

# Design Strategies for **HIGH-SPEED** Lightweight Robots

Weight is one of the design goals of robots. Benefits such as faster and more accurate motion, but the hazards could lead to lower performance. This problem can be approached through design options that address an important requirement.

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**I**ndustrial robots today can lift objects no heavier than about five percent of their own weight. Imagine a robotic weight lifter competing against the current Olympic human record of 750 lb. By today's standards, that robot would have to weigh about 15,000 lb, as opposed to its human competitor, who would weigh 165 lb (and who is "rated" at 450 percent of body weight).

While this analogy is inexact, the point stands that improvements in the performance of robotic manipulators require engineers to consider the weight of the structural and drive components. The advantages of lighter weight include faster motion times for large motions, smaller actuators, lower energy consumption, reduced mounting requirements, and less weight to be transported. But there are also penalties such as lower (structural) strength and lower stiffness. The stiffness constraint arising from the dynamic and

static behavior of the arm is the more critical for most uses of robotic arms. Therefore, we have concentrated on controlling the motion of robotic devices that have lightweight structures.

## **Lightweight Structures: Pros and Cons**

What happens if one tries to reduce the structural mass of a motion system? With conventional servo control, the actuating torque depends on an error signal (the difference between a measured variable and its desired value) for joint position and perhaps velocity, as shown in Figure 1. In addition, some open loop prediction of the needed torque can be used. The accuracy of tracking and final position and the speed of response in small motions depends on the size of the gain that multiplies the error signal. Increasing actuator gain gives more actuating force for the equivalent error. A balance of  $K_v$  and  $K_p$ , the velocity and position feedback gains, is required to prevent overshoot and oscillation. Consider a simple model of a lightweight arm with two masses separated by a spring and a dashpot that provides a small amount of damping. As one increases actuator gain, it is no longer possible to find  $K_v$  and  $K_p$  which give a

suitable response. Figure 2 shows the response if these gains are chosen, without regard to flexibility, to obtain the common damping ratio of 0.707. A bandwidth above about one-half the first natural frequency of the arm, with all joints clamped, cannot be obtained because of the lightly damped oscillations.

Notice we modeled the actuator as a perfect torque source that provides desired torque on demand and can be back driven. A joint that will not back drive aggravates the problem because energy from the beam vibration cannot be absorbed by the joint.

It is not possible to move a light arm quickly without structural deflection. Light arms can be accelerated faster than heavy arms with the same actuators, but a fast change of configuration (gross motions) is followed by a small (fine) motion of reduced speed (as in Figure 2). At least this is the case for conventional designs and controls.

Strength and buckling, the other common design constraints, must be considered as well. These constraints are not usually encountered in conventional robots. Static positioning error with gravity loading is a problem encountered in robots which can be aggravated by structural flexibility. Sens-

ing the end point relative to the work piece can solve these problems, although this solution creates other dynamic problems [1].

**Solving flexible arm control problems.** The problem of flexible arm control can be solved in several ways, but each choice presents its own constraints. These options include:

- Materials and shapes with higher stiffness-to-weight ratios and higher damping ratios.
- Feedback control algorithms that account for the flexible dynamics.
- Strategies of arm use that avoid the problem whenever possible.
- Arm trajectories which do not unnecessarily excite flexible behavior.

The highest performance requires a combination of these choices. Our approach has concentrated on the first two, although we will briefly discuss the others also.

### Material Improvements

Most industrial robots are made of steel. Carbon fiber composites for structural members further increases their strength by a factor of from 3 to 7 and the stiffness by a factor of from 3.5 to 10, without increasing the weight. However, this is expensive and therefore limited to aerospace and other relatively exotic applications. Even arms where carbon fiber composites have been used can benefit further from the other three choices.

**Improving the damping ratio.** Increased damping in the structure will not significantly affect the amount of deflection, but it will reduce the "settling time" for oscillations. What is the significance of the obtainable damping increase? A typical damping ratio for steel is .002, while the same structure made of composite material would have twice as much damping. Since a damping ratio of 1.0 on the dominant mode of the arm's response is desired, this increase seems insignificant.

Damping treatments can be applied to either metals or composites that will typically increase the damping much more (with an increase of from 0.4 to .06) as shown in Figure 3 for a single

