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

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Abstract
The construction of future space structures in Earth orbit such as solar power stations and space telescopes will require coordinated teams of autonomous space robots. These robot teams can excite undesirable vibrations in the structures while manipulating or assembling them. Controlling robot teams physically interacting with structural elements in space is challenging. The combined system dynamics are described by sets of nonlinear partial differential equations. Here, these dynamic equations are transformed into a set of linear time-varying ordinary differential equations. The control of the high-frequency robots is then decoupled from the control of the much lower frequency structures. This allows linear optimal control theory to be used to control the robots and minimize structural vibrations. Simulation and experimental studies shown here demonstrate the validity of the approach.

Keywords
Space robot, coordinated control, vibration suppression, on-orbit assembly, space structures

1. Introduction

1.1. Motivation

Teams of autonomous space robots will be needed for future space missions, such as the construction of large solar power stations and space telescopes in orbit [1, 2]. The structures for such systems are expected to be very large, with dimensions of hundreds of meters to kilometers [2]. These large flexible structures will need to be assembled on orbit. Astronauts’ extravehicular activities would be too expensive and dangerous to be practical. It is expected that this work will be done by teams of autonomous space robots [3, 4].

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The team members will be heterogeneous because the structural assembly tasks are too complex to be done by a single robot type [2] (Fig. 1). These teams might include remote free-flying robots (with thrusters and manipulators), simple observation robots for sensing, and worker robots that can walk across structures and perform fine manipulation for assembly and maintenance [4].

However, the control of teams of robots manipulating large space structural systems with complex changing geometry and significant dynamic behavior is not well studied. Structural vibrations present a major problem [5]. The robots can excite vibrations when transporting and assembling the structures. Vibrations can be large as the components are likely made of lightweight materials that are very flexible and have low damping [6].

The control of these structural vibrations while teams of space robots are constructing large flexible space structures is a challenging technical problem. For effective control, sensors must measure the robots’ and structures’ state, but practical issues such as weight, complexity and reliability limit available sensing in space [7, 8].

The objective of this work is to develop control algorithms to enable teams of space robots to manipulate and assemble large flexible space structures while minimizing degrading vibrations, operating in limited time and subject to limited sensory information and actuation.

1.2. Background Literature

Mission concepts for the construction of future large space solar power structures stations have been proposed that require space robots to perform manipulation and assembly tasks [2, 9, 19]. For the construction of such large structures, it is necessary to transport raw materials on orbit, build subassemblies and then assemble these subassemblies into larger structures, and possibly transport these structures and substructures into high Earth orbit. Assembly of simple structural elements
such as rod or beam components has been experimentally demonstrated in the laboratory, but demonstration missions have not yet been flown [11, 12].

Coordinating the control of the multi-robot teams to manipulate large flexible space objects has not been well studied. Studies have looked at cooperative control of teams of robots on Earth for tasks such as exploration, clustering in formation or pushing objects [13]. Teams of mobile robots have demonstrated coordinated behavior with leader–follower formations and on-orbit multi-robot formation flying has been studied [14]. However, these studies did not generally consider dynamic physical interactions between teams of robots and between the elements they are manipulating — the major issue to be addressed in this study. Here, the robots and the structures are connected. Motion of one component of the system disturbs the other components.

This problem is made more complex because the size of the robots is expected to be small (typically 2–20 m) compared to the size of the structural elements they will need to manipulate (100–200 m). To mitigate these coupling disturbances, the robots must be able to control the interactive forces they apply to the structures. Previous studies of dynamic interactions between robot teams have been limited to cases where the robots were not free-floating or free-flying in orbit such as mobile robots on a planetary surface moving simple single rigid beams [1]. Previous research has included dynamics in planned trajectories for terrestrial mobile robots, with payloads but without flexibility [15]. Preshaping methods can reduce vibrations for certain problems with flexibility, but the system model must be well known (which is not necessarily true for systems under construction) [16]. However, when the plant is well known preshaping can be used in a high-order planner in concert with the methods presented here to achieve even better performance. When vibration has been considered for transportation problems, it is treated as a disturbance [17]. The previous studies did not attempt to minimize the vibrations of the transported structures or control the dynamic interactions of the system.

