An Experimental Study of the Control of Space Robot Teams Assembling Large Flexible Space Structures

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Abstract

Future very large space structures, such as solar power stations and space telescopes, will need to be assembled in orbit by teams of cooperating space robots. Controlling these space robots is difficult due to the dynamic interactions forces between the robots and the large and very flexible structures. Sensing and actuation are also limited in space. A number of control algorithms have been proposed that address these problems. However, the experimental verification of these algorithms has largely yet to be studied. This paper briefly summarizes a set of algorithms being developed at MIT for the control of a free-flying multi-robot team assembling a highly flexible space structure. An MIT experimental testbed designed to evaluate these algorithms is described. Then the experimental performance of one of the flexible control algorithms is presented.

1. Introduction

The construction of future large solar power stations and large space telescopes will require teams of autonomous space robots (see Figure 1) [6][9][13]. The control of space robots performing these missions is complicated because of the dynamic interactions between the space robots and the objects they are trying to manipulate. Structures in space are typically large, light and flexible [11]. It is important that the space robots do not excite structural vibrations, which could damage the objects or the robots [14][15]. Control of the space systems is complicated by the nonlinear equations which describe the robots and the time-varying nonlinear partial differential equations which describe the flexible structures which undergo large motions. Also, in space sensing and actuation are limited and expensive [12]. Sensing is necessary to compensate for disturbances due to joint friction, thermal warping effects, and modeling errors. Finally, reaction jet fuel for space robots is very limited.

Control algorithms have been proposed for the control of space robots manipulating of large flexible space structures [7][14]. However, experimental verification of these algorithms has not yet been demonstrated. This paper describes an experimental testbed which was built to experimentally verify planning and control algorithms for space robots. The testbed consists of a team of space robots floating on air bearings to emulate microgravity conditions, see Figure 2 [1][4][8]. Each robot has a full set of reaction jet thrusters and fully instrumented manipulators including force/torque sensors mounted between each manipulator and the robot. The robots are self-contained with their own on-board electronics, computers and power supplies. The structural elements used in the experiments are relatively large and flexible. The motions of the robot/structural systems are measured by distributed accelerometers, three-dimensional laser range finders, and overhead cameras.

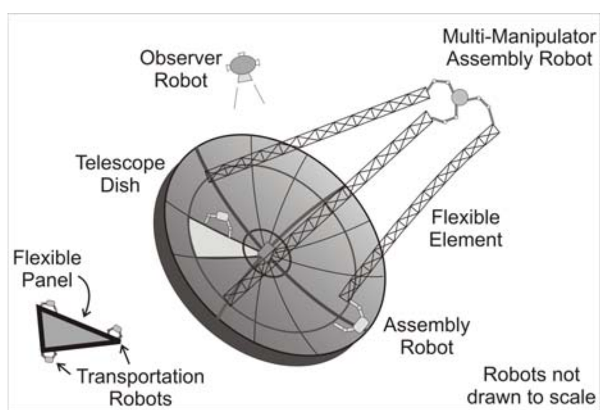


Figure 1. On-orbit construction of a flexible telescope by teams of space robots

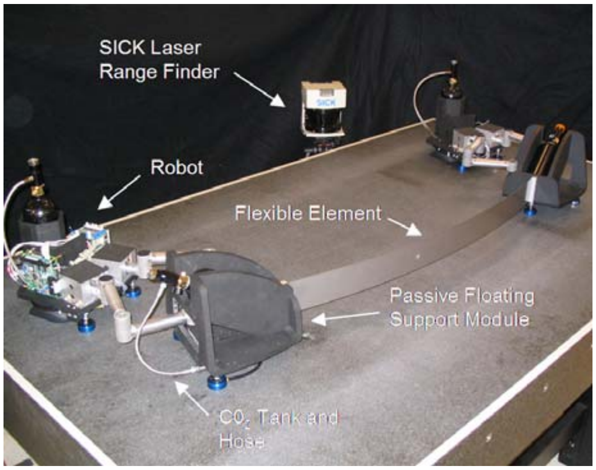


Figure 2. The MIT experimental testbed

This testbed is being used for the experimental verification of the planning and control algorithms. Experimental results which demonstrate the effectiveness of the proposed control algorithms are presented here along with a brief description of future experimental work.

