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IDENTIFICATION AND CONTROL OF A SINGLE-LINK FLEXIBLE MANIPULATOR

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Abstract

Model identification and control of a single-link very flexible manipulator is carried out in this paper. The objective of this paper is to first find the transfer functions relating the tip position to the motor position and the motor position to the motor current, and then use these transfer functions to control the tip position of the manipulator. Because of the nonlinearities introduced by the static friction of the motor and due to very low damping of the manipulator, classical frequency domain techniques cannot be used to find these transfer functions. A new method to find these transfer functions is proposed in this paper. A set of experiments were performed and transfer functions which fit this data were obtained. The control scheme contains an inner loop for the motor position and an outer loop for the tip position. For the outside loop, feedforward control and the computed torque techniques are evaluated.

Summary

1. Experimental Set Up

A very flexible, single-link arm, actuated by a direct-drive dc motor was used as the basis for developing tip-control algorithms. The arm is a straight piece of music wire clamped to the motor shaft. A relatively heavy disk attached to the end of the wire provides the mass whose position is to be controlled. The disk floats on an air table to minimize the effects of friction and gravity, and has a pivot joint which precludes the generation of bending moments at the tip of the wire. The arm behaves practically as an undamped, single degree-of-freedom system for moderate deflections and frequencies. Though the motor has available torque many times the structural limit of the arm, and frequency response an order of magnitude higher than that of the tip, static friction torque is of the order of the torque limit of the arm. Thus, frictional effects must be considered in the design of control system.

2. Identification Method

The identification method is based on the frequency domain approach and is carried out in three stages. First, the position control of the motor is performed to make the motor follow a reference sinusoidal signal. Motor friction is assumed to consists of a viscous term (proportional to velocity) which created linear damping; and a Coulomb or static term with constant magnitude and sign of the motor velocity. That is, the static friction of the motor is a square wave signal in phase with the velocity of the motor. Because motor torque is proportional to current, the friction appears as a square wave superimposed on the sinusoidal current driving the linear portion of the system. The magnitude of the static friction (amplitude of the square wave signal) is then calculated by making the spectral analysis of the current of the motor, using the third harmonic from the Fourier series expansion as an indicator of the square wave function. Finally, a correction to the frequency data (obtained for the system) is performed to remove the distorting effects of the static friction. The classical frequency analysis can now be carried out using the corrected data. A set of experiments were performed in order to test this method, and some transfer functions which fit the data were obtained for the flexible arm and are given by

$$\frac{\theta_t(s)}{\theta_m(s)} = G_1(s) = \frac{43.75}{s^2 + .06s + 43.75} \tag{1}$$

and

$$\frac{\theta_m(s)}{i(s)} = G_2(s) = \frac{395(s^2 + .06s + 43.75)}{s(s + .085)(s^2 + 2.181s + 208.95)} \tag{2}$$

where θ_m, and θ_t are the motor and tip positions in radians and i(t) is the current of the direct drive motor in amperes. The main advantage of this method is that is provides a mean values of the static friction for all velocities, while the other methods, which are based on the temporal analysis, give the static friction only for some specified velocities. Another advantage of this method is that we can obtain both the static friction and the transfer functions by performing one set of experimentation, whereas in other methods it is necessary to perform two set of experiments, one to characterize the static friction and the other to get the transfer functions.

3. Control of the Single-Link Flexible Manipulator

Most of the schemes used for the control of flexible manipulators in the literature are based on a model of the manipulator that considers the current of the motor as the input and the angles of the motor and tip as the output. In other words, these control schemes are based on two transfer functions: motor position to current and the tip position to current. These transfer functions have the same poles but different zeros. Using these transfer functions an optimal controller is designed using pole placement or some other control technique. These techniques do not take into consideration the friction of the motor. Friction changes the poles of the two transfer functions, thus making the controlled system sensitive to the actual value of the friction. We propose a control scheme which is based on the transfer functions of the model obtained in the previous section. Note that the variation in the friction produces changes only in the poles of the transfer function given by equation (2). The transfer function given by equation (1) remains unchanged because it depends only on the mechanical structure of the beam. A robust control scheme may be designed to minimize the sensitivity of the system to changes in the friction by first closing the inner loop for motor position with high gain after compensating for friction and coupling between the tip and motor position and then closing the outer loop for the tip position. The control signal generated by the outer loop is the motor position reference for the inner loop. The control schemes for the outer loop used in this study were the feedforward control and computed-torque techniques [4, 5]. The first part of this section deals with the design of the motor control inner loop and the second part with the design of the tip control outer loop.

