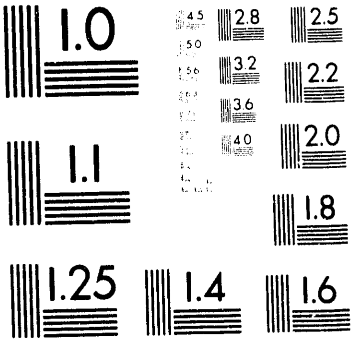
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ACTIVE DAMPING OF OSCILLATIONS IN A LONG COMPLIANT MANIPULATOR LINK

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ACTIVE DAMPING OF OSCILLATIONS IN A LONG COMPLIANT MANIPULATOR LINK

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ABSTRACT

A flexible manipulator test bed consisting of a fifteen foot long fixed-free compliant beam (representing a compliant manipulator link) with a Schilling Titan II dextrous manipulator mounted on its free end has been constructed at Pacific Northwest Laboratory (PNL). A comprehensive dynamic model which includes flexible body effects has been developed at PNL using a commercially available multibody dynamics code. A linearized version of the model is used to develop control strategies which use inertial forces generated by movements of the dextrous manipulator to damp out induced oscillations in the beam. These control strategies are tested on the model and shown to be feasible, and then implemented in the flexible manipulator testbed. Results from the hardware experiments are analyzed and compared with the model results.

INTRODUCTION

The remediation of hazardous waste sites at US Department of Energy facilities will require the use of remote equipment. Due to conditions at some of these waste sites remotely operated manipulators with reach capabilities greater than thirty feet will be needed. Access restrictions for these manipulators, particularly in large underground storage tanks, will result in manipulators with relatively flexible links and low natural frequencies of oscillation. New and advanced algorithms for active damping control will allow productive and effective use of these types of manipulators. A long reach flexible manipulator control test-bed, and associated facilities at Pacific Northwest Laboratory (PNL), are making possible the development and testing of active damping control systems for long reach manipulators. This paper presents a description of the test-bed and associated facilities at PNL and a new active damping control algorithm with results from the simulation and experiment.

DESCRIPTION OF TEST-BED FACILITIES

One class of long reach manipulators being considered for the remediation of underground storage tanks, and possibly for buried waste sites, is configured as a coarse positioning long reach manipulator (LRM) with a more dexterous, lighter duty short reach manipulator (SRM) mounted on its tip. Each link of the LRM would be from eight to fifteen feet long. The long reach flexible manipulator test-bed shown in Figure 1, simulates the last link on such an LRM with the SRM mounted on its end. The test-bed consists of a steel beam 15 feet long by 1 foot high by 0.75 inches thick, fixed at one end and free to move in a horizontal plane at the other. The free end is supported off the floor by an air bearing which provides a low friction interface with the floor while restricting any torsion about the longitudinal axis of the beam. Limiting the torsion in the beam in this manner is necessary to avoid buckling. A six degree of freedom hydraulic manipulator (Schilling Titan II) is mounted on the beam at the free floating end.

Hardware for implementing advanced feedback control for oscillation damping includes sensors and data acquisition and control computers. The beam is instrumented with strain gages located near the root and at about 4/5 of the beam length from the root. These two inputs provide indications of both the first and second modes of vibration. The SRM is instrumented with joint position and velocity sensors. Sensors to measure the forces generated at the joints of the manipulator are currently being designed and tested, and will be incorporated into the manipulator in the future.

The SRM has its own low level control system consisting of proportional position control loops for each joint. Positioning commands can be sent to the manipulator by setting joint position set points using a host computer. The host computer system consists of a Motorola 68030 based computer, and an analog to digital interface to the sensor systems, all housed in a VME backplane. This computer system, which runs under a real–time operating system, provides a platform which is highly capable of implementing advanced and complex control algorithms in real time.

In addition to the test-bed hardware shown in Figure 1, a dynamic model of the test-bed has been built using a Sun SPARC-station computer and DADS, a dynamic modeling and simulation software package developed by CADSI, Inc. The dynamic computer model of the test-bed allows researchers to test advanced control algorithms by using computer simulation prior to implementation on the test-bed hardware.

