Conf-950232--17

PNL-SA-25159

MICRO MANIPULATOR MOTION CONTROL TO COUNTERACT MACRO MANIPULATOR STRUCTURAL VIBRATIONS

J. Y. Lew
D. J. Trudnowski
M. S. Evans
D. W. Bennett

February 1995

Presented at the
American Nuclear Society 6th Topical Meeting on Robotics
and Remote Systems Meeting
February 5-10, 1995
Monterey, California

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830 -

Pacific Northwest Laboratory
Richland, Washington 99352

DISCLAIMER

Micro Manipulator Motion Control to Counteract Macro Manipulator Structural Vibrations

Jae Y. Lew, Dan J. Trudnowski, Mark S. Evans, David W. Bennett

Applied Physics Center
Pacific Northwest Laboratory[1]
Richland, WA 99352
(509) 375-4489; fax (615)375-3614
E-mail: j_lew@pnl.gov

Abstract

Inertial force damping control by micro manipulator modulation is proposed to suppress the vibrations of a micro/macro manipulator system. The proposed controller, developed using classical control theory, is added to the existing control system. The proposed controller uses real-time measurements of macro manipulator flexibility to adjust the motion of the micro manipulator to counteract structural vibrations. Experimental studies using an existing micro/macro flexible link manipulator testbed (shown in Figure 1) demonstrate the effectiveness of the proposed approach to suppression of vibrations in the macro/micro manipulator system using micro-manipulator-based inertial active damping control.

Introduction

A major goal in many telerobotic applications is to provide both a large manipulator workspace and high accuracy. The concept of a micro manipulator mounted on the end of a long-reach manipulator may help achieve that goal. The macro manipulator would position the micro manipulator to the place of interest within a large workspace. The micro arm would then perform fine motions. The flexibility of the macro manipulator structure can be a major obstacle to controlling the micro/macro manipulator within the desired performance range.

Over the past 10 years, many researchers have worked on active damping control for flexible-link manipulators, but still no clear solution has been found for the multiple-link case. Much of the previous research work in active damping has focused on compensating for vibrations in a macro manipulator by modulating its own actuators. It is often found, however, that the bandwidth of macro manipulator actuators limits the effectiveness of this approach. If the bandwidth of macro manipulator actuators is high enough, using these actuators to damp out vibrations may be dangerous because of the large amount of energy of energy required.

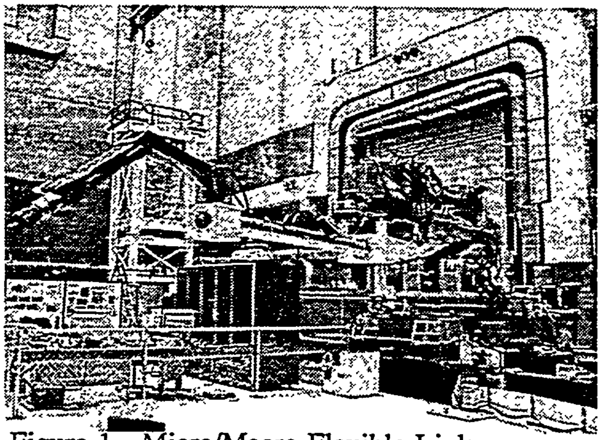

Figure 1 - Micro/Macro Flexible Link Manipulator Testbed

In this paper, we propose to utilize the inertia of the micro manipulator for active damping of the macro manipulator. In most cases, the micro manipulator actuators have the required bandwidth to achieve this goal. The proposed controller uses real-time measurements of macro manipulator flexibility in an additional feedback loop to adjust the motion of the micro

---

[1] Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830. Work Supported by the U.S. Department of Energy's Office of Technology Development.

manipulator to counteract structural vibrations.

A major advantage of the proposed controller is that the flexible-motion compensator has an independent loop from the rigid-motion controller. This architecture makes implementation of the active damping controller simpler. When a manipulator has a structural vibration problem, the flexible-motion compensator can be added to the existing rigid-motion controller.

