

## Dealing With Vibrations in the Deployment Structures of Space Robotic Systems

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### ABSTRACT

Robots are needed for important missions in field environments, including space. A very promising class of field systems is long reach manipulator systems (LRMS) consisting of a robotic manipulator carried by a very large deployable structure that provides a large working envelope. The dynamic interactions between the manipulator and its supporting structure can excite degrading vibrations in the structure. Here a planning method, called the Coupling Map, that finds manipulator motions that reduce the levels of structural vibrations is presented. A control approach, called Inferred End-Point Control (IEC), that works with low vibration planning algorithms to compensate for any remaining residual vibrations is also discussed. The results of experimental evaluation of these methods are presented.

### INTRODUCTION

Robotic systems have been proposed for important missions in field environments, such as nuclear and toxic waste cleanup, construction and infrastructure inspection, and for space missions (Goldsmith, 1990; Weisman, 1992; Waltz, 1993). A very promising class of field systems for space is the long reach manipulator system (LRMS). LRMS consist of a relatively small high performance robot carried by a very large deployable structure. The proposed Special Purpose Dexterous Manipulator mounted on the Space Station Remote Manipulator System (SPDM/SSRMS) and the Japanese Experiment Module Remote Manipulator System (JEMRMS) are examples of long reach manipulator space systems now being developed, see Figure 1 (Hunter, 1994; Mori, Iwata and Oda, 1993). LRMS would have important uses on earth as well. Such examples are the repair of high voltage power transmission towers and lines, the inspection of underground storage tanks, and bridge maintenance (Soler and Guillet, 1993).

The deployable structure of the LRMS provides it with a large working envelope, while its manipulator provides fast and precise motion and forces required for the systems task. In most space missions the deployable structure will be stationary, its actuators locked, while the small manipulator performs its functions. The system can be modeled as a rigid manipulator mounted on a flexible supporting structure.

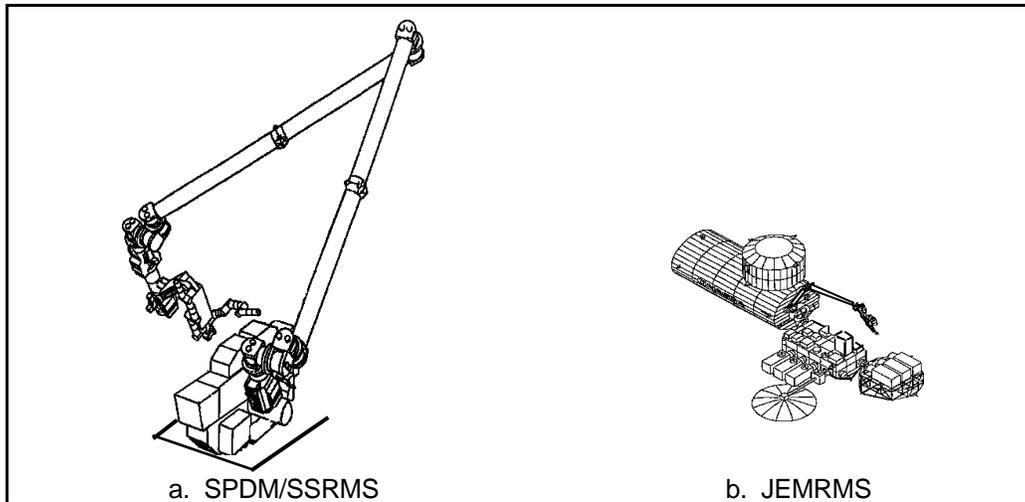


Figure 1. Examples of Long Reach Space Robotic Systems

While offering important advantages, space LRMS's present some challenging technical problems. Even though the deployable structure is in a nominally stationary extended configuration during the execution of the system's tasks, the motion of the small manipulator can excite vibrations of the supporting structure. These low frequency, undesired, and uncontrolled vibrations can degrade the accuracy of the system, increase task times, reduce system safety, and in general make the overall control of the system more difficult. It has been estimated that many cumulative hours would be spent, over 15 Space Station Freedom-assembly Shuttle flights, waiting for vibrations in the RMS to damp down to within  $\pm 1$  inch amplitudes (Scott, Gilbert and Demeo, 1991). Given the astronomical costs of space flight time, reducing this time would result in very significant cost saving.

