cameron (Massachusetts Institute of Technology), Olivier De Weck (Space Systems Laboratory), Jeffrey Hoffman (Massachusetts Institute of Technology),

Presentation: George Lordos, Monday, March 9th, 09:00 PM, Lamar/Gibbon

Space systems development choices made decades ago, such as decisions for the Space Shuttle and the International Space Station (ISS), still influence and constrain human spaceflight technology development in the present day. Similarly, upcoming decisions in NASA's Artemis program and other Moon / Mars programs will likely influence the development of human spaceflight capabilities for subsequent decades. Given this, we argue that space systems architects require a new approach suitable for tradespace exploration across decades, and we have developed a new metric and tools to illustrate this approach. Typical tradespace exploration approaches trade off metrics for cost and benefit. The main families of metrics are monetary, utility and physical. Unfortunately, dollar, mass or utility metrics are fraught with weak assumptions when applied to decades-long timelines and to space settlements that will benefit from reusable rockets and in-situ resource utilization. Past work by two of the authors had proposed a new physics-based cost metric suitable for multi-decade architectures termed Lifetime Embodied Energy. Here, we propose a new benefit metric which may be of interest to diverse stakeholders and suitable for the comparison of alternative long-lived architectures: the Sustainable Long-term Growth Rate (SLGR). The SLGR has two components, a sustainability test to be defined by the architect and an average growth rate for key internal and external Figures of Merit (FOM). We show the application of the SLGR metric to a (future) long-term Mars base campaign using only Apollo-derived notional elements without ISRU, and to a case of a human settlement on Mars using future in-situ resource utilization technologies. The key FOM in both scenarios are habitable volume, stock of life support equipment and stock of consumables, as well as their derivative, which is carrying capacity of humans. We use a System Dynamics model to simulate the long-term growth, decline and stability behaviors of these FOM variables under each design option. For this model, we defined the SLGR's sustainability test as avoidance of collapse, meaning that the key FOM's per capita must remain above predefined dynamic thresholds at all times within the multi-decade model horizon. Architectures which collapse are deemed potentially fragile and discarded. For the remaining, potentially robust architectures, the growth rate of each of the key FOM across the multi-decade model horizon is its SLGR. We conclude with an assessment of SLGR compared to other metrics, a discussion of potential pros and cons, and a framing of the SLGR methodology in terms of pathfinding as opposed to traditional tradespace exploration.

13.0118 Risk and Performance Assessment of Generic Mission Architectures: Showcasing the Artemis Mission

Clemens Rumpf (MCT/NASA Ames Research Center), Oscar Bjorkman (University of California, Berkeley), Donovan Mathias (MCT/NASA Ames Research Center),

Presentation: Clemens Rumpf, Monday, March 9th, 09:25 PM, Lamar/Gibbon

Recently, NASA has initiated a strong push to return astronauts to the lunar vicinity and surface. In this work, we assess performance and risk for proposed mission architectures using a new Mission Architecture Risk Assessment (MARA) tool. The MARA tool can produce statistics about the availability of components and overall performance of the mission considering potential failures of any of its components. In a Monte Carlo approach, the tool repeats the mission simulation multiple times while a random generator lets modules fail according to their failure rates. The results provide statistically meaningful insights into the overall performance of the chosen architecture. A given mission architecture can be freely replicated in the tool, with the mission timeline and basic characteristics of employed mission modules (habitats, rovers, power generation units, etc.) specified in a configuration file. Crucially, failure rates for each module need to be known or estimated. The tool performs an event-driven simulation of the mission and accounts for random failure events. Failed modules can be repaired, which takes crew time but restores operations. In addition to tracking individual modules, MARA can assess the availability of predefined functions throughout the mission. For instance, the function of resource collection would require a rover to collect the resources, a power generation unit to charge the rover, and a resource processing module. Together, the modules that are required for a given function are called a functional group. Similarly, we can assess how much crew time is available to achieve a mission benefit (e.g. research, building a base, etc) as opposed to spending crew time on repairs. Here we employ the method on the proposed NASA Artemis mission. Artemis aims to return United States astronauts to the lunar surface by 2024. Results provide insights into mission failure probabilities, upand downtime for individual modules and crew-time resources spent on the repair of failed modules. The tool also allows us to tweak the mission architecture in order to find setups that produce more favorable mission performance. As such, the tool can be an aid in improving the mission architecture and enabling cost-benefit analysis for mission improvement.

13.02 Management and Risk Tools, Methods and Processes

Session Organizer: Jeremiah Finnigan (Johns Hopkins University/Applied Physics Laboratory), Robin Dillon Merrill (Georgetown University),

13.0201 NASA Risk Management Metrics: Evaluating the Effectiveness of the Risk Management Process

Robin Dillon Merrill (Georgetown University), John Van Sant (NASA Goddard Space Flight Center), Gerald Klein (SGT, Inc),

Presentation: Gerald Klein, Wednesday, March 11th, 04:30 PM, Madison

The goal of Risk Management (RM) is to identify and mitigate problems before they become detrimental to a project. Lessening the impact to the project from risks being realized can result in substantial monetary savings for NASA, and is critical for projects to maintain schedules and forward momentum. Realized risks, or problems, that have either already occurred or are currently inevitable regardless of the risk management

strategy, are categorized as "Issues" by NASA. The purpose of this research is to determine how well projects predict Issues from their inventory of risks. While one cannot examine Issues that were successfully prevented from occurring, we can examine if the Issues that did occur were foreseen. The researchers collected data from the project monthly reports for ten projects and compiled them in spreadsheets for further analysis. A column was created for each month to assemble a time line, recording when each Risk and each Issue were reported over the project life cycle. By organizing the Risks and Issues in this manner, the analysis examined if Issues all originated from previously identified Risks. We would propose that if all Issues were previously identified as Risks, this is an indication of a well-functioning RM process. In addition to providing this insight for each individual project, once completed for all projects, the data can be compared project-to-project, between projects of the same mission class, and between projects at specific life cycle phases. This is very valuable insight into individual projects and the overall RM process effectiveness, providing a path toward consistency, better effectiveness, and improved methods for tracking progress. For the set of projects reviewed, the results are helpful in understanding how well RM processes are documenting Risks before they become Issues, and therefore informing management of the potential problems before they arise.

13.0202 Unintended Side Effects in Complex Systems: Managing Risks and Fires

Robin Dillon Merrill (Georgetown University), Gerald Klein (SGT, Inc), Edward Rogers (NASA Goddard Space Flight Center),

Presentation: Robin Dillon Merrill, Wednesday, March 11th, 04:55 PM, Madison

Effective project management will try to mitigate risks and prevent them from becoming issues where an issue means that a problem is impacting the project's ability to meet planned commitments. If not successful in preventing the risk from becoming an issue, project management will need to take immediate action to resolve the issue and avoid more impacts. Both of these activities rely on a common, fixed set of project resources for mitigation. This dual challenge is similar in many ways to the decisions faced in other fields to allocate resources between risk prevention and problem suppression such as in wildfire management. For most of the last century, the US Forest Service has focused on fire suppression when wildfires start. Rather than allowing frequent, small fires to burn, fire suppression leads to the accumulation of dead wood and other fuels leading to larger, hotter, and more dangerous fires, often consuming the oldest and largest trees which would have survived smaller fires unharmed. Therefore, wildfire management becomes a balancing between proactive prevention and reactive suppression in a system where physical and political dynamics interact. Important lessons can be learned for NASA project managers from the wildfire management case study. Effective risk management in space projects also balances suppression and prevention activities where an effective process will avoid project "fire-fighting." Fire-fighting in project management is what happens when teams must fix problems late in the development cycle, and on most NASA projects, this needs to be done within the current resources available. Often successful fire-fighting is rewarded as heroism and is a sought after characteristic for project managers. The rewarding of successful fire-fighting can discourage future prevention activities because it is harder to recognize managers for problems that do not occur and is one of many factors that can contribute to unintended side effects. After exploring the dynamic interactions between components of wildfire management and space systems, we provide insights into improving risk management for NASA projects from our comparative case study method.

13.0203 Configuration Management of the NASA Power and Propulsion Element MBSE Model(s)

Edith Parrott (NASA Glenn Research Center), Laura Spayd (Vantage Partners, LLC),
Presentation: Edith Parrott, Wednesday, March 11th, 09:00 PM, Madison

Co-written by the NASA Power and Propulsion Element (PPE) Model Based Systems Engineering (MBSE) Lead and Configuration and Data Management (CM/DM) Lead, this paper presents a discussion of the challenges and adjustments made while applying the five pillars of Configuration Management to the MBSE environment. Particularly focused on managing MBSE models for NASA PPE requirements, it covers solutions and implementation of Configuration Management and Planning, Configuration Status Accounting, Configuration Identification, Configuration Change Management, and Configuration Verification & Audit. Additionally, this paper details how certain technical information was data managed to institute tighter controls of models while still allowing development within branches to be worked in conjunction with or outside of the formal change approval process. Traditionally, configuration management of requirements has been accomplished in published documents while team development and work on requirements has migrated to Model Based Systems Engineering (MBSE) tools. The PPE team at NASA Glenn Research Center is working to institute and mature methodology to perform configuration and data management of flight system requirements and other systems engineering deliverables within the MBSE model itself. The team presents and preserves the model as the source of truth for the requirements and relegates the requirements document to an artifact as one representation of the requirements model. Our continued development of this approach also includes plans to manage verification and validation data within the model, where possible. The paper provides some detail on tracking actions and working the technical side of MBSE modeling as well as process adaption of CM practices for workflow, status accounting, and change verification. Special considerations discussed include document security and markings (for Export Control and Sensitive but Unclassified) and IT challenges with integrating within and external to the team. We present lessons learned and identify opportunities for further process improvement and future work in an ongoing NASA project.

