

Path-Planning for Elastically-Mounted Space Manipulators: Experimental Evaluation of the Coupling Map

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Abstract

The Coupling Map has been proposed as an analytical tool to describe the dynamic interaction between space manipulators which are either elastically mounted or carried by free-flying spacecraft. The Coupling Map has yielded a number of path-planning algorithms which have been successfully demonstrated in simulation to improve system performance. This paper presents an experimental evaluation of the Coupling Map and some of its path-planning algorithms. These experimental results show that the Coupling Map based path-planning algorithms are valid and viable candidates for practical implementation on space manipulator systems.

1 Introduction

Telerobotic manipulator systems have been proposed as alternatives to costly and hazardous Extra Vehicular Activities. These proposed systems are expected to perform a variety of tasks which may range from servicing a satellite or a spacecraft in orbit to assembling space structures [1]. An example of a proposed space manipulator system is the Special Purpose Dexterous Manipulator (SPDM) mounted on the Space Station Remote Manipulator System (SSRMS) [2,5]. In this system, the low-bandwidth, less accurate SSRMS will provide a large working envelope while the higher-bandwidth, more accurate SPDM will provide fast and precise motion and forces.

Based on current design specifications, vibration problems are expected in the proposed SSRMS, when it is excited by the motion of the two-arm 19 degree-of-freedom SPDM. Operating the SPDM slowly would reduce these SSRMS vibrations, but at the cost of reducing overall system effectiveness by increasing the time required to perform tasks. Consequently, before space manipulator systems such as the SSRMS and the SPDM are deployed, reliable and effective methods for modelling, controlling and planning the motion of these systems must be developed.

In many tasks, the large SSRMS will be stationary, its joints locked, while the small SPDM performs its

functions. It is expected that this mode of operation will be an operational constraint placed on the system. It will allow the system to be modeled as a rigid redundant manipulator mounted on a highly flexible supporting structure.

A literature survey conducted recently (see [12,13]) reveals that a number of studies have treated problems related to free-floating or free-flying space manipulators or have dealt with flexible link manipulators in terrestrial or industrial systems, and have focused on control problems by using pre-filtering techniques, or end-point control or an equivalent [6,9]. Pre-filtering techniques work successfully with linear systems such as simple one-link manipulators and have been extended to some nonlinear systems. However, the technique have not been applied to the problems of flexibly-supported manipulators. Methods for controlling vibrations based on some type of end-point sensing are not easy to implement in space, particularly for large manipulator motions. Moreover, end-point control methods leave the supporting system vibrations virtually uncontrolled, which could present serious hazards in space. Clearly prefiltering and end-point control approaches would have less work to do if manipulator paths were found which resulted in low levels of vibrations. In fact if very "graceful" paths were found these methods may not be required in many cases.

The problem of planning manipulator motion to reduce vibration in elastically mounted space manipulator systems has only recently been addressed. A new analytical tool called the Coupling Map has proven effective in understanding the problem of dynamic interaction between the motion of the space manipulator and vibrations in its elastic support, and in finding paths that reduce such interaction [12,13]. The Coupling Map has been used to develop a number of path-planning algorithms which have been proven, in simulation, to be effective methods for reducing the amount of support vibration produced by manipulator motions. The Coupling Map exploits the nonlinear dynamic characteristics of an effectively rigid manipulator, mounted on a highly flexible supporting structure to reveal directions of manipulator motions in joint space that, when followed, result in minimum or maximum transfer of energy between the manipulator and its supporting structure. This energy is directly related to the amount of support vibration excited by

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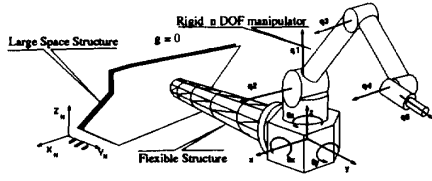


Figure 1: Elastically Constrained Space Manipulator

the manipulator's motion.

The effectiveness of the Coupling Map as a technique for describing manipulator-base interaction and as a tool for path-planning has so far been proven only in simulation using a wide range of system models [12,13]. The results of these extensive simulations has shown that the Coupling Map is a potentially an effective tool. However, before the Coupling Map can be seriously consider for implementation in real systems, it must be experimentally validated. This paper presents the results of an experimental evaluation of the Coupling Map and its path-planning algorithms. The experimental evaluations were conducted on the MIT Elastic Base Manipulator (EBM) testbed and on the Martin Marietta Harmonic Drive Planar Arm System (HDPAS).