Our proposed controller is studied experimentally on an existing micro/macro flexible link manipulator testbed. This testbed consists of a Spar 2500 manipulator that has been modified by attaching a 3.4-m-long aluminum alloy flexible link on the tool plate to make the reach 12 m. At the tip of the link, a Schilling Titan II manipulator is installed as a micro manipulator. The testbed is designed to have a reach and natural frequency similar to the macro/micro manipulator system that is expected to be used in large nuclear waste underground storage tanks. The testbed is oscillated in the vertical and horizontal planes by the motion of either the Spar or Schilling manipulator. The proposed inertial damping controller is added to the existing proportional and derivative independent joint controller for the Schilling. The inertia-damping controller will measure the flexible motion of the link using strain gages,. System identification is carried out off-line, and then used on-line to compensate for the motion of the micro manipulator.

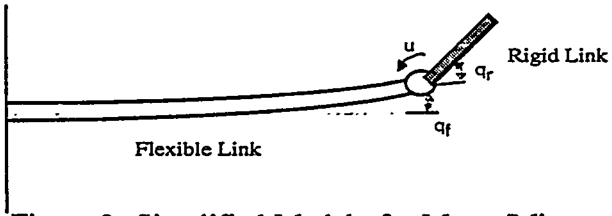

Figure 2- Simplified Model of a Macro/Micro System

Modelling

Deriving the dynamics of multiple flexible link manipulators can be complex. Lagrangian formulation with the assumed modes method has been widely used (Book 1984). Also, an efficient method is available for deriving the equation of motion for serially coupled micro/macro systems (Lew 1992). In this work however, we used a simple, one flexible-link and one rigid-link model to understand the general characteristics of the micro/macro system. This simplified model gives a conceptual base-line for the control strategy. The equation of the motion of the simplified model, as shown in Figure 2, can be obtained as

$$\begin{bmatrix} M_{rr} & M_{rf} \\ M_{fr} & M_{ff} \end{bmatrix} \begin{pmatrix} \ddot{q}_r \\ \ddot{q}_f \end{pmatrix} + \begin{bmatrix} 0 & N_{rf} \\ N_{fr} & 0 \end{bmatrix} \begin{pmatrix} \dot{q}_r \\ \dot{q}_f \end{pmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & K_{ff} \end{bmatrix} \begin{pmatrix} q_r \\ q_f \end{pmatrix} = \begin{bmatrix} I \\ b \end{bmatrix} u$$

where

$$M_{rr} = I_r$$

$$M_{rf} = M_{fr} = \psi(l_f)\, m_r l_r \cos(q_r)/2$$

$$M_{ff} = m_2 \psi^2(l_f) + \int_0^{l_f} \psi^2(x)\, \rho A dx$$

$$N_{rf} = N_{fr} = -\psi(l_f)\, m_r l_r \sin(q_r)\dot{q}_r/2$$

$$K_{ff} = \int_0^{l_f} E_f J_f \left(\frac{\partial^2 \psi(x)}{\partial x^2} \right)^2 dx$$

$$b = \left. \frac{\partial \psi(x)}{\partial x} \right|_{x=l_f}$$

I_r is the inertia of the rigid link about rotational axis; m_r is the mass of the rigid link i; l_i is the length of rigid or flexible link; $\psi(x)$ is the mode shape function(only one mode considered); q_r is the joint angle of rigid link; q_f is the flexible mode time dependent coordinate; E is the Young's modules of the flexible link; J is the cross sectional inertia about the neutral axis of the flexible link; ρ is the density of the link material; and A is the cross sectional area of the link.

