The Coordinated Control of Space Robot Teams for the On-Orbit Construction of Large Flexible Space Structures

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***Abstract*—Teams of autonomous space robots are needed for future space missions such as the construction of large solar power stations and large space telescopes in earth orbit. This work focuses on the control of teams of robots performing construction tasks such as manipulation and assembly of large space structures. The control of the robot structure system is difficult. The space structures are flexible and there are significant dynamic interactions between the robots and the structures. Forces applied by the robots may excite undesirable vibrations in the structures. Further, the changing configuration of the system results in the system dynamics being described by a set of non-linear partial differential equations making the control problem difficult. Limited sensing and actuation in space present additional challenges. The approach discussed here is to transform the system dynamics into a set of linear time-varying ordinary differential equations. The control of the high-frequency robots is decoupled from the control of the low-frequency structures. This approach allows the robots to apply forces to the structures and control the dynamic interactions between the structures and the robots. The approach permits linear optimal control theory to be used. Simulation studies and experimental verification will be presented.**

I. INTRODUCTION

A. Motivation

The construction of large solar power stations and large space telescopes will require multiple robot teams of space robots because the structures are too large and the space environment is dangerous for astronauts (see Fig. 1) [1][2][3]. These teams might include free-flying observation robots for measuring system's state, robots for transportation and manipulation of components; and robots that can walk on structures during assembly [4].

The control of robot teams manipulating large space structures that experience changing geometry during construction and significant dynamic behavior is difficult. Structural vibrations present a major problem [4][8]. Practical considerations such as the robots' high joint friction and nonlinear thruster actuation also make the construction and assembly of large flexible space structures using space robots challenging.

B. Objective

The objective of this paper is to outline briefly some recent work on this problem. Control algorithms are developed to enable teams of space robots to manipulate and assemble large flexible space structures while minimizing residual vibration and operating in limited time, subject to limited sensory information and limited actuation.

C. Approach

The system dynamics consist of highly nonlinear partial differential equations (the structures) and highly nonlinear ordinary differential equations (the robots). The approach is to transform these equations into a set of time-varying linear equations. The system control decouples the low natural frequency structures from the control of the high frequency robots. The robots to serve as interactive force sources that

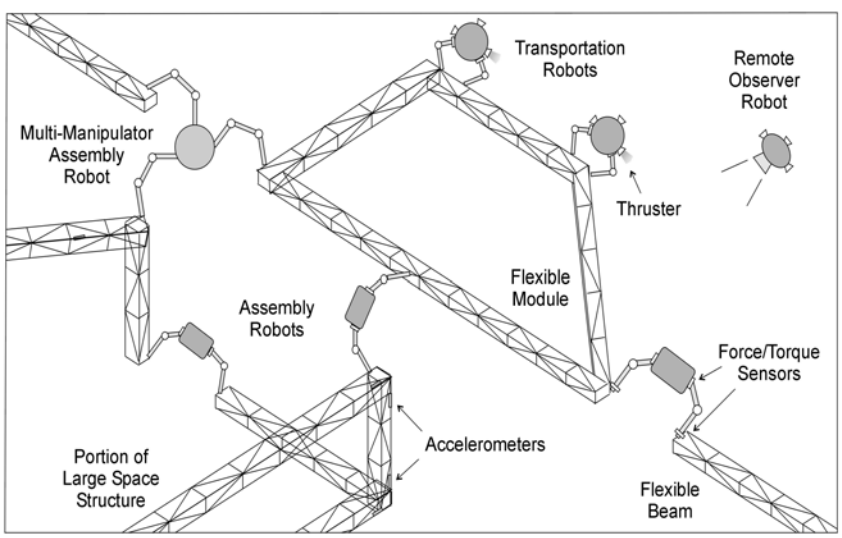

Fig 1. On-orbit construction of large flexible space structures by heterogeneous robotic teams

apply forces to the structures. Linear optimal control methods are used to find the forces that position the structures while minimizing their vibration. This approach needs to have a good knowledge of the structural vibration and to have high precision. The control architecture considers limited sensing and actuation.