ACTIVE DAMPING CONTROL USING INERTIAL FORCES

The first set of active damping control algorithms designed for testing on the test-bed controls the motion of the SRM to generate inertial forces designed to annihilate the oscillations sensed in the flexible beam. Very little research has been conducted on this form of manipulator oscillation damping, although it has been proposed by Book[ ]. The problem is challenging as many considerations must be addressed; some of the more critical issues include:

1. Flexible mechanical structures can oscillate at an infinite number of modes. With the PNL test-bed, as with most structures, the first few modes dominate; therefore, a controller must damp these modes while having very little or no detrimental effect on other modes.
2. The dynamic and kinematic interactions between the LRM and the SRM are nonlinear and complex. Therefore, it can be extremely difficult to accurately model.
3. System oscillations can be initiated by a variety of excitations including exogenous disturbances and operator-controlled movements. While operator-controlled movements can be tempered and smoothed, unknown disturbances such as impact with unseen objects are impossible to predict.
4. Loading conditions and system configurations may vary during manipulator operation. With each new load and configuration, the dynamic response the system changes. Therefore, a control system must provide damping under a wide variety of operating conditions (i.e., the controller must be *robust* to varying system conditions).
5. Because measurement and operating systems are prone to partial failures (e.g., sensor failure), the control system must satisfactorily operate under various measurement errors and system failures (i.e., the controller must be *reliable*).

With the constraints in place on the PNL test bed, motions of the flexible link are limited to the horizontal plane. This substantially restricts the number of vibration modes which can be observed in the system. In fact, the first two flexural modes are primarily of interest, as they are most easily excited. These modes can be controlled by the azimuth actuator of the SRM. The other joints of the SRM are held fixed, with the manipulator reaching out parallel to the axis of the flexible link. This means that only one of the degrees of freedom of the manipulator is used in damping vibrations. In the future, the test bed will be allowed additional degrees of freedom, and more complex motions of the SRM will be required in order to damp vibrations.

CONTROLLER STRUCTURE AND DESIGN METHODOLOGY

Figure 1 shows the structure of the damping control system.

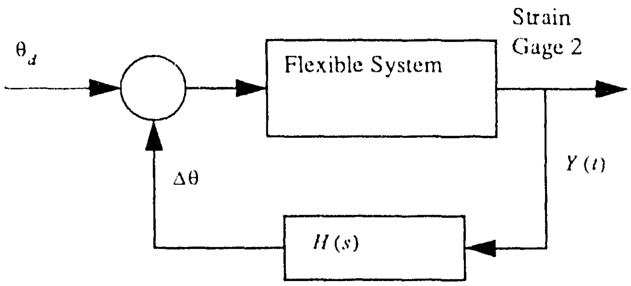

FIGURE 1. Control System Structure

This initial controller was designed around data which had a relatively small mode one component, and larger mode two component. Hence, it is designed to primarily annihilate mode two vibrations, which are accurately tracked by the output from strain gage two. This output is passed through the controller $H(s)$. The controller output is subtracted from the desired steady state azimuth angle (θ_d), and then passed to the SRM as the desired azimuth angle. The objective is to design $H(s)$ to satisfactorily address the five issues listed in the previous section. The first step in designing a damping control system is to model the dynamics of the robotic system in the appropriate form under all possible conditions (e.g., various loading conditions). This results in a family of models. Using these models, the parameters of $H(s)$ are designed.

Two levels of modeling are required for the manipulator system. The first level involves nonlinear modeling using the DADS program. This model acts as a test bed for controller methodology development. The second level of modeling involves representing the dynamics of the system with a set of linear constant-coefficient differential equations. This set of models (termed the *control design models* (CDMs)) are required for choosing parameters in the feedback controllers.

There are two possible approaches for developing the CDMs. With one approach the DADS model is linearized about a set of operating conditions. The second approach is to use a system identification method to optimally fit linear models to the input-output data of the DADS model. This second method has a clear advantage in that it can be directly applied to the flexible system through laboratory tests; therefore, the controller design is not dependent on the accuracy of the DADS model.

The CDMs for the flexible manipulator system at PNL were developed using the system identification approach. Prony analysis[2] was used to identify linear transfer functions based on the step response of the robotic system. A step function command is applied to the azimuth angle of the SRM and the strain gage data are monitored. The responses are then analyzed using Prony analysis to identify optimal linear transfer function models. For this initial controller, a single payload case is analyzed. Future developments include analyzing the system for multiple payloads.

Prony analysis is very well suited for developing models of high-order linear oscillatory systems[4]. The Prony analysis software used at PNL is call IPRONYID[5] and is an advancement of a program developed by the Bonneville Power Administration used to analyze electromechanical oscillatory dynamics in large power systems.

The frequency response of the robotic system azimuth joint is shown in Figure 2.