The gravity term is ignored in this formulation. Assuming a small motion, the system dynamics is linearized about an operating point. The transfer function can then be computed as

$$G_r(s) = \frac{\overline{q_r(s)}}{\overline{u(s)}}$$

$$= \frac{(M_{ff} - bM_{rf})s^2 + K_{ff}}{(M_{rr}M_{ff} - M_{rf}M_{fr})s^4 + K_{ff}M_{rr}s^2}$$

$$G_f(s) = \frac{\overline{q_f(s)}}{\overline{u(s)}}$$

$$= \frac{(bM_{ff} - M_{fr})s^2}{(M_{rr}M_{ff} - M_{rf}M_{fr})s^4 + K_{ff}M_{rr}s^2}$$

G_r and G_f describe the mathematical relationship between input torque and output variables. The upper denotes the Laplace transformation.

Controller Design

Based on the conceptual simplified model, the controller is designed for the testbed as shown in Figure 3. Sequential loop-closure (Maciejowski 1989) is used to design a PD (proportional and derivative) controller and a flexible-motion compensator. With this technique, the PD controller is designed and applied to the system first. Then the flexible-motion compensator is designed for the system with the PD control. This control architecture can utilize the existing control system, and implements an additional feedback loop to make the necessary adjustment of the actuator signal.

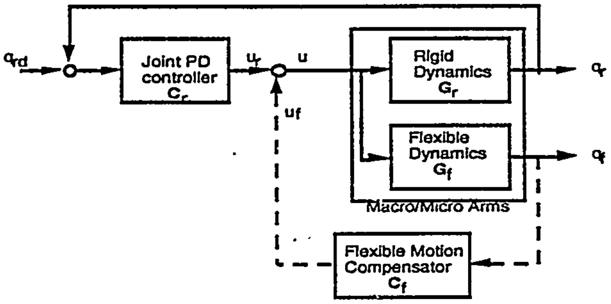

Figure 3 - Block Diagram of Control Scheme

First a feedback controller is designed for the Schilling Titan II manipulator (micro arm) fixed to the ground. The controller is designed by ignoring the macro manipulator dynamics and using classical PD tuning methods (Kuo 1982). The PD gains closely matched those provided by Schilling, Inc. The PD controller provides the desired joint-angle motion with relatively good disturbance rejection. Second, the Titan II manipulator is attached to the macro arm (flexible link and SPAR). A step input was applied to the system as a desired trajectory. Tests show that Titan II motions excite the macro arm's first vibrational mode.

The flexible-motion compensator (damping controller) is added to improve the macro manipulator settling time. Having the damping controller add to the output of the PD prevents any steady-state error that may be introduced into the joint angle from the damping control loop. Ideally, both flexible mode(q_f) and its rate would be used for feedback in the damping controller. Realistically, measuring the flexible rate is difficult; therefore, dynamic compensation was used in the damping controller.

The system model described previously is a highly simplified one that is not sufficient for controller design. To obtain a more accurate system model, laboratory system identification experiments are conducted and the identified model is used to construct a damping controller. Several step and frequency response signals are applied to the system, and a system model is identified using Prony analysis (Pierre, Trudnowski, Hauer 1992) and frequency domain techniques (Trudnowski 1992).

Classical techniques are used to design the damping controller (e.g., root locus methods). The objective is to compensate the flexible mode, q_f to provide damping to the first mode while limiting the bandwidth in order not to excite higher mode. The resulting controller has the form

$$C_f(s) = \frac{T_1 s}{1+T_1 s}\frac{k}{1+T_2 s} \cdots\cdots$$

where T_1 is a high-pass time constant to remove steady-state offset from the strain signal, T_2 is a low-pass time-constant to decrease the high-frequency gain, and the remaining terms are lead-lag blocks to provide proper phase compensation.

The flexible motion compensator is carefully designed such that it adds damping and does not cause instability for the joint-angle motion. After the flexible compensator is added, the system has the same closed-loop characteristics equation for both the rigid-motion and flexible mode

$$1 + C_r(s)\,G_r(s) - C_f(s)\,G_f(s) = 0.$$

As long as the flexible-motion compensator is designed to be stable, the joint-angle motion remains stable.