13.0204 Parker Solar Probe's Approach to Mission Assurance

Jennifer Fischer (Johns Hopkins University / Applied Physics Laboratory), Luke Becker (JHU/APL),
Presentation: Jennifer Fischer, Wednesday, March 11th, 09:25 PM, Madison

This reflective paper documents the successful approach to mission assurance management by the Johns Hopkins University Applied Physics Laboratory (JHU/APL), NASA's mission implementer for the Parker Solar Probe (PSP) Mission. From initial requirements formulation through launch in August 2018, JHU/APL's approach to leading and managing this decade long mission assurance effort is explored. A discussion of SMA within APL's Space Exploration Sector provides context to the paper. Implementation details of the PSP SMA approach including attributes such as responsibilities, requirements, consistency, and distributed leadership are highlighted as part of this paper. Hierarchical, Institutional, and Inter-Organizational relationships are viewed as a key driver that led to risk mitigation and overall project success. In order to manage the system of assurance on this highly complex NASA mission, clearly defined roles and responsibilities were established early within the mission assurance leadership team. Ownership and authority within these roles emulated attributes of distributed leadership empowering SMA personnel to make risk-based decisions in alignment with the ultimate goal of mission success. Early SMA engagement assisted in a clear understanding of requirements and for timely development and execution of effective mission assurance activities and deliverables. These activities and deliverables included an SMA staffing plan that was developed by taking a holistic view of the project across all mission

phases to determine how SMA involvement could be value added to the overall process. SMA staff, dependent upon project phase, were categorized into either proactive or reactive mission assurance efforts. In addition to data products and assurance activities, open communication was key and allowed for the development of effective working relationships with SMA personnel at institutional partners and major subcontractors. As a result of this approach, early SMA engagement, that was completely integrated yet independent, positively impacted the development of an efficient and effective SMA team within the project. This integration permitted value added independent assessments that were welcomed by the project team. The overall SMA approach also provided valuable opportunities for potential career growth within the SMA profession. Career growth within the profession is the ultimate risk mitigation against relearning difficult lessons. Finally, this SMA leadership approach mitigated risk by enabling the establishment of an open platform for continuous and consistent communication resulting in the effective transfer of knowledge across both SMA and the broader project team. This platform contributed not only to the overall success of the project, but also in improving the SMA process by establishing a foundational model for future projects.

13.03 Cost and Schedule Tools, Methods, and Processes

Session Organizer: Eric Mahr (Aerospace Corporation), Stephen Shinn (NASA - Goddard Space Flight Center),

13.0302 Applying System Readiness Levels to Cost Estimates – a Case Study Part 2

Patrick Malone ,

Presentation: Patrick Malone, Wednesday, March 11th, 08:30 AM, Gallatin

Applying SRLs to Cost Estimates - Part 2 looks specifically at long running Department of Defense weapon system development programs that have been chronicled in the Government Accountability Office's (GAOs) annual review of selected weapons systems and related reports. We will augment GAO's knowledge point framework with SRL methods to add fidelity that highlight areas needing additional maturity to bring the system up to the required standards. This paper assesses reports from 2009 to 2019 where we selected two programs of the 82 reviewed to analyze and contrast using their historical reports. Systems and systems of systems (SoS) continue to become more common, interrelated and complex. To understand how cost and schedule is impacted, System Readiness Level (SRL) techniques can be applied to forecast program cost and schedule to initial and full operational capabilities. A prior paper applied SRL techniques to validate the method against an actual NASA flagship program, the James Webb Space Telescope (JWST). It was demonstrated that a Technology Readiness Assessment applied to a large complex system provides optimistic results with the actual Technology Readiness Level being much lower when including system integrations. The result shown on JWST was unexpected cost growth and schedule delays. The application of SRL techniques provided a data point that adds merit and objectiveness to the method when estimating cost and schedule of weapon systems. Additionally, it isolates specific sub systems needing additional maturity during program development. Demonstrating that System Readiness Levels (SRLs) techniques work require rigor and objective assessment. Applying heuristic cost and schedule analysis reinforces capabilities for pre-development cost estimates and schedule completions within the acquisition lifecycle. Up to now, theoretical and analytical approaches are in the literature. This and the prior paper build on actual program cost and schedule history through program development. Augmenting SRL forecasting techniques to aforementioned approaches using actual program data adds to its validity. Evaluations from multiple programs begin to provide a basis for the null hypothesis and demonstrate a statistically significant approach that can influence cost and schedule estimating process improvement. While more analysis is needed, this is a first step. Moreover, cost and schedule realism at the start of “Program of Record” can be defined with higher confidence. Future research will add more program data points to enhance robustness of the method; then model enhancements can be confidently made adding to a population defining cost and schedule drivers within the systems and SoSs.

13.0303 Space Chicken: A Historical Look at How the Critical Path Changes over a Mission’s Development

Stephen Shinn (NASA - Goddard Space Flight Center), Robert Bitten (The Aerospace Corporation),
Presentation: Stephen Shinn, Wednesday, March 11th, 08:55 AM, Gallatin

The critical path in schedule analysis defines the series of tasks that have no schedule slack leading to the delivery of a system. The critical path for NASA science missions, which typically runs through a spacecraft subsystem or a scientific instrument, is dynamic and changes over the development lifetime of a project. Often the critical path at the start of preliminary design will be through a specific spacecraft subsystem while the final, delivered critical path item is often a scientific instrument that is delivered late. The research for this paper looks at the postulated critical path at different milestones, and the actual critical path item at final delivery, for a variety of NASA science missions to understand what elements are impacting the delivery schedule the most. Recommendations are made based on these quantitative results relative to what elements should potentially be considered more often in early development schedules to more robustly plan for development issues.

13.0304 Flexible Design Opportunities in Small-Satellites Launch Infrastructures

Davide Lasi (University of Bern), RICHARD DE NEUFVILLE (MIT),
Presentation: Davide Lasi, Wednesday, March 11th, 09:20 AM, Gallatin

The emergence of new small launchers for 100–250 kg satellite payloads makes the case for new space launch complexes that can support the future growing demand for launches of constellations in high-inclination and polar orbits. However, development timeline and architecture of new launchers, as well as launch demand, are uncertain. Therefore, there is great uncertainty about the economic viability of any specific design for the development of new launch infrastructure projects. This study demonstrates how flexible design of the launch facility can increase the financial feasibility of new launch infrastructure projects. We do this by comparing the economic performance of fixed and flexible designs, considering uncertainties about the type of launchers that will succeed on the markets, their development time, and launch demand. The fixed, inflexible designs involve upfront decisions to realize launches using a single propellant (solid, liquid, or hybrid). The flexible design invests only in a minimal set of initial flexible facilities that can support various propellants, while holding the option to add later propellant-specific infrastructure. The economic analysis applies Monte Carlo simulation to a spreadsheet of the discounted cash flows of revenues and expenses over the life to the project, hypothetically located in Europe, where there is a high-uncertainty about the future emergence of new launchers. This leads to estimates of the distribution of both Expected Net Present Value (ENPV) and the 5% Value at Risk (VAR) of a new launch infrastructure project. The results show that, the flexible infrastructure has a higher economic value, greater ENPV, compared to the designs for solid, liquid, and hybrid alternatives. This is because a flexible project results in an active facility no matter which technology succeeds on the market, whereas an inflexible launch facility designed around a single specific propellant may turn out to be technologically useless. The flexible design will generate positive cash flows for any future propellant pathway. These more than compensate for the higher costs of flexibility that requires a superset of facilities that allow for different propellants. The flexible design does however imply higher

initial investment, higher CapEx, than the inflexible designs. This means that, in the worst case, as when the market for launch facilities does not materialize, the flexible design has the lowest Value at Risk. This reflects the fact that flexibility in design provides a form of insurance that the facility is fit for purpose, and – as often the case, this insurance comes at a cost. The ultimate design issue is then: should we aim for all-around good performance – or bet on a specific solution which has strong risks of failure? This case study provides developers and stakeholders of new launch infrastructure with a set of principles and a practical approach to plan development in the face of substantial market and technical uncertainties. It provides guidelines for the economic assessment of new launch infrastructure, and shows how flexibility in design can hedge against risks and capture the opportunities offered by the uncertain future of large projects.

13.0306 NASA Cubesat Cost Model

Michael Saing (Jet Propulsion Laboratory / California Institute of Technology), Joseph Mrozinski (Jet Propulsion Laboratory), James Johnson , Melissa Hooke (Jet Propulsion Laboratory), Alexander Lumnah (NASA Jet Propulsion Lab),

Presentation: Michael Saing, Wednesday, March 11th, 09:45 AM, Gallatin

The “CubeSat Or Microsat Probabilistic and Analogies Cost Tool”, or COMPACT, is a NASA Headquarters funded effort to fill the gap in cost estimating capabilities for CubeSats, as well as other Microsat spacecraft. The COMPACT team has been collecting mainly cubesat mission’s technical, programmatic, and cost data to date from various NASA sponsored programs led by NASA, research laboratories, and/or universities. The presentation contents will touch up on a prototype cost modeling approach using k-nearest neighbors (k-NN), which can be used in early concept maturity study phase to get a ballpark cost estimate grounded by historic actual costs and design. The presentation will also touch up on COMPACT on its web base platform.