2 Analytical Development

2.1 System Dynamic Model

Our model is an n degree-of-freedom (DOF) rigid body manipulator mounted on a flexible support in a zero gravity environment, see Figure 1. The support is modeled as a linear 6 DOF elastic structure. The distributed mass of the structure is assumed to be small compared to the mass of the manipulator and its base in Figure 1. For this system, a set of generalized coordinates are written as $\xi = [\phi, q]^T$; ϕ represents the 6 generalized coordinates describing the position and orientation of the manipulator's base frame with respect to a Newtonian reference frame. The n -element vector q represents the n manipulator joint displacements. A corresponding generalized force vector is defined as $\Xi = [\tau_\phi, \tau_q]^T$, and the system equations of motion are written as:

$$H(\xi)\ddot{\xi} + C(\xi, \dot{\xi})\dot{\xi} + K\xi = \Xi \quad (1)$$

where $H(\xi) \in \mathfrak{R}^{(n+6) \times (n+6)}$ is a symmetric, positive-definite inertia matrix, $C(\xi, \dot{\xi})\dot{\xi} \in \mathfrak{R}^{n+6}$ is a vector accounting for centrifugal and Coriolis effects, and:

$$K = \begin{Bmatrix} K_b & 0 \\ 0 & 0 \end{Bmatrix} \in \mathfrak{R}^{(n+6) \times (n+6)} \quad (2)$$

is a symmetric matrix representing the stiffness of the system. K_b is the stiffness matrix of the base. The control torques for the manipulator joints are contained in Ξ .

A generalized momentum vector π for the system based on the selection of generalized coordinates is written as:

$$H(\xi)\dot{\xi} = \pi \quad (3)$$

where the elements of $\pi = [\pi_\phi, \pi_q]^T$ correspond to the components of the generalized momentum in the direction of the generalized coordinates. Equation (3) is used to develop an algorithm for computing the Coupling Map discussed in the next section.

2.2 The Coupling Map

The Coupling Map is an analytical tool used to describe the sensitivity of a manipulator to the transfer of vibrational energy into its supporting structure. In general, factors affect to this energy transfer are the instantaneous direction and velocity of the manipulator motion, the instantaneous motion of the base, the mass properties of the manipulator and the base, the stiffness of the compliant structure and the configuration of the system. To simplify the problem the Coupling Map is developed using the following assumptions:

- Gravity forces are negligible.
- The forces and torques exerted on the manipulator by the structure are small.
- The disturbances of the manipulator on its structure do not excite structural resonance effects.
- The manipulator begins its motion from rest.
- The end-effector does not contact the environment during the manipulator motion.

Although used in the analytical development, some of the above assumptions, may be violated in practice. However, simulation has shown that the technique yields good results even in such cases [14]. Given the above assumptions, the total generalized momentum of the manipulator remains small and Equation (3) becomes:

$$H(\xi)\dot{\xi} = \pi = 0 \quad (4)$$

The inertia tensor $H(\xi)$, based on the choice of generalized coordinates, is written as:

$$H(\xi) = \begin{Bmatrix} A & B \\ C & D \end{Bmatrix} \quad (5)$$

where $A \in \mathfrak{R}^{6 \times 6}$ is a symmetric submatrix relating the linear and angular velocity vectors of the manipulator base to its linear and angular momenta, and $B \in \mathfrak{R}^{6 \times n}$ is a mass submatrix relating manipulator joint motion to manipulator base linear and angular momenta. Submatrix $C = B^T$ and submatrix $D \in \mathfrak{R}^{n \times n}$ relates the manipulator joint velocities to their momenta. Using Equation (5) and recalling that $\dot{\xi} = [\dot{\phi}, \dot{q}]^T$, we solve Equation (4) for $\dot{\phi}$, yielding:

$$\dot{\phi} = -A^{-1}B\dot{q} \quad (6)$$

When we replace the derivative operation by a variation, and let $G = -A^{-1}B$, Equation (6) becomes