Recently, studies have examined multi-robot on-orbit assembly for cases with dynamic interactions between robots. An interesting approach to beam assembly uses tethers [18]. However, stability problems were experienced in initial verification tests with air table experiments. A study of space robots mounted on compliant bases manipulating a flexible structure used preplanned force trajectories by constraining vibration and showed that coordinated control is difficult [5]. Simulations of two robots transporting a flexible beam on orbit showed it is possible to reduce attitude control fuel consumption over thruster-based control methods by controlling large motions with thrusters while damping vibrations with the manipulator [10, 19]. Experimental verification found the method is sensitive to errors and noise, but demonstrated reduced vibration and fuel use with the addition of compliance control [11]. While past research has developed some interesting and useful algorithms, the general coordinated control problem of the manipulation of large flexible space structures that consider dynamic interactions remains a challenging unsolved problem [20]. This paper presents a general architecture to address this problem.
Here, the unique characteristics of teams of robot manipulating large structures in space are exploited to transform the problem into a tractable one. First, the relatively slow change in the configuration of the large space structures is exploited to transform the nonlinear equations into linear time-varying equations. This permits the use of well-known methods for linear systems to be used to determine the forces that the robots need to apply to the structure. Then exploiting the faster response of the robots under force control the robot algorithms are configured to produce these forces without regard to the physical coupling of the large structure onto the robots. Hence, the problem is decoupled and is solvable under certain conditions described in the paper. While some of the components of the architecture rely on algorithms that are not new, the architecture that enables the solution of how teams of robots in space can handle large flexible space structures has been an unsolved problem.

2. Solution Approach

The architecture developed here for the coordinated control of teams of robots during the assembly and transportation of large flexible space structures exploits the unique dynamics of the problem, and of the frequency separation between the structures and the robots [21]. The system dynamics of the system are represented by a set of nonlinear partial differential equations (PDEs; the structures) and nonlinear ordinary differential equations (ODEs; the robots). Here, this system is transformed into a set of slowly time-varying linear equations by linearizing about a nominal trajectory. The resulting system is time-varying because the structures may undergo large displacements. The transformation is possible since it is expected that the positions of the robots and the structures will never be very far from their desired positions, so the equations of motion can be transformed using perturbation coordinates [22].

The system is controlled by decoupling the control of the structures from the control of the robots. The system can be decoupled assuming the highly flexible structures have low dominant natural frequencies while the robot controllers are high bandwidth. Decoupling the control allows the robots to serve as interactive force sources that apply forces to the structures. Linear optimal control methods determine forces needed to position the structures while minimizing their vibration.

2.1. System Modeling and Assumptions

An example of an on-orbit construction task is shown in Fig. 2. For the space systems considered in this work, the structures’ mode shapes and frequencies are assumed to be known within a certain tolerance. Including the effects of disturbances such as thermal warping, solar pressure and gravity gradient is beyond the scope of this work. The effect of orbital mechanics is also neglected since the timescale for assembly operations is assumed to be short compared to the orbital period. The orbit is also assumed to be high enough that aerodynamic effects are small.
Figure 2. Assembly of a flexible space structure.

From fundamental mechanics, the equations of motion for the flexural vibration of each structural element are PDEs of the form:

\[-\frac{\partial^2}{\partial z^2} \left( EI(z) \frac{\partial^2 w(z, t)}{\partial z^2} \right) + f(z, t) = m(z) \frac{\partial^2 w(z, t)}{\partial t^2}, \tag{1}\]

where \( z \) is the vector of body-fixed spatial variables (containing the local coordinates \( x \) and \( y \) shown in Fig. 2), \( t \) is the time, \( w(z, t) \) is the displacement from some nominal position, in this case the commanded position, \( f(z, t) \) are applied forces, \( m(z) \) is the mass density, \( E \) is the modulus of elasticity and \( I(z) \) is the moment of inertia \((EI(z) \) is known as the flexural rigidity) \([6]\). Finite element methods or a sum of assumed displacement functions to represent \( w(z, t) \) allow approximation by nonlinear ODEs. A number of methods are available for finding these equations. For the studies performed here, displacement functions were used to find kinetic and potential energy, and solved via Lagrange’s equation to result in the nonlinear second-order equations of motion:

\[ M'(u_r, t)\ddot{u}_r + D'_f(u_r, \dot{u}_r, t)\dot{u}_r + K'(u_r, t)u_r = B'_f(u_r, t)F(t), \tag{2} \]