Experimental Results and Discussion

The system natural frequencies are measured in the vertical and horizontal planes. An impulse force is applied at the tip of the Schilling Titan II manipulator, and an accelerometer signals in both directions are measured at the base of the manipulator. The lowest natural frequency is observed at 2.14 Hz in the vertical plane. The second mode was observed around 10.5 Hz, but it was very small and insignificant. The strain gage is installed at the base of the link to efficiently measure the first mode behavior.

Starting with the Titan II manipulator stretched out all the way with the shoulder joint positioned 20 degrees up from horizontal, the shoulder was moved down to horizontal with rigid-motion feedback only. Figure 4.1 shows the shoulder joint-angle response, and Figure 4.2 shows the strain signal response at the base of the flexible link. Although the joint-angle researches the desired angle in 0.5 seconds without large overshoot, the rigid motion of Schilling manipulator causes significant vibration in the macro manipulator (SPAR and Flexible link). The vibration lasts more than 40 seconds, with a maximum amplitude of 2.6 cm. This structural vibration caused the small oscillation in the joint-angle as shown in Figure 4.1.

With the flexible-motion compensator installed, the system response improves significantly. In Figure 4.2, the solid line displays the improved performance. The structural vibration is damped out within 2 seconds. This is a 2000% improvement over the previous controller with the rigid controller in the settling time. The shoulder joint angle have a slightly larger overshoot, but settled faster. This overshoot action of the micro arm was generating inertial force to damp out the structural vibrations. Figure 4.3 shows the actuator input signal required to control the Schilling Titan II shoulder joints in both cases. The flexible-motion compensator requires little control effort. A slight change of the actuator input achieves significant damping in the response. Demonstration video tapes are available of the above experiments in the various configurations.

Conclusion

This experimental study demonstrated the effectiveness of the inertial force damping control in micro/macro manipulator. The micro manipulator not only moved to a desired position, but also counteracted against the structural vibration of the macro manipulator. The time-response results showed that the proposed controller improved by 2000% in the settling time.

Inertial force damping can be effective in the micro/macro manipulators system as presented in this paper. However, this does not guarantee that it will work for every micro/macro