13.0307 Deployment Strategies for a Financially Viable Remote Sensing Constellation

Alejandro Trujillo (MIT), RICHARD DE NEUFVILLE (MIT),

Presentation: Alejandro Trujillo, Wednesday, March 11th, 10:10 AM, Gallatin

Satellite-based remote sensing can be defined as a service which obtains, processes and provides data on terrestrial scenes as gathered by imaging technologies onboard space-based assets. Several commercial imaging architectures have been deployed which vary in terms of quantity, size and capability of the satellite systems. Traditional architectures are characterized by small quantities of large, monolithic, expensive satellites as exemplified by DigitalGlobe’s WorldView family. In recent years, constellations of CubeSats have emerged as a competitive challenge to this approach, as exemplified by Planet’s Dove constellation. These large, coordinated deployments of miniaturized spacecraft trade the higher resolution payloads of large satellites for other benefits such as faster revisit times, larger coverage, and lower unit costs. Despite these benefits, an Earth-imaging CubeSat constellation is a complex engineering undertaking not without significant technical and financial risk. To that end, this paper investigates the strategic decisions that make for a successful commercial remote sensing constellation. A system model is developed to capture the impact of design and business decisions, along with external economic and technical uncertainties, which impact the success of the venture, as measured by Net Present Value (NPV). Technical parameters of the model include constellation size and deployment phasing, orbital characteristics, and coverage requirements. Major sources of uncertainty considered include demand for satellite imagery, viable price points for imagery sales, realized satellite lifetimes, launch costs, and launch failures. These uncertainties lend a stochastic nature to the output of the model which is then captured via a Monte Carlo analysis. The system model is implemented for two architectural approaches. The first is a “rigid strategy” where business decisions and cost commitments are made during the standard design phases prior to deployment, when best guesses for the realization of uncertain parameters are required. This might represent a traditional approach as might be carried over from a large satellite design effort. The second architectural approach is a “flexible strategy” which leverages the physically and temporally distributed deployment of a small satellite constellation to make responsive decisions as the future unfolds and uncertainties are better understood. The system model encodes this flexibility by (a) tying annual launch numbers to realized demand for satellite imagery and (b) triggering upgrade expenses in the event of lower than expected satellite lifetimes. Comparison of the Monte Carlo results reveals that employing flexible strategies can yield up to 30% increases in average NPV, nearly double maximum expected NPV, and improve Value at Risk (VAR) figures by as much 60% over a rigid strategy. This work confirms that commercial success of a remote-sensing constellation is as dependent on technical decisions as on the realization of an uncertain future. Thus, the most prudent course of action is to understand these uncertainties and adopt a reactive and flexible deployment strategy.

13.0308 Mission Operations Cost Estimation Tool (MOCET) 2020

Marc Hayhurst (The Aerospace Corporation), Elliott Tibor (Aerospace Corporation), Brian Wood (the aerospce corp), Cindy Daniels (NASA - Langley Research Center), Lissa Jordin (NASA), Washito Sasamoto ,

Presentation: Marc Hayhurst, Wednesday, March 11th, 10:35 AM, Gallatin

The Mission Operations Cost Estimation Tool (MOCET) is a model developed by the Aerospace Corporation in partnership with NASA’s Science Office for Mission Assessments (SOMA). MOCET provides the capability to generate cost estimates for the operational, or Phase E, portion of NASA science missions. The underlying Cost Estimating Relationships (CERs) are based upon actual historical monthly cost data from NASA Planetary, Earth Science, Explorer, and other missions. The monthly cost data has been separated into operational phases, and CERs are fitted to each phase allowing for a building block approach to generating an overall Phase E cost estimate. MOCET was first released in 2015 and has been updated annually to improve the model and incorporate the latest data from NASA science missions. A summary of updates to the tool and user community statistics for the year 2019 as well as planned updates for the year 2020 will be presented in this paper. In 2019, new missions have been added for Explorers, Earth Science, and Planetary models as well as updating those ongoing missions already found in the tool. Additional enhancement capabilities for MOCET such as CERs for Instrument Only missions, reserves capability, level II Work Breakdown Structure (WBS) estimates, and extended mission estimates will also be discussed. An overview of the state of the user community will be presented including statistics from the One NASA Cost Engineering (ONCE) model portal and software.nasa.gov.

13.0309 aView, a Browser-based Tool for Analyzing FTE, WYE across NASA Science Missions

Justin McNeill (The Aerospace Corporation),

Presentation: Justin McNeill, Wednesday, March 11th, 11:00 AM, Gallatin

When reviewing and evaluating the basis of estimate for mission phases, it is important to understand how the labor basis of estimate compares with past NASA science missions. As such, it can be very valuable to understand the labor loading [Full-time Equivalents and Work Year Equivalents (FTE/WYE)] for historical missions and how the final, actual staffing levels compare with the initially planned staffing levels for these missions at certain project milestones. The FTE Tool is a legacy, Microsoft Excel application-based plotting capability built upon a detailed repository/database of mission programmatic data. The tool has been in use and available to perform comparative analysis in staffing profiles since 2009. It provides high-level views of the historical data for over twenty NASA missions for development Phases C and D as well as the operations Phase E. FTE Tool is available via the One NASA Cost Engineering Database (ONCE). To modernize and enhance this capability, a new web browser-based application, aView, is being developed on an open source software platform: chart.js for its front-end and an SQLite database for its back-end. The name aView is short for Aerospace Viewer of NASA Project Staffing Data. As with the FTE Tool, in aView, the user may select from a set of predefined plots that give a wide variety of views into the missions' programmatic data. One can plot FTE/WYE versus dollar cost for multiple missions during specific phases of development or during operations. Other plots provided by the tool include planned versus actual annual FTE/WYE and FTE/WYE and dollar cost per fiscal year. In addition to the plotting capabilities, aView is a repository of fairly detailed mission information and data. Individual fact pages have been compiled for each mission. Each page provides an illustration of the mission's space vehicle and instruments and the associated technical data and programmatic information, i.e., estimated and/or actual program cost, major development milestones including launch date, launch vehicle, mission trajectory, links to mission website. All of the fact pages are crafted based on information drawn from the NASA Cost Analysis Data Requirement (CADRe) documents and from the project's monthly management/status reviews (MMR/MSR). This paper will discuss the general capabilities and construction of aView. In addition, the paper will explore some use cases (scenarios of application) to illustrate how this application may answer specific programmatic questions. The presentation may include a brief video or live demonstration.

13.0310 Development of the Small Satellite Cost Model 2019 (SSCM19)

Eric Mahr (Aerospace Corporation),

Presentation: Eric Mahr, Wednesday, March 11th, 11:25 AM, Gallatin

Prompted by the rise in the use of small satellites throughout the space industry in the late 1980's, The Aerospace Corporation began to study small satellites to better understand the design principles that were being employed in their implementation. These studies highlighted the fact that cost models developed for traditional large satellites were not applicable to small satellites. This led to the development of the Small Satellite Cost Model (SSCM) in the mid 1990's. This model estimates subsystem- and system-level costs for satellites weighing less than 1000 kg using cost estimating relationships (CERs) derived from actual costs and technical parameters. Over the years, SSCM has evolved to account for the increasing number of small satellites that have been launched, which has included refining the CERs and increasing the scope of the model. This paper will discuss the development of the current version of SSCM released in 2019 (SSCM19). The topics covered will include the history of SSCM, the CER generation process, updates from the previous version of SSCM, the application of the model and future efforts to enhance the model.

13.0311 Cost Estimation of Electronic Parts in NASA Space Missions

Meagan Hahn (Johns Hopkins University/Applied Physics Laboratory), Rachel Sholder (Johns Hopkins University Applied Physics Lab),

Presentation: Rachel Sholder, Wednesday, March 11th, 11:50 AM, Gallatin

This presentation provides a cost model to develop early estimates for Electronics, Electrical, and Electromechanical (EEE) parts costs during early design phases for instruments and spacecraft. Often, the EEE parts group is required to generate a detailed cost estimate for instruments and spacecraft during preliminary design phases. This requires a premature development of a Bill of Materials (BOM); it is therefore no surprise that EEE parts costs grow as a given design is refined and finalized and the required BOM is established. The aerospace cost estimating community lacks sufficient data and understanding of what contributes to EEE parts costs. This analysis seeks to identify several high level parameters that can be identified early in the design phase (pre-Phase A through Phase C) to generate a realistic range of EEE parts. This can be used to inform the estimating process, and provide program management with the potential cost risk for appropriate reserve allocation. Actual costs of JHU/APL missions, instruments, and EEE parts are used. Technical leads provide the potential cost drivers as well as the technical data. These cost drivers (such as parts class, radiation, board area, and complexity of design and requirements) are investigated through multiple linear regression analysis. The regression results are used to develop Cost Estimating Relationships (CERs) by determining the best predictors of EEE parts cost. It benefits the NASA and DoD cost communities to obtain a rough estimate of EEE cost during the design phase to more properly budget and provide a reasonable cost risk assessment

13.05 Concurrent and Collaborative Engineering in the Aerospace Industry

Session Organizer: Rob Stevens (Aerospace Corporation), Jairus Hihn (Jet Propulsion Laboratory),

13.0501 A SysML Profile for MIL-STD-882E (System Safety)

Ross Raymond (The Aerospace Corporation), Myron Hecht (The Aerospace Corporation),
Presentation: Ross Raymond, Tuesday, March 10th, 08:30 AM, Cheyenne

MIL-STD-882E is the DoD standard for Systems Safety Engineering (SSE). It mandates a process of hazard identification and tracking throughout system development, operation, sustainment, and disposal. These analyses are required to be documented in a series of reports set forth in the standard. For large systems, performing these analyses and producing the reports requires a significant effort with a corresponding cost and resource impact on the overall program. Furthermore, while such analyses should be integrated with the development processes, they are often done after design decisions are made and without the involvement of the primary development team. MBSE, and specifically the Systems Modeling Language (SysML) provides a means of integrating systems safety and the tasks of MIL-STD-882 with the design process while improving the overall capability of the system models. In this paper, we present a means of using SysML, extended through a profile, to meet the requirements of MIL-STD-882E and ease performing the system safety process. The profile, created in No Magic’s Cameo Systems Modeler tool, extends the modeling language by providing constructs for • representing and tracking hazards and their associated risk and mitigations (Task 106), • managing the analysis of the system design (Task 200 Series), • tagging hazardous and explosive material data (Task 402 and 403), • automatic generation of key reports defined in the standard (e.g. Task 301), • and provides other utilities, such as custom diagrams and model validation.