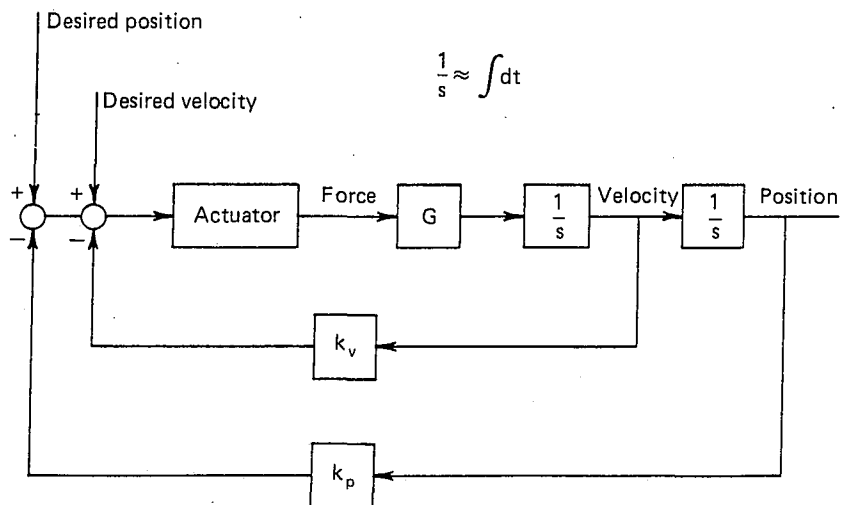


Fig. 1 Position and velocity feedback block diagram.

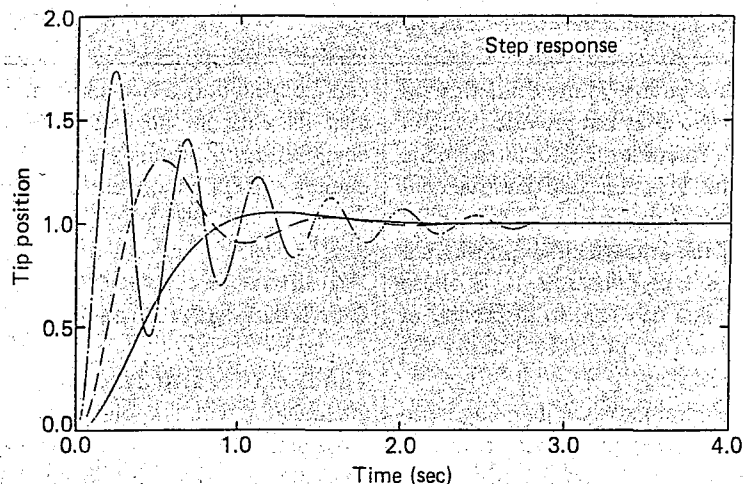


Fig. 2 Step responses for the simple control of a flexible model.

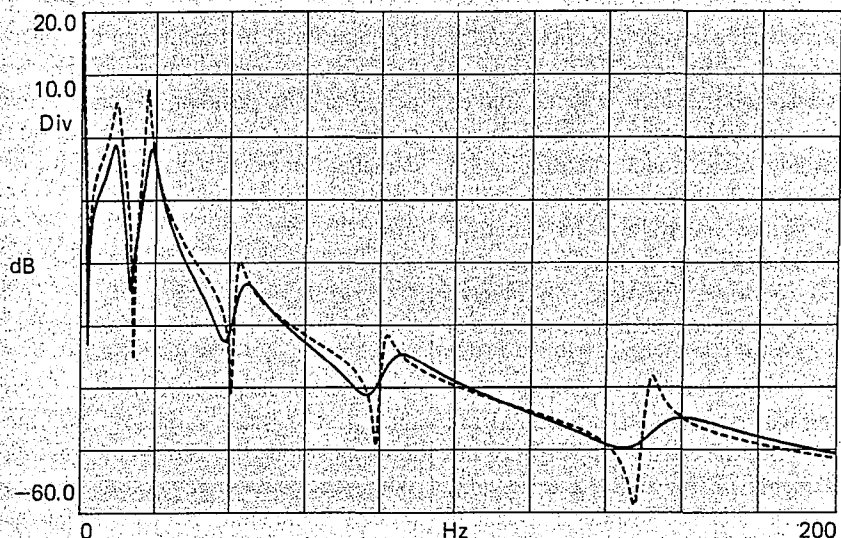


Fig. 3 Frequency response, torque to hub velocity. Each peak is a resonant frequency.