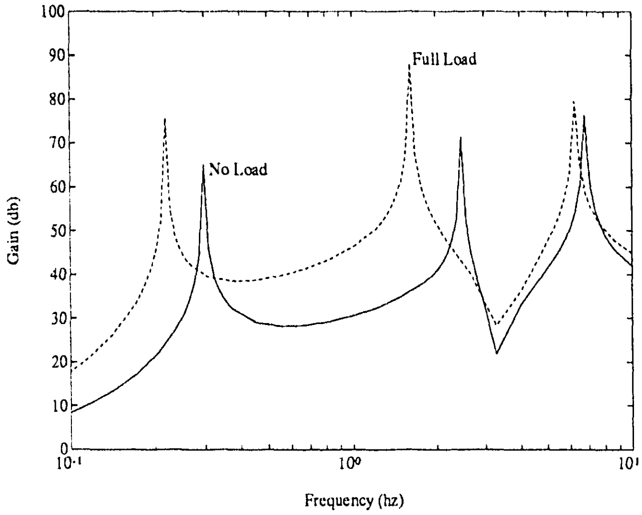

FIGURE 2. Frequency Response from commanded azimuth angle to strain gage two.

From Figure 2, one sees that the transfer function for the tip position is dominated by the first two modes. Therefore, a feedback loop for the tip position would have the most effect on these two modes. Likewise from Figure 2, the second and third modes are most easily affected by a feedback on the tip velocity.

Modal gain alone does not determine the best feedback structure; phase must also be considered. Figure 3 and Figure 4 show the root-locus plots for the tip position and velocity transfer functions under full load conditions. For both feedback signals, the loci move in opposite directions, i.e., their phasing is opposite. Mode 3 loci move in the same general directions as mode 2. This phasing is challenging for feedback control. Similar phasing occurs for the no load case.

