Cyber–Physical Systems: Close Encounters Between Two Parallel Worlds

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I. EMERGING TRENDS IN THE PHYSICAL WORLD

Technology, science, and engineering continue to redefine physical world capabilities. Take mobility of humans, for example. In the 20th century, transportation systems moved us to unimaginable distances, speeds on earth and made us set foot on the Moon. *Star Trek* popularized teleportation, a fictitious technology that instantly allows us to "go where no person has gone before." Before end of the century, Internet and wireless networking helped to create the parallel "cyber world," virtually "teleporting" us great distances to interact with remote objects, people, and places. In the new millennium, our restless society's need for such ground-breaking capabilities in time and space has never been greater.

Today the world is at unfamiliar crossroads, facing formidable challenges intimately connected with daily life and economic fabric. Human mobility on roads in the United States illustrates the gravity of these challenges. Despite sophisticated vehicle features, every year, road accidents cost thousands of fatalities, millions of injuries, and billions of dollars. Traffic congestion expends billions of gallons of fuel and man hours and increases greenhouse gas emissions. Most industrial sectors across the globe, such as aviation, medical, and energy, are suffering severe limitations and not having the growth capacity to meet future demands of society. People meanwhile aspire for capabilities to enhance physical, mental, social well-being and to safely, independently, economically, comfortably experience the physical world. A revolutionary breed of systems is central to quickly, affordably meet these ominous technical, economical, and societal challenges.

II. CYBER–PHYSICAL SYSTEMS OF TODAY AND TOMORROW

Cyber–physical system (CPS) is a promising new class of systems that deeply embed cyber capabilities in the physical world, either on humans, infrastructure or platforms, to

transform interactions with the physical world. Advances in the cyber world such as communications, networking, sensing, computing, storage, and control, as well as in the physical world such as materials, hardware, and renewable "green" fuels, are all rapidly converging to realize this class of highly collaborative computational systems that are reliant on sensors and actuators to monitor and effect change.

A core differentiator of CPS is the tight conjoining of and coordination between cyber and physical resources, which yields unprecedented capabilities. Traditional cyber systems were usually considered to be the passive, "dumb" part in the physical world, but with CPS, we have to now take into account what is being moved or changed in the physical world. A major difference between CPS and a regular control system or an embedded system is the use of communications, which adds reconfigurability and scalability as well as complexity and potential instability. Furthermore, CPS has significantly more intelligence in sensors and actuators as well as substantially stricter performance constraints. Today, examples of nascent CPS are emerging across sectors, such as flight control and electrochromic cabin windows in airplanes, adaptive cruise control and antitheft devices in cars, location services in cell phones, field devices in power grids, pacemakers in humans, robotic vacuum devices at homes, entertainment, gaming, and haptic systems. However, many existing systems either do not focus on cyber–physical interactions or are far more capable of richer cyber–physical interactions.

Tomorrow's CPS is expected to enrich cyber–physical interactions by intimately coupling assets and dynamics of the physical and engineered systems with the computing and communications of cyber systems, at grand scales and depths from nanosystems to geographically dispersed systems-of-systems. Cyber capabilities are embedded in every physical process and component (e.g., brakes and engines of vehicles), networking is employed at multiple and extreme scales, complexity lies at multiple temporal and spatial scales, dynamics exist in system reoganization and reconfiguration, high degrees of automation and control loops close at all implemented scales, system longevity ranges from years to decades (e.g., buildings, aircraft), and extreme heterogenity is seen across devices and protocols. This vision makes a phenomenal leap, significantly undermining capacity and capabilities of the state-of-the-art, enabling systems that human lives and public weal can depend and thrive on.