where \( u_r \) is a vector containing position and orientation, \( M'(u_r, t) \) is the mass matrix, \( D'_f(u_r, \dot{u}_r, t) \) is the damping matrix, \( K'(u_r, t) \) is the stiffness matrix, and \( B'_f(u_r, t) \) is a coefficient matrix. These matrices are converted to linear slowly time-varying matrices using Gardner’s method \([22]\). In this method, the equations of motion are first developed in perturbation coordinates and then are simplified based on engineering analysis of the relative contributions of terms. For the space structures studied here the terms remain small in perturbation coordinates. It is assumed that the structures are never far from the commanded position. The vector \( u_r(t) \) is a function of time and is written as the sum of the nominal position \( u_n(t) \) and the perturbation coordinates \( u_d(t) \):

\[ u_r(t) = u_n(t) + u_d(t). \tag{3} \]
The terms in the mass matrix $M'$ and the other matrices contain sines and cosines. Making the small angle approximation for sine and cosine results in the time-varying linearized equations of motion:

$$M(u_d, t)\ddot{u}_d + D_f(u_d, \dot{u}_d, t)\dot{u}_d + K(u_d, t)u_d = B_f(u_d, t)F(t),$$  \hspace{1cm} (4)$$

where $M(u_d, t)$ is the linearized mass matrix, $D_f(u_d, \dot{u}_d, t)$ is the linearized damping matrix, $K(u_d, t)$ is the linearized stiffness matrix and $B_f(u_d, t)$ is the linearized coefficient matrix. The system coordinates are transformed to modal coordinates $q_m$ to allow reduction of the order of the system, particularly when the original system has a large number of high-frequency components that do not substantially contribute to the system behavior:

$$\ddot{q}_m + 2Z\Omega_1\dot{q}_m + \Omega_1^2q_m = B'_fF.$$  \hspace{1cm} (5)$$

For space structures, damping ratios are typically not well known and are usually prescribed. For convenience, proportional damping is assumed here for the structural modes [6]. The equations of motion written in state space form are:

$$\dot{x}(t) = A(t)x(t) + B(t)u(t),$$

$$y(t) = C(t)x(t) + D(t)u(t),$$  \hspace{1cm} (6)$$

where $x$ is the state vector containing position and velocity components of the rigid-body and flexible modes of the structural elements, $u$ is the control vector, and $A(t), B(t), C(t)$ and $D(t)$ are coefficient matrices. The vector $y$ contains the output. Using perturbation coordinates results in linearized matrices that are slowly time-varying to allow effective control of structures undergoing large displacements and rotations needed for construction tasks such as transportation and assembly [22]. For transportation tasks, the robots move the structures from one location to another, following the desired trajectory in the specified time and minimizing vibration and thruster fuel consumption. For assembly tasks, the robots move the structures to a desired position and bring their connection points together while minimizing vibration and actuator effort (Fig. 2).

2.2. Trajectory Planning

The trajectories are preplanned to find the nominal motions of the structural elements and move the system from its initial to final state. A number of methods have been developed to find the optimal motion of free-floating systems. The path for a beam transported in space can be determined by minimizing fuel consumption [11]. Preshaping methods can be used to find trajectories that attempt to minimize residual vibration [16]. Non-holonomic path planning methods have been developed for space manipulators that optimize the motion based on the dynamics of the system [23, 24]. For this study, the nominal trajectories are cubic splines found using a rigid-body model of the system that assumes the structures are rigid and ignores any flexibility. The splines match initial and final positions and velocities.
2.3. Control Approach

To perform these tasks, the robots are controlled to act as forces sources where their end-effectors apply specified forces to the space structures. The control of the individual robots can be decoupled from the control of the larger flexible structure. The controller is shown in Fig. 3. The inner loop shows a space robot controlled as a force source. The outer loop shows the large flexible space structure controlled by the applied forces.