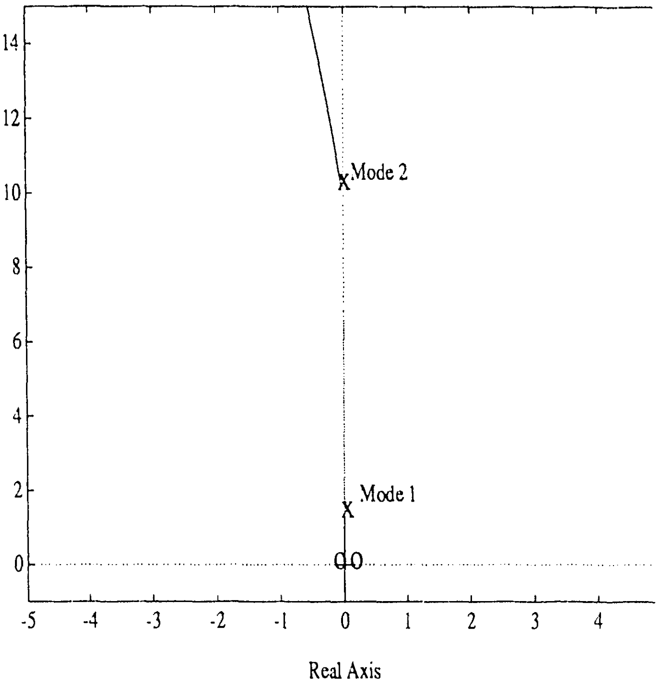

FIGURE 3. Root Locus Plot for Tip Position, Full Load

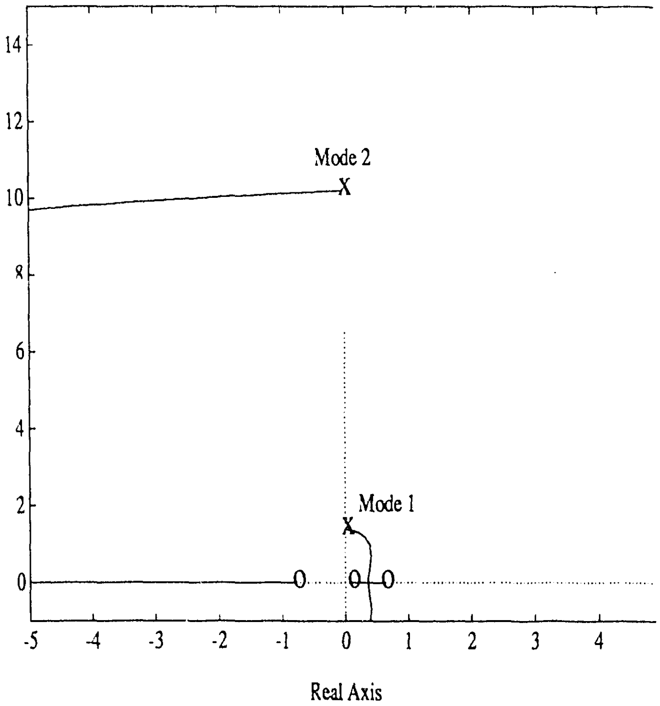

FIGURE 4. Root Locus Plot for Tip Velocity, Full Load

One solution to choosing a feedback controllers is to design a series of controllers, each impacting only a specific mode or group of modes. For this problem, we have elected to assign our initial controller ($H(s)$) to damp mode two oscillation; later controllers will damp other modes. This means that the controller should have little effect on activity in modes other than mode two. Also, the controller must have significant roll-off properties outside its effective bandwidth for effective noise rejection. The ultimate set of controllers having each controller assigned to a different mode should be highly decoupled, resulting in an inherently reliable control structure.

The structure for $H(s)$ is a series of lead-lag blocks with an overall gain, which can be written in the Laplace domain as

$$H(s) = \frac{K_p (s + b_{p,1})(s + b_{p,2}) \dots}{(s + a_{p,1})(s + a_{p,2}) \dots} \qquad \text{(EQ 1)}$$

Sequential loop closure[6] is used to design the controllers. First the parameters of H_v are chosen and that loop is closed, then the parameters of H_v are chosen using the system with H_v closed as the design model. The full load CDM are used to design the control parameters because this represents the highest gain condition (as seen in Figures and 2).

Once parameters have been chosen, the reliability and robustness of the controllers are tested. Robustness tests are passed if the controllers provide a specified degree of damping under all operating conditions. The tests are based on the system satisfying a minimum Nyquist circle criterion (which guarantee certain gain and phase margins) for both full load and no load operating conditions. Reliability is tested if the controller remains stable under all loading conditions and possible sensor failures. In this case this requires testing both position sensor and velocity sensor failures for both loading conditions. Parameters are adjusted until reliability and robustness criteria are met.

The methodology for choosing the parameters for H_p and H_v involves a some what ad hoc procedure primarily based on the concept of loop-shaping[3] and root-locus design. The coefficients of H_p are chosen to provide the proper phase to the make the pole representing mode 1 move farther into the left-hand-plane while having very little effect on modes 2 and 3. H_v is adjusted so that it provides proper phasing to modes 2 and 3, while having little effect on mode 1.

Both controllers are designed to have low gain at frequencies higher than the third mode to avoid control spillover (i.e., unexpected effects on higher unmodeled modes). Effects on modes higher than the 3rd is expected to be null to very little as initial analysis indicates that these higher modes are very weak for the robotic system.

CONTROLLER DESCRIPTION

The control design methodology was applied to the robotic system resulting in the following controllers:

$$H(s) = \frac{10}{(s + 6\pi)} \qquad \text{(EQ 2)}$$

Figures 5 and 6 show the frequency response for the closed-loop system. The damping on mode 1 is increased by a factor of 50 or more, while the damping on modes 2 and 3 are increased by a factor of 4 or more.

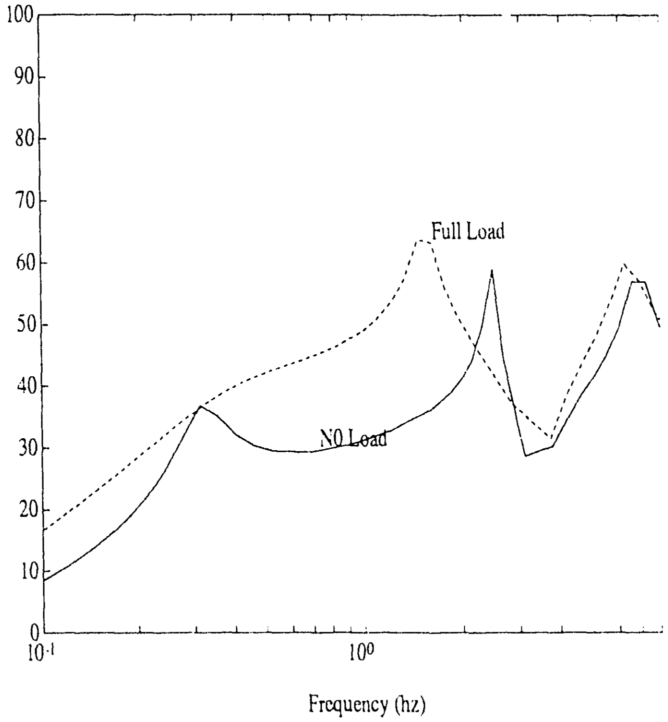

FIGURE 5. Closed Loop Frequency Response for LRM Velocity

The system is very robust and reliable. The worst robustness occurs when the sensor for H_p fails. In this case the gain margin is guaranteed to be greater than 3.5 db, and the phase margin greater than 47 degrees. This means the gain of the velocity controller could nearly double and the phase could change 47 degrees before mode 1 became unstable.