II. Background and Literature

Mission concepts for the construction of future large space structures have been proposed using robots for the transportation of raw materials and assembly of the structures [3][4][5][6]. To date, assembly of simple structural elements has been demonstrated only in the laboratory [7].

The on-orbit robotic assembly of large flexible structures is challenging because of vibration caused by the dynamic interactions between the lightweight and low damping structures [4][8]. The coordinated control of multi-robot teams to manipulate large flexible large space objects has not been well studied. Studies have looked at cooperative control of teams of robots on earth [13][14][15][17]. However, these studies do not generally consider dynamic interactions between teams of robots, a major issue in this problem. Dynamics has been included in planned trajectories for simple mobile robots with payloads, but without considering flexibility or where the resulting vibration is treated as a disturbance [16][17][18][19].

Studies have begun to examine multi-robot on-orbit assembly for cases with dynamic interactions between the robots. These studies have shown the challenge of this work due to stability issues, the complexity of coordinated control, and the excessive use of robot reaction jet fuel [8][20][21]. Recently, studies have shown that controllers can be developed to solve the problem [8][20]. These are briefly reviewed in the following technical discussion section. These results show that sensing, knowledge of the state of the structure, and precise control of the actuation of the robots manipulators and thrusters is critical to control effectiveness.

Sensors must measure structure's state including vibration and rigid body motions. Large numbers of accelerometers mounted on a space structure can be used to provide the state feedback. However, practical issues such as weight, complexity and reliability limit the number of sensors that can be used in space. Remote vision sensors and laser range finders can see large areas of the structure but are limited by scan rate. An effective sensor fusion estimation method called Fused Sensor Estimates (FSE) has been developed to estimate mass properties, vibration modes as well as rigid body motions for large space structures by combining acceleration and vision sensors to overcome the individual limitations of each [9][10]. FSE is used in the results presented here.

The controllers presented here require high precision motion and force control using space robot thrusters and manipulators. The controllers rely on precise actuation and the ability to measure forces and torques. Light-weight space systems with high gear ratio transmissions and dry lubrication have high nonlinear Coulomb joint friction that corrupt the fidelity of the actuator's outputs. Similarly, thrusters or reaction jets used by the robots are also highly nonlinear and imprecise. For this work a control method called Base Sensor Control (BSC) provides precise estimates for nonlinear thruster behavior and the joint torques [11][12].

III. Technical Discussion

In this section, a controller for the manipulation and assembly of large flexible structures is presented. First, the method is outlined. Then results for three cases are shown. These cases are:

(a) Two free-flying robots are transporting a structural element while minimizing fuel and vibrations.