Here, the problem of finding the robot forces is formulated as a finite-time optimal tracking control problem. Since the system is assumed to be time-varying linear, linear quadratic, optimal control methods can be used to find desired interactive forces [25]. Using the system equations (6), a performance index $J$ that would have the system follow a trajectory $\tilde{x}(t)$ with minimal control effort $u$ is written as the linear quadratic cost function:

$$ J = \left[ x(t_f) - x_{des} \right]^T M_f \left[ x(t_f) - x_{des} \right] $$

$$ + \int_{t_0}^{t_f} \left\{ \left[ x(t) - \tilde{x}(t) \right]^T Q \left[ x(t) - \tilde{x}(t) \right] + u(t)^T R u(t) \right\} dt. \quad (7) $$

The weighting matrices $M_f$ and $Q$ are assumed to be positive semidefinite, and $R$ is positive definite (since $R$ must be inverted in the solution). The first term of the function is the cost of moving the structures to their desired position and velocity state $x_{des}$ at the terminal time $t_f$. The first term inside the integral is the cost of following a specific trajectory from the initial time $t_0$ to the terminal time (when no trajectory is specified only residual vibration is minimized so $Q = 0$). The last term of the cost function in (7) specifies the actuation (or fuel) cost. For a transportation maneuver, the actuation cost includes the external forces that are applied to the system by the reaction jet thrusters. The state vector $x$ contains the vibration

![Figure 3. Block diagram of large space structure assembly controller.](image-url)
modes, so vibration suppression is accomplished by specifying the weighting matrices $M_f$ and $Q$. The relative weights of $M_f$, $Q$ and $R$ are adjusted to trade-off goals of vibration suppression and fuel use.

The optimal control $u^*(t)$ is [25]:

$$u^*(t) = -R^{-1}B^T \left\{ W(t_r)x(t) + \frac{1}{2}V(t_r) \right\}, \quad (8)$$

where time remaining is defined as $t_r = t_f - t$. This control are the desired forces to be applied to the flexible structure in the block diagram shown in Fig. 3. The matrix $W(t_r)$ is calculated from the matrix Riccati equation:

$$\frac{dW}{dt_r} = W(t_r)A + A^TW(t_r) - W(t_r)BR^{-1}B^TW(t_r) + Q, \quad (9)$$

and the matrix $V(t_r)$ can be found from $W(t_r)$:

$$\frac{dV}{dt_r} = A^TV(t_r) - W(t_r)BR^{-1}B^TV(t_r) - 2Q\ddot{x}(t), \quad (10)$$

with end conditions $W(t_r = 0) = M_f$, $V(t_r = 0) = -2M_fx_{des}$, and using the time-varying forms of $A$ and $B$. These equations can be solved numerically to find the optimal control forces for the robots to apply to the structures. The matrices $W$ and $V$ in (9) and (10) are computed off-line (preprocessing), and (8) is evaluated in real-time in the feedback loop shown in Fig. 3. A closed-form solution is available to the matrix Riccati equation via the Hamiltonian matrix and a similarity transformation to its Jordan form. However, this form was found to be numerically ill-conditioned in practice, so numerical integration is used in this work for finding the optimal control.

2.4. Sensing, Actuation, Stability and Robustness Issues

Structural dynamic motions measurements are critical to the method. Fortunately, effective sensor fusion and estimation methods have been developed to estimate mass properties, vibration modes, as well as the rigid-body motions for large space structures [7, 20]. The precise force control required by the method can be degraded by high levels of nonlinear Coulomb joint friction in the robots’ manipulator joints [26]. Similarly, the highly nonlinear and imprecise thrusters used by the robots can also be problematic [8]. A control method called Space Base Sensor Control has been developed to compensate for nonlinear thruster behavior and manipulator joint friction [27, 28]. This compensation algorithm can be used to achieve the precise control required by the space robots.

The stability of the closed-loop time-varying system requires that the system be stabilizable and detectable [25, 29]. In general, no closed form solution exists for the time-varying systems studied here. However, for the simulated systems it is possible to evaluate controllability and observability gramian integrals numerically. The large time-varying flexible space systems studied here were determined to be controllable and observable (and, hence, stabilizable and detectable). Other issues,
such as ‘modal spillover’, can lead to reduced system performance and stability. However, space limitations here prevent a detailed discussion of these issues and the reader should refer to references [21, 25, 29].

3. Simulation Studies

A number of simulation studies were performed in Matlab and Simulink to evaluate the performance of the proposed algorithm. The simulations study representative transportation and assembly tasks that might be necessary for the on-orbit construction of future large flexible structures, such as the space telescope shown in Fig. 4, which shows transportation robots moving flexible structures over long distances, and assembly robots joining elements to make larger structures such as the supports needed for the space telescope. The robots and structures in the drawings are enlarged to make them clearer. For example, Fig. 5 shows a rendering drawn to the

![Figure 4](image1.png)  
**Figure 4.** Simulations demonstrate assembly and transportation of flexible support structures for a space telescope. Scale is enlarged to emphasize details.