2. Control Algorithms

A set of control algorithms have been developed for the robotic maneuvering of large and flexible structures in orbit [5][7]. These algorithms are called decoupled control. In these algorithms the robot thrusters perform the large translations and rotations while the manipulators minimize vibration. The control can be decoupled since the robots operate at higher frequencies than the low dominant frequencies typical of a vibrating space structure. A block diagram for this controller is shown in Figure 3. An outer loop performs position and attitude control while the inner loop controls forces applied to the flexible structure.

The decoupled controller commands the robots to apply a set of vibration controlling forces to the flexible structure. It has been shown that real-time measurements of the rigid body and vibrational states of the flexible elements are required [7]. Although a number of sensors can be used to measure these system states, sensing is limited in space due to reliability, complexity, weight and expense. The sensors required to measure the system state can be minimized by fusing vision and acceleration measurement [1]. The ability of the control to achieve its function is degraded by the nonlinear manipulator joint friction and thruster nonlinearities and lack of precision. 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 [2][3]. For this reason, such force/torque sensors are included in the experimental testbed robots.

3. Experimental System

The MIT Field and Space Robotics Lab (FSRL) Free-Flying Robotics Testbed (FFRT) was built to study the effectiveness of these planning and control algorithms for flexible element manipulation and large space structure assembly. The testbed can also be used to study other orbital robot missions, such as satellite capture. The testbed contains several kilogram scale multi-arm manipulator robots floating on CO_2 bearings to emulate microgravity in two dimensions. This section describes the experimental facilities, experimental robots, flexible structures and associated hardware and sensors.

3.1. Experimental Facilities

Small scale experiments are run on a 1.3 m by 2.2 m granite table with a polished surface (see Figure 2).

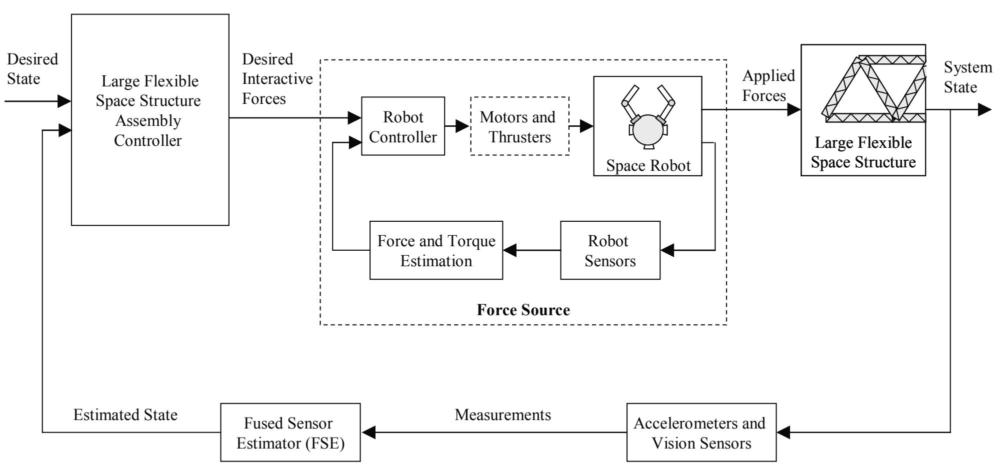


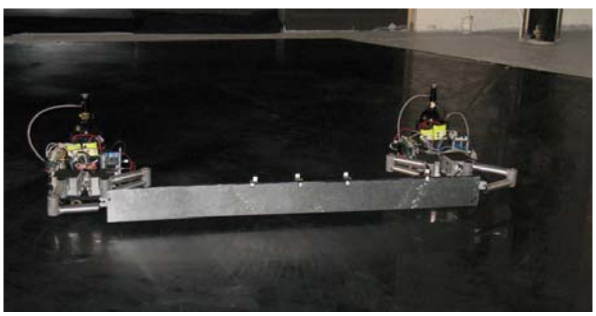
Figure 3. Block diagram for the decoupled controller

The table is finely leveled to enable the gas bearing supported robots and structural elements to simulate a microgravity environment. Overhead cameras and SICK laser range finders serve as remote observer robots.