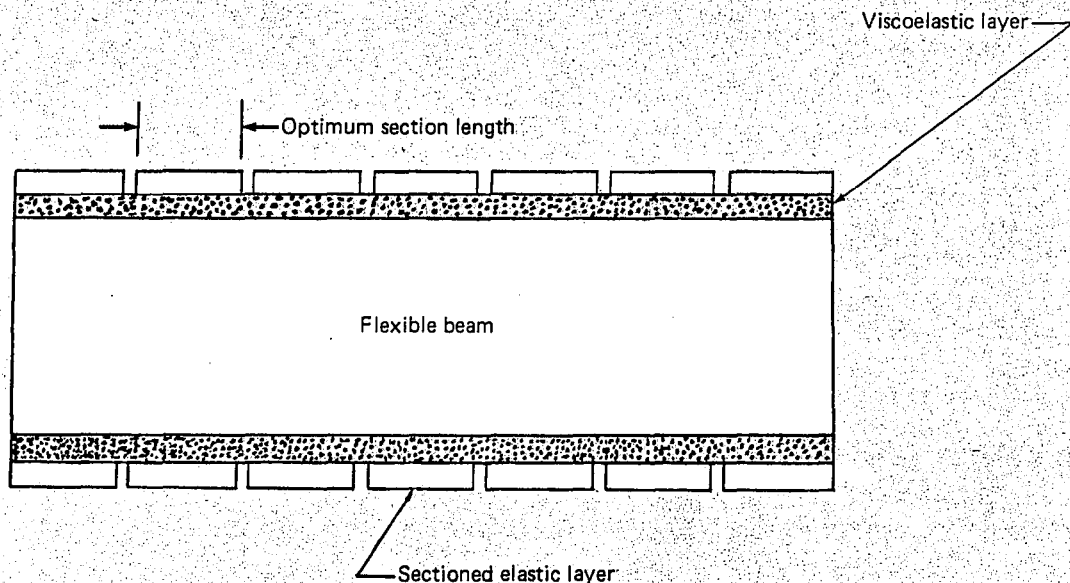


Fig. 4 Length-optimized constraining layer.

link with a rotary joint. Still, this increased ratio does not provide much of an improvement for the dominant mode of the arm. This damping (passive control) is very important on the higher modes of the arm which are more difficult to actively control. It is these modes which can lead to instability of more advanced control systems (as we'll explain later).

The constrained layer damping treatment has been explored with considerable success [2]. It consists of a viscoelastic material sandwiched between the structure and a thin, stiff, constraining layer as shown in Figure 4. The constraining layer should be sectioned to achieve the optimum damping in the most critical modes [3]. Damping of bending modes, which has been studied extensively, is easily performed. Damping of torsional modes has not been studied in respect to robot motion and we are uncertain of its effectiveness. In any event, torsion in an articulated robot of one link will involve bending in the adjacent link, which will absorb energy.

The constrained layer damping treatment will not significantly stiffen the arm. Since the additional weight of the treatment will be about five percent, this investment in structural weight is worthwhile. If the same weight were added to the underlying structure, one

could expect only a two-and-a-half percent increase in the first natural frequency due to the square root in frequency = SQRT (stiffness/mass).

### Advanced Feedback Control Algorithms

**The essence of arm dynamics.** A rigid manipulator with six joints has six degrees of freedom (DOF), which one can describe by six joint positions  $q_1$  through  $q_6$ , with an actuator for each joint producing a torque or force  $u_1$  through  $u_6$ . The equation below gives the form of the rigid arm dynamics if the joint force or torque can be specified.  $J$  is the inertia matrix which depends on joint position,  $f$  is the vector of nonlinear Coriolis, centrifugal, and damping forces, and  $g$  is the vector of gravity forces.

$$J(q)\ddot{q} + f(\dot{q}, q) + g(q) = u \quad (1)$$

The nonlinear, second order system thus has 12 state variables, e.g. the joint positions  $q_i$  and velocities  $\dot{q}_i$ . Within the actuator constraints, the velocities of the joints can be specified as a function of time. An arm with distributed flexibility has an infinite number

of flexible DOF but only one actuator per joint. The same degree of control of flexible DOF is not possible. How can we represent the flexible dynamics in a practical model of the arm? Typically, the deformed shape of a flexible segment of the arm between two joints will be represented as having a deformed shape  $w$  described relative to the undeformed position as a summation of terms:

$$w(x, t) = \eta_1(t)\phi_1(x) + \eta_2(t)\phi_2(x) + \dots + \eta_n(t)\phi_n(x) \quad (2)$$

The space variable  $x$  designates the axial position along the beam. Functions of  $x$  and the time variable  $t$  have been assumed separable and expanded in a series to allow the approximation of the distributed parameter system's partial differential equation with an ordinary differential equation. The accuracy of the approximation depends on the number of terms retained and the shape functions  $\phi_i(x)$  assumed. These terms can be used to describe the arm kinematics for the derivation of equations by Lagrange's techniques [4] or by other ways [5]. The flexible arm dynamics further complicate the already complex dynamics of the rigid arm. A six-joint arm with two flexible links would require a minimum of six