![Figure 5](image2.png)  
**Figure 5.** Maya rendering of an assembly maneuver. At scale, details are barely visible.
Table 1.
Simulated flexible beam parameters

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Length                     | 200 m                  |
| Width                      | 1 m                    |
| Height                     | 1 m                    |
| Mass                       | 600 kg                 |
| Out of plane inertia       | $2 \times 10^6$ kgm$^2$|
| Young’s modulus            | 0.156 Gpa              |
| Lowest natural frequencies | 0.18, 0.51, 1.01, 1.85, |
|                           | 2.90, 4.49, 7.48 Hz    |

Table 2.
Simulated space robot parameters

| Parameter                    | Value                  |
|------------------------------|------------------------|
| Manipulators per robot       | 2                      |
| Links per manipulator        | 2                      |
| Manipulator reach            | 10 m                   |
| Spacing between manipulator bases | 5 m                |
| Total mass                   | 600 kg                 |
| Maximum thrust (large motions) | 400 N                |
| Maximum thrust (attitude control) | 25 N                 |

scale with the simulation parameters given in Tables 1 and 2; details of the robots and structures are barely visible.

3.1. System Description and Assumptions

A prototypical on-orbit flexible beam developed for use in a large space solar power collector is the basis of the simulated structures and the parameters for the other structures used in simulation are derived in relation to it [5]. See Table 1.

The parameters for the simulated robots that can transport and maneuver these large flexible structures are estimated from analysis of current space robots and space satellites, such as the Space Station Remote Manipulator System, ETS-VII and Orbital Express, and projections of future space robot capabilities [1, 2]. Table 2 gives estimated robot parameters.

The simulated cases ignore disturbances from thermal warping, aerodynamic and gravity gradient effects. Relative positioning information about the location of connection points where the structures are to be joined is assumed to be available via on-board cameras or range sensors. Vibration amplitudes are provided from sensor fusion techniques combining on-board accelerometer data that measure high
temporal frequencies but low spatial distributions with low temporal high spatial frequency camera or laser range finder data [30]. The robot links are assumed to be rigid bodies. The simulated robots are assumed to be able to precisely provide the forces needed.

3.2. Controllers

Simulations compare the controller developed (which considers flexibility) to a rigid-body controller. The rigid-body controller translates and rotates structures assuming the structures are rigid, ignoring the flexibility of the system. For the simulations, the same trajectory is used to compare controllers and is represented using cubic splines. The $M_f$, $Q$ and $R$ cost function matrices of the linear quadratic controller are chosen to be diagonal. The initial values in these matrices are obtained from Bryson’s rule [25]:

$$M_{i,ii} = \frac{1}{\text{maximum acceptable value of } (x_i(t_f) - x_i,\text{des})^2}$$

$$Q_{ii} = \frac{1}{\text{maximum acceptable value of } (x_i - \bar{x}_i)^2}$$

$$R_{ii} = \frac{1}{\text{maximum acceptable value of } (u_i)^2}. \quad (11)$$

These initial values are adjusted to improve performance.

When the gains are determined, the matrix Riccati equation is integrated numerically to find the control gains along the trajectory. Control gains and control effort are calculated by preprocessing in Matlab. The LQR rigid-body and flexible controllers are designed to command zero forces after the assembly point is reached, because they assume no errors or disturbances in the system. In a real system, there are accumulated errors; a space system would not be left without control, so the simulations switch to a PD controller that attempts to eliminate accumulated or continuing errors when the optimal controllers complete their function.

3.3. Performance Metrics

The performance metrics for the controllers are based on residual vibration at the end of a motion and how much non-renewable thruster fuel they consume to perform a maneuver. To perform the assembly cases, it is assumed that the manipulators use automatic latch mechanisms that join the components together when they are brought within a threshold distance needed by the mechanism design to perform the latch, here assumed to be 10 cm. Hence, residual vibration is measured at assembly points, the endpoints for a flexible element or the corners of a flexible frame or structure. The settling time is the time for transients to decay so that the amplitude of relative vibration is below a given value, in this case 10 cm.