$$\delta\phi = G\delta q \quad (7)$$

The matrix G , called the system's disturbance matrix, relates infinitesimal manipulator motion, δq , to infinitesimal base motion, $\delta\phi$, for a free-floating system [3,11,12]. Since Equation (7) is based on the assumption of zero external forces or torques acting on the system, while this is true for free-floating systems, it is not strictly true for elastically supported systems. However, it can be argued that the forces and torques in the directions that are susceptible to large vibrations, those with low stiffness, are small if, in fact, low-coupling paths are found and vibrations remain small. The quantity $\delta\phi$ represents a measure of the dynamic coupling between the manipulator and its supporting structure. For the systems considered in this study it is called the instantaneous base dynamic disturbance. The quantity $\delta\phi$ has been shown to be proportional to the reaction forces/torques that would be required to keep the manipulator's base stationary [3,11-13]. Thus, when manipulator motion causes a relatively low dynamic disturbance, $\delta\phi$, low forces/torques would be needed to restrain the system. So the forces and torques required from the supporting structure to restrain the manipulator base are proportional to the dynamic disturbance $\delta\phi$, or:

$$\tau_\phi \sim \delta\phi \quad (8)$$

These manipulator restraining forces and torques, which are equal and opposite to the forces and torques acting on the structure which, result in energy being transferred into the elastic supporting structure during the manipulator's motion. The residual vibrations excited by the manipulator's motion are, in turn, directly related to the magnitude of this energy. So, for a system with *given stiffness characteristics* and a given speed of maneuver, manipulator paths that have low instantaneous disturbances along the path, $\delta\phi$, will produce relatively small forces/torques acting on the supporting structure; hence relatively small amounts of energy will be transferred to the structure. Low residual vibrations would be expected as a result.

The energy transferred to the supporting structure will also be a function of the stiffness characteristics of the structure for a given set of disturbance forces and torques. As simple mechanics show, more strain energy is required for a soft structure to resist a given force than for a stiff structure to do so. Hence, the strain energy that will be produced in a supporting structure is a function of how the structure's effective stiffness matrix "aligns" with the disturbance force/torque vector. This is modeled as follows.

The strain energy V , stored in the compliant structure, can be written in terms of the stiffness matrix K_b , and the force/torque exerted on this structure by the manipulator base, as:

$$V = \frac{1}{2} \tau_\phi^T K_b^{-1} \tau_\phi \quad (9)$$

Equation (8) gives the forces/torques which would act on the structure, assuming the system is at rest with no significant elastic deformation, and the manipulator joints move by a small amount. The strain en-

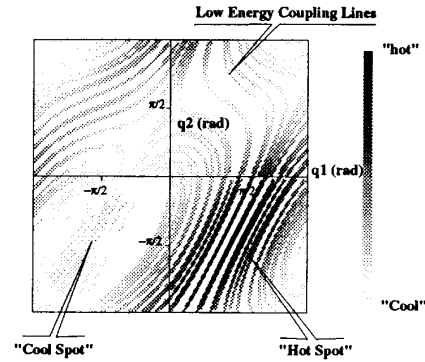


Figure 2: The Coupling Map

ergy introduced into the structure, then, using Equation (9), is:

$$V \sim \delta\phi^T K_b^{-1} \delta\phi \quad (10)$$

By recalling Equation (7), we can write Equation (10) as:

$$V \sim \delta q^T G^T K_b^{-1} G \delta q \quad (11)$$

A matrix Q , called the Coupling Matrix, is now defined as $Q = G^T K_b^{-1} G$; Equation (11) is written as:

$$V \sim \delta q^T Q \delta q \quad (12)$$

The Coupling Matrix Q is a function of the manipulator's configuration and is a measure of the system's sensitivity to the transfer of vibrational energy to its supporting structure. The matrix K_b enters the formulation so that directions of base motion with low stiffness carry a higher weight than those with high stiffness.

A singular value decomposition of the Coupling Matrix Q yields directions and magnitudes of maximum and minimum energy coupling in the 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 these minimum energy lines plotted in an n -dimensional joint space, see Figure 2.

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. Motions perpendicular to minimum energy lines are likely to result in a local maximum transfer of energy to the system's elastic supporting structure, causing large residual vibration. On the Coupling Map, areas of relatively high coupling, or *hot spots*, are represented by darker lines and areas of relatively low coupling, or *cool spots*, are represented by lighter lines.