This paper presents an overview of some of the results of a research program that is developing new control and planning algorithms for space LRMS that are able to mitigate and compensate for the degrading vibrations found in these systems and produce substantially improved systems performance. These algorithms are based on studying the fundamental dynamic character of these systems. Specifically, a planning technique called the Coupling Map generates graceful systems motions that do not cause excessive excitation of the supporting structural vibrations is discussed. Experimental results using a planning algorithm based on the Coupling Map, called the Hot Spot method, and the MIT Vehicle Emulation System (VES MOD II) are presented.

A control algorithm, called Inferred End-Point Control (IEC), that compensates for any remaining residual vibrations is discussed. It is shown that IEC can control a long reach robotic system, in spite of uncontrolled vibrations of its supporting structure using only on readily available strain measurements. Experimental tests of this algorithm using MIT's Elastic Base Manipulator testbed are also presented. The results show that IEC is effective and practical.

## COUPLING MAP BASED PLANNING ALGORITHMS

Since the motions of the small manipulator can excite vibrations of the LRMS deployment structure, it would be very desirable to plan the manipulator's actions so that the excitation was minimized. Recently a method, called the Coupling Map (CM), has been proposed for studying such "graceful path" motions (Torres and Dubowsky, 1993; Torres, Dubowsky and Pisoni, 1994). The Coupling Map shows how the nonlinear dynamic characteristics of the manipulator can be exploited to develop planning algorithms that find manipulator motions in joint space that result in a minimum transfer of energy between the manipulator and its supporting structure. This minimizes the amount of support vibration excited by the manipulator's motion.

The Coupling Map development assumes an  $n$  degree-of-freedom (DOF) rigid-link space manipulator mounted on a linear 6 DOF elastic structure with a stiffness matrix  $K_b$ , see Figure 2. The following brief development assumes gravity forces, contact forces, and the forces exerted on the manipulator by its structure are small. The structure's mass and damping are also assumed to be small. For a more complete development of the CM see (Torres and Dubowsky, 1993). The system's generalized coordinates are written as  $\mathbf{q} = [\mathbf{q}_b^T, \mathbf{q}^T]^T$ , where  $\mathbf{q}_b$  are the 6 generalized coordinates describing the inertial position and orientation of the manipulator's base and  $n$ -element vector  $\mathbf{q}$  represents its joint displacements. A generalized momentum vector  $\mathbf{h}$  for the system can then be written as:

$$\mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{H}(\mathbf{q}) \dot{\mathbf{q}} \quad (1)$$

$\mathbf{H}(\mathbf{q})$  is a symmetric, positive-definite inertia matrix:

$$\mathbf{H}(\mathbf{q}) = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix} \quad (2)$$

$\mathbf{A}$  is a symmetric  $6 \times 6$  submatrix relating the linear and angular velocity vectors of the manipulator base to its linear and angular momenta, and  $\mathbf{B}$  is a  $6 \times n$  submatrix relating manipulator joint motion to manipulator base linear and angular momenta. Submatrix  $\mathbf{C} = \mathbf{B}^T$  and submatrix  $\mathbf{D}$  is a  $n \times n$  matrix relating the manipulator joint velocities to their momenta.