3.1. Motor Position Control

The results of the identification of the manipulator show that the differential equation that describes the behavior of the motor contains two undesirable terms: a nonlinear term because of the static friction and a coupling term between the motor and the beam. These terms, which were evaluated from the identification method, can be removed from the differential equation by adding them to the control current of the motor

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$$I(t) = i(t) + \frac{S(t)}{K} + \frac{C}{K}(\theta_m(t) - \theta_t(t)) \qquad (3)$$

where I is the desired current for the motor, i is the commanded current (output of the motor controller), St is the static friction, K is the motor constant and the last term in equation (3) is the torque coupling between the tip and the motor position. After correcting for these terms, the transfer function between the $\theta_m(t)$ and i(t) is given by

$$\frac{\theta_m(s)}{i(s)} = G_m(s) = \frac{395}{s(s + 12.2)} \qquad (4)$$

The block diagram of the motor position control system can now be drawn as shown in Fig. 1. The block z^{-1} in Fig. 1 represents the computational delay of the control algorithm. The design of the digital controllers was carried out to satisfy the following specifications:

1. Steady – state error to be equal to zero.
2. Settling time to be minimal.
3. Overshoot allowed is minimal and possibly zero.
4. Maximum motor current = 6 amperes (The amplifier saturates at 5 amperes)

The values for the optimal controller (shown in Fig. 1) obtained form the design are: a0 = 17.442, a1 = 2.442, b0 = 6.667, and b1 = 5.667. The controllers were implemented and verified experimentally. The settling time obtained was 33 msec. The control system was found to be robust to the variations in friction value. The complete control scheme for the inner loop is shown in Fig. 2.

3.2. Tip Position Control

A block diagram of the tip position control system may be drawn as shown in Fig. 3. The tip position control system contains inside its loop the motor position control system. Since the settling time of the motor control system is very small as compared to the tip position, the transfer function of the motor control system was assumed to be equal to 1 for the sake of simplicity in the design of tip controller. Two control schemes are being evaluated for this control: feedforward control and computed torque technique. The block diagram of the feedforward control is shown in Fig. 4 and computed torque technique is shown in Fig. 5. Preliminary experimental results for both the methods looks promising. Experiment results along with a comparison between the two methods will be communicated later.

4. Conclusions

Model identification and control of a single–link very flexible manipulator with friction in the joint is presented in this paper. A new method to find the transfer functions of the manipulator is proposed. The control scheme presented contains an inner loop for the motor position and an outer loop for the tip position. Feedforward and the computed–torque techniques are evaluated for the outer loop.

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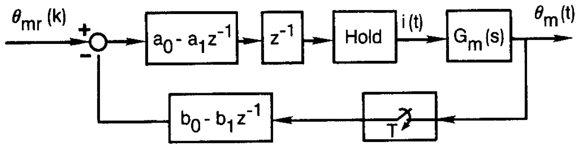

Figure 1. Block diagram of the motor position control.

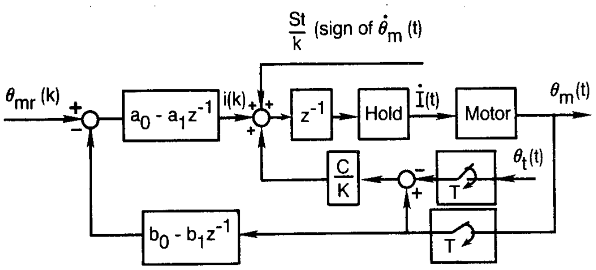

Figure 2. Detailed control scheme for the motor position.

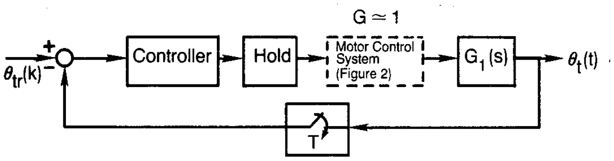

Figure 3. Block diagram of the tip position control.

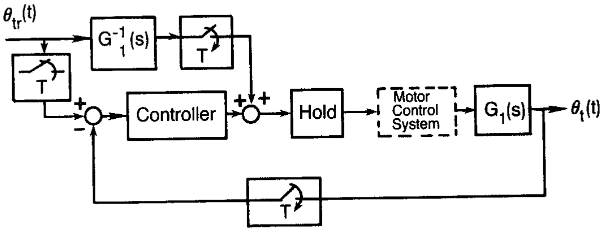

Figure 4. Block diagram of the feedforward control of tip position.

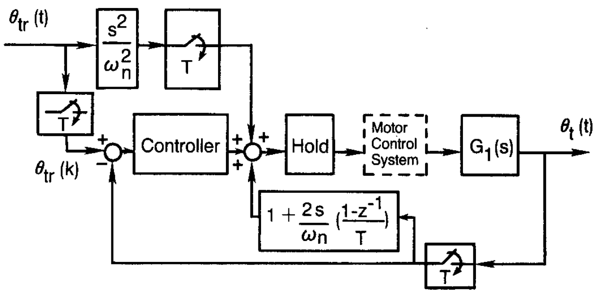

Figure 5. Block diagram of the tip position control using computed torque technique.