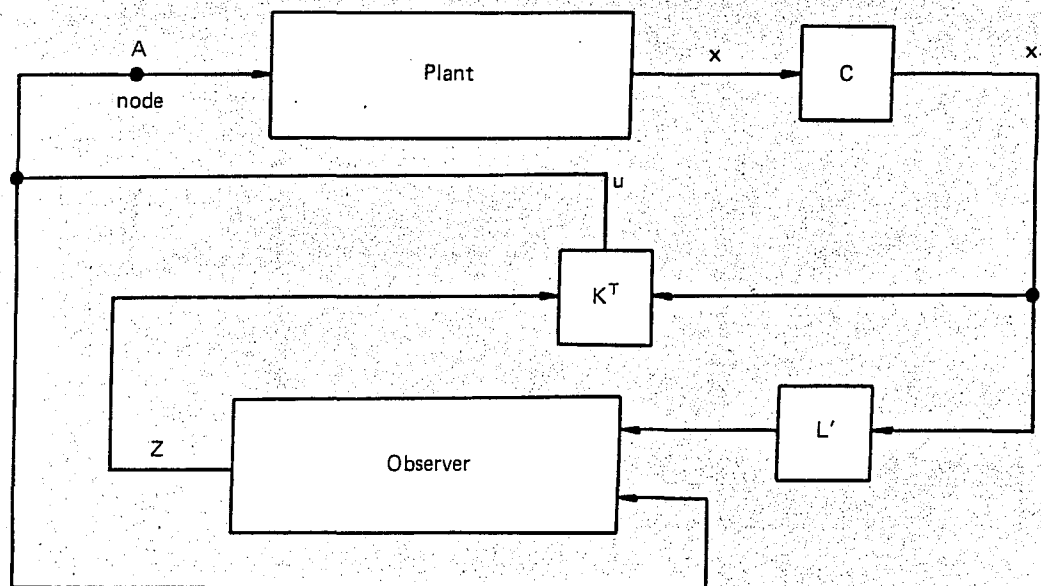


Fig. 5 Reduced order Luenberger observer to compute torque input.

flexible degrees of freedom corresponding to two bending and one torsional mode per link. Thus the number of states can easily be twice that for a rigid arm. Simplifications are possible of course. Another source of flexibility can be compliant drive components which introduce additional states. Many of today's industrial manipulators also have this problem.

**What to control?** Robot designs no longer call for one actuator per DOF. Flexible degrees of freedom are excited by the joint motion and vice versa. What do we want the flexible arm to do? Usually, one wants the end of the arm to be positioned rapidly and then stopped. Stopping the joints is not sufficient for stopping the end point in a flexible manipulator. They must also be manipulated to actively damp out vibrational energy. Passive damping can be added to augment this process.

**How to control?** Ideally, a designer of robots specifies the joint torques as a function of time to minimize travel time between the two end points. This has been attempted, with nonlinear arm behavior, for a simple one-link case, and is the basis in the following experimental results [6]. Here, the torque amplitude was restricted to a maximum value so that the torque control scheme

is of the "bang bang" type; the arm is accelerated and decelerated by switching between maximum and minimum torque. Additional switching during motion cancels the oscillations set up at the beginning as well as those that occur at the end of the motion. Unfortunately, slight inaccuracies in these switching times reinforces rather than cancels these oscillations. So, by itself, open-loop control is doomed to failure because of uncertainties and time variations in the dynamics.

Feedback control helps damp out these vibrations, but it can also cause the system to become more unstable. Feedback depends on the measurement of variables from which the state of the arm can be determined. Theoretically, just one measurement could be used, but more robust behavior is possible with more measurements. Joint position and velocity measurements are important, but even with a slight amount of Coulomb friction, unwanted vibrations can exist that can't be detected in these measurements. Strain measurement has proven effective in our research, although others have used position sensing of the end point [1].

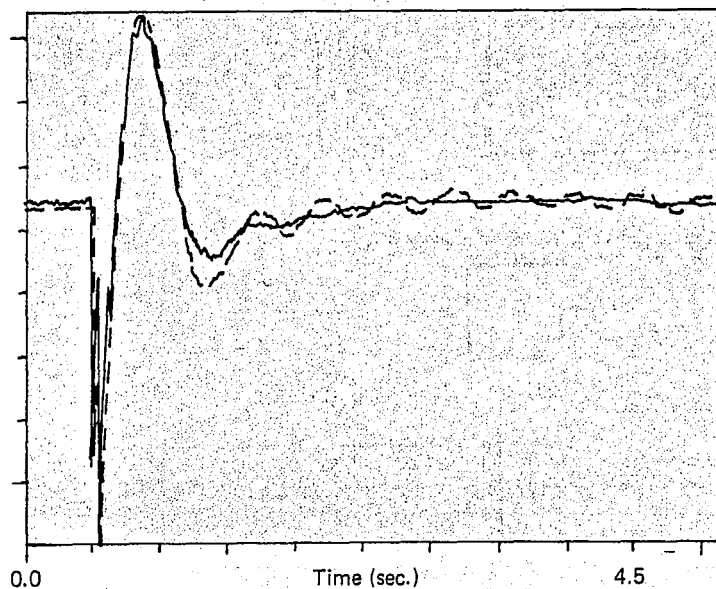
### Design of Feedback Control

We designed the control system for a single-link, flexible arm, about four ft

long, with the first clamped natural frequency about two Hz. The design was based on the linear state space technique for regulators with a quadratic performance integral. This design, in addition to minimizing the mean square of the error of response and control effort, guaranteed a stability margin for the controlled model.

The resulting control structure assumes that all system states are available for feedback. Unmeasured states can be estimated by a dynamic estimator, in this case a reduced order Luenberger observer, since the system is observable. Figure 5 shows the overall structure. We have chosen to deal with the same variables for control that have been used in developing a model: the joint angle positions and velocities and the flexible shape amplitudes and their derivatives. A number of strain gauge measurements can be used to reconstruct the same number of modal amplitudes directly as a weighted sum. No dynamic estimator is needed for these reconstructions, although the rate of change of the amplitudes must be estimated by the dynamic observer.