Also, because the controllers are decoupled, failure of H_p has little effect on the damping of modes 2 and 3, and similarly, the failure of H_v has little effect on the damping of mode 1.

INITIAL RESULTS OF ACTIVE DAMPING CONTROL

In order to study the effectiveness of the control algorithm, a dynamic model of the test-bed was built using the DADS dynamic modeling and simulation software package. Advanced control algorithms can be tested and evaluated via computer simulation prior to implementation on the test-bed hardware. Preliminary results indicate that control algorithms developed by this methodology can effectively damp oscillations in the structure.

The DADS model of the test-bed uses results from the ANSYS finite element code to model the flexible body dynamics of the system. The flexible body results are incorporated into the DADS model, which also incorporates the mass and inertia properties of the SRM, air bearings, and other hardware. The system flexibility and natural frequencies predicted by DADS are comparable with those observed in the lab.

In the interests of computational efficiency, the model used to test control algorithms does not include the actuator dynamics and low level controls used in the SRM. Future control designs will incorporate the effects of the SRM dynamics. These dynamics dictate the bandwidth of the SRM and determine limits on the modes which can be damped. However, experimental results show that the SRM can be used to excite the lowest two modes, so it has sufficient bandwidth to damp them as well.

Using the control parameters in Equation 2, active damping controllers have been implemented on the computer model of the test-bed and on the test bed hardware. Figures 7 and 8 show the robotic system response to a step function of 0.1 radians in the desired azimuth angle θ_d, and Figure 9 shows the controlled azimuth angle applied to the SRM under full load. The damping is considerably improved with little required swings from the SRM.

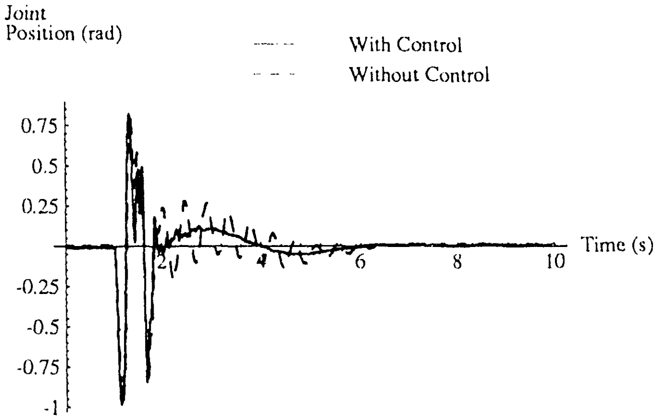

FIGURE 6. Strain gage two readings with and without damping controller

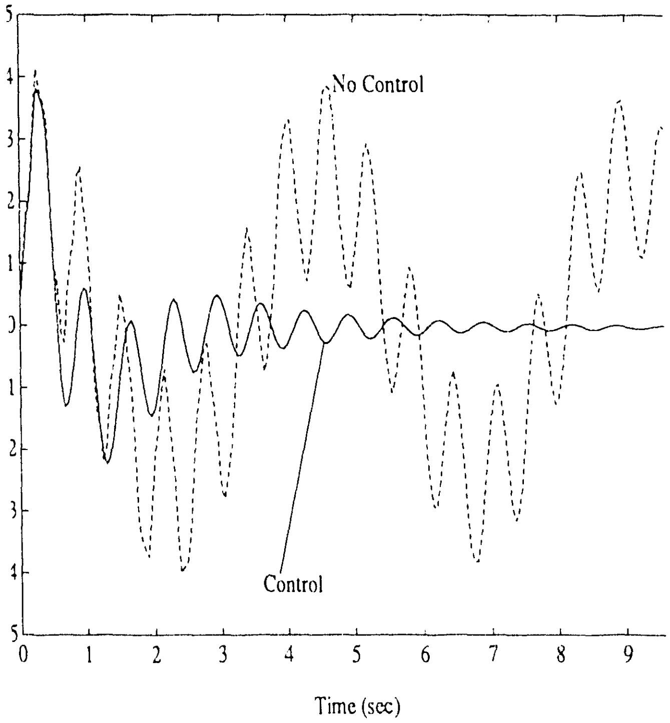

FIGURE 7. Step Response of LRM Tip Position Under Full Load with Both H_p and H_v.