13.0503 Weaving a Digital Thread into Concept Design

Rob Stevens (Aerospace Corporation),
Presentation: Rob Stevens, Tuesday, March 10th, 08:55 AM, Cheyenne

In the last quarter century, collaborative engineering has been a chief practice used by space systems engineers to rapidly develop system concept designs. The engineering models and tools have improved over time, as has the need to link them together and share data to form a more comprehensive system representation. Models and tools used by different disciplines need to “talk” to each other to share data in a way that ultimately leads to informed decision-making. A method is presented that connects disparate models and tools together to help engineers visualize trade space options, analyze candidate designs, and compare results against requirements. To visualize vast trade space options and their impact on system performance, disparate system models are connected to create coupled plots or nomographs. Engineers and other stakeholders can use these nomographs to observe trends and “knees in the curve” as they select candidate configurations. These connected performance models are also used to provide holistic system analyses and to verify that a proposed system meets mission requirements. The outputs of these analytical models are input to a descriptive SysML model in the form of activities that verify a system’s mission requirements, thus providing a traceable framework, or digital thread, spanning across disparate functional areas.

13.0504 Applying a Model-Based Approach to Develop a Standardized Template for CubeSat-class Satellites

John Gregory (United States Naval Academy), Jin S. Kang (U.S. Naval Academy), David Kaslow , Ronald Sega (Colorado State University), George Downey ,

Presentation: John Gregory, Tuesday, March 10th, 09:20 AM, Cheyenne

CubeSats have most commonly been used by students and researchers as a cost effective means of accessing space. As demand grows for more complex space systems, however, the complexity and capability of CubeSat systems must also increase. One drawback of increased complexity is the increase in obscurity of how a change in one area of the design propagates through the rest of the system. Dealing with this added complexity takes away from student education experiences while also increasing the design cycle time, taking CubeSats further away from the key characteristic advantages that define them. One solution to this is to apply Model-Based Systems Engineering (MBSE) methodology to CubeSats, providing a standardized template that the developers can use to make the design cycle more efficient. Lately, the practice of MBSE has become increasingly nuanced and advances have focused on the application of tools and practices to aid in the development of space systems. This includes efforts concerned with the development and description of CubeSats. Most recently, the development of the CubeSat System Reference Model (CSRM) by the International Council on Systems Engineering (INCOSE) Space Systems Working Group (SSWG) has better enabled the description of CubeSat systems using common modelling language. At the U.S. Naval Academy (USNA), the Small Satellite Program has been developing and launching student-built project satellites since 2001 and CubeSats since 2012. Given the time constraints and minimal funding of an undergraduate education program, the need for a simple build template for CubeSats was recognized and the PSAT1U system was conceived. PSAT1U is a 1U CubeSat designed to be utilized as a modular architecture with easily accessible parts allowing students to focus on designing and implementing their on-board payload and mission systems without spending more time carrying out trade studies on well understood subsystems and components. The USNA has used the CSRM along with documentation from the development of PSAT1U to create a Model-Based representation of the PSAT1U system. The aim of this model is to aid in the education of undergraduate engineering students in their capstone design course as well as to reduce design and development times for future CubeSat systems. This paper will present an overview and description of the PSAT1U model, outline the design of the physical system as well as the development of the MBSE model and discuss its implementation in a classroom setting as well its potential role in the development of future systems. Finally, the propagation of system changes through the model will be demonstrated to illustrate the utility of describing a CubeSat system this way.

13.0505 Development and Application of the CubeSat System Reference Model

David Kaslow ,

Presentation: David Kaslow, Tuesday, March 10th, 09:45 AM, Cheyenne

The International Council on Systems Engineering (INCOSE) Space System Working Group (SSWG) has created the CubeSat System Reference Model (CSRM), a representation of the logical architecture of a CubeSat system, intended to be used by system architects and engineers as a starting point as they develop the logical architecture of the Space and Ground components of the CubeSat mission of interest to them. The CSRM is based on Model-Based System Engineering (MBSE) principles, is System Modeling Language (SysML) compliant, is hosted in a graphical modeling tool, and is intended to introduce quality enhancements and economies associated with reusability. The CSRM has been vetted by System Engineering professionals and has been introduced to the CubeSat mission development team community with favorable results. It has been submitted to the Object Management Group (OMG) as a CubeSat specification, and is being evaluated for that role. The SSWG has created a notional outline describing how the CSRM can be applied to a specific mission development effort; and has also identified possible future efforts to expand the applicability, value, and use of the CSRM by the satellite development community.

13.0506 Rapid SmallSat Mission Formulation: Integrated and Concurrent Modeling in JPL's Team Xc

Alex Austin (Jet Propulsion Laboratory), Robert Miller (University of Alaska Fairbanks), Jonathan Murphy (Jet Propulsion Laboratory), Kristina Hogstrom , Anne Marinan (Jet Propulsion Laboratory),
Presentation: Alex Austin, Tuesday, March 10th, 10:10 AM, Cheyenne

The Innovation Foundry at NASA's Jet Propulsion Laboratory (JPL) is developing a new tool suite for rapid concurrent and collaborative spacecraft mission architecture design with Team Xc. Team Xc is JPL's agile and rapid design team for Earth orbiting and interplanetary CubeSat and SmallSat missions of "ESPA-class" (approximately 180 kg mass) and below. Previously successful spacecraft designs that have come from Team Xc include the MarCO CubeSat mission that traveled with the Insight lander to Mars in 2018, as well as the RainCube mission that continues to operate successfully in Earth orbit. Since Team Xc began in 2013, concurrent design models and data transfer across spacecraft subsystems have been critical to its success as a rapid design center. These models allow engineers to collaborate and share information, enabling the construction of a self-consistent design by passing parameters such as mass and power between study participants. The current model framework is built using Excel and Phoenix ModelCenter, but JPL has embarked on a multi-year effort to migrate these models to a new web-based framework that gives more flexibility, features, speed, and performance. Called the Foundry Furnace, this framework is composed of three main applications: the Integrated Modeling Environment, which allows study participants to build spacecraft designs and create analysis models, the Hardware Catalog, which stores spacecraft hardware components and their associated parameters across subsystems, and the Common Resources Database, which defines the ontology that allows the individual applications to communicate with each other across a common language. The Foundry Furnace is enabling a new model architecture for Team Xc, one that allows study participants to conduct integrated analyses and trade studies across subsystems, such as resizing required reaction wheel torques based on the size of the solar arrays, within the same modeling environment. Study participants also have access to a rich catalog of hardware items which can be expanded over time as new systems become available. This paper will provide an overview of the Foundry Furnace architecture, with particular emphasis on the construction and integration of Team Xc models across multiple subsystems. Current results indicate that the model framework shows great promise in its applications moving forward, as Team Xc transitions to using it operationally for customers.

13.0507 How Your Concurrent Engineering Team Can Bootstrap Your Organizations Programmatic Capabilities

Jairus Hihn (Jet Propulsion Laboratory),
Presentation: Jairus Hihn, Tuesday, March 10th, 10:35 AM, Cheyenne

Developing space missions and especially space science missions presents many programmatic challenges. Foremost is that there are not that many missions from which to learn and that science missions typically have significant unique elements, especially planetary missions. Clearly, it is very difficult to estimate and plan any project with major unique and new elements. So, what do you do when it is necessary to generate at least reasonable cost estimates at the earliest Concept Maturity Levels (CML 1 and CML 2) and you never flew anything like this before? What do you do when you have so few historical data points that they do not span the design-cost parameter space? For example, all of ones past missions are orbiters and now we need to design and cost a lander, a rover, or an orbiter with probes. For organizations with early concept design teams such as JPL's Team X that include cost estimates as one of their products you can 'bootstrap' your available parameter reference set by combining technical and cost parameters from historical actuals, high quality design studies, and winnable proposals into a single database. The data from these not flown concepts have informational value but with greater uncertainty then historical data. They provide insight into technical and cost parameter combinations associated with mission designs that are in the 'ballpark'. This data can be used to improve our ability to estimate cost and technical parameters by providing a source of analogies as well as the ability to develop, calibrating and with the actuals validating the performance of a wide range of models. Models that use a small number of inputs with wide confidence intervals and model with greater fidelity and tighter confidence intervals. In this paper we will describe (1) the integrated Team X design-costing process, (2) the web-based database that is under development along with how the data is obtained, vetted and processed, (3)m the complete set of analogy tools, rule-of-thumb and parametric models that are maintained, (4) how everything plays together nicely (most of the time), and finally (5) the algorithms and methods used to enable combining data from different sources. All of which enables an organization to estimate early and often, Most of what is described is to varying degrees reproducible in other organizations.