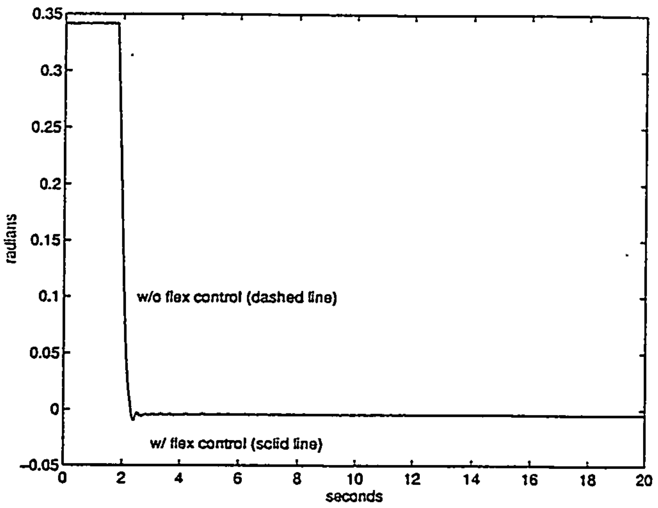

Figure 4.1 - Step Response of Schilling Titan II Shoulder joint Angle

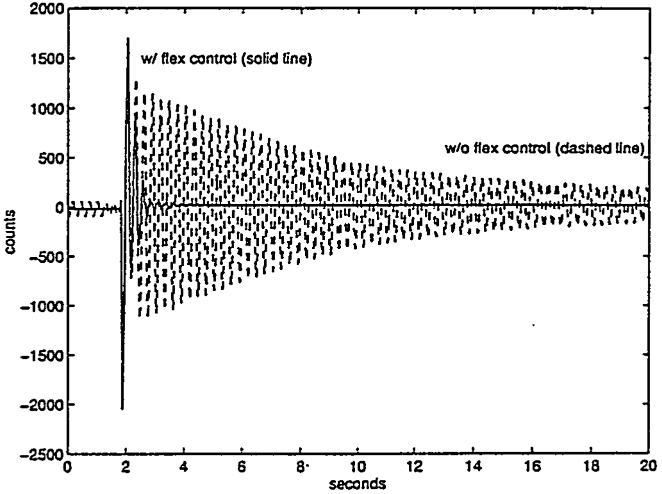

Figure 4.2 - Step Response of Flexible Link Vertical Strain Measurement

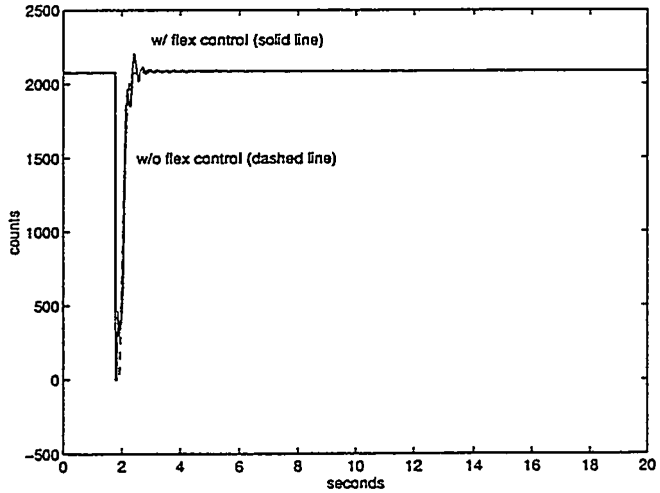

Figure 4.3 - Schilling Titan II Shoulder Joint Actuator Input

manipulator. For example, the inertia of a micro manipulator may not generate enough force to feasibility of inertial force damping is to check damp out the structural vibration of the system if the micro arm is too small or is positioned at some configuration. One way to examine the controllability of the system with the joint angle of the micro manipulator as the input and the structural mode as the output.

The remote operation of the testbed was demonstrated at the 1994 DOE Robotics Forum (Albuquerque, New Mexico, USA). The testbed was located in Richland, Washington, and the operator sent motion commands from a remote input station location in Albuquerque, New Mexico. Two sites are over 2500 km apart, and they were connected by internet. Using real-time video of the testbed in motion and displaying the system response such as joint angles, strain measurement, and actuator inputs, the effectiveness of the proposed controller was demonstrated.

References

Book, W.J. 1984. “Recursive Lagrangian Dynamics of Flexible Manipulator Arm,” International Journal of Robotics Research,Vol.3. No.3. pp.62-75.

Kuo, B.C. 1982. Automatic Control Systems, Prentice-Hall.

Lew, J.Y., W.J. Book. 1992. “Dynamics of Two Serially Connected Flexible Arms,” Advanced Control Issues for Robot Manipulators:ASME92 Winter Annual Meeting. DSC-Vol.39. pp.17-22. Anaheim CA.

Maciejowski, J.M. 1989. Multivariable Feedback Design. New York: Addition-Wesly Publishing,

Pierre, D., D.Trudnowski, J, Hauer, 1992. “Identifying Linear Reduced-Order Models for Systems with Arbitarary Initial Conditions Using Prony Signal Analysis,” IEEE Trans. on Automatic Control. Vol.37. No. 6. pp.831-835.

Trundnowski, D. 1992. “Frequency Domain Transfer Function Identification Using the Computer Program SYSFIT,” Report PNL-8455. Pacific Northwest Laboratory. Richland WA.