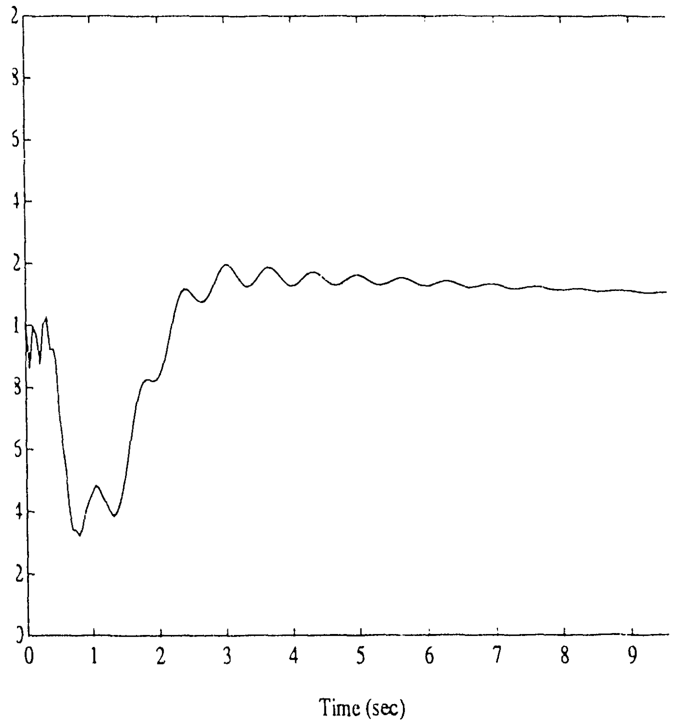

FIGURE 8. Step Response of LRM Tip Velocity Under Full Load with Both H_p and H_v.

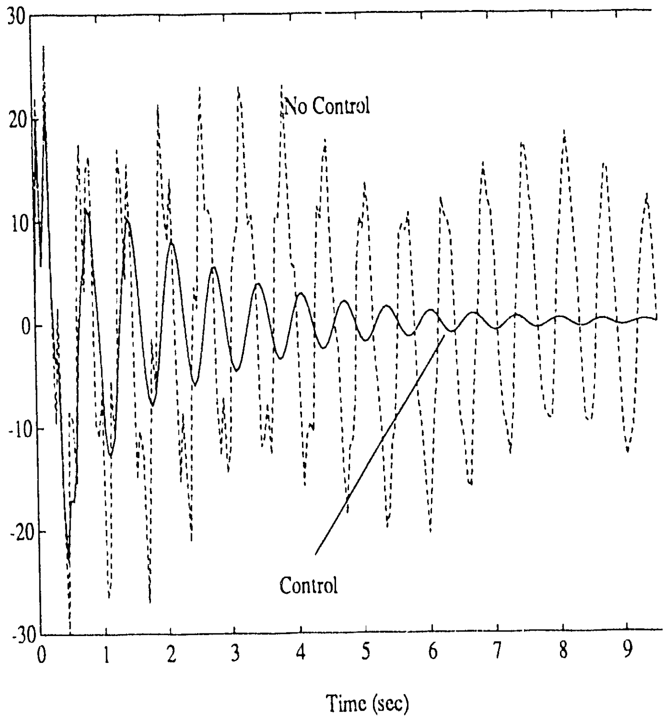

FIGURE 9. Controlled Azimuth Angle for Response in Figure 7.

Figures 10 and 11 show the step response under no load. Under no loading, the controlled damping is not as high because the robotic system gain is less. That is, the SRM has more leverage when it is carrying a load. The no load damping could be improved by increasing the gain of the controllers, but this would jeopardize the controllers reliability and robustness at the full load condition. This is the cost of forcing the control system to be robust.