13.0508 Efficient Trade Space Exploration

Alfred Nash (Jet Propulsion Laboratory),
Presentation: Alfred Nash, Tuesday, March 10th, 11:00 AM, Cheyenne

Two of the principal challenges in efficient trade space exploration are (1) quickly evaluating options, and (2) quickly convincing stakeholders to accept the results of the evaluation. This paper describes the process and tools that have led to a factor of three improvement in the efficiency of trade space exploration of space systems in Team-X at the Jet Propulsion Laboratory. The principal method that has enabled this increase in efficiency is the separation of the exploration figures of merit into two distinct types, which are then addressed in an efficient order. The figures of merit in a trade space exploration of N subsystems either scale with the number of interactions between subsystems, O(N2-N), or with the number of interactions between the subsystems and the external constraints, O(N). It is more efficient to filter against O(N) figures of merit first, and only proceed to filtering against O(N^2-N) figures of merit if warranted, than the other way around. However, the latter is the typical approach in space systems engineering organizations. In addition to the efficiencies gained through a more time efficient in/out sorting algorithm, efficiencies are also gained in interaction with stakeholders. The explanation of the elimination of options due to the external O(N) constraints on the total system such as system cost, system performance, and system technical constraints on the total system (e.g., launch mass) take less time than the O(N^2-N) “what ifs” that follow an explanation of why a particular option was eliminated due to technical inconsistencies internal to the system.

13.06 System Simulation and Verification

Session Organizer: Virgil Adumitroaie (Jet Propulsion Laboratory), James Hant (Aerospace Corporation),

13.0601 Utilizing High Altitude Balloons as a Low-Cost CubeSat Test Platform

Hunter Hall (NASA Jet Propulsion Lab), Samuel Holt , Van Duong (Georgia Institute of Technology), Matthew Chamieh (Boston University), Rohan Daruwala (University of Wisconsin), Kyle Weng (California Institute of Technology), Christine Yuan , Jonathan Chu (Harvard University), Adrian Stoica (Jet Propulsion Laboratory), Michael Lally (New York University), Daniel Jeong , Peter Soon Fah (California State Polytechnic University Pomona), Chrishma Singh-Derewa (NASA JPL), Luan Nguyen , Ramin Rafizadeh (University of Maryland College Park),

Presentation: Hunter Hall, Friday, March 13th, 08:30 AM, Lake/Canyon

While building and launching a CubeSat is lower in cost compared to a standard satellite, verifying the flight-readiness of CubeSat hardware and software prior to launch remains a costly and time-consuming process. During the summer of 2019, student-interns under the Innovation to Flight (i2F) program at the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL) utilized high altitude balloons (HAB) as a means of performing pre-verification tests on an in-house built 6U CubeSat bus and mock internal payload. The team also tested a Qualcomm Snapdragon flight computer onboard the a HAB, as the computer's first high-altitude tech demonstration. The entire flight vehicle was designed to simulate a generic JPL 6U CubeSat to be flown on the Zephyrus X HAB flight demonstration. The Zephyrus X flight demonstration took place on August 2nd and flew to a near-space environment of ~36 km (~120,000 ft) experiencing almost identical thermal and environmental conditions that it would experience on orbit as well as being far enough away from the team to test long-range comms. The entire launch cost (excluding the cost of the CubeSat) was under $1,000, showing that one could successfully test many components and conditions in one flight test for pre-verification testing, saving thousands of dollars and many hours.

13.0602 DIORAMA as a System Simulation and Modeling Tool

Matthew Carver (Los Alamos National Laboratory),

Presentation: Matthew Carver, Friday, March 13th, 08:55 AM, Lake/Canyon

The Distributed Infrastructure Offering Real-time Access to Modeling and Analysis (DIORAMA) codebase is a software framework developed to support the United States Space Nuclear Detonation Detection (SNDD) program by providing system level modeling and simulation capabilities. It offers a broad set of packages able to simulate the physics of neutron, x-ray, gamma-ray, optical, and EMP phenomenologies from emission (generic or nuclear), to propagation through the atmosphere, and sensing onboard current or future satellite constellations. Communication between satellites and downlinks to ground stations as well as analysis algorithms based on received signals are also modeled. We will present an overview of the framework, its history and purpose, as well as provide examples of its simulation functionality.

13.0603 Emirates Mars Mission Flight Simulator: FlatSat Overview

Ali AlSuwaidi (MBRSC),

Presentation: Ali AlSuwaidi, Friday, March 13th, 09:20 AM, Lake/Canyon

—The Emirates Mars Mission (EMM) was announced in July 2014, the mission is expected to launch July of 2020. Paving the road forward for the development of the

science sector in the region is one of the main objectives of the mission. EMM is led by Mohammed Bin Rashid Space Center (MBRSC), with international partners from the University of Colorado - Laboratory for Atmospheric and Space Physics (LASP), Arizona State University (ASU), and the University of California at Berkeley's Space Sciences Laboratory (UCB). Due to extremely high cost, lead time, and sensitivity associated with flight hardware; engineering models are essential when it comes to building a spacecraft from scratch. FlatSat is a term used in the aerospace field that refers to a setup with a high-fidelity representation of the flight model in both the hardware and software functionality. FlatSat provides a venue for procedure development, verification and risk reduction testing. In addition, it is utilized as a verification test to determine any changes required prior to the development of flight models, especially with low technology readiness level (TRL) components. FlatSat is used to detect interface issues between components and help resolve them. In addition, FlatSat allows that interface control document to be robust and error-free by holding high similarity with the observatory. Developing an interplanetary mission in just six years is a challenge. FlatSat has been a great asset to this mission. Starting with the development of the Electrical Ground Support Equipment (EGSE) to the final mission scenario testing and fault protection. FlatSat has been developed through three phases, phase one consisted of the basic EGSE and avionics functionality, then the communication and attitude control functionality were added as the second phase. Lastly the third phase encoded the simulated functionality for the spacecraft with the addition of payload simulators. Those three phases are lined up with the spacecraft schedule to ensure vigorous tests are performed on the units before the development of the flight models. EMM has developed two FlatSat benches, each located in a different time zone, to be operated around the clock. The time difference has strategically been applied to execute long-duration testing on one of the FlatSat test benches while keeping the other bench useable for spacecraft support. This operation has reduced some of the overhead associated with the test schedule.

13.0604 Rapid Design and Exploration of High-Fidelity Low-Thrust Transfers to the Moon

Jackson Shannon (University of Maryland), Martin Ozimek (Johns Hopkins University/Applied Physics Laboratory), Justin Atchison (Johns Hopkins University Applied Physics Laboratory), Christine Hartzell (University of Maryland),

Presentation: Jackson Shannon, Friday, March 13th, 09:45 AM, Lake/Canyon

As space agencies look to further Lunar exploration campaigns, low-thrust propulsion systems are especially relevant due to their superior propellant efficiency. This efficiency enables higher spacecraft payload ratios or the use of a smaller launch vehicle. In the extreme, a lunar exploration spacecraft with a low-thrust propulsion system can replace a substantial portion of the launch vehicle's required performance and escape from a bounded Earth orbit. This can reduce overall mission cost and enable ride-share opportunities from common orbits. For example, a small spacecraft could reasonably launch as a ride-share into a Geostationary Transfer Orbit (GTO), from which it would spiral escape over many months prior to capturing and circularizing at the Moon. This was demonstrated by the SMART-1 mission. The drawbacks of this mission type are much longer flight times and a very challenging optimal control problem to solve. The problem complexity and computational burden can force analysts to only generate locally optimal point solutions rather than developing insight into the global trade space. This work offers a computationally fast approach for generating spiral trajectories that escape Earth and capture at the Moon. With a rapid low-thrust trajectory solver, an analyst can explore the global trade space, including assessing different initial orbits as may be required for a ride-share mission, comparing target lunar orbits to meet science objectives, and varying key propulsion parameters such as thruster selection or operating power level. We solve for these end-to-end, Earth spiral escape to lunar spiral capture trajectories using a parallelized forward-backward Q-Law guidance method that is wrapped in a multi-objective evolutionary algorithm. The resulting Q-Law solutions are then used as an initial guess for direct collocation to optimize the trajectory. We selected the GPOPS-II software for the final trajectory optimization. GPOPS-II uses an hp-adaptive Legendre–Gauss–Radau collocation method and transcribes the optimal control problem into a nonlinear programming problem to be solved by the general purpose solvers IPOPT or SNOPT. All trajectory phases are constructed with continuity constraints, resulting in a continuous trajectory from GTO to the target Lunar orbit. The dynamics model can have arbitrarily high fidelity and include eclipses. We demonstrate this method on a problem inspired by the SMART-1 mission and compare our results to existing values in literature. We also present a mission scenario with a modern departure epoch and updated spacecraft specifications. This method rapidly explores the trajectory trade space and effectively provides multi-phase initial guesses for direct optimization.

13.07 System Verification & Validation and Integration & Test

Session Organizer: Leslye Boyce (NASA), Benjamin Solish (Jet Propulsion Laboratory),

13.0701 Planned Deployment of the NISAR Engineering Payload Mission Testbed

Oleg Sindiy (Jet Propulsion Laboratory), Antonette Feldman (JPL), Nicholas Zhao ,
Presentation: Oleg Sindiy, Thursday, March 12th, 08:30 AM, Cheyenne

This presentation describes the planned deployment of the supporting NISAR Mission Testbed (MTB) for the NASA JPL-provided Engineering Payload for the NISAR mission. It provides an overview of the MTB facility composition, capabilities, and known limitations; MTB team responsibilities; plans for MTB integration, checkout, and validation for certification; and details of the planned uses of the NISAR MTB.