The vibration damping contribution should come primarily from the manipulators instead of the thrusters, as the thruster fuel is non-renewable on orbit. Using manipulators for vibration damping is space robots has been shown to substantially reduce the amount of thruster fuel required [11, 19]. The actuation effort for
combined thrust and manipulation is calculated from the integral of the net forces applied to the structure by the robot. The net impulse $I_{\text{net}}$ is defined as:

$$I_{\text{net}} = \int_0^t \| F \| \, dt,$$

where $F$ is the applied force. The higher frequency components of this effort and much of the damping effort can come from the manipulators, but the thrusters must provide the net external forces to transport a structure across a distance. For the assembly cases, the thrusters are not used and the robots apply all forces with their end-effectors while operating in free-floating mode.

### 3.4. Results

Figures 6 and 7 show typical results for robotic assembly. Two non-symmetric flexible elements are formed into an A-shaped support truss for the telescope as shown in Fig. 2. While being assembled, the flexible elements undergo large displacements and rotations. An assembly robot at the top holds both flexible structures and applies forces to bring the parts together while transportation robots fire their thrusters at the lower corners of the two structures to push the ends together. The commanded trajectory for the motion of the flexible element is represented by a cubic spline fitting the initial and final positions and velocities. Figure 6 shows the position error at the top of the structure and Fig. 7 shows the same information magnified.

**Figure 6.** Magnitude of position error at the top of the assembly. Detail of area close to latching tolerance is shown in Fig. 7.

**Figure 7.** Detail of magnitude of position error at the top of the assembly.
The dashed line shows the rigid-body controller applied to a flexible model, while the solid line shows the controller designed for a flexible model applied to a flexible model. The flexible controller’s objective is to remove residual vibration and it does not try to minimize vibrations along the trajectory. Just before the structures reach the assembly position there is a large position error while the controller counteracts the vibration induced by the motion of the structures. The flexible controller reduces the gap to a small distance almost immediately at the desired assembly time, while a rigid-body controller applied to flexible model does not reduce the gap to below 10 cm until 38 s have passed (8 s into assembly time).

Figure 8 shows the applied forces in the body-fixed transverse direction for the rigid-body and flexible controllers. The optimal control forces for the given trajectory are shown as dashed lines for the rigid body. The optimal rigid-body controller is unable to complete the task at the assembly time of 30 s, so the PD controller removes the remaining residual vibrations. Most of the vibration is in the body-fixed transverse direction. The forces for the flexible controller (the solid line) take into account vibrations along the trajectory and hence oscillate about the rigid-body trajectory. Little control effort is needed after the assembly time. A higher performance controller such as an optimal LQR regulator could be used instead of the PD controller at the end. Nonetheless, a second controller is required to remove vibration for the rigid-body controller, while the optimal flexible controller essentially only needs station-keeping after the desired assembly point.

For the example three-dimensional case shown in Fig. 9, an assembled frame structure is transported to be attached to the telescope. As shown in Fig. 9, the structure rotates 540° about the z-axis while translating 400 m resulting in helical motion.

Figure 10 shows the z position errors at the corners held by Robot 1. Most of the flexibility is in the z direction since the x and the y directions are constrained. The rigid-body controller does not control the flexibility well and the system vibrates. The flexible controller is designed to remove residual vibration and while it permits

![Figure 8. Force applied in the transverse direction to the left structure.](image-url)
flexing during transportation, the controller has removed almost all of the vibration when the structure reaches its destination at 60 s.

The rigid-body controller requires more effort to remove the vibrations at the destination point and thus the rigid-body controller requires more thruster fuel to apply the forces (Fig. 11). The first phase in Fig. 11 shows the need for fuel to accelerate the structure. During transportation, little additional fuel is required. Then the robots use their thrusters to bring the structure to a stop. Finally, position errors and residual vibration are removed. The forces for the flexible controller (the solid line) take into account vibrations along the trajectory so little control effort is needed after the assembly time. Additional effort is required to remove vibration for the rigid-body controller.

A key requirement of the proposed method is that the robot control systems have much higher frequency response than both the dominant natural frequencies of the structures and the frequencies of the required optimal control forces calculated by the linear quadratic controllers. Therefore, the robots are able to act as accurate force sources. Simulations quantify this frequency separation for varying band-
The bandwidth is 20 times or less than the highest mode frequency, a substantial reduction in system performance is observed.

The simulation results show the need for vibration control when manipulating large flexible structures on orbit. For assembly and transportation tasks considered here, a controller designed without consideration of flexibility results in a controller unable to meet the task objectives.

