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Implementation of frequency-shaped tip reference in conjunction with learning controller for improved tip-tracking control [†]

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Abstract

In the flexible manipulator control, tip-tracking control of flexible manipulator results in non-colocated control problem, which has a non-minimum phase dynamic characteristic. The level of tip-tracking performance in the non-colocated control system depends on the characteristics of the tip reference trajectory to be followed, as well as on the characteristics of the flexible manipulator system itself. In a previous research the use of a tip reference trajectory, filtered by a properly designed time-delay command shaping filter, has been proposed and a multirate repetitive learning control (MRLC) has been used as the tip-tracking controller. The practical implementation of this approach, however, requires estimation of the tip position, which is not easy to obtain. In this paper, a practical implementation of the approach is considered and the tip position is estimated with a fourth-order Kalman filter. The experimental results show that, with the use of Kalman filter, the proposed scheme results in a drastic reduction in residual tip vibrations and the required actuation effort.

Keywords: Flexible manipulator; Tip-tracking control; Command shaping filter; Tip position estimation; Learning controller

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1. Introduction

Tip-tracking control of robotic manipulators with flexibility is difficult owing to the non-minimum phase dynamics that result from the finite speed of propagation of a mechanical wave along the manipulator link. This difficulty often renders the control objective of a flexible manipulator system as the point-to-point position control or regulation, the main task of which is to suppress the residual vibrations [1].

Recently, a flexible manipulator tip controller using a learning controller has been developed where a conventional periodic desired reference trajectory to be tracked by the tip is given and the repetitive learning control is used to determine the corresponding base motion required. However, the use of the conventional tip-position reference resulted in the extremely large control torque at the joint [2].

Rhim and Hu have proposed the use of the tip-tracking reference, which is filtered by a properly designed time-delay command shaping filter in conjunction with the same repetitive learning controller as the tip-controller [3]. The implementation of these two approaches, however, requires the estimation of tip position on-line, which is not easy to obtain.

In this paper, in order to realize and make the method proposed in Rhim and Hu implementable, a fourth-order Kalman filter is developed to estimate the tip position of the flexible manipulator. Using the Kalman filter estimation of the tip position, time-delay filtered reference position is used for tip-tracking control in conjunction with MRLC. The experimental results demonstrate a drastic reduction in residual tip vibrations and the required actuation effort.

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2. Control system

2.1 Controller configuration

A schematic illustration of the typical flexible manipulator system considered in this research is shown in Fig. 1. The discrete-time block diagram representing the control system proposed in this paper is shown in Fig. 2, where *C*(*z*) represents a command-shaping filter, *D*(*z*)is a conventional PD feedback controller used to apply the required control force to the joint, *H*(*z*) is the transfer function of a flexible manipulator system, and MRLC represents a multi-rate repetitive learning controller [4, 5].

As shown in the figure, MRLC is used as a tip controller; and to modify the motion trajectory, the base mass of the actual system is commanded to follow x_d. Repetitive learning controller estimates, through practice, the control input required to theoretically achieve perfect tracking of a periodic desired trajectory. The gradual modification of the periodic reference trajectory obtained by adding a progressively refined x_{learn} term to it forms an x_d that, when rigorously followed by the base mass, leads to e_{tip} approaching zero. A PD controller *D*(*z*) has input $e_{base}=x_d - x_{base}$ and output *u* that actuates the joint.

2.2 Kalman filter design

The Kalman filter is an optimal estimation method that adopts a nominal system model and seeks to reconstruct the system's states as an estimation that is progressively corrected by an error term. The error term is partly made up of the difference between the expected (i.e., computed) output based on the nominal system model and the actual measured output. In addition, the Kalman filter considers sensor noise in the error term.

When we consider only the first elastic mode in the system, the flexible link system can be modeled as a two-mass system coupled by a spring and damper in parallel (Fig. 3). The base mass, m_1, which is constrained to move back and forth on a straight, horizontal track, is driven by an actuator. The input force applied by the linear motor is denoted as *u*. The tip mass, m_2, is regarded as the endpoint of the flexible manipulator.

Based on the two-mass system model, a Kalman filter is designed. The system model used in the paper regards the joint position as the input and the tip acceleration is designated as the output, which we call *y*.