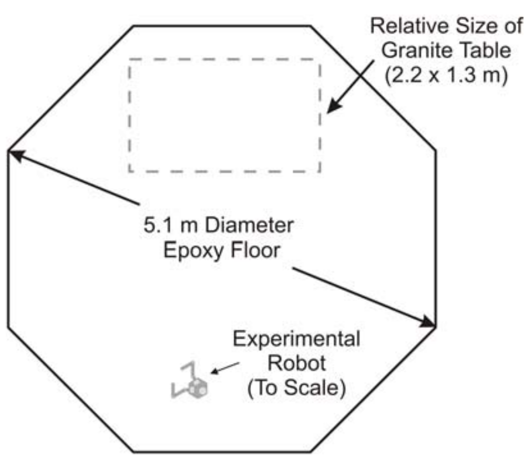
Larger scale experiments are run at the MIT Space Systems Laboratory (SSL) on a large polished epoxy floor (see Figure 4(a)). The SSL epoxy floor is in the shape of an octagon, 5.1 m in diameter (see Figure 4(b)). A positive pressure system in the room minimizes particulates (dust or dirt on the floating surface creates drag on the floating modules). Due to differences in surface finish the floating systems are run at a higher pressure on the epoxy floor than on the granite table (80 psi vs. 60 psi).

3.2. Experimental Robots

Each experimental space robot is equipped with two manipulators, eight thrusters, two position sensors, four manipulator joint angle encoders, and two force/torque sensors (see Figure 5 and Figure 6). The robots have 7 DOF in total (2 DOF translation, 1 DOF rotation, and 4 DOF for the manipulator joints), all of which are controllable and observable.



(a) Laboratory



(b) Floor dimensions

Figure 4. SSL flat epoxy floor with experimental robot

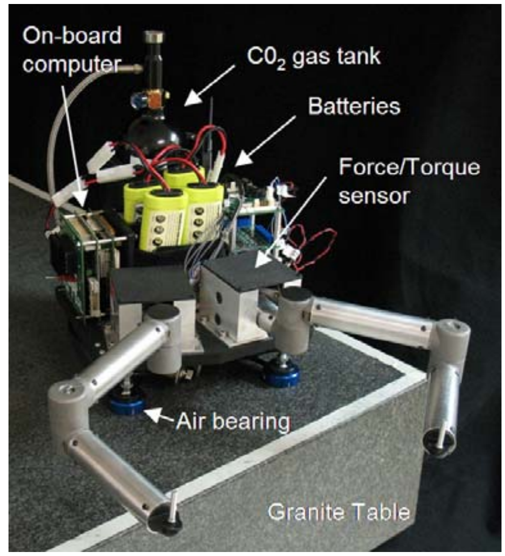


Figure 5. Experimental space robot

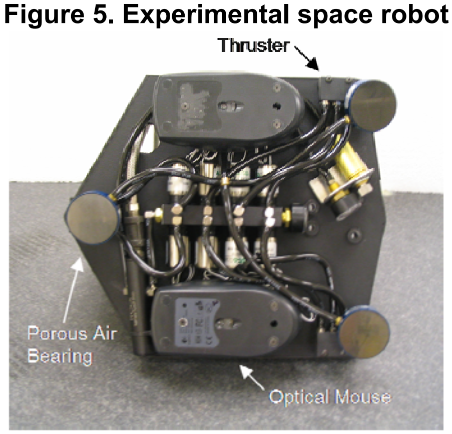


Figure 6. Underside of experimental robot

The robots can operate in free-flying mode (thrusters on) or free-floating mode (thrusters off). The robots are designed to emulate the dynamics of robots on orbit. The spacecraft base is light weight in relation to the manipulators and to the loads they carry. Motion of the manipulators significantly perturbs the motions of the base such as would be found in future orbital robots.