4. Experimental Studies

An MIT Field and Space Robotics Lab (FSRL) testbed was used to experimentally study the methods presented here (Fig. 12) [7, 10, 21, 30]. The testbed consists of a team of space robots floating on a 1.3 m × 2.2 m polished granite table to simulate planar microgravity. Previous experiments with the testbed have demonstrated tasks such as the transportation of flexible linear elements using a decoupled controller [11].

4.1. Experimental Description

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 power, computers and electronics, thus eliminating the need for tethers that could affect the system dynamics.

Each experimental space robot is equipped with two manipulators, eight thrusters and two force/torque sensors (Fig. 13). The robots have 7 d.o.f. (2 d.o.f. translation, 1 d.o.f. rotation and 4 d.o.f. for the manipulator joints). The robot’s ‘spacecraft’ base is lightweight in relation to its manipulators. Motion of the manipulators significantly perturbs the motions of the base as is found in orbital robots. The robots are completely self-contained.

For the experiments presented here, the flexible element used is a simple aluminum beam, 1.22 m long and 0.80 mm thick, shown in Fig. 12. The beam’s lowest natural frequency is 2.8 Hz and it has a damping ratio of 0.15. The beam is pinned to the end-effectors of the manipulators. Accelerometers mounted on the beam measure its vibration and provide the vibration states needed by the flexible algorithms.
The structural elements used in the experiments are relatively large and flexible to provide relatively representative low natural frequencies and low damping ratios.

4.2. Experimental Controllers

For the assembly case shown in Fig. 12, the controller block diagram is given in Fig. 14. Due to limitations on the robots’ force/torque sensors, the limited control
bandwidth and system communication delays, the experimental robot force controller is unable to follow the force trajectory called for by the approach needing a bandwidth separation of 20 times. However, the controller is still able to achieve meaningful results. The experimental assembly controller shown in Fig. 14 resembles the controller used for flexible element transportation cases using a vibration controller and a compliance controller [11].

Note that the LQR controller state does not contain the rigid-body modes of the structure, so the vibration controller does not control the rigid-body motion of the structural elements. The rigid-body motions of the structures are controlled by the manipulator compliance controller. The robots are commanded to bring the manipulators together.

4.3. Performance Metrics

The performances of the control methods are compared experimentally using three metrics: damping ratio, settling time and success in assembly latching. For the assembly case, success is measured by the ability to latch the elements together. For assembly tasks on orbit it is expected that an automatic latching system would fasten the flexible elements together once they are in close proximity. For the experimental system, the latching mechanism is a pair of magnets. If the controller brings the assemblies close together in the correct orientation, the magnets snap together and latching takes place. If the orientation is not correct it is possible for the magnets to be close together and not latched.

4.4. Results

For a typical parallel assembly maneuver, two robots support the ends of two flexible elements, shown in Fig. 12. The objective is to bring both sets of endpoints of the flexible structures together. For the first 3 s, the structures are moved together. Then the structures are at the assembly point and the robots attempt to latch the assembly.
pieces together. The difference in latching ability between the controllers can be seen clearly in Figs 15 and 16. Figure 15 shows the relative position in the axial direction of the flexible elements for a typical assembly experiment for the controller without vibration control and Fig. 16 shows the vibration controller result for the same case. For assembly cases, although the transverse directions of the flexible elements are aligned, the motion of the assembly operation excites enough vibrations to demonstrate the difference in controllers. Both controllers bring the endpoints close together, but the orientation is misaligned for the case without vibration control and the assembly latching does not take place. The vibration controller is able to bring the latching magnets within the 1 cm axial distance needed to allow the latching to take place at approximately 4 s into the maneuver.

The robot’s controller actively controls the vibration of the structure using the space robots’ manipulators while performing the fine assembly maneuver. The 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 no apparent performance degradation from these unmodeled effects. The experimental results suggest that the practical application of this algorithm is feasible.
5. Conclusions

This work presented a general solution for transporting, manipulating and assembling large flexible space structures on orbit using teams of space robots. The structures are able to undergo large displacements and rotations, but can be controlled with linear optimal control methods. The approach presented here transforms the nonlinear system model into a set of time-varying linear equations. The method decouples the control of the high-frequency robots from the control of the low-frequency structures. In the method, the robots act as force sources, and effectively maneuver and assemble these large, flexible space structures while minimizing vibration. The simulation and experimental results demonstrate the efficacy of the proposed controller for these cases.

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