This control structure will theoretically work for linear systems which approximate our robot arm, but how well do they work in practice? The arm equations are not linear nor are they



**Fig. 6 Strain response with colocated (broken line) versus modal (solid line) feedback.**

exact. While time-varying linear models can be derived at many points along the path of motion, precision is most important at the motion's end. Hence one might accept degradation during motion in exchange of a simpler control algorithm. We are more concerned with nonlinearities and dynamics that have been ignored in deriving the models. The actuators, filters, and sensors are the sources of these deviations.

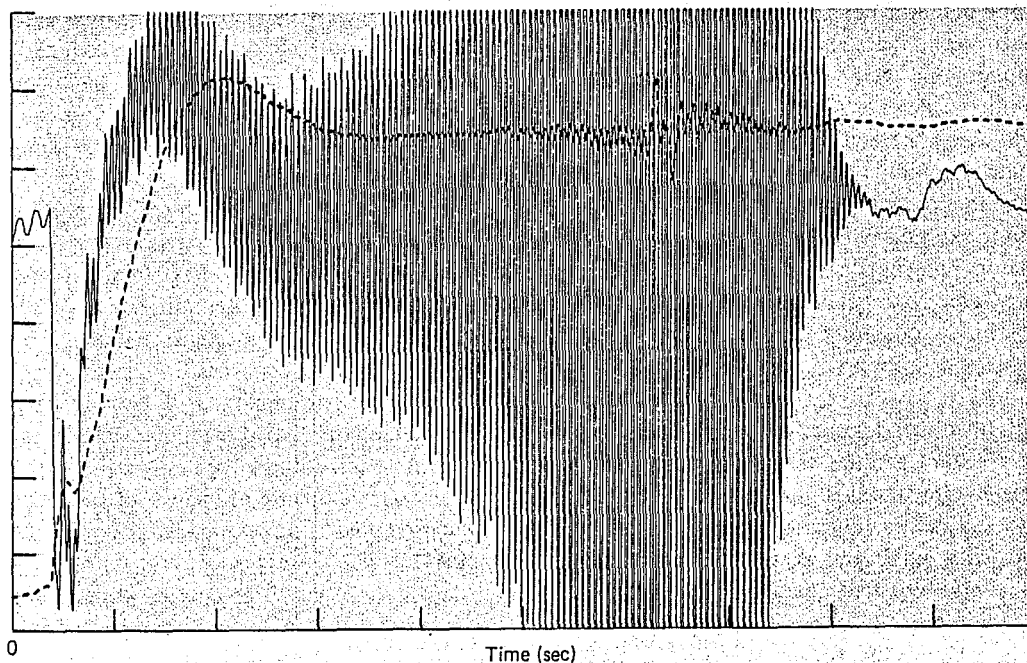
An experiment was arranged to test

this theory with real hardware. These experiments have only tested a single link and a single joint, but much has been learned that will be used in the multi-jointed experiments now underway. Other researchers have conducted experiments that vary somewhat in hardware and approach, although generally for only a single joint and a single flexible link.

Our experiments, whose results follow, show that:

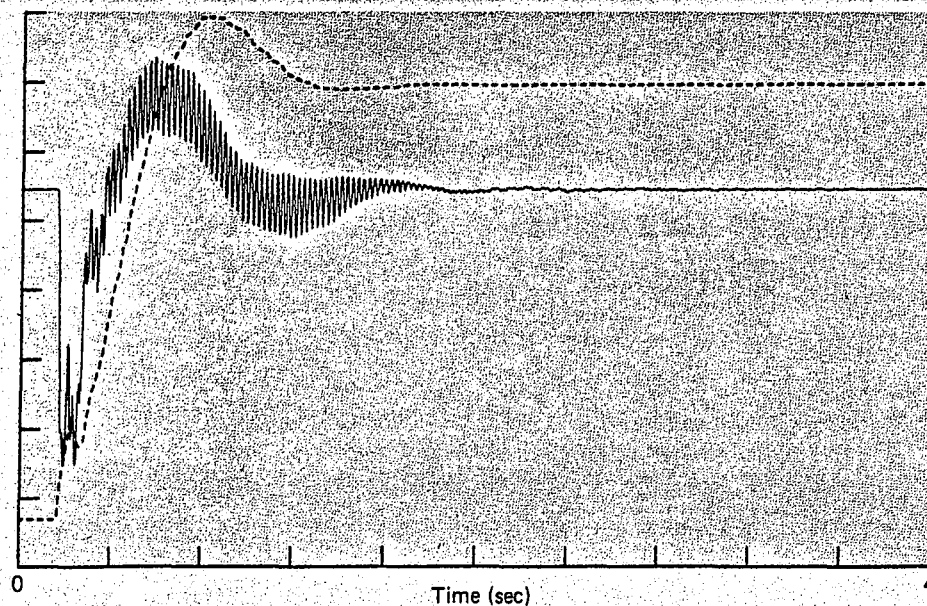
- Improved response of light-weight arms is possible through linear state feedback based on incomplete measurements.
- Limitations to further increases in the arm bandwidth ultimately arise from limited computing speed; they manifest themselves as instabilities in the higher modes.
- The robustness of the resulting high-performance algorithm in modeling inaccuracies and perhaps even computing limitations is greatly improved through passive damping treatments.