The structures of the robots are made of a composite material, with a hexagonal base approximately 23 cm in diameter. The two manipulators each have a force/torque sensor at their base. A hexagonal structure supports the CO_2 gas tank. The robots are completely self-contained to eliminate any need for tethers that could affect the dynamics of the system. The electronic boards are mounted vertically on one side. Four 7.2-V NiMH batteries sit in the middle and additional batteries can be attached. The gas system, including thrusters and air bearings, is mounted underneath along with the position sensors (mice).

The scale of the manipulators is shown in Figure 7. The manipulator's motors and encoders are mounted inside of its structure. The manipulator's end-effectors are designed to be interchangeable depending on tests to be run. An end-effector designed to carry a laser for trajectory following experiments is shown in Figure 8. For the flexible module transportation and assembly experiments, a pin joint end-effector that transmits forces but not moments is used (see Figure 5).

Custom force/torque sensors are placed at the base of each manipulator (see Figure 9). They measure the two planar forces and one torque (Fx, Fy, and Txy) by using four strain gauges. The sensors' four flexures deform linearly with the forces and torque. From their strains the forces and torque applied by the manipulator are estimated

The robotics electronics consist of an on-board PC104 computer with host CPU and motherboard, a power board, wireless LAN, a Softing CAN-AC2-104 peripheral board, the CANBus (twisted pair wires), and the interface electronic circuit boards with microcontroller firmware. A diagram of the electronics is shown in Figure 10.

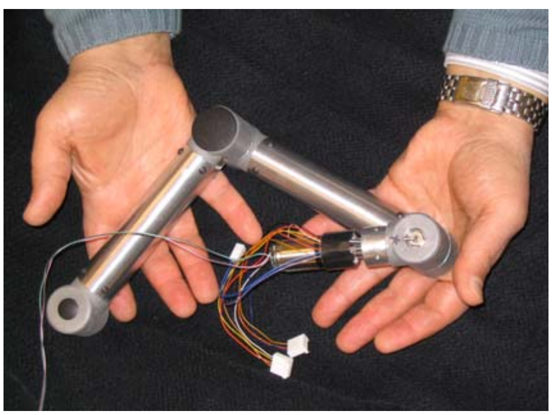


Figure 7. Manipulator arm

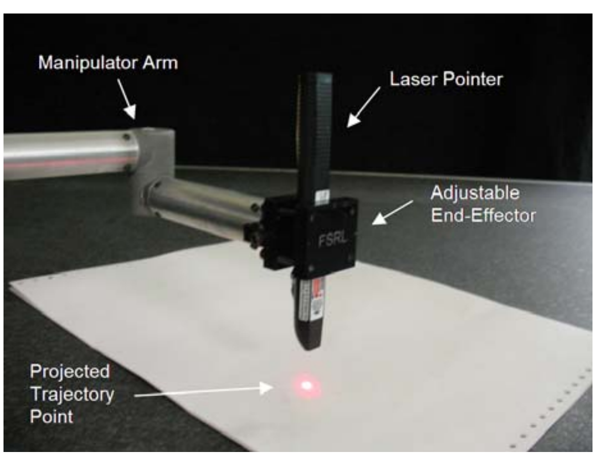


Figure 8. End-effector holding laser pointer

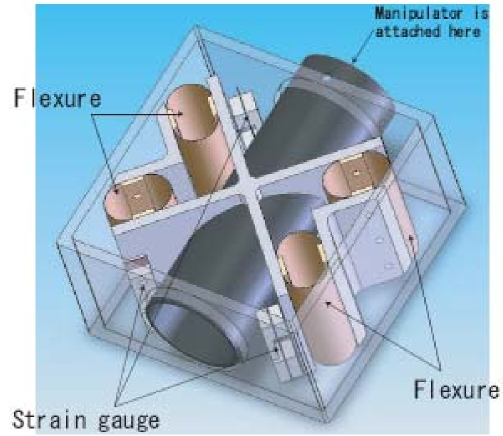


Figure 9. Force/torque sensor design

Communication between the PC104 and the actuators and sensors uses multiple layers of software, firmware, and hardware. The top layer is the high-level robot controller software, written in Matlab and Simulink.This top layer is responsible for coordinating sensor and actuator activities, computing control laws, filtering and processing data, and managing the other aspects of an experiment. The robot's on-board computer is the Diamond Systems Morpheus PC/104 System. The robot is also equipped with a Wireless LAN router to allow wireless access between the on-board computers from the operator's control station.