The strain energy introduced into the structure,  $V$ , due to the manipulator's joint motions,  $\mathbf{q}$ , can be shown to be given by (Torres and Dubowsky, 1993).

$$V \sim \mathbf{q}^T \mathbf{Q} \mathbf{q} \quad (3)$$

$\mathbf{Q}$ , is called the Coupling Matrix and it is equal to  $\mathbf{G}^T \mathbf{K}_b^{-1} \mathbf{G}$ .  $\mathbf{G}$  is a function of the matrices in Equation (2), or  $\mathbf{G} = -\mathbf{A}^{-1} \mathbf{B}$ . The Coupling Matrix,  $\mathbf{Q}$ , can be seen to be a function of the manipulator's configuration, its mass properties and the stiffness matrix of the deployment structure. A singular value decomposition of  $\mathbf{Q}$  yields directions and magnitudes of maximum and minimum energy coupling in the

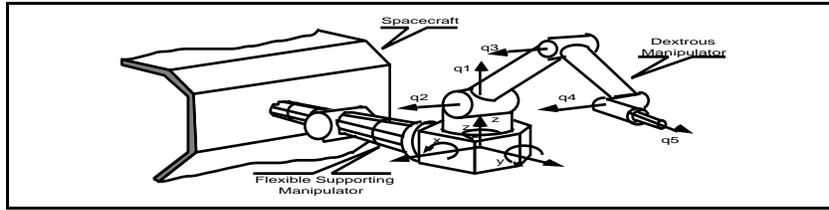


Figure 2. A Model of a Long Reach Space Robotic System

configuration space defined by manipulator joint motions,  $q$ . The directions of minimum coupling are used to plot lines of minimum energy in this space. The Coupling Map consists of representations of these minimum energy lines in an  $n$ -dimensional joint space. Figure 3 is the coupling map for a two DOF system.

Manipulator movement along these lines is likely to result in relatively low amounts of strain energy being transferred into the system's elastic supporting structure, causing little vibration. Motion perpendicular to minimum energy lines is likely to result in a local maximum transfer of energy to the system's elastic supporting structure, causing large residual vibration. Coupling Map areas of relatively high coupling, or *hot spots*, are represented by darker lines. Areas of relatively low coupling, or *cool spots*, are represented by lighter lines.

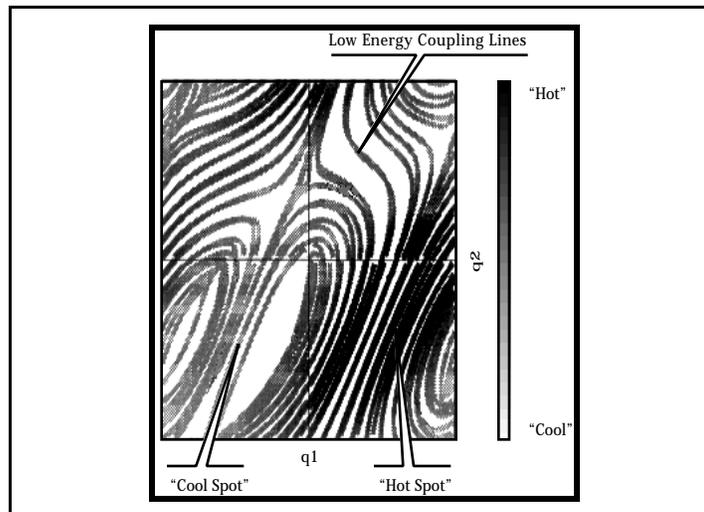


Figure 3. A Coupling Map

### THE HOT SPOT PATH PLANNING ALGORITHM

The Coupling Map has led to several graceful motion path-planning algorithms. Below, the *Hot Spot* Algorithm (Torres and Dubowsky, 1993) is briefly described and its experimental testing are presented. The Hot Spot algorithm finds paths in joint space that prevent the manipulator from moving perpendicular to the minimum coupling lines when the manipulator is in a *hot* region. The Hot Spot Method is based on the following heuristic rule:

*If a path must enter a CM region of high coupling, a hot spot, then it should follow minimum coupling lines as closely as possible.*

When coupling is low, at a *cool spot*, the path may move across the minimum coupling lines.