**Verification.** Figure 6 shows the strain at the joint end of the link for stepped changes in commanded position of the test arm under two types of control: modal control, such as the advanced control of Figure 5; and colocated control (simple joint position and velocity feedback control). The gains have been chosen to give about the same speed of response. The oscillatory motions of simple colocated control continue with significant amplitude more than five times the settling time of the modal control. The joint imperfections of Coulomb friction act in this case to lock the joint for small vibrations, halting the measurements and hence prema-



**Fig. 7 Modal control with inadequate observer speed (factor of 2.5).** Here and in Figure 8, the broken line is the joint angle and the solid line is the strain measurement near joint.





**Fig. 8 Modal control with an increase in observer speed (factor of 5).**

turally halting the control action.

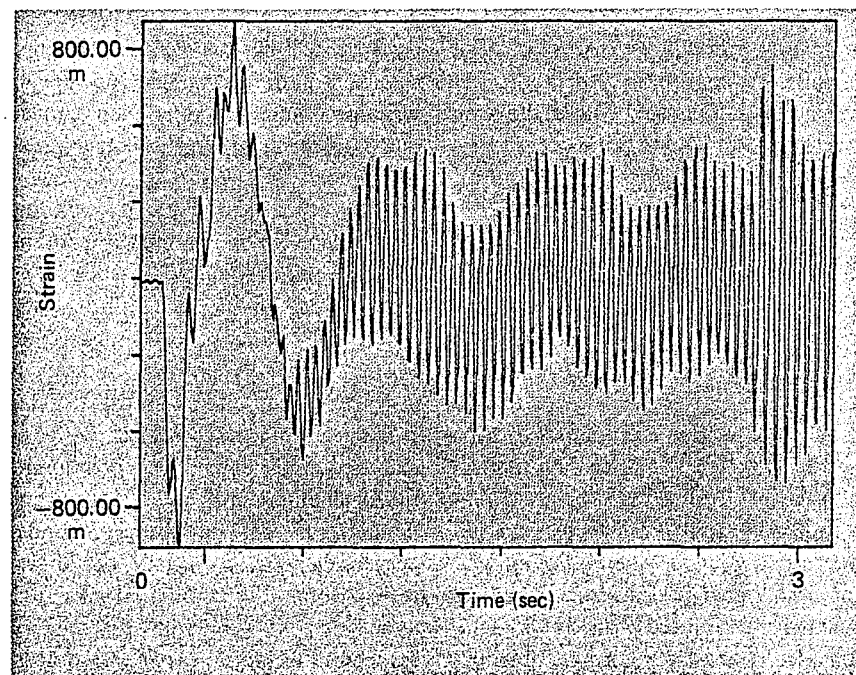
#### Computing power and sample rate.

Limited computing power is reflected in a lower sample rate as the control law is updated. Reducing the sample rate from 500 Hz to 178 Hz, for example, results in lighter damping of the mode near the third clamped-joint frequency. Advanced control schemes (such as the modal control) require even greater computational resources because the observer is a dynamic system that must be faster than the behavior it is supposed to estimate. Figure 7 shows a response with inadequate separation of the observer and plant dynamics, where the observer dynamics were 2.5 times as fast as the plant dynamics being estimated. As the observer dynamics were made five times faster than the plant dynamics, the response seen in Figure 8 resulted. The remaining lightly-damped oscillation is one frequency above that modeled and hence needs to be estimated. Further increases in the observer speed might further improve behavior, and even allow a more complicated model to be used. However, observations are performed digitally, and the speed of the observer is thus constrained by the sample time of the controller. Even with the colocated controller, inadequate sample times result in instabilities.