3 Experimental Evaluation

The Coupling Map has led to three path-planning algorithms designed to find manipulator motions that

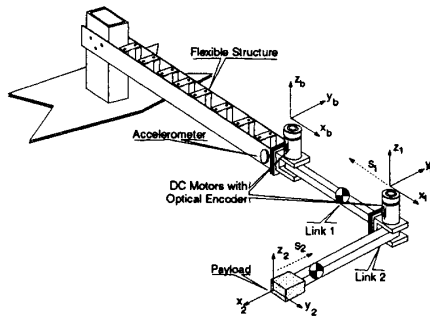


Figure 3: The MIT Elastic Base Manipulator Testbed (EBM)

result in a reduction of the amount of energy transferred to the manipulator base due to manipulator maneuvers. These algorithms are known as the *Base Relocation Algorithm*, the *Hot Spot Method* and the *Redundancy Resolver Algorithm* [12,13]. Here experimental results are presented for the Base Relocation Algorithm and the Hot Spot Method. Due to space limitations, only a brief description of these algorithms will be presented in this paper. For more detailed descriptions of these algorithms, the reader is referred to [11], [12] or [13]. In addition, as part of this experimental evaluation, the Coupling Map is combined with a pre-filtering technique.

3.1 Experimental Setup

Two experimental manipulators were used to evaluate the Coupling Map. These are the Martin Marietta Harmonic Drive Planar Arm System (HDPAS) and the MIT Elastic Base Manipulator EBM testbed. A brief description of each of these two systems is given below.

The MIT Elastic Base Manipulator Testbed

The MIT Elastic Base Manipulator (EBM) testbed, consists of a two-link planar manipulator supported by a flexible structure. See Figure 3. The EBM's structure has low stiffness characteristics for bending in the horizontal plane and high stiffness characteristics for vertical bending and for torsion. This results in a one-DOF flexible base manipulator system with a base natural frequency of about 1 Hz.

The manipulator is 0.5m long with each of the joints powered by DC motors each with a 33.1:1 reduction drive and equipped with an optical encoder at the motor side to measure absolute joint angle. A 0.25 Kg. payload is attached to the end of the second link. The EBM is controlled by a HEURICON single board computer. This system is based on the 32-bit Motorola 68030 microprocessor running at 20MHz. VxWorks is used as a real-time operating system.

Base vibrations in the y_b direction (see Figure 4) are measured with a Bruel & Kjaer accelerometer, model 4370, which is mounted on the structure at the manipulators base.

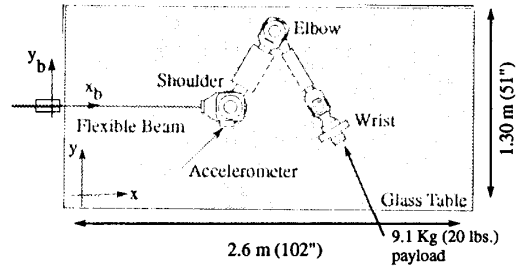


Figure 4: Martin Marietta Harmonic Drive Planar Arm System (HDPAS)

The Martin Marietta Harmonic Drive Planar Arm System

The Martin Marietta Harmonic Drive Planar Arm System (HDPAS), see Figure 4, was designed as a research testbed to study a number of fundamental problems related to the control of space manipulator systems. The HDPAS is a three-link planar manipulator supported by air bearings on a glass plate for near frictionless motion. The actuators are DC motors with an 80:1 harmonic drive transmissions. Local joint torque feedback loops allows the arm to behave as a frictionless direct-drive system. Each joint has a motor-side tachometer, an output torque transducer, and a resolver to measure joint angle.

For these experiments, the HDPAS was mounted to a 0.886m aluminum beam which gave the base a 2-DOF flexibility allowing translational vibrations along the y_b and rotational vibrations about the base z_b , see Figure 4. An accelerometer was mounted at the outer casing of the shoulder joint to monitor base vibrations. A 20 lb (9.1 kg) payload was attached to the manipulator wrist joint. The wrist was locked as shown in Figure 4. The HDPAS base vibration was between 0.45 to 0.5 Hz, depending on the manipulator configuration. The mass properties of the HDPAS are given in [13].