13.0702 Developing and Implementing a Process to Verify and Validate InSight's Instrument Command Products

Nimisha Mittal ,
Presentation: Nimisha Mittal, Thursday, March 12th, 08:55 AM, Cheyenne

The InSight Mars lander is a robotic spacecraft which is investigating the interior structure of Mars through a series of seismological measurements and experiments. InSight landed on Mars in November 2018, carrying a scientific payload that includes a seismometer, a heat probe, and a suite of weather sensors. The command structure used to operate instrument activities included 'blocks' – reusable functions written in Virtual Machine Language stored onboard the spacecraft– and sequences (series of commands) that were created by teams to operate their instruments. It was vital that these blocks and sequences (collectively called command products) be thoroughly examined prior to onboard execution using a comprehensive test program to reduce risk to the spacecraft and instruments and ensure smooth operations on the surface of Mars. We designed a verification and validation (V&V) process that included reviewing each product with both instrument and spacecraft experts and exercising them through a series of in-house tools to check them for errors. Detailed test scripts were created to execute command products in higher fidelity simulators, and results were reviewed by experts. This was an iterative process and had to be repeated if command products were updated. The process had to account for inputs and participation needed from our international and domestic foreign partners. The uniqueness and complexity of each command product led to the development of various creative methods to meet functional and schedule needs. The V&V process was implemented during the months leading up to launch and landing, but some aspects of it were also used post-landing. The process successfully uncovered a number of issues ranging from minor ones such as incorrect syntax to

major ones such as the use of invalid parameters or logic that could have “safed” an instrument in flight, leading to operational delays, or worse – caused potential hardware damage. The process also helped adapt ground tools to better model onboard activities, and create operational principles to avoid unintended consequences during flight. A database was created to track command product testing details and proved useful as a reference to the flight team during surface operations. Overall, the V&V exercise helped the InSight mission meet its surface operations goals in the desired timeframe. This paper describes the development of the V&V process that was implemented on InSight’s instrument command products, its contribution to mission success, and the challenges faced. Lessons learned can not only be applied to future Discovery Class missions and projects with distributed teams, but also serve as a guideline for the development of a comprehensive test program for disparate command products in a short timeframe.

13.0703 GOES-R Series EXIS Remote Monitor and Command

Tyler Redick (University of Colorado, Boulder),
Presentation: Tyler Redick, Thursday, March 12th, 10:10 AM, Cheyenne

For large spaceflight systems, engineers, operators, and support staff are distributed across a variety of sub-contractors and physical locations. These physical separations can create logistical challenges for large missions which directly translate to negative mission costs and schedule impacts. In an ever increasingly interconnected world, there are numerous benefits to remote connectivity. This paper discusses the Geostationary Operational Environmental Satellite, R Series (GOES-R) Extreme ultraviolet and X-ray Irradiance Sensors (EXIS) Remote Monitor and Command (RMC) system used to support the GOES-17 (formerly GOES-S) Spacecraft Integration and Test (I&T) campaign at the Laboratory for Atmospheric and Space Physics (LASP) in Boulder, Colorado. While remote access to flight-critical Ground Support Equipment (GSE) is standard for many I&T campaigns, the RMC takes this paradigm one step further by providing real-time operations and test support from the sub-contractor’s home location to the spacecraft integration facility. Programmatic benefits of the RMC include reduced logistics, reduced travel, and associated cost savings. Personnel and team benefits of the RMC include reduced time away from home, less interruption to personal lives, and greater flexibility for personnel absence due to illness or other matters. Network and data security is the largest concern when operating remotely. This paper presents the RMC solution for data security and the architecture to support secure operations in real-time utilizing flight critical GSE that includes encrypted access over the internet to the sub-contractor’s remote testing facility. Virtual presence of the test-team at the spacecraft integration facility is another major concern and this paper will present the RMC solution for keeping teams integrated and connected even while each sub-contractor remains at their home location by utilizing the long-standing Goddard Space Flight Center’s (GSFC) operational voice network. A programmatic cost benefit comparison between the GOES-16 (formerly GOES-R) traditional I&T and the GOES-17 Remote I&T campaigns is presented. Risk reduction in system implementation, current limitations, and recommendations for future improvements or new systems is also discussed in detail.

13.0704 Security-Informed Verification for Space Systems

Carsten Maple (University of Warwick),
Presentation: Carsten Maple, Thursday, March 12th, 09:45 AM, Cheyenne

Verification of complex systems remains a significant challenge. It is recognised that formal verification of complex systems in open contexts (as defined by Poddey et al., 2019) is beyond current techniques and resources, fundamentally due to state explosion. On the other hand, informal methods such as simulation, have also long been recognised to have limitations; in particular their “effectiveness in finding corner-case bugs significantly decreases" over time. As such, hybrid techniques have been proposed and used in research and practice for a number of years (see Bhadra et al, 2007 for a survey of early hybridization techniques). These methods involve a mixed approach of formal and informal methods for verification, to generate a level of confidence in the system. Given that such methods cannot cover all states of the system it is important to consider which states should be prioritised to provide adequate confidence in the correct functioning of the system. In this paper we consider verification of space systems. While space systems have previously been developed by a small, closely controlled set of organisations, reduced costs and access to technology has led to a much wider ecosystem with a more diverse supply chain. This has, in turn, led to a reduction in the ability for control and oversight, as well as an increase in complexity. Coupled with this is an increase in the ability and attractiveness of attacking space systems. While verifying systems operation in open (real-world) environments is a challenge, introducing an adversary into the consideration raises the challenge by an order of magnitude. To address the challenge of assuring complex space systems in the presence of an adversary we present a novel methodology that we term security-informed verification. In order to present the concept, we discuss formal and informal techniques for verification before undertaking a threat modelling exercise to identify the threat actors, motivations and methods used to compromise space systems. We then present a methodology that combines the two approaches that results in the verification strategy being sense-checked against threat modelling, and conversely using threat modelling to inform the strategy for verification. The method provides the opportunity to redefine the requirements of the system based upon the results of the threat modelling. We illustrate the methodology by discussing the scenario of space construction performed by two space robots. Typically these robots may be considered cooperative, non-cooperative or semi-cooperative and requirements may be developed to consider the behaviours of the robots in each of these cases. Rather than modelling and verifying the system without considering an attacker, we consider the changes to the specification in the case that an attacker can control one of the robots so that it is anti-cooperative. This leads to a change in the requirements and specification before we then undertake the verification strategy.

13.0705 Integration & Test Challenges of Parker Solar Probe

Sarah Bucior (Johns Hopkins University Applied Physics Laboratory),
Presentation: Rosanna Smith, Thursday, March 12th, 09:20 AM, Cheyenne

On August 12, 2018, NASA and the Johns Hopkins Applied Physics Laboratory (APL) successfully launched Parker Solar Probe (PSP) on a mission to study the Sun, as part of NASA's Living With a Star program. As of this writing, the spacecraft has successfully completed its third close approach to the Sun and is returning new data to scientists here on Earth. The journey leading up to this point was difficult and full of many unique challenges. PSP will be flying within the corona of the sun over twenty times and traveling more than seven times closer than any spacecraft has come before (1). PSP was designed to withstand intense heat by sitting behind a first-of-its-kind Thermal Protection System (TPS), while still being able to perform all of its necessary functions. This mission required an extensive knowledge base and multiple teams working in conjunction to bring this flight to fruition. This paper will discuss some of the many difficult integration and test challenges faced leading up to launch; their origin, development, and steps that the team executed to overcome them and ensure success. The spacecraft was exceptionally complex, with multiple systems that were redundant, and required an extremely large portion of the schedule to be dedicated to testing. The Autonomy system had to be very robust as the mission is designed to have large periods of time where the spacecraft will be out of contact with the Earth. PSP was also mass constrained; all of the systems had to fit into a relatively small bus that restricted the integration order of operations and limited the amount of activities that could be performed in parallel. Due to these numerous challenges, the team had to be very flexible and adaptable to the needs of the spacecraft and the mission. From the integration of the bus at APL, to environmental testing at the Goddard Space Flight Center, to the final pre-flight processing at Astrotech Space Operations and on the Delta IV Heavy launch vehicle at the Cape Canaveral Air Force Station, PSP was a learning experience every step of the way.

13.0706 VCC Ceres: Challenges and Lessons Learned in an Undergraduate CubeSat Project

Gustavo Gargioni (Virginia Tech), Seth Hitefield , Hovhannes Avagyan (Virginia Tech), Minzhen Du (Virginia Tech), Nicholas Angle (Virginia Tech), Gavin Brown (Virginia Tech), Zachary Leffke (Virginia Tech), Stephen Noel (Virginia Tech (Space@VT)), Jonathan Black (Virginia Tech), Madison Brodnax , Bryce Clegg , Kevin Shinpaugh (Virginia Tech),

Presentation: Gustavo Gargioni, Thursday, March 12th, 10:35 AM, Cheyenne

This paper describes challenges and lessons learned throughout the assembling, integrating, and testing for hardware and software of VCC Ceres, the first Virginia Tech CubeSat built and designed by undergraduates. The project started in 2016 as part of the Virginia CubeSat Constellation (VCC), Virginia Tech (VT), Old Dominion University (ODU), University of Virginia (UVA), and Hampton University in collaboration with the Virginia Space Grant Consortium (VSGC). In July of 2019, the three CubeSats were successfully launched from the International Space Station (ISS). The project's mission is to obtain measurements of properties of the Earth's atmosphere in low earth orbit as well as to collect orbital data throughout their lifespan to develop a drag profile for CubeSats launched from the ISS. To develop the Virginia Tech's spacecraft, VCC Ceres, over 50 different undergraduate students participated. In this process, they reached many breaking points and tough decisions. This paper builds the challenges and lessons learned from assembling, integrating, and testing hardware and software. Furthermore, it describes the initial period of the operations phase, right after deployment, where the students had the opportunity to attempt contact with their satellite. This study comprises of an analytical point of view from the senior monitoring group and other engineers that work at the Center for Space Science and Engineering Research, known as (Space@VT), summarizing the experience from an undergraduate CubeSat project. The outcome of this paper is to share an experience that leads to bolster future CubeSat missions at Virginia Tech and other institutions.