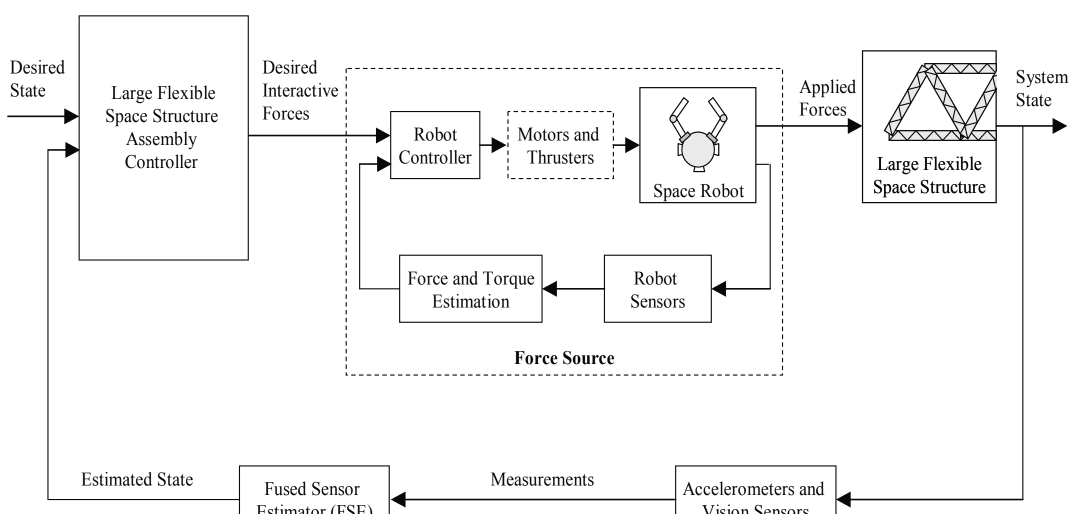

Fig 2. Block diagram of large space structure assembly controller

(b) Two robots mounted on a partially assembled large flexible structure are adding a beam to the structure while minimizing vibrations of the beam and the base structure.

(c) Three free-flying robots are assembling three large flexible structural elements to form a subassembly while minimizing the vibration of all the elements.

A. Flexible Controller

A block diagram of the decoupled controller is shown in Fig. 2. The control approach is to decouple the control of the high-frequency robots from the control of the low-frequency structures. The inner loop shows a space robot controlled as a force source. The space robot's end-effectors apply forces to the large flexible space structure. The outer loop shows the large flexible space structure controlled by the applied forces. Fig. 3 shows details of the large flexible assembly controller. A nominal assembly plan is developed neglecting flexibility. Then a linear time-varying dynamic model of the system including flexibility is constructed. Finally, linear quadratic (LQ) methods are used to find the optimal control forces that make the system follow the nominal motions while minimizing vibration.

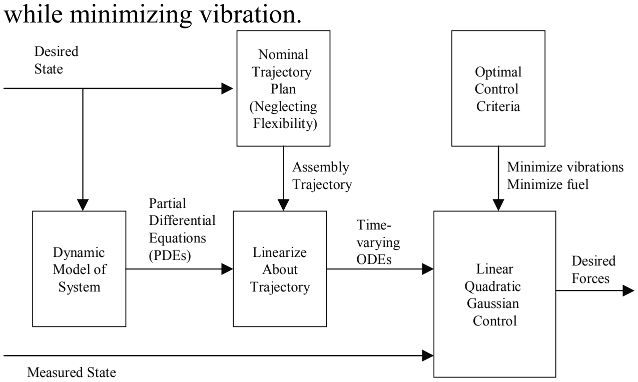

Fig. 3. Details of flexible assembly controller.

B. Estimation of Forces and Torques (BSC)

The controller requires the robots to apply the desired forces from the LQR to the structure despite such nonlinear effects as joint friction and thruster nonlinearities. These effects can be measured using a number of complex sensors. This is not very practical. However, it has been shown that a single sensor placed between the manipulator and the space robot can provide estimates of both the joint torques and the reaction jet forces [11][12]. This method, called Base Sensor Control (BSC), is here. Fig. 4 shows a block diagram of BSC.

C. Estimator for System State Using FSE

The Fused Sensor Estimator (FSE) discussed earlier is shown in Fig. 5 and is used to estimate the structure state [9][10]. Here the advantages of onboard accelerometer sensors and vision sensors carried on free-flying robots are exploited by using them in concert. The high spatial resolution provided by the vision system is complementary to the high temporal resolution provided by the structure-mounted accelerometers. In this approach, the low-frequency vision data is fused with high-frequency acceleration measurements in a nonlinear Kalman filter to provide an estimate of the flexural generalized coordinates.