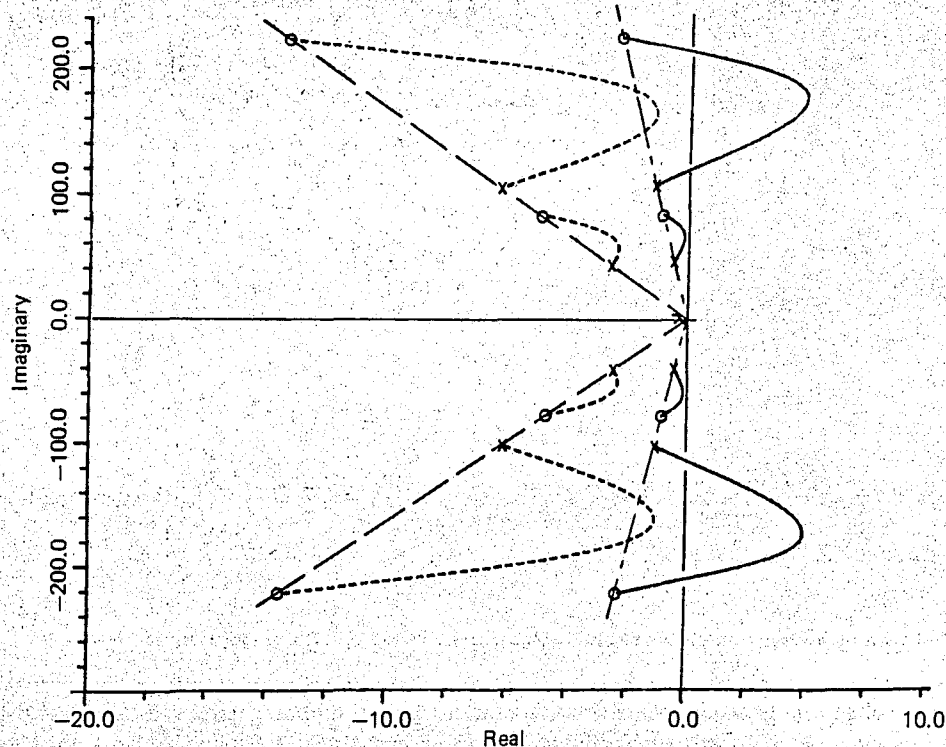
One solution is more powerful computers. Indeed, our equipment's floating point cycle of 19 microseconds is not state-of-the-art. An analog observer is another solution. A more attractive possibility is the use of passive damping. While this has not been verified for the above case, we're encouraged by its success in desensitizing the design to other model imperfections.

#### Advantages of passive damping. Ide-

ally, colocated control should never be unstable, assuming an ideal torque source; in reality, delays due to filtering, actuator time constants, and computation will cause the type of instabilities observed in Figure 9. The root locus in Figure 10 shows how modeling of these realities can account for instabilities as the gains are increased. Modal control design including these complexities would be of a much higher order, but this would also require more



**Fig. 9 Unstable system with colocated feedback and without passive damping. The oscillation is 22 Hz.**



**Fig. 10 Closed-loop root locus.** The broken line has a damping ratio of 0.06, the solid line, a damping ratio of 0.010.

**The highest performance will require arms in which more of the actuator energy is applied to moving the payload and less is applied to moving the arm itself.**

computer power. By using passive damping, poles are shifted to the left (as shown in Figure 10) and the step response stabilized to appear as in Figure 11. Similarly for the modal control, the addition of passive damping converts a marginally stable response (as in Figure 12) to the satisfactory response shown in Figure 13.

### Changeable Arms

Since we need different types of arms for different types of motions (e.g., a lightweight, flexible arm for gross motions and a rigid one with lesser high-inertia penalties for fine motions), why not simply change arms when needed? No magic is required if one is willing to consider strategies such as "bracing" [7]. This technique is used effectively in human motion when the arm is held

rigid by resting the heel of the hand against a stationary object, as during writing. Manipulation is then carried out with the hand's precision degrees of freedom.

Robots today are limited to operating from a base which is often far from the work piece in a large total work envelope. To use bracing, we still need the control capability already described. Force control for lightweight arms is also needed to maintain the bracing contact during fine motion. Bracing also requires sensors for positioning the small motion manipulator at the end of the large arm, but these are under development at a variety of laboratories around the country. Tasks such as welding and assembly as well as inspection of large vessels, structures, and vehicles are prime candidates for bracing.

Variations on bracing have been proposed. A "jig hand," for example, braces against a stationary object. It incorporates a special hand with kinematic constraints in selected directions for rigidization but allows the existing joints of the arm to move the end point in other directions [8]. A small "fast" wrist has been proposed and tested at Stanford which does not require a large arm to make contact. This small manipulator is capable of keeping the end point stationary even if its base, the large arm, is moving.

**Less exciting arm trajectories needed.** Trajectory planning specifies the robot's speed along its path. Simple velocity profiles in common use today ramp up to a constant maximum speed, then back down to zero. This does not account for wide variety in inertias or complex dynamics of the arm which form the actuator load. Further, the transition between constant acceleration and constant speed involves discontinuous acceleration which aggravates the flexible arm's behavior. Recent advances in trajectory planning for rigid arms has produced minimum time trajectories which account for these

aspects [9] but further aggravate the sharp change from acceleration to deceleration. A modification of these procedures which inhibits the excitation of flexible modes is needed.