Figure 4 shows a Coupling Map with initial, I, and final, F, manipulator configurations. A Low-Coupling Path that is chosen using the Hot Spot Method is shown. It moves the manipulator along the minimum coupling lines in the Hot region and it moves across the lines when they are cooler. High-Coupling Path is also shown. The manipulator moves perpendicular to the low coupling lines inside the hot spot. This path should yield the greater residual vibration.

The effectiveness of the Hot Spot algorithm was verified using the MIT VES MOD II Space Emulation System carrying PUMA 560, see Figure 5. The VES is able to emulate the full micro-gravity spatial behavior of LRMS. For a more detailed description of this system refer to reference (Dubowsky, Durfee, Corrigan Kuklinski and Muller, 1994).

With the VES emulating a full spatial flexible structure the Coupling Map can no longer be displayed as a simple diagram. However computer path-finding algorithms can be used to search the CM for low-coupling paths in higher dimension maps using the Hot Spot Method. Figure 6 shows the energy transferred to the emulated supporting structure for the PUMA moving along a low and a high coupling path selected with the Hot Spot algorithm. The two paths have the same endpoints and took the same time. The “Low Coupling” path clearly results in substantially lower vibrational strain energy in the structure. The vibrations in this case are smaller in amplitude and decay to a small level much faster than the “High Coupling” path. These experiments such this one demonstrate the effectiveness of the Hot Spot Method in selecting manipulator paths that reduce the vibration of a system's flexible base.

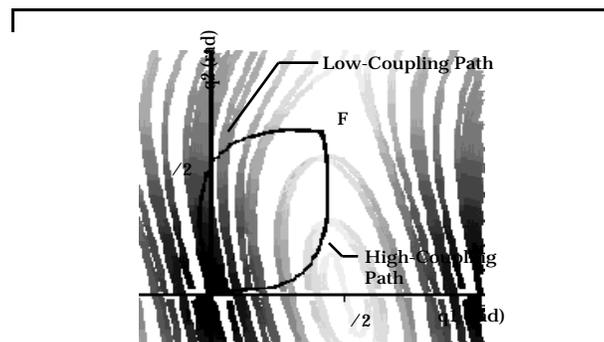


Figure 4. A CM with High and Low Coupling Paths Between Points I and F.

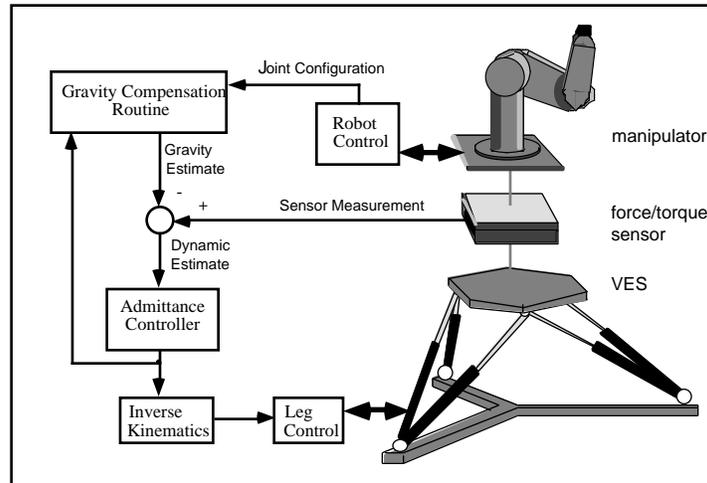


Figure 5. VES II Space Emulation System Schematic

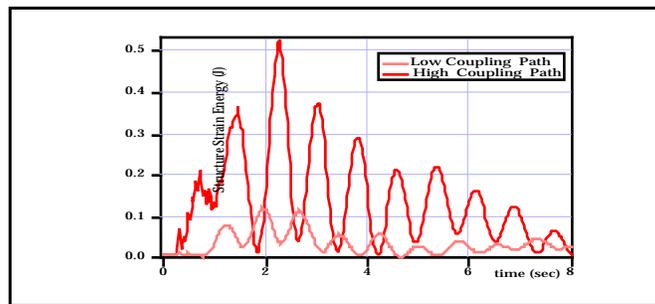


Figure 6. Structure Strain Energy versus time for Hot Spot Test.