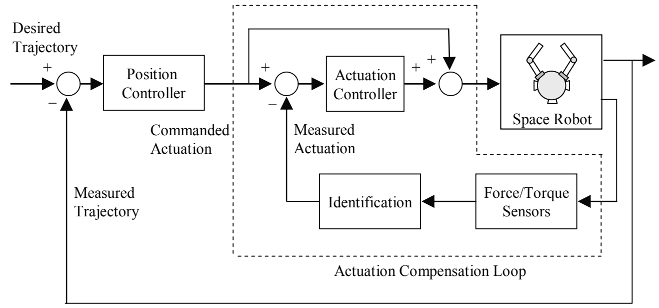

Fig. 4. Base Sensor Control (BSC). Inner loop identifies and compensates for actuator efforts while outer loop tracks desired trajectory

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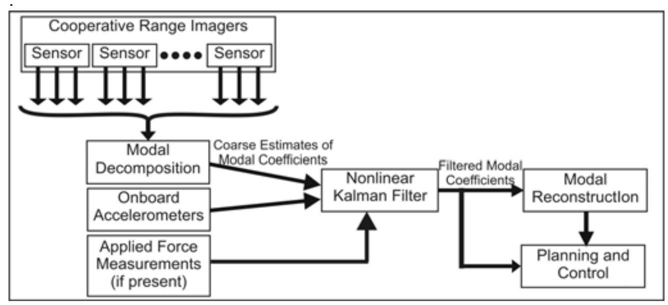


Fig. 5. FSE Estimation architecture

D. Examples of Controller Performance

In the first example, shown in Fig. 6, two robots transport and rotate a flexible structural element. Fig. 7 shows the displacement at the tip end for the decoupled controller. This is compared to a thrust only controller for reference. The decoupled controller substantially reduces vibration.

In the second example, shown in Fig. 8, two space robots mounted on a flexible structure assemble a large flexible beam. The forces the robots apply to the structure are controlled to perform the manipulation task. The robots exploit redundancy to improve performance and to avoid collisions. The robots are able to maneuver the beam accurately while only exciting low residual vibration in the beam and the supporting structure. Fig. 9 shows that the base reaction forces for the flexible structure are reduced by the control method.

In the third example, shown in Fig. 10, three space assembly robots bring the ends of three beams together while minimizing residual structural vibration. Fig. 11 shows the position and velocity errors for the lower right hand corner. When the structure is assembled with a nominal controller, the structure continues to vibrate after the beams reach their final position preventing final assembly. The controller eliminates this residual vibration.

As discussed above, the decoupled controller relies on precise control of the robot joint and thrusters using Base Sensor Control (BSC). Results for a sample satellite capture task are given in Fig. 12. Both the robot's reaction jet thruster forces and joint friction are estimated from a single force/torque sensor mounted between the spacecraft base and the manipulator. It can be seen that the actual force values experienced by the spacecraft are substantially different than the commanded values. However, the BSC method provides good agreement between the estimated actuation value and the actual value.

The decoupled controller also uses the Fused Sensor Estimates (FSE) of the vibration and rigid body motions of the flexible space structures. Sample experimental results combining accelerometer and vision sensing are shown in Fig. 13. These were taken using the system shown in Fig. 14 and discussed below. A range of sensor configurations that meet the specification are shown. One configuration that meets the specifications uses 3 accelerometers and a vision sample rate of 9-Hz . In the cases studied it was found that using the sensors together the significantly reduced the demands on a single sensor suite.

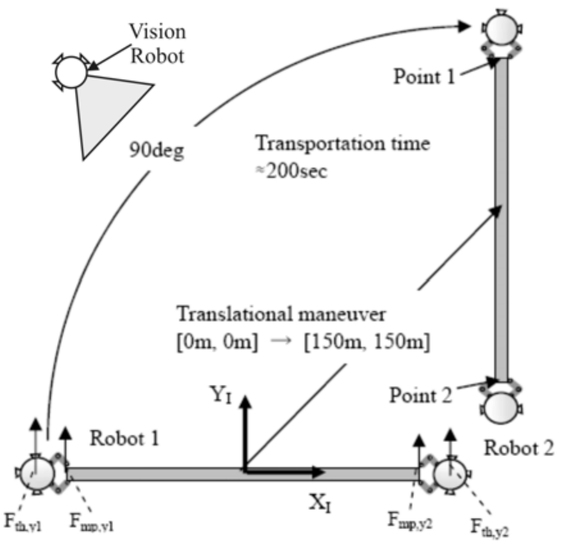


Fig. 6. Transportation maneuver using a team of robots.