The controllers communicate with the CANbus peripheral board using an I/O block library provided by Mathworks that translates high-level commands and requests into small packets of data to be transmitted and received over the CANbus. The CANbus peripheral board is the hardware that physically puts data packets (CANbus *frames*) onto the CANbus physical medium. Custom electronic boards are attached to the other end of the CANbus physical medium.

Four kinds of custom electronics boards are used to drive on-board sensors and actuators: manipulator boards, force/torque sensor boards, base module boards, and accelerometer boards. All of them except the force/torque sensor board have Microchip PICs for the operation of the sensors and actuators. The manipulator board controls DC motors and reads the digital angle encoders. A motor's speed is controlled by PWM (pulse width modulation). The base module board controls thrusters and reads mice. The force/torque sensor board has instrument amps and operational amps to amplify the signal of the force/torque sensors. These amplified signals are A/D converted on manipulator boards. The accelerometer board interprets the digital PWM signal from accelerometers on the flexible element.

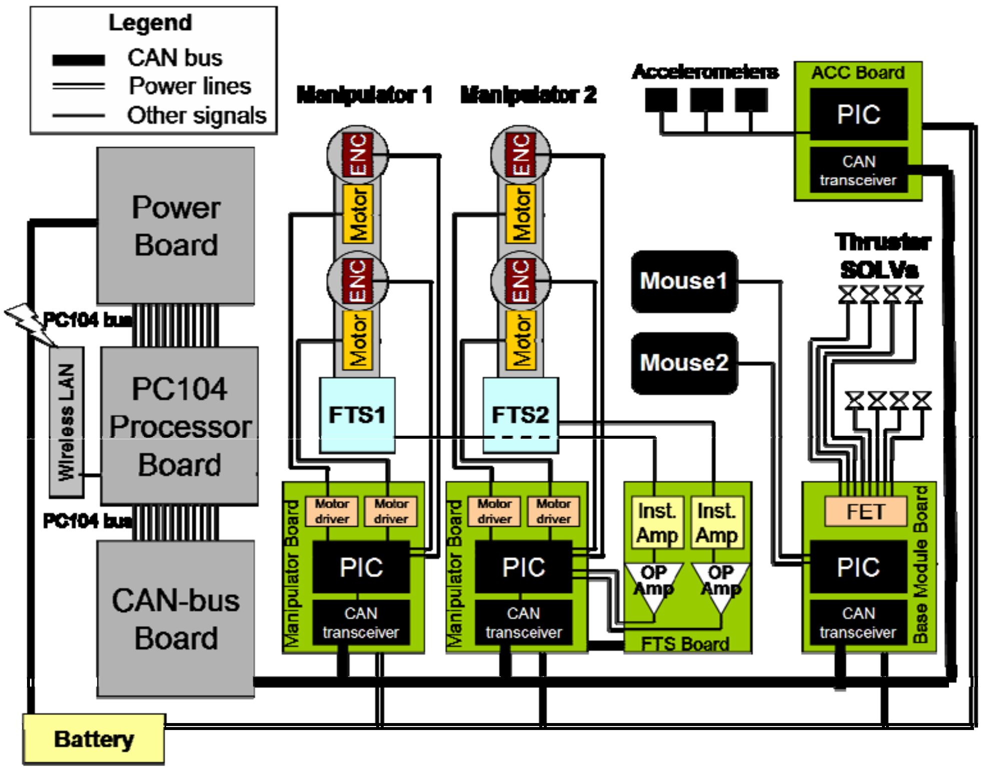


Figure 10. Electronics Diagram

The software for the simulations and the experimental system is written with Matlab and Simulink. The real-time software is implemented with the Matlab xPC Target. The controllers are implemented in Simulink and simulations are written using SimMechanics plants. When the simulations are debugged and working, the SimMechanics plant blocks are removed from the Simulink model and replaced with xPC plant blocks which communicate directly with the experimental hardware via a layer of CAN software provided by Matlab. The real-time software is compiled on a laptop, downloaded onto the PC104 computers on the robots, and triggered via wireless link. During the experiments, the controllers execute on the target without communicating with outside systems. After completion of an experiment the PC104 transfers data back to the host laptop.

A schematic diagram of an experimental robot is shown in Figure 11. The figure shows the local and inertial coordinate systems. The local coordinate system for each robot has its X axis aligned with the robot's axis of symmetry. Joint zero is the location of the force/torque sensor. Joint zero and link zero are fixed to the base; joint one is the first movable joint. Note that the center of mass of the spacecraft base is not on the axis of symmetry due to electronics and battery placement.