## Towards Optimum Performance

The highest performance will require arms in which more of the actuator energy is applied to moving the payload and less is applied to moving the arm itself. The four current approaches to accomplishing this can be applied simultaneously. In order to effectively lighten the arm components, new dynamic behaviors must be taken into account in control design to allow more complex control algorithms. Passive damping treatments make these algorithms much more robust and should be seriously evaluated in any practical attempt to control a lightweight motion system. ■

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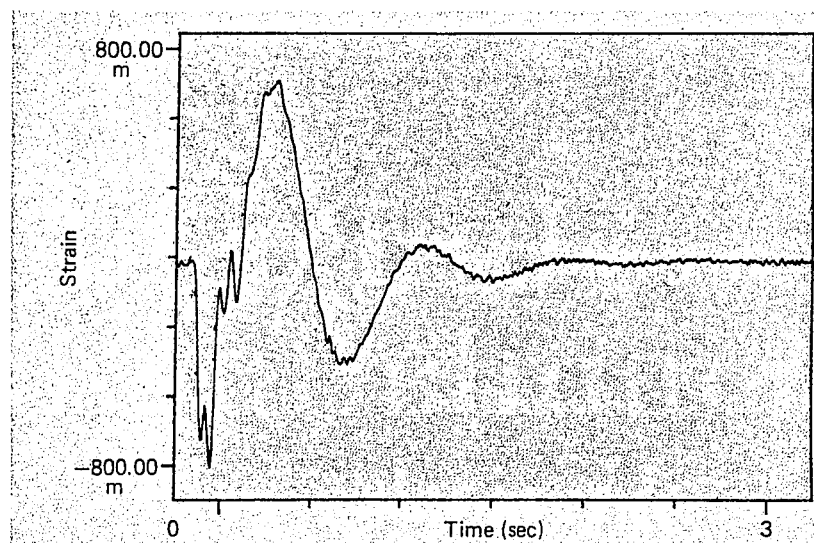


Fig. 11 System stabilized by addition of passive damping. Colocated feedback only.

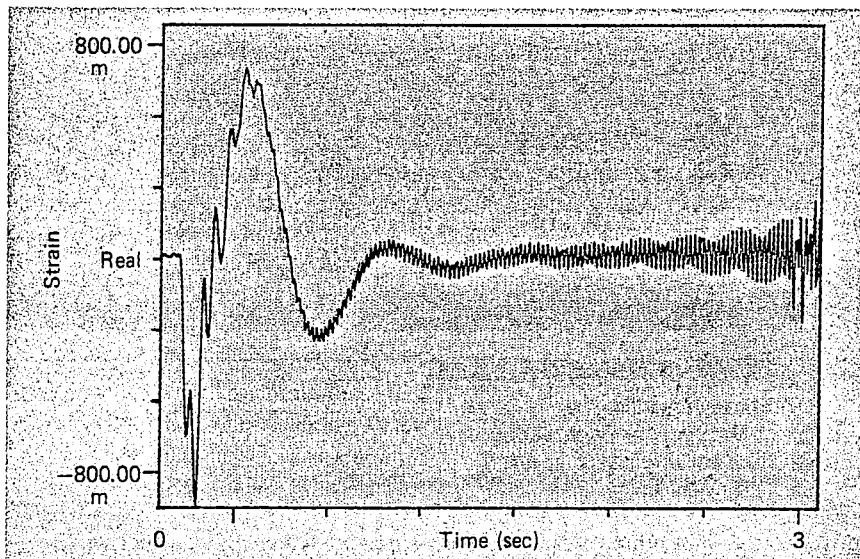


Fig. 12 Unstable system with modal feedback and without passive damping. The oscillation is 41 Hz.

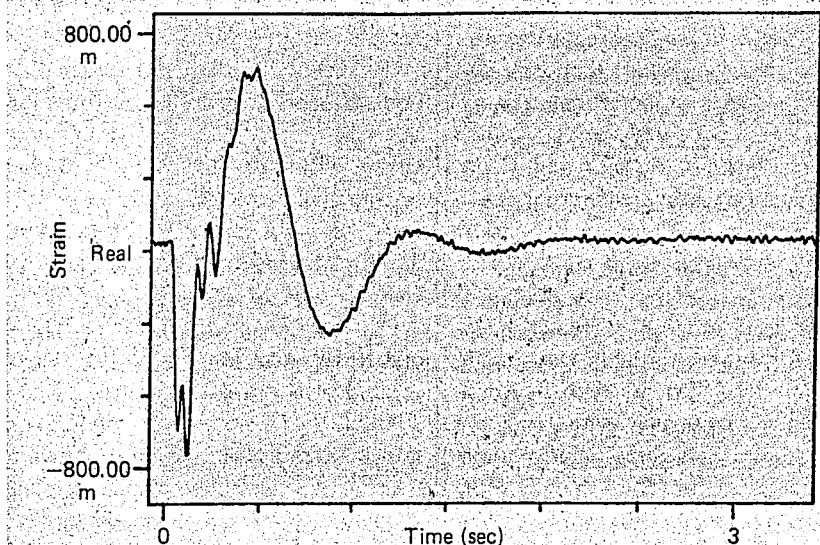


Fig. 13 System stabilized by addition of passive damping with modal feedback.