IV. Experimental Validation

Controllers discussed above are currently being experimentally validated using a system called the MIT Microgravity Robotic System Testbed. The testbed consists of a granite table platform for space robot assembly experiments (see Fig. 14). Free-flying robots float on porous air bearings emulating 2D weightless conditions (see Fig. 15). Each robot has two 2DOF manipulators and eight thrusters. Force/torque sensors are mounted on the robots along with joint encoders and spacecraft state sensors. The robots can operate in free-flying mode (thrusters on) or free-floating mode (thrusters off) while the end-effectors track trajectories or firmly grasp floating flexible space structures.

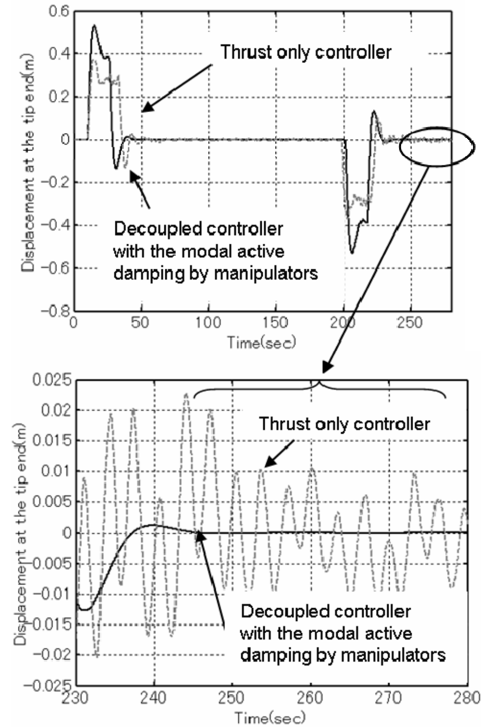


Fig. 7. Residual vibration during transportation reduced with decoupled control.

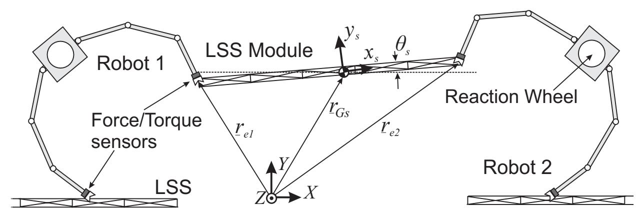


Fig. 8. Model of robots manipulating a large flexible space structure module (module is not drawn to scale).

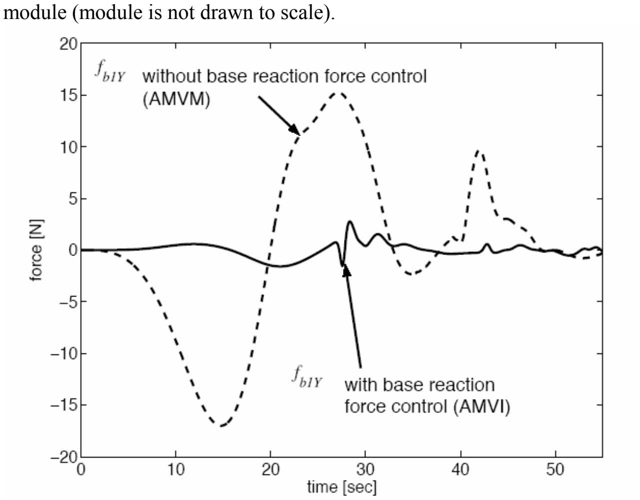


Fig. 9. The vertical component of the base reaction forces for the left robot with and without base reaction force control action.