3.3. Flexible Elements

The flexible elements are representative of flexible orbital structural modules. The experimental flexible elements are designed to similar low natural frequencies and low damping ratios (like the orbital modules) to evaluate the flexible assembly control algorithms. The experimental system's vibration amplitudes are designed to be relatively large to make visible the differences between algorithms.

For the experiments presented here, the flexible element is a simple aluminum beam, 1.22 m long, 0.80 mm thick, shown in Figure 4. The beam's lowest natural frequency is 2.8 Hz. It is supported by and pin-jointed to the end-effectors of the robots' manipulators. Accelerometers mounted on the beam measure its vibration and provide the vibration states needed by the flexible algorithms (see Figure 4).

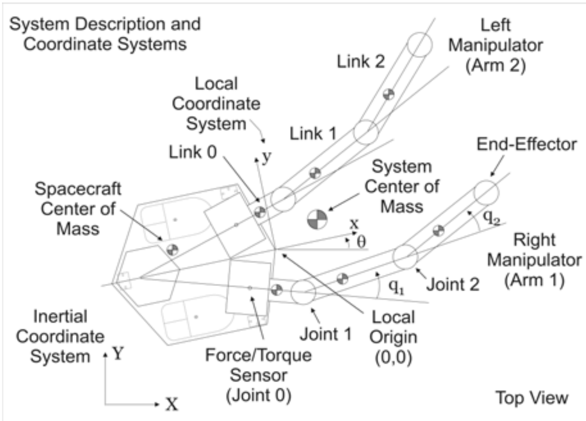


Figure 11. Robot system description

The flexible elements can also be supported by passive floating modules, as in Figure 2. Alternative designs for the flexible element such as a zig-zag beam (see Figure 12) or a lumped-mass beam built with metal shims and rigid composite elements (see Figure 13) were also considered. The zig-zag design allows substantial axial as well as transverse vibrations, complicating the control of the structure. The zig-zag beam has large amplitude of vibrations and a low damping ratio but suffered from significantly sag under its own weight. The lumped-mass structure consists of lumped masses (polymer tubes) separated by springs (thin metal shims). The natural frequencies of this beam could be tuned by varying the lumped masses and the lengths of exposed shim, but this beam is more complicated to fabricate.

The flexible elements would have their vibrations excited by thrusters in an on-orbit system. It is difficult to have the low amplitude forces of the CO_2 thrusters excite large amplitude easily visible vibrations. However, the motions of the manipulators are able to produce easily visible amplitudes.

4. Experimental Results

The results from a typical experiment to study the effectiveness of planning and control algorithms for flexible systems are presented here for a transportation maneuver experiment. For this experiment, two space robots transport and manipulate a beam structure using the decoupled controller shown in Figure 3. The initial and final positions for this maneuver are given in Figure 14. The decoupled control uses thrusters to control large motions and manipulator control to minimize residual vibration. For this experiment, the robots support the flexible element directly (the passive floating modules are not used).