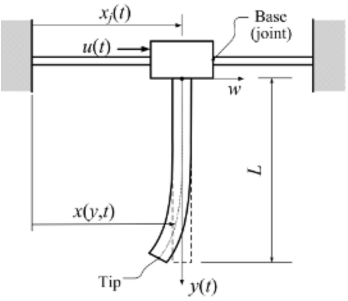

Fig. 1. Schematic diagram of a flexible manipulator.

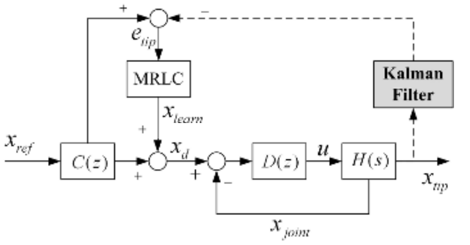

Fig. 2. Control system configuration.

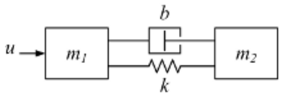

Fig. 3. Simplified model of a flexible link.

$$m_2\ddot{x}_{tip} = k(x_{joint} - x_{tip}) + b(\dot{x}_{joint} - \dot{x}_{tip}) \tag{1}$$

$$y = \frac{k}{m_2}(x_{joint} - x_{tip}) - \frac{b}{m_2}(\dot{x}_{joint} - \dot{x}_{tip}) \tag{2}$$

where x_{joint} and x_{tip} are joint position and tip position, respectively.

Then, the system in Eq. (1) can be equivalently expressed in observable canonical form as

$$\dot{\mathbf{x}}_t = \mathbf{A}_t\mathbf{x}_t + \mathbf{B}_t x_j \tag{3}$$

$$y = \mathbf{C}_t\mathbf{x} + \mathbf{D}_t x_{joint} + \mathbf{E}_t\dot{x}_{joint} \tag{4}$$

where

$$\mathbf{A}_t = \begin{bmatrix} -b/m_2 & 1 \\ -k/m_2 & 0 \end{bmatrix}, \quad \mathbf{B}_t = \begin{bmatrix} b/m_2 \\ k/m_2 \end{bmatrix},$$

$$\mathbf{C}_t = \begin{bmatrix} -k/m_2 & -b/m_2 \end{bmatrix},$$

$$\mathbf{D}_t = k/m_2, \quad \mathbf{E}_t = b/m_2$$

With the above nominal model, the Kalman filter may now be designed. Letting $\hat{\mathbf{x}}$ denote the estimate of

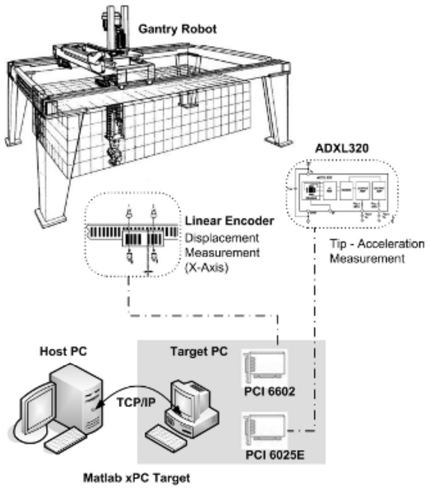

Fig. 4. Experimental testbed configuration.

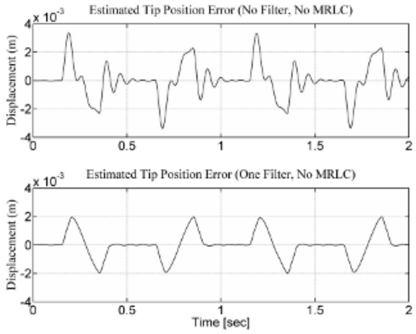

Fig 5. Estimated tip-tracking error (top: no filter, no MRLC, bottom: one filter no MRLC).