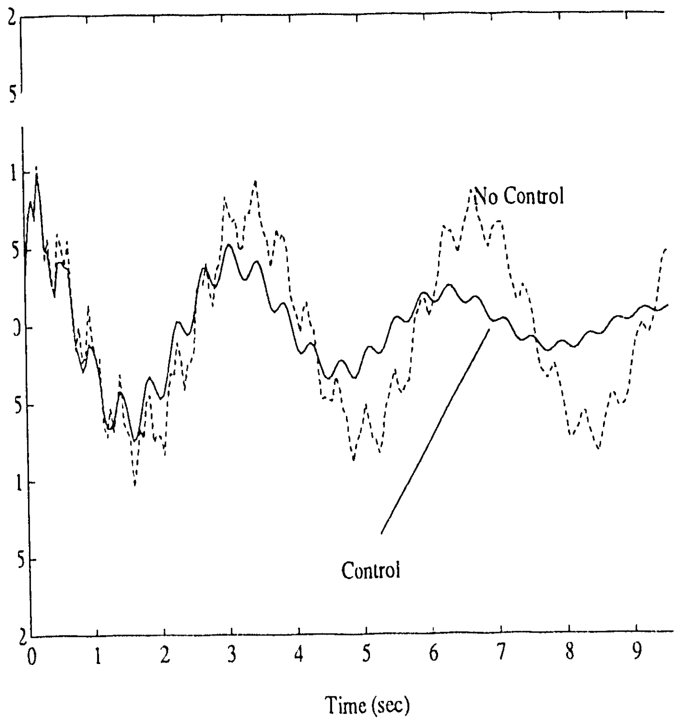

FIGURE 10. Step Response of LRM Tip Position Under No Load with Both H_p and H_v.

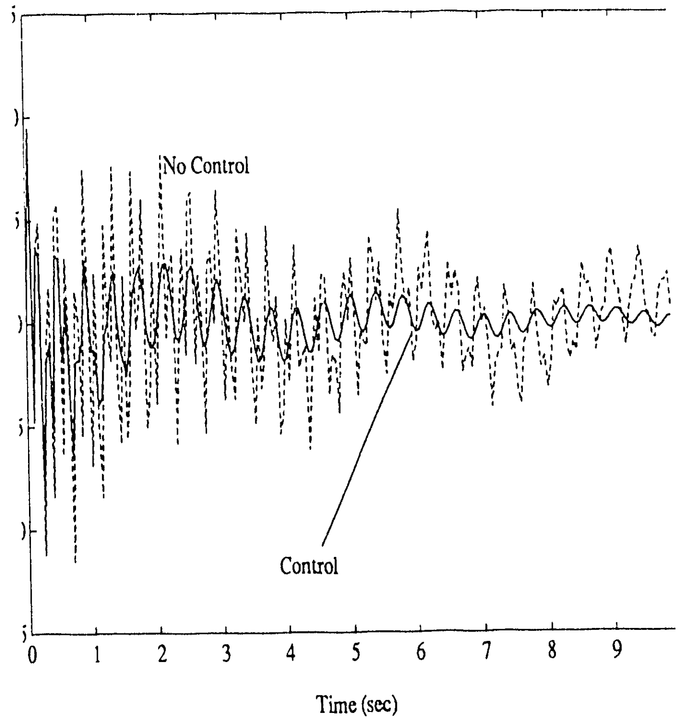

FIGURE 11. Step Response of LRM Tip Velocity Under No Load with Both H_p and H_v.

The controller reliability is demonstrated in Figures 12 and 13. Figure 13 shows the system response with controller H_p removed (simulating a sensor failure). Note that the second and third modes are still damped in this case by H_v. The loss of H_v is shown in Figure 12. In this case, H_p still performs well.

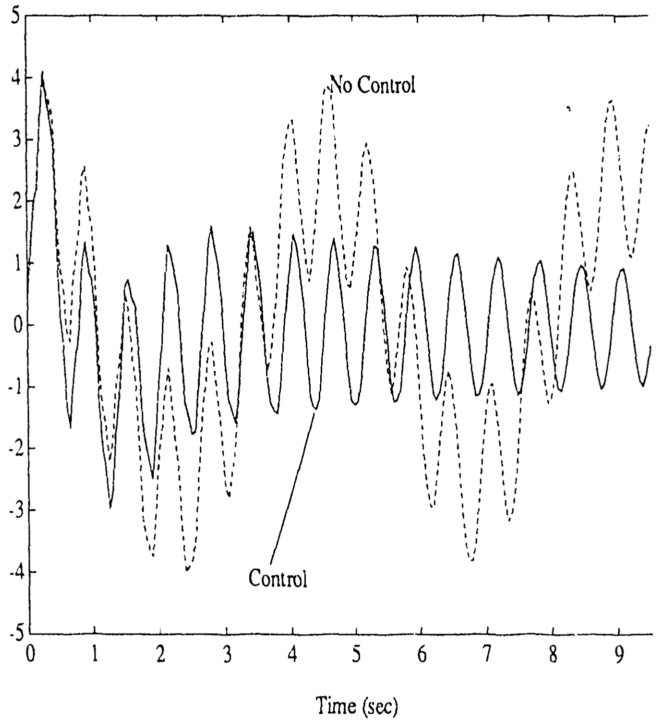

FIGURE 12. Step Response of LRM Tip Position Under Full Load With H_p Only.