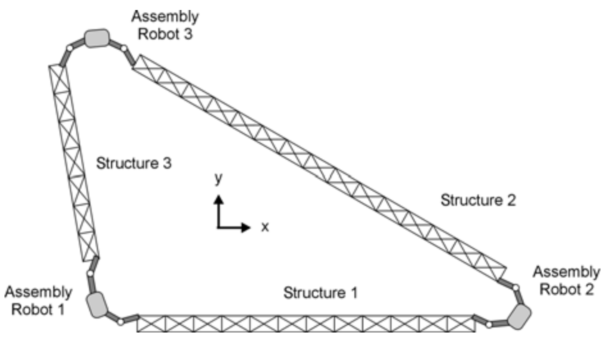
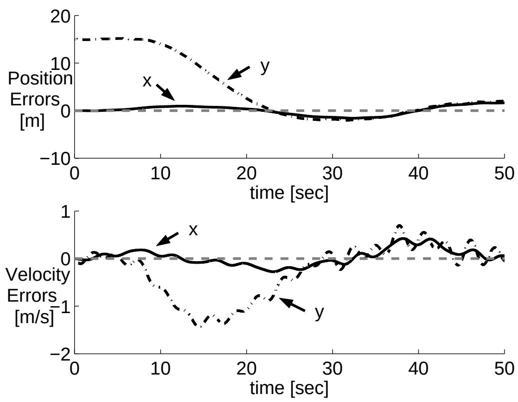
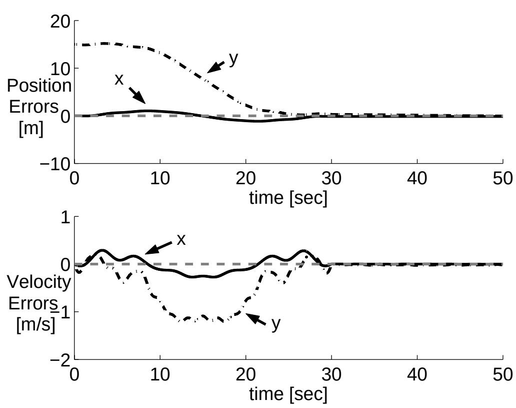


Fig. 10. Sample flexible structure assembly task.



(a) Nominal Controller



(b) Decoupled Controller

Fig. 11. Position and velocity errors for right corner of assembly task.

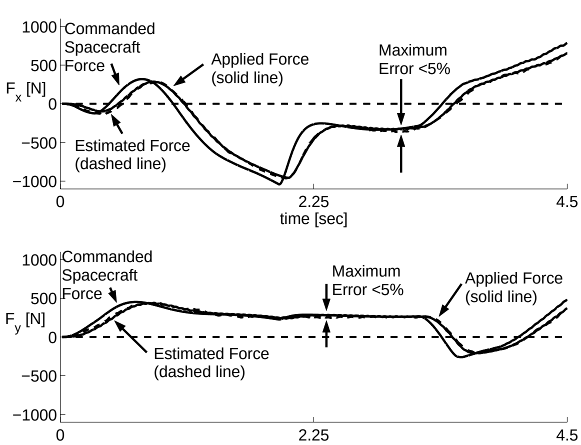


Fig. 12. Continuous x and y commanded net thruster forces for a large satellite capture task under BSC control.

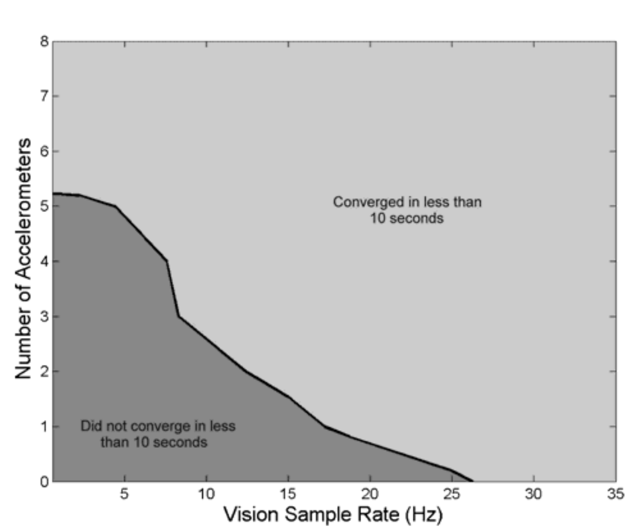


Fig. 13. Experimental results for sensor fusion of accelerometers and vision sample rate are used to find vibrations of experimental space structure.