3.2 Base Relocation Algorithm

The Base Relocation Algorithm finds a base location from which a path of low energy coupling can be found for a given task. This can be especially useful for positioning of the supporting manipulator so that the destrous manipulator can perform tasks that require repetitive manipulator motions, such as loading space equipment, assembling space structures or repairing a satellite in orbit. In many cases, there is some choice in the location of the manipulator base. The Coupling Map can be used to find a *good* base location from which the manipulator can perform a task by following a low energy path and, hence, experience relatively low levels of base vibration.

Figure 5 shows the HDPAS with its end-effector in a location labeled I in inertial space. In a this scenario, the cantilever beam can represent a large flexible manipulator, such as the SSRMS, designed to move the HDPAS's base to a given location in inertial space. The system is required to move its end-effector from point I to a given final point F (shown in Figure 5)

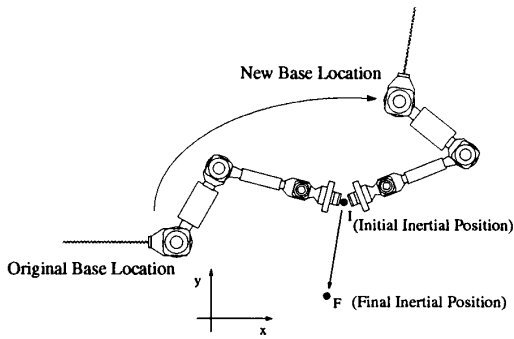


Figure 5: HDPAS with its End-effector at it Initial Position for Two Manipulator Base Locations.

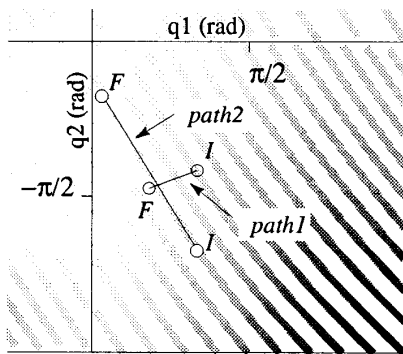


Figure 6: System's Coupling Map with; Straight-Line Path (*path1*) and Low Disturbance Path (*path2*)

and after some period of time move it back to point I. This task will be repeated a number of times. Figure 6 shows the Coupling Map for this system and a straight line path, called *path1*, that can take the manipulator from point I to point F and back. Given the location of the base, the inertial points I and F are represented on the Coupling Map by the points I and F. Figure 6 shows that the selected inertial path, *path1*, lies perpendicular to the lines of minimum coupling. Therefore, it is expected that this path will generate relatively large residual base vibrations. This behavior is confirmed experimentally, the results of which are shown in Figure 7.

Changing the location of the base in inertial space changes the position of points I and F in the Coupling Map as shown in Figure 6. For this example, the Base Relocation Algorithm (see Reference [11, 12]) was used to relocate the base, to a new location also shown in Figure 5. Figure 6 shows the new Coupling Map path, called *path2*, for the new base location. Notice that like *path1*, *path2* takes the manipulator's end-effector from point I to point F in inertial space, but the maneuver is now along a minimum coupling line. Therefore, it is expected that this maneuver will

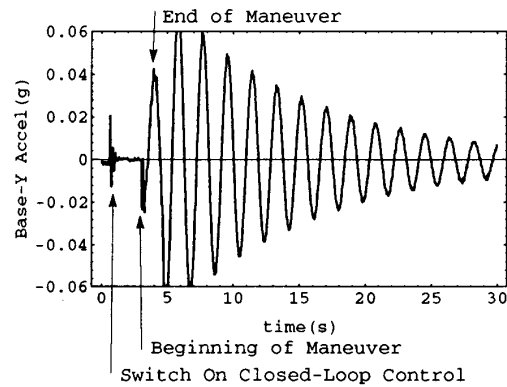


Figure 7: Experimental Results of the HDPAS Performing *path1* in 1.6 Seconds.