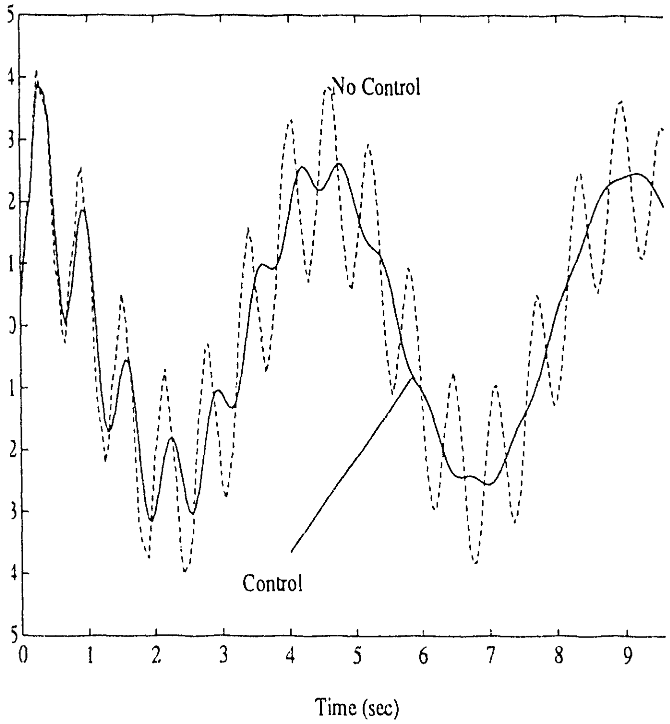

FIGURE 13. Step Response of LRM Tip Position Under Full Load With H_v Only.

These results indicate that significant damping can be added to the system through such control. Current efforts at PNL are focusing on the implementation of this controller on the test-bed hardware. Also, efforts are being made to investigate alternative design methods.

CONCLUSIONS AND PLANNED DEVELOPMENT ACTIVITIES

A full scale single link testbed for developing and testing advanced oscillation control algorithms for long reach flexible manipulators has been developed at PNL. This testbed will play a key role in the development of manipulator technologies required for the remediation of hazardous and radioactive wastes at several DOE sites, and may have application at other hazardous waste sites as well. A new controller which uses the inertial forces generated by a small dexterous manipulator to annihilate oscillations in the long reach manipulator has been developed and tested using a computer simulation of the testbed facility. The results of this testing indicate that the new controller is effective in damping out oscillations in the long flexible beam, while being quite robust in its ability to effectively operate under different loading conditions. The system has also been shown to be very reliable in the event of sensor failures.

Currently the control algorithm is being implemented on the hardware in the testbed, with initial results expected in the near future. Future enhancements planned for the testbed include actuation of the flexible beam at its base, instrumentation of the SRM with joint force sensors, and the application of passive damping materials to the flexible beam.

Future research to be performed using the testbed and associated equipment will include the following:

Extend specialized dynamic modeling techniques developed thus far for interacting flexible and rigid manipulators to more closely represent the long reach flexible manipulator/short reach dexterous manipulator combination being considered for underground storage tank remediation. Included in this dynamic modeling are cases in which the end of the arm is interacting with the environment (e.g. grasping, bracing, cutting, etc.).

Evaluate other alternatives for the control and design of long reach flexible systems with short reach dexterous manipulators. This includes the design and optimization of passive damping coupled with active oscillation control methods. It also includes the investigation of alternative algorithms of interacting flexible and rigid arms such as coupled vs. decoupled, active damping using inertial forces, and/or flexible arm joint servos based on joint force/torque feedback. It may also include disturbance rejection with force and/or acceleration measurements at the end of the flexible arm.

Developing and testing new methods for sensing the forces and torques at the joints of manipulators. Active damping of manipulators with flexible links and joints using joint servo control algorithms based on joint force/torque feedback will be investigated.

Investigating methods of stabilizing images from video cameras mounted on flexible or mobile robots using fuzzy logic controllers.

Developing better methods of reducing backlash and flexibility in telescoping manipulator links.

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