## CONTROLLING THE EFFECTS OF DEPLOYMENT STRUCTURE VIBRATIONS

The above results show that while “graceful” planning algorithms can reduce the vibration excitation they can not completely eliminate it. This will require control algorithms to compensate for these base vibrations. While substantial research has been done to develop methods to control the vibrations of flexible space manipulators using their active joints (Scott, Gilbert and Demeno, 1991; Prakash, Adams and Appleby, 1991) relatively little work has been done on the vibrations control of manipulator systems with passive supporting structures. One method that has been shown to be very effective uses the small manipulator controller to increase the supporting structure damping coefficient so that its vibrations damp-out quickly (Torres, 1993). However it requires very low gains that limit its use to times when the manipulator is not performing a task.

It has been shown that if the end-point, or the manipulator’s base, positions and orientations of the flexible based manipulator are measured in inertial or task space then it is possible to control its end-point in spite of uncontrolled supporting structure vibrations (Chiang, Kraft and Cannon, 1991; Hootsman, Dubowsky and Mo, 1992). In the laboratory, these measurements can be measured relatively easily. However, making 6 degree of freedom position and orientation direct measurements in space can, in practice, be very difficult.

In this research program an end-point control method for space LRMS without the need for *direct* end-point or manipulator base position and orientation measurements has been studied (Mavroidis, Rowe and Dubowsky, 1995). The method, called Inferred End-Point Control (IEC), is an operational space control algorithm that uses estimates the inertial position and orientation of the base of the manipulator using strain measurements on the structure and a relatively simple static model of the structure, see Figure 7. This base position information is used by the manipulator's controller to infer the inertial end-point position and orientation and compensate for the vibrations of the structure. Simulation and experimental results obtained in this study suggest that the method is effective and can be practically implemented. IEC can be used in conjunction with planning methods, such as the Coupling Map to control the effects of any residual vibrations.

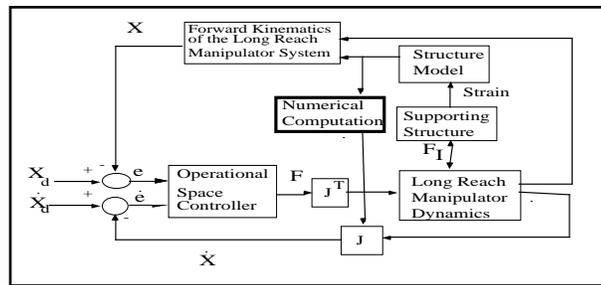


Figure 7. Inferred End-Point Control Algorithm for Long Reach Manipulators

- $F$  is an  $n \times 1$  vector of virtual end-effector forces and moments.
- $X, \dot{X}$  are  $n \times 1$  vectors of actual inertial end-effector positions and velocities.
- $X_d, \dot{X}_d$  are  $n \times 1$  vectors of desired inertial end-effector positions and velocities.
- $e, \dot{e}$  are  $n \times 1$  vectors of the inertial end-effector position and velocity errors
- $\tau$  is a  $(6+m) \times 1$  vector of the joint torques and manipulator/structure interaction forces and moments.
- $F_I$  is a  $6 \times 1$  vector of manipulator/structure interaction forces and moments
- $J$  is a  $n \times (m+6)$  augmented Jacobian matrix of the total system.
- $\theta$  is an  $m \times 1$  vector of the manipulator joint angles.
- $p$  is a  $6 \times 1$  vector of the manipulator base positions and orientation.

IEC control has been tested in simulation and in the laboratory experimental. Figure 8 shows the MIT's Elastic Base Manipulator testbed used for these experiments. This system consists of a two link, two degree of freedom, planar manipulator mounted on a flexible structure. The system's simple planar design minimizes the effects of gravity to enable it to study quickly algorithms for space applications. A complete description of this system is given in reference (Mavroidis, Rowe and Dubowsky, 1995).