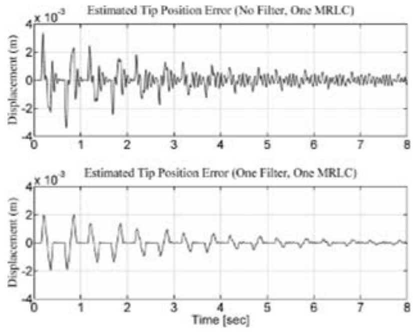

Fig. 6. Estimated tip-tracking error (top: no filter, one MRLC, bottom: one filter, one MRLC).

the state vector **x**, we may write the typical estimator relationship as

$$\dot{\hat{\mathbf{x}}}_t = \mathbf{A}_t \hat{\mathbf{x}}_t + \mathbf{B}_t x_{joint} - \mathbf{L}(\hat{y} - y) \tag{5}$$

where

$$\hat{y} = \mathbf{C}_t \hat{\mathbf{x}} + \mathbf{D}_t x_{joint} + \mathbf{E}_t \dot{x}_{joint} \tag{6}$$

is the estimate of the output y computed using the estimated state $\hat{\mathbf{x}}$ and the input, x_{joint}, and its first-time derivative. Both y and x_{joint} are assumed to come from the measurements. In the current paper, y is measured from an accelerometer and x_{joint} is measured using an encoder. For our digital implementation, we are required to discretize (6).

3. Simulation results

Fig. 4 shows a schematic of the various components of the actual system that is the basis of our model. An encoder is used to measure x_{joint} to a resolution of 10^{-6} m. A Kalman filter is used to obtain an estimate of x_t in real time. The input to the system model is the encoder reading, that is, the joint position x_{joint}. The output of the system model is the tip acceleration. The actual tip acceleration y can be measured using an accelerometer that is affixed to the tip of the link. The approximation of tip position y is calculated using the expression in (6); x_{joint} is approximated using a finite-difference approximation based on the present encoder reading and one previous encoder reading.

In order to verify the accuracy of the Kalman filter and to guide the tuning of the parameters that characterize the noise of the encoder and the accelerometer, we used a machine vision system employing a CCD camera to measure the tip position directly. From the camera measurement and the system identification experiments, we determined the system parameters, as well as the Kalman filter parameters.

Fig. 5 shows the estimated tip-tracking errors obtained from the experiments where the filtered tip reference input was used. Fig. 6 shows the estimated tip-tracking error where MRLC was used. The top plot shows the tip-tracking error when only MRLC was used without command shaping filter and the bottom plot shows the tip-tracking error where both the MRLC and an effective command shaping filter were used. It is apparent that in both cases, the MRLC gradually reduces the tip-tracking error by learning the required feedforward effort; however, the use of filtered reference tip position input reduces the tip-tracking error significantly.

Fig. 7 and Fig. 8 show the estimated tip position of the flexible link. It is apparent that the use of both MRLC and the command-shaping filter result in much smaller vibration at the residual period.

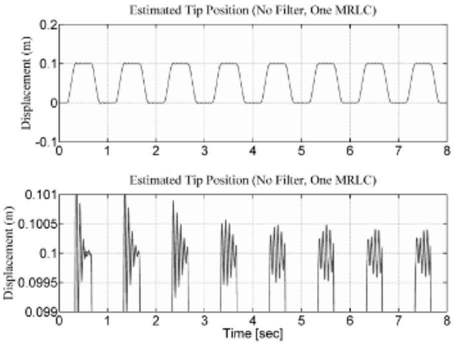

Fig. 7. Estimated tip position (no filter, one MRLC).

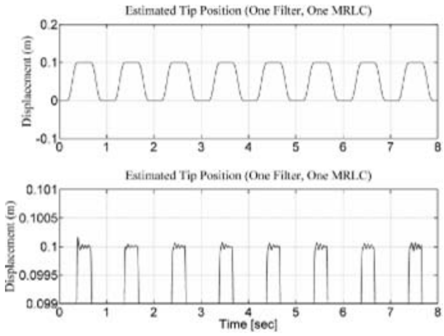

Fig. 8. Estimated tip position (one filter, one MRLC).

4. Conclusions

The development and result of implementation of a filtered tip reference input in MRLC to the problem of non-colocated control of a flexible manipulator is described. The experimental results show that the use of the MRLC results in a significant reduction of the tracking error when following a fairly aggressive periodic trajectory. To fully simulate the practical implementation of the proposed method, a Kalman filter is designed and implemented to estimate the tip position based on the measured tip acceleration. The measurement noises are also modeled and included in the Kalman filter.

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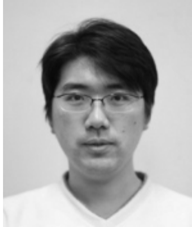

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