The flexible controller's performance with the robots transporting the structure using their thrusters while controlling the vibration using their manipulators is evaluated by comparison with two cases. In the first controller the robot thrusters transport the beam without controlling vibration (the joints of the robot manipulator are locked). In the second controller the robots both transport the structure and control its vibration using only their thrusters. Typical results are given in Figure 15. This figure shows the vibration magnitude of the first mode for the three controllers. The top plot shows the case with no vibration control. The middle plot shows the case with thruster control. The third plot shows the decoupled controller, with the manipulators used for vibration control. Figure 15 shows that the case of manipulator control quickly damps the vibration compared to no vibration control or trying to use the thrusters.

At the same time, the manipulator control used virtually the same fuel as the non-control cases. The fuel consumption is the total amount of fuel (CO_2 gas) consumed between the start of the vibration control and the time when the robots are within 3 cm of their final destination. The fuel consumption did not include the CO_2 gas used to float the robots. The thruster vibration control case used substantially more fuel but

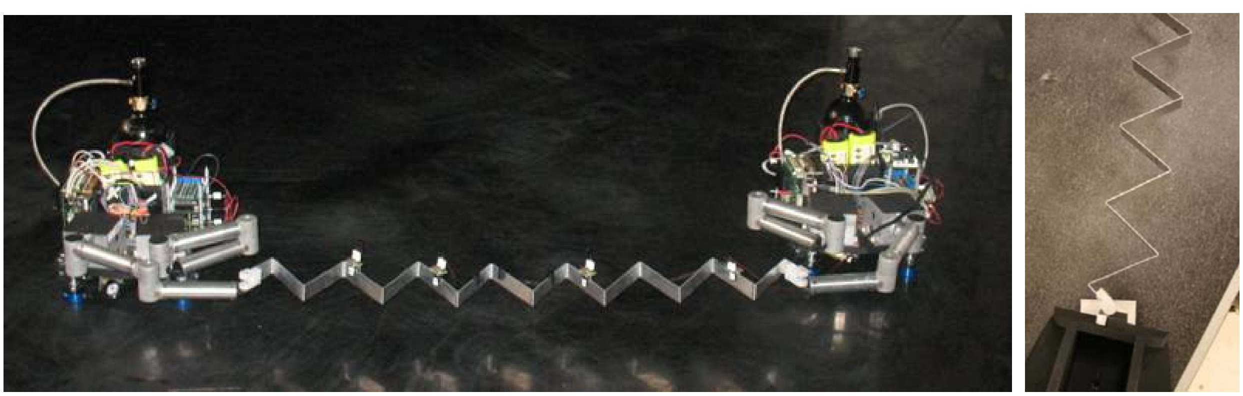


Figure 12. Zig-zag flexible element prototype

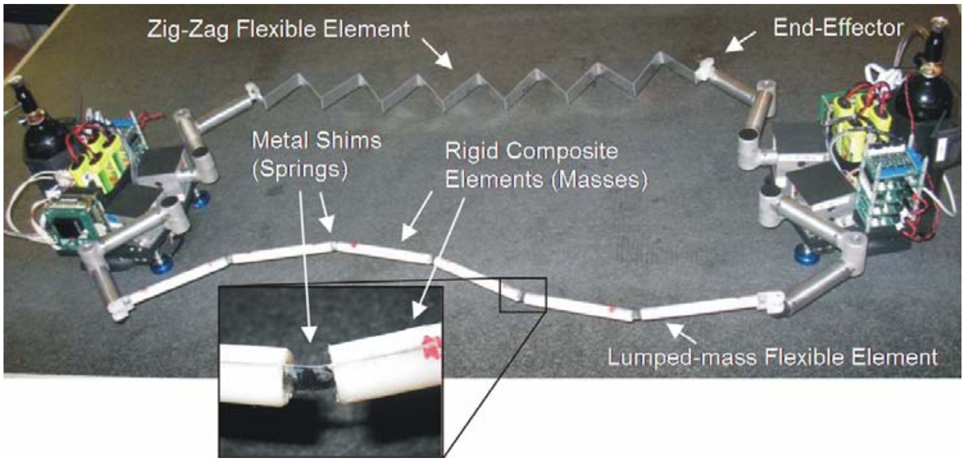


Figure 13. An overhead view of two robots manipulating lumped-mass and zig-zag beam

achieved no advantage over doing nothing. Fuel usage would be critical in a large scale on-orbit context. The conclusion is that robotic transportation vehicles with active manipulators can be more effective than transfer vehicles without manipulators that only use thrusters for control.