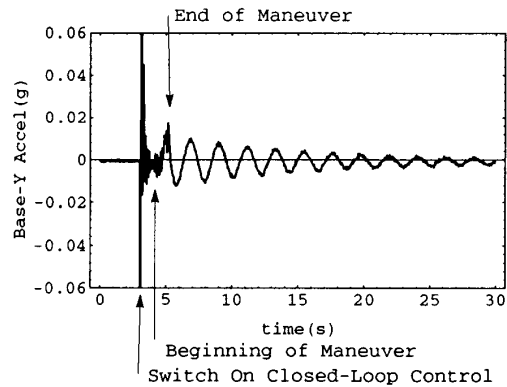


Figure 8: Experimental Results of the HDPAS Performing *path2* in 1.6 Seconds.

result in relatively low residual vibrations compared to the maneuver using *path1*. This maneuver was also confirmed experimentally and the results are shown in Figure 8.

Path2 resulted in a 75% reduction in the magnitude of the residual vibration compared to the residual vibration produced by *path1*. These experimental results agree with the results predicted by the Coupling Map and validate the Coupling Map as a tool for significantly reducing residual vibration through base relocation.

3.3 Hot Spot Method

A second algorithm based on the Coupling Map is the Hot Spot Method [11-13]. The Hot Spot Method is a technique for path-planning that uses the information provided by the Coupling Map to find 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 go through a Coupling Map region of large energy coupling, a hot spot, then it should follow

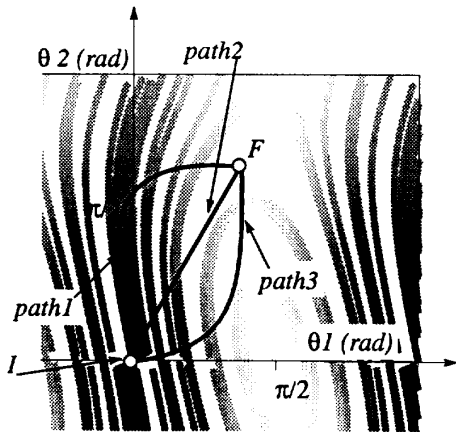


Figure 9: Coupling Map of the EBM with its Initial and Final Configurations and Three Paths

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

The Hot Spot approach can be applied even when nonrepetitive tasks are being performed.

The effectiveness of this algorithm was experimentally studied using the EBM, shown in Figure 3. For this experiment, a task was selected which consisted of moving the EBM payload between an arbitrary initial and final position. Figure 9 shows the Coupling Map with the initial, I , and final, F , configurations in joint space. Notice that the initial configuration, point I , lies in a hot spot in the Coupling Map. Therefore, motions of the manipulator perpendicular to the low coupling lines in the vicinity of I should result in a relatively high transfer of energy to the system's flexible structure.

To verify this prediction, three paths are considered. As shown in Figure reishakyCM, the first path, called $path1$, is chosen using the Hot Spot Method. The second path, called $path2$, is simply a straight line path between points I and F in joint space. Finally, $path3$, is chosen for comparison. It moves the manipulator joints perpendicular to the low coupling lines inside the hot spot and thus should yield the greatest residual vibration to the manipulator base. Each path is chosen to take 1.4 seconds to complete with zero initial and final joint velocities.

Figure 10 shows the position history of the manipulator base during and after the three maneuvers. The path chosen using the Hot Spot Method, $path1$, yields the lowest vibrational amplitude and settling time. The path chosen which contradicts the Hot Spot rule, $path3$, yields the highest residual vibration, agreeing with the predictions of the Coupling Map. The straight line path, or $path2$, which is the shortest path in joint space, results in substantially more vibration than $path1$.

These experimental results demonstrate the effectiveness of the Hot Spot Method in selecting manipulator paths that reduce the vibration of a system's

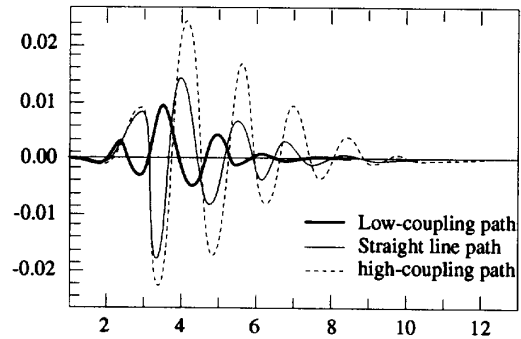


Figure 10: Motion of the EBM Base During and After Manipulator Maneuvers along $path1$, $path2$ and $path3$