13.0708 Magnetic Levitation for Spherical Drag-free Sensor Ground Testing

Abdulrahman Alfauwaz (Stanford University),

Presentation: Abdulrahman Alfauwaz, Thursday, March 12th, 11:00 AM, Cheyenne

Testing drag-free proof mass systems for gravitational physics requires a ground test system that simulates space conditions as closely as possible. In this experiment, a magnetic levitation system was built, which can levitate, hold, and spin a hollow sphere in a vacuum to simulate operations in a zero-G environment. An optical shadow sensor consisting of an infrared emitter and a pair of photodiodes is used to determine the position of the sphere. A custom-made electronic board converts the analog signal to digital. The board has a switch to reverse the current direction through the coil in case the sphere becomes magnetized and is attracted to the coil in the vacuum. Digital control code has been developed to create a stable feedback control system to drive the coil and hold the sphere in a stable levitating position. The position of the sphere can be adjusted digitally. The system is designed to achieve initial levitation and to restore the sphere to its levitating position if it drops out of lock. COMSOL Multiphysics[1] was used for thermal and magnetic simulation and system analysis. Importantly, the heat generated by the coil is not easily dissipated in the vacuum. The design is optimized to

ensure that the coil can be run for at least two hours without overheating. The sphere is spun using four coils driven by digitally generated sine and cosine functions to produce a rotating magnetic field around its equator. Operation up to 18 Hz is easily achieved. The system can be used to test the three-axis optical sensor system Differential Optical Shadow Sensor (DOSS)[2], which is being developed separately, by rapidly switching to the DOSS sensor while the sphere is levitating. Small magnetic pulses can also be used to simulate thruster perturbations in the plane orthogonal to the support axis.

13.0709 Validation on the Europa Clipper Mission in the Formulation Phase

Priyanka Srivastava (NASA Jet Propulsion Lab), Ian Harris ,

Presentation: Priyanka Srivastava, Thursday, March 12th, 11:25 AM, Cheyenne

The Europa Clipper mission will perform a detailed investigation of Europa's environment and habitability by placing a spacecraft into a looping orbit around Jupiter and performing repeated close Europa flybys. The Europa Clipper Project Verification and Validation (V&V) team is responsible for verifying that the Project System is compliant with the science and engineering requirements levied on it and validating that it is capable of meeting the mission objectives. The Project V&V team has developed a V&V framework to ensure that mission capabilities are realized at a reasonable confidence level prior to launch. The team will coordinate the validation activities defined by this framework throughout the project life cycle as the spacecraft evolves from design to implementation. Validation of space missions is typically grouped into three categories: 1) requirements validation, 2) model validation, and 3) system validation. System validation, along with verification activities, are often the primary focus of V&V programs and peak in the implementation phase. However, increasing reliance of exploration missions on models and simulations, and the complexity of the Europa Clipper mission, have dictated attention to requirements and model validation in the formulation phase. This paper discusses the development of the Europa Clipper V&V framework with emphasis on the validation of models and simulations, and of requirements. Approaches include the adaptation of guidelines in the NASA-STD-7009 document to create a formal project model V&V plan and the use of tools such as DOORS NG to plan model validation and requirement quality metrics.

13.0714 Testing Early and Often: DART's End-to-end Test Strategy

Evan Smith (Johns Hopkins University/Applied Physics Laboratory), Steven Zhan (JHU Applied Physics Lab), Elena Adams (Johns Hopkins University/Applied Physics Laboratory), Michelle Chen (Johns Hopkins University/Applied Physics Laboratory), Dmitriy Bekker (Johns Hopkins Applied Physics Laboratory), David Carrelli (Johns Hopkins University/Applied Physics Laboratory), Christopher Heistand (Johns Hopkins Univ Applied Physics Lab (JHU APL)), Justin Thomas (The Johns Hopkins University Applied Physics Laboratory), Luis Rodriguez (Johns Hopkins University/Applied Physics Laboratory), Minh Quan Tran (JHUAPL), Andrew Badger ,

Presentation: Evan Smith, Thursday, March 12th, 11:50 AM, Cheyenne

The NASA Double Asteroid Redirection Test (DART) is a technology demonstration mission designed, built and operated by the Johns Hopkins Applied Physics Lab (JHU/APL). The mission's primary objectives are to 1) achieve a hypervelocity kinetic impact with the secondary member of the binary asteroid (65603) Didymos and 2) downlink at least two images of the target with a pixel sample distance of 66 cm or better. Impact guidance is achieved using the on-board Small-body Maneuvering Autonomous Real-time Navigation (SMART Nav) system developed by JHU/APL. The SMART Nav system ingests images from an on-board imager, performs image processing and ultimately guides the S/C to impact. In parallel to SMART Nav operations, the spacecraft streams images back to the ground in real-time. At least two images are required from the last twenty seconds of imaging to achieve the desired pixel sample distance. Both on-board

guidance and real-time image streaming drive strict data latency requirements. These requirements are levied across multiple subsystems and interfaces, making verification challenging. The highly-integrated spacecraft design and compressed integration schedule also preclude DART from fully testing these data-streams on the flight system before launch. DART has prioritized an early, end-to-end system-test effort with engineering model components and high-fidelity testbeds to address these concerns. This risk reduction effort seeks to demonstrate critical interfaces with adequate data latencies well before the start of the Spacecraft Integration and Test phase. This paper describes 1) the data latency requirement drivers, 2) the resultant avionics architecture, 3) the risk reduction test philosophy, 4) the test platforms and 5) this efforts' effects on the development and execution of future system-level testing.

13.0715 More than Just Numbers on a Screen: The Dynamic Telemetry Displays of Parker Solar Probe I&T

Gregory Duerr (JHU/APL),
Presentation: Gregory Duerr, Thursday, March 12th, 04:30 PM, Cheyenne

A discussion of some of the telemetry displays and graphical user interfaces developed by the Integration and Test team for NASA's Parker Solar Probe mission.

13.08 Technology Planning, Management and Infusion

Session Organizer: Daniel Lockney (NASA), Hemali Vyas (Jet Propulsion Laboratory),

13.0801 Balancing Pragmatism and Values in Business Decision Making

Rahul Dixit ,
Presentation: Rahul Dixit, Monday, March 9th, 11:00 AM, Dunraven

Abstract— Decision making is fundamental to every business. The questions that are key to any business are 'what to do' and 'how to accomplish purpose'. In recent years, in the defense & aerospace monopsony, there has been a sea-change reversal, where now, the commercial industry is leading technological innovation, and is executing agile-product development – enabling faster time to market, with more robust products. This paper uses a mixed-methods research approach to compare and contrast portfolio management (PM) and new product development (NPD) practices in the commercial industry with those practiced in the defense industry. There are many unique aspects to the defense industry that differentiate it from many other industries. Primary amongst these is secrecy – that is, much work in the industry is classified, and/ or deliberately obfuscated. Thus there is scant published research on defense industry PM practices and NPD decision making processes. To address this, the researchers analyzed published studies on commercial industry to extract the PM and NPD decision-making factors used in large-sized commercial technology companies. And, then used peer-interviews and broad-area surveys to examine the applicability of these factors in the defense industry's PM and NPD practices. The initial conclusions are that PM and NPD decision-making processes, in both the commercial and in the defense industry share a common frame work. The factors include, market conditions, company's internal processes, and individual organization's assessment of the value-proposition. Often most decisions are made based on a combination of strategic intent and opportunistic reactions. A surprising finding is the unique role that middle managers play in the defense industry in shaping and in the outcome of PM and NPD decisions.

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13.0802 New Trends in Technology Transfer at NASA's Jet Propulsion Laboratory

Daniel Broderick (Jet Propulsion Laboratory),

Presentation: Daniel Broderick, Monday, March 9th, 11:25 AM, Dunraven

The commercial space industry is undergoing a paradigm shift from the time when governments and very large space companies dominated the industry. A confluence of laws allowing commercial space companies to operate in unprecedented ways, new technologies enabling new commercial space applications, and an influx of risk capital has drastically changed the space industry landscape. As small and medium-sized companies enter the commercial space realm, they will seek a competitive advantage, and universities and the NASA space centers are positioned to offer such advantages. The commercial space industry has recently become an active area of technology partnering and licensing, even for technologies that have experienced poor licensing performance in the past. The Jet Propulsion Laboratory is seeing unprecedented technology transfer activity in the areas of spacecraft navigation, mission design, space antennas, thrusters, radio occultation, and specialized satellites. Intellectual property rights and partnering play a crucial role in the ability of the private sector to invest in these technologies and to drive space technologies forward. Participants in this burgeoning field seek the most cutting-edge innovations to attain a competitive advantage, and it is crucial for those in the university and public sector to gain an understanding of the market forces that are driving the commercial space business.