The healthy and competitive future of public and private sectors, such as transportation, power grid, medical, energy, environment, defense, law enforcement, and construction, heavily relies on CPS applications. Advances in CPS can make applications faster, more spatially and temporally precise (e.g., telerobotic surgery), robust to hostile or inaccessible environments (e.g., autonomous search and rescue, disaster recovery), perform distributed coordination of large scale systems (e.g., automated road and airspace traffic control), demonstrate high efficiency (e.g., zero-net energy buildings), augment human capabilities (e.g., body sensor nets, brain–computer interfaces), and enhance quality of life (e.g., ubiquitous healthcare). Cyber–physical coupling itself has enormous impact. For example, the coupling can define a "DNA" fingerprint in the cyber world to virtually realize human DNA forensics. User-specific features, such as age, physiology, psychology, cultural properties, can be brought into the system design to outperform present day systems designed for the universal user and some individual user preferences. CPS promises to hence streamline paradigm shifts in our society.

III. COMPLEX INTERFACE AND INTERACTIONS BETWEEN CYBER AND PHYSICAL WORLDS

The design and realization of the complex interface between cyber and physical worlds for flawless interactions is not easy. Relentless, concurrent nature and laws of physics govern our world, as opposed to discrete and asynchronous nature of the cyber world. The most alarming factor is that human lives depend on this interface, and mission objectives and system performance goals are expected to be enhanced multiple folds. Nanoscale timing and spatial precisions, 24/7 availability, 100% connectivity, predictability and repeatability, are extremely critical for the cyber–physical interface. It is hence vital to build new theoretical foundations, scientific models, abstractions, and clear demarcation between cyber and physical worlds for the interface, and rethink or reinvent interface functions, such as coordination, integration, monitoring, and control.

CPS changes the notion of the physical system (e.g., aircraft, vehicle) to include human, infrastructure, and platform in a system-of-systems, creating a uniquely large scope and context in which the system behavior must be predictable and provable. The resulting systems-of-systems are highly networked and dynamic in nature, with complexity, e.g., software size, growing at an exponential rate, with increasing time-critical interactions between purely physical elements and highly intangible cyber elements. Current approaches to system design, development, certification, and operation are not sufficient to produce such systems. Hence, we are reaching a tipping point today in our ability to handle complexity and dependability of the cyber–physical interface and interactions.

IV. GRAND CHALLENGES AND SOLUTIONS IN CPS

The goals of CPS applications are unprecedented and solution impact is far-reaching; for example, how to achieve instantaneous, accident-free, energy independent, zero emissions, and affordable mobility in road transport; how to design systems that provide features and behaviors

demanded by the customer and regulating authorities, yet require minimal development, software, and certification costs, enable push-button verification and validation, demand zero prototypes, and with zero defects and no recalls. Responding to such challenges requires dramatic advances in the state-of-the-art. A clean-slate, multidisciplinary approach is warranted to understand and develop science, models, abstractions, methods, architectures, and solutions for CPS, presenting an extremely fertile area for ground-breaking research and technologies.

Analytical techniques must evolve at an accelerated rate for CPS design and analysis. Most existing tools are designed to help us reason about single dimensions, and not a multidimensional cyber–physical state space. A dramatic increase in the ability to perform true cyber–physical codesign—where the physics of surface friction, moments of inertia, and computer hardware and software behavior can be simultaneously observed—is critical to advance both how CPS is engineered and how it is deployed. Testing and analyzing a CPS is expected to be challenging even in a simulated environment; the challenges multiply as testing progresses to "hardware in the loop" and target platform (e.g., flight test and vehicle test tracks).

Tomorrow's CPS must be able to adapt rapidly to anomalies in the environment and embrace the evolution of technologies while still providing critical assertions of performance and other constraints. Whether the anomaly is a degraded performance of sensors, a failure of another connected system, or an infrastructure malfunction—naturally, accidentally, or maliciously induced— these systems must adapt to whatever situations they encounter and virtually heal to yield the best possible system performance under those conditions. Advances need to be made in how these systems are designed and implemented, and in the supporting infrastructures, to make this capability viable.