The experimental results demonstrated the effectiveness of the IEC approach. Figure 9 and 10 show some the results from a very simple test that clearly demonstrates the effectiveness of the method. In this test the base structure is disturbed by an external force. It is very flexible and lightly damped. Figure 9a shows the structure's motion. It has a range of approximately  $\pm 4$  cm. The manipulator is commanded to hold its endpoint fixed in inertial space. Figure 9b shows that the endpoint is just a fraction of a cm. Figure 10 is a sketch indicating the relative range disturbance rejection of the control algorithm is able to achieve. It should be note that this performance is accomplished measuring strains only at a single point on the structure and a static model.

Tracking tests of IEC also showed very stable and accurate control. The results indicate that this approach could be combined with the use of simple to

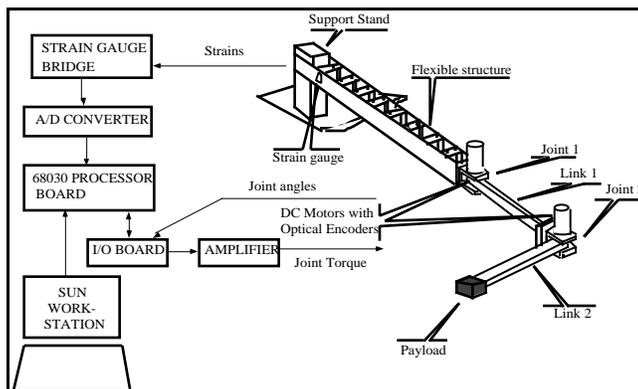


Figure 8. The MIT Flexible Base Manipulator

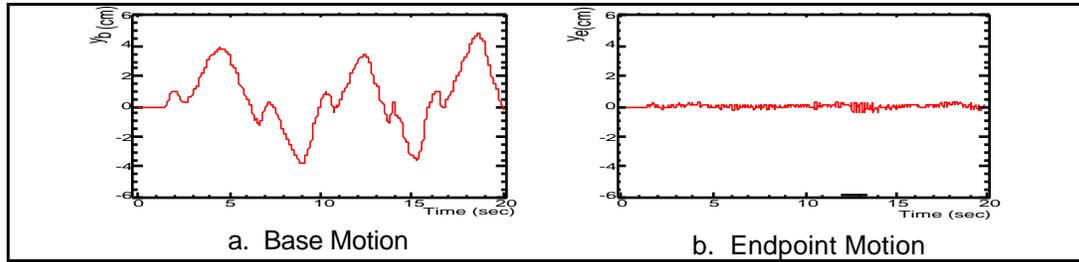


Figure 9. Experimental Results of IEC Disturbance Tests

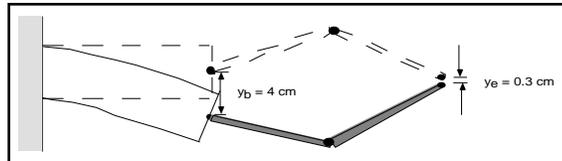


Figure 10. Disturbance Rejection Performance of the IEC Algorithm.

implement small range end-point sensor to enable the manipulator to “lock in” the end-effector on its final end-point position very quickly.

## CONCLUSIONS

This paper has addressed some of the planning and control issues associated with long reach robotic systems for space applications. The problem of the vibrations of the deployment structures used in this important class of systems present some very challenging technical problems. This paper has discussed the use of the Coupling Map and Inferred Endpoint control to treat these problems. It might be noted that a NASA In Space Technology Experimental Program (INSTEP) program is now under development to demonstrate these methods under flight conditions. Under this program a system is being designed to fly on the space shuttle to test these methods by a team consisting of MIT, Martin Marietta Astronautics Group, NASA Langley Research Center, and the University of Puerto Rico.

While some methods for planning the and controlling the motions of long reach space robotic systems have been suggested and evaluated, a number of very important problems in this field remain to be solved.

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