The experimental results confirm previous simulation results [7][10]. These results show that algorithms that consider the effects of structural flexibility have significant performance advantages over ones that do not. Although the algorithms did not include many effects such as computation and sensor delays, the experimental results show that these unmodelled effects do not substantially degrade their performance. The experimental results suggest that practical application of these algorithms is feasible.

Experiments are currently in progress to study the performance of additional planning and control algorithms for the manipulation and assembly of large flexible space structures by teams of space robots. The testbed will also be used for evaluating planning and control algorithms for the capture of uncontrolled satellites and for algorithms that compensate for the effects of limited sensing and actuation.

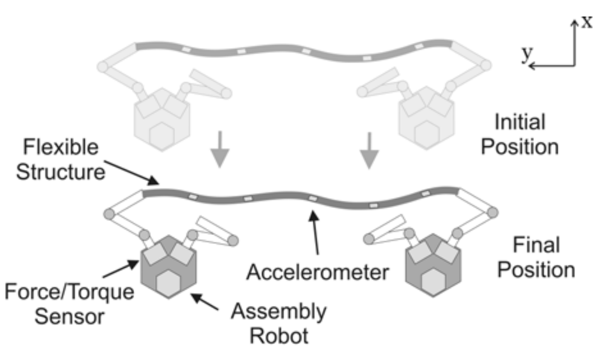
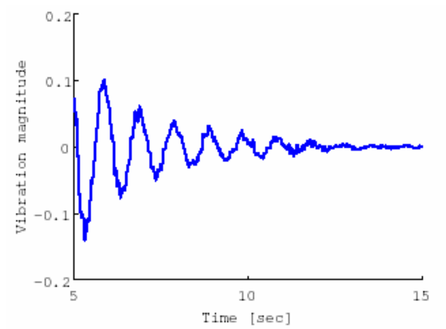
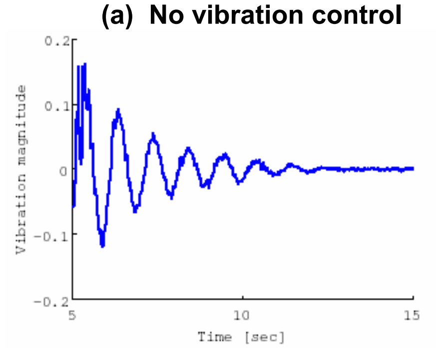


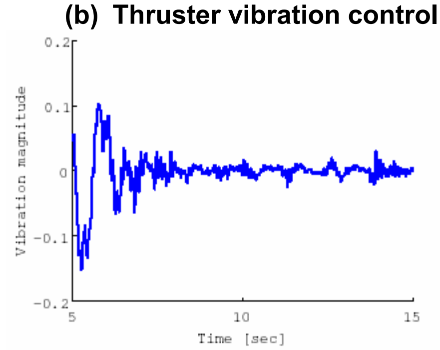
Figure 14. Transportation maneuver



(a) No vibration control



(b) Thruster vibration control



(c) Decoupled control (Vibration control by manipulators)

Figure 15. The first mode of vibration of the experiment

5. Conclusions

Planning and control algorithms have been developed for teams of space robots performing construction of large flexible space structures by manipulating and assembling flexible components. This work describes a planar experimental testbed built to verify these algorithms. Experimental results demonstrate the effectiveness of the algorithms in removing residual vibration from flexible structures undergoing large motions, while at the same time reducing fuel consumption over alternative methods such as thruster control. This shows the advantages of using robots with manipulators versus simple transfer vehicles without active manipulation.

6. Acknowledgments

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7. References

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