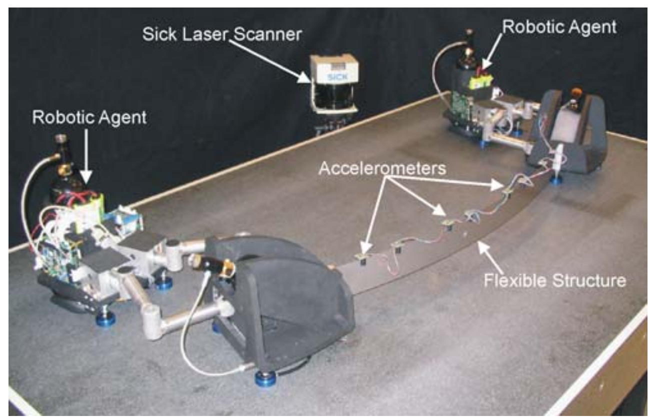


Fig. 14. Experimental system setup for sensor fusion experiments.

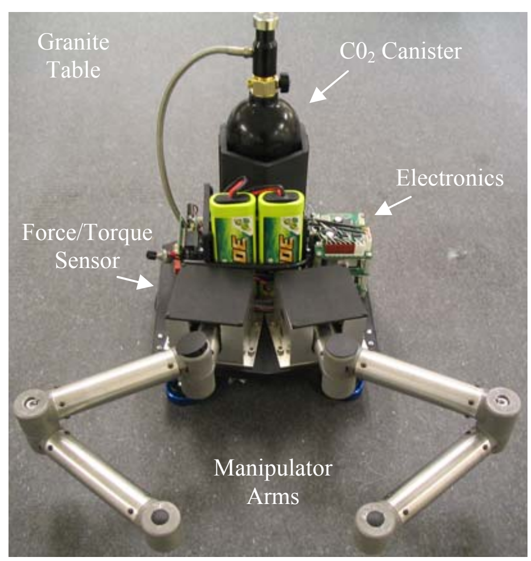


Fig. 15 (a) Front view of experimental space robot.

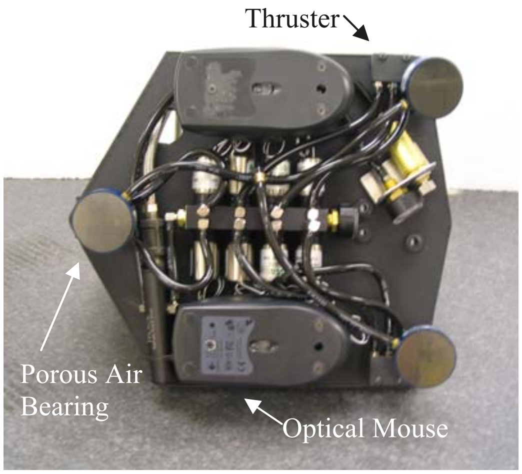


Fig. 15 (b) Bottom view of experimental space robot.

V. Summary and Conclusions

A control architecture has been shown for on-orbit construction of large flexible space structures by teams of cooperative space robots. The method decouples the control of the space robots from the space structures. The high-bandwidth robots are controlled as force sources that apply forces to the low-frequency large space structures. This approach enables control of the significant dynamic interactions between the robots and the structures. Estimation is used to compensate for limited sensing and actuation. The control method is verified by simulation and laboratory experiments.

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