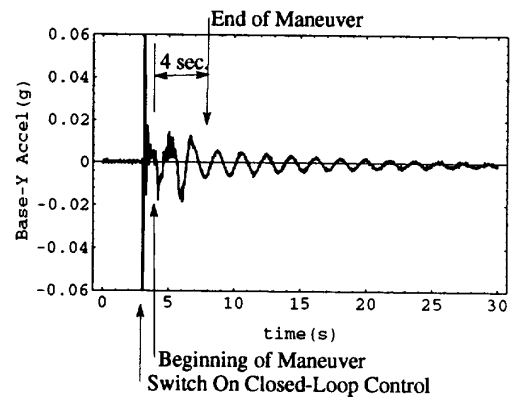


Figure 11: Experimental Results: HDPAS Base Acceleration for $path1$ with Pre-Filtering. The initial acceleration is due to the switching on of the closed-loop control system.

flexible base.

3.4 The Coupling Map and Pre-filtering

Pre-filtering, or command-shaping, techniques have been proposed to reduce residual vibrations in computer-controlled flexible machines [7,9]. Pre-filtering methods are used to select the velocity profile along a specified path to reduce residual structural vibrations. The Coupling Map provides paths with reduced vibration. In this experiment, the Coupling Map is used with pre-filtering techniques to improve system performance by using a pre-filtered velocity profile along low-disturbance paths.

For this experiment, we used the HDPAS testbed and selected two paths called $path1$ and $path2$. These paths are the same as those used in the base relocation experiment described earlier in this paper and are shown in Figure 6. $Path1$ generates relatively large residual vibrations when compared to $path2$.

In the first part of the experiment, the HDPAS is commanded to move along $path1$ using a three-impulse pre-filter [9]. Recall that the HDPAS's base has a damped frequency between 0.45 to 0.5 Hz, depending on the manipulator configuration. Therefore, for this

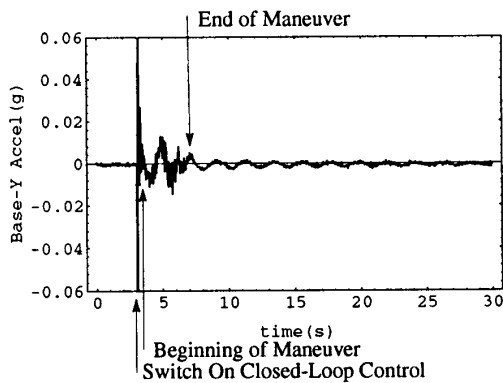


Figure 12: Experimental Results: HDPAS Base Acceleration for path2 with Pre-Filtering

maneuver a three-impulse pre-filter was selected to cancel out a 0.5 Hz frequency. The motion of the HDPAS's base during and after the maneuver are shown in Figure 11. Despite the pre-filter, the system experienced some residual vibrations. This is probably due to the nonlinear behavior of the base vibration, i.e., the damped frequency of the system's base is function of the configuration of the manipulator.

For the second part of the experiment, the HDPAS was commanded to move along *path2* (the low disturbance path) again using the same three-impulse pre-filter. The motion of the HDPAS's base for this maneuver is shown in Figure 12. *Path2* clearly results in less residual vibration when compared to *path1*. The selection of a low coupling path helped attenuate the residual vibrations that the pre-filter does not completely eliminate. These results show that the Coupling Map can be used with other time-domain path-planning algorithms to improve their performance.

4 Conclusion

This paper presents experimental evaluation of the Coupling Map on two different two-link planar manipulator systems. The results show the validity of the Coupling Map for describing the dynamic interaction between a manipulator and its flexible supporting structure. These experiments also demonstrate that the Coupling Map's Base Relocation and Hot Spot algorithms can be used to generate low coupling paths that give significantly reduced residual vibration and, therefore, reduce the vibration settling time. Finally, the experiments demonstrate that the Coupling Map can be used effectively to improve the performance of time-domain pre-filtering techniques.

The Coupling Map is currently being experimentally evaluated for more complex systems using the MIT Vehicle Emulation System II, or VES II [4]. Also, the Coupling Map has been proposed for experimental flight evaluation aboard the NASA Space Shuttle as part of a NASA In-Step proposal [10] by Martin Marietta Astronautics Group, NASA Langley Research Automation Technology, MIT and the University of Puerto Rico.

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