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13.0803 Space Startup Accelerator Pilot

Edward Sewall (Jet Propulsion Laboratory), Thomas Cwik (Jet Propulsion Laboratory), Richard French (Jet Propulsion Laboratory), Andrew Shapiro (Jet Propulsion Laboratory),

Presentation: Andrew Shapiro, Monday, March 9th, 11:50 AM, Dunraven

This paper describes a 3-year accelerator pilot program with the objective of enabling or enhancing future science missions at the Jet Propulsion Laboratory (JPL) through infusion of commercial technologies from early stage companies. Success criteria for Year 1 will support a decision to proceed to the second year. The pilot is funded by a consortium from government and industry. Techstars, a leading corporate accelerator operator, supported by Starburst Aerospace, manages the program. The program accelerates growth of ten companies through seed investment, mentorship, networking, agile processes, and investor pitch development. The startups have not received prior significant investment but have core teams and some discriminating characteristics; e.g., a product with traction or a compelling technology with commercial potential. The pilot provides a pathway for maturing necessary relationships to ultimately infuse those technologies. The pilot is a pathfinder for JPL as well as future efforts sponsored by the NASA, and meets the spirit of NASA's strategic objective to align partnerships with missions and programs, increasing efficiency and effectiveness. The challenges JPL faces in partnering with startups, in particular cultural barriers and minimal experience with the entrepreneurial sector, are acknowledged. Specific success criteria acting as leading indicators of infusion are used to assess pilot efficacy across two categories: content and culture. A range of value propositions are discussed. Pre-program elements include formulation, technical sub-themes, marketing and communications, recruiting, candidate review and selection, due diligence, and conflict of interest. Key roles include mentors, program management, and partner liaisons. The actual program takes place over 13 weeks in Los Angeles, with objectives and results tracked as a group to build relationships and opportunities across the class. During the first month, the companies receive product/market fit analysis, customer discovery, technical mentoring, hiring support, investor introductions, go-to-market strategy assistance, and market understanding. In the second month, they meet potential customers and push forward commercial opportunities. In the final month, the companies work closely with program management to develop a compelling story while pushing commercial deals and building traction as well as collaborations with sponsors. Finally, each company works to secure at least one major partnership. Longer-term post-program activities lead to infusion of technologies into future missions. Other ongoing activities for class and consortium members are described. Over 300 applications to the accelerator pilot were begun with a high level of credible, applicable, and quality applications being considered in the selection. All but one success criteria met at least the threshold values, with some exceeding the goal levels. To date, JPL has engaged in multiple partnerships and commercial engagements

with program participants. JPL has purchased an electric propulsion system from Morpheus Space, which may be included in future JPL missions if testing is successful. JPL is working with Zeno Power Systems to test the feasibility of their radioisotope power system, which if successful may be an enabling technology for upcoming missions. JPL has purchased multiple licenses for SciArt's topology optimization software to facilitate design engineer activities across the Lab. Other partnership opportunities continue to develop.

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design engineer activities across the Lab. Other partnership opportunities continue to develop.

13.09 Promote (and Provoke!) Cultural Change

Session Organizer: Rob Sherwood (Aerospace Corporation), David Scott (NASA - Marshall Space Flight Center), John Ryskowski (JFR Consulting),

13.0902 Factors Encouraging the Creation of Spin-offs from Student Satellite Projects

Triin Teppo (ESTCube),

Presentation: Triin Teppo, Monday, March 9th, 08:30 AM, Dunraven

Student satellite projects are a widely used measure for introducing space technology industry to students as potential future workforce, entrepreneurs and innovators. This study presents factors encouraging the creation of space industry spin-offs from student satellite projects. Between April 2018 and June 2018, seven semi-structured interviews were conducted with the alumni of the student satellite project ESTCube-1 and Aalto Satellite Program (satellites Aalto-1 and Aalto-2), who started their own companies during or after their participation in these satellite projects. In this thesis, student entrepreneurship is being studied through the following factors previously outlined in university spin-off related research – assets related to intellectual property, knowledge and social capital, and additionally personal characteristics relevant to entrepreneurship. The results showed that the capabilities of student satellite projects depend on access to relevant human capital and the objectives of the projects. Currently the capabilities of these projects in terms of innovation and spin-off creation are limited. Nevertheless, by supporting the sustainable growth of student satellite projects and student's personal growth, student’s evolvement from being entrepreneurial to becoming entrepreneurs can encourage the creation of spin-offs, and therefore help along with emergence of new technology companies. The results also showed that students' and alumni as agents can help to supplement the missing gap of science and entrepreneurship.

13.0903 Life Cycle Assessment: A Tool for Designing Sustainable Space Technologies

Amy Landis (Colorado School of Mines), Tyler Harris (Colorado School of Mines),

Presentation: Amy Landis, Monday, March 9th, 08:55 AM, Dunraven

Life cycle assessment (LCA) is a commonly used tool to quantify the environmental impacts of a given engineered systems throughout its entire life, starting with raw materials acquisition and including manufacture, use, and end-of-life. The International Organization for Standardization (ISO) has published a series of LCA standards: ISO 14040:2006 and ISO 14044:2006. A life cycle assessment enables an engineer to identify areas of the system life-cycle that have significant environmental burdens, and then test alternative designs to reduce those burdens. LCA also enables comparison among different final product designs, comparison to competitors’ products and different product choices in the supply chain. LCA results typically quantify environmental impacts such as global warming potential, resource depletion, ecotoxicity, acidification, eutrophication, and human health effects. This research will review the basic methods for conducting an LCA and describe how these methods can be adapted to be more useful in design and evaluation of space technologies. The three LCA methodologies discussed and reviewed include: process-LCA, economic input-output LCA (EIO-LCA), and hybrid-LCA. The main challenges facing the use of LCA for design and improvement of space technologies include creating robust production and supply chain databases and adding new life cycle impact assessment categories that are relevant to current and future space applications, such as orbital debris and direct orbital volume use (i.e. the volume of space occupied in a given orbit per unit time). This research explores the use of LCA for evaluating and improving the design of a space elevator. The space elevator concept is based on simple space tether mechanics, with a carbon nanofiber ribbon attached to the Earth's equator and satellite counterbalance in high Earth orbit allowing tether climbers to gently transverse the ribbon to and from geosynchronous orbit (GEO). Though there are numerous designs published in the literature, the most comprehensive space elevator design by Swan et al. (2013) was used for this research. Three design options were evaluated: a one-tether initial space elevator, a two-tether initial space elevator, and an additional one-tether space elevator, and a utilization sensitivity analysis was completed. Between the two initial space elevator design options the two-tether space elevator showed reduced impacts in all categories, and a reduction of 50% utilization of the designed capacity would no more than double the expected impact per kilogram delivered to GEO.

13.0904 Artificial Intelligence and Machine Learning in Sparse / Inaccurate Data Situations

Rahul Dixit ,

Presentation: Rahul Dixit, Monday, March 9th, 09:20 AM, Dunraven

Abstract— Machine Learning (ML) and other artificial Intelligence (AI) techniques have been developed for real-time decision making, and are gaining traction in data-rich situations. However, these techniques are less proven in sparse-data environments, and at present are more the subject of research than application. Typical implementations of ML and AI require a cross-disciplinary decision engine that, once "trained," can cognitively respond to changes in input. The key to successful training is to a) have a defined decision-basis (answer-key), and/or b) facilitate sufficient learning, both of which require ample data (observability) and ample time for the machine to develop a logical outcome. Much research has been focused on developing decision algorithms using various logical formulations, dimensionality reductions, neural techniques, and learning reinforcements for tasks that traditionally require human intelligence. What is missing in most current research streams are implementations of ML and AI for decisions that are fundamentally rooted in human intuition and empathy, e.g., situations in which the decision requires a holistic view and the outcome is based on a qualitative judgement based on context and fact. This paper is intended to benefit a wide range of readers considering Artificial Intelligence, from the merely curious to "techies" from other disciplines to experienced practitioners and researchers. Using a qualitative/ characteristics base perspective of data and AI, we examine defense industry procurement, operational, tactical, and strategic decision scenarios, then identify where AI can currently promote better informed decisions and which arenas need would benefit by letting AI technology and sophistication evolve further.

13.0905 Shared Leadership and Just Culture: Tools to Promote SMS Hazard Reporting

Bettina Mrusek (Embry Riddle Aeronautical University),

Presentation: Bettina Mrusek, Monday, March 9th, 09:45 AM, Dunraven

Overview of shared leadership and a Just Culture. Emphasis on how they can be leveraged to improve communication within an aviation maintenance environment in an effort to promote safety management system hazard reporting. The role of human error is also discussed within this context.

13.0907 Strategic Evolution of the Innovation Lab at the Aerospace Corporation

Rob Sherwood (Aerospace Corporation),

Presentation: Rob Sherwood, Monday, March 9th, 10:10 AM, Dunraven

Rapid changes in the National Security Space domain require new innovative approaches to keep pace with our adversaries. In this presentation, I will describe the programs we created to stimulate an innovative culture at the Aerospace Corporation, how those programs and the organization have evolved to address customers' strategic needs, and examples of employee innovation that have resulted from those programs.

TRACK 14: GOVERNMENT PLANS, POLICIES AND EDUCATION

Track Organizers: Dave Lavery (NASA Headquarters),

PANEL 14.01: Competition Robotics for Education and Workforce Development

Session Organizer: Dave Lavery (NASA Headquarters),

PANEL 14.02: Technology Development for Science-Driven Missions

Session Organizer: Patricia Beauchamp (Jet Propulsion Laboratory),

PANEL 14.03: Emerging Technologies for Mars Exploration

Session Organizer: Charles Edwards (Jet Propulsion Laboratory),

PANEL 14.04: Access to Space and Emerging Mission Capabilities

Session Organizer: Eleni Sims (Aerospace Corporation),

PANEL14.05: Model-Based Engineering – Paradigm Shift or Business as Usual?

Session Organizer: Sanda Mandutianu (Jet Propulsion Laboratory),

PANEL 14.06: Progress and Plans for The Deep Space Human Exploration Architecture

Session Organizer: Marshall Smith (NASA HQ), Erin Mahoney (Stardog Union),

PANEL 14.07 : Mars Exploration Science: Mars Sample Return and Beyond

Session Organizer: Michael Meyer (NASA HQ),

PANEL 14.08: ISS Transition and the Commercialization of LEO

Session Organizer: Robyn Gatens (NASA - Headquarters),

PANEL 14.09 : Mars Helicopter Flight Experiment

Session Organizer: J (Bob) Balaram (Jet Propulsion Laboratory), Benjamin Pipenberg (AEROVIRONMENT, INC), Matthew Keennon (AV Inc.), Havard Grip (Jet Propulsion Laboratory),

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