Active or passive human participants are an important component as more assistive and autonomous behaviors emerge in CPS. Understanding and developing systems that are intuitive and that integrate with human behaviors in high-stress environments are essential in communicating critical information and supporting decision processes of drivers, pilots, and other vehicle and infrastructure operators. While we have significant data and experience with the systems of today, the degree to which human behavior has been modeled and incorporated into system design has varied. Many of the envisioned CPS goals, i.e., zero fatalities, can only be met by designing systems with a comprehensive formal understanding of human behavior under varying situations including emergency or stressful scenarios. Research gaps, such as human behavior abstraction and representation and bridging natural language representation and formal language framework, are needed for CPS design, development, and operation.

Certification and validation of today's systems, such as in aviation, is a long, difficult, and extremely costly process. As these systems morph into complex CPS with critical electronics in the control of the physical components, the probability of undesired emergent behaviors during runtime interactions only increases. The current practices of "testing in quality" or "postfacto certification" prove to be methods that sometimes are ineffective in persuasiveness and costs. New, cost-effective, time-efficient verification and validation tools and techniques are needed that scale to CPS state spaces and systems-of-systems, as well as handle mixed-critical interactions. These must be applicable to industrial-sized CPS with tens of millions of lines of code, tens to hundreds of nodes per platform, thousands of nodes across platforms, and usable by engineers, enabling cost-effective and timely development of dependable, certifiable systems.

Dramatic and rapid changes in engineering practice and education

are needed to institutionalize the advances of CPS. A strong, vibrant, and knowledgeable workforce is crucial for the short-term energizing and long-term health of the socially and economically crucial areas of CPS. These high-quality technical personnel must be capable of working in a multidisciplinary realm with complex, safety-critical, life-critical requirements. The current educational and workforce training frameworks are not sufficient to meet these needs. CPS ties multiple academic disciplines, hence requiring course offerings that combine, for example, control theory and embedded system computing, computer science with engineering and computational physics, and computer science and engineering with anthropology and sociology. Software developers and testers must transition from traditional testing methodologies to new formal-analysis methodologies. Policy makers must be educated to understand safety, reliability, and security challenges and requirements involved with emerging cyber–physical interactions.

CPS commonalities among industrial sectors are substantial and significant. For instance, a recent workshop claims up to 60% commonalities exist across transportation domains.[1] Several sectors share a common vision of future systems as well as technologies, such as GPS and wireless networking, which must demonstrably satisfy safety, reliability, and security requirements. Sectors also share core technology areas such as distributed control and autonomy, mixed criticality, long-lived platforms and infrastructure, verification and validation, model-based design and development, and tool chains. For instance, automotive, aviation, and medical sectors are moving to an infrastructure characterized and enabled by distributed collaboration and autonomy. Cooperative cruise control will soon be a reality in vehicles, air traffic management systems will begin distribution of air traffic control tasks

[1]http://www.ee.washington.edu/research/nsl/aar-cps/NCO_June_2009.pdf.

between aircraft and ground control centers, and medical devices will collaborate to provide care for a patient. Recently, sector-specific communities have organized national and international workshops to establish a CPS view of critical infrastructures and critical infrastructure protection. However, despite a commonly shared interest across different sectors, current research thrusts are typically dedicated to individual sectors, or even individual domains within each sector.

V. FUTURE CPS COMMUNITY EFFORT

Acknowledging the unprecedented intricacies, critical challenges, and the significance of the economic, technical, societal impact of CPS, the PROCEEDINGS OF THE IEEE will have a special issue in the future. The special issue will bring different sectors, including aviation, automobile, energy, medical, and manufacturing, to highlight the sector-specific challenges, commonalities, and re-search directions in CPS. The role of key academic disciplines, including sensing, networking, communications, control, safety, and security, in CPS foundations, methods, tools, and applications will be explored. The collection of papers in this special issue will offer leading experts views of the present and the future of CPS as well as advances and innovations in science, design, development, testing, certification, applications, and education. ∎