A Robust Input Modification Approach for High Tracking Control Performance of Flexible Joint Robot

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Abstract: A robust input modification approach to the control of flexible joint robot is presented. In our previous study, we developed an observer based state feedback control for the suppression of residual vibration of a robot. The control was very effective in suppressing the inherent vibration of a flexible joint robot. However it did not meet high performance requirements under high speed motion and model uncertainties. As a solution of the problem, we present an input modification method with robustness against parametric uncertainties. The main idea of the proposed input modification method is to generate a modified reference position command for fast and accurate motion of the robot. Using this proposed method we can reduce the servo delay and settling time by about 60% and substantially improve the path accuracy.

Keywords: robust input modification, state feedback control, flexible joint robot

1. INTRODUCTION

Recently, there are increasing demands from industries for improved robot control system which can achieve given tasks more quickly, accurately, and vibrationlessly. An observer based state feedback control was developed in our previous study for the suppression of residual vibration of a robot [1]. The control was very effective in suppressing the inherent vibration of a flexible joint robot. However it is necessary to enhance the control scheme to meet the high tracking control performance at high speed.

Robot manipulators, which are controlled only by a feedback scheme, show large amount of position tracking error when operated at high speed. The error is caused by a servo delay. One possible approach to improve the tracking performance is to employ a dynamic model based feedforward control in addition to the feedback control. However it is hard to obtain the exact inertial parameters of the robot. Furthermore, in case of flexible joint robot, it is not easy to implement the control algorithm into the control hardware system because of extremely complicate dynamics caused by high-order dynamic model. Recently, some advanced feedforward controls have been reported. The representative example is to adopt an iterative learning control (ILC) scheme in feedforward control [2]. Trajectory tracking performance is substantially improved by using ILC. However it has some iterative processes to find adequate parameters of the control algorithm. And a vision sensor based predictive control scheme was presented to improve a tracking performance of an industrial robot [3]. However it requires additionally the camera and image processing device.

This paper introduces a robust input modification method to enhance the tracking control performance of a conventional feedback control. The main idea of the proposed input modification method is to generate a modified reference position command for fast and accurate motion of the robot. This method also has a robust aspect which is able to maintain the control performance in spite of parametric uncertainties.

This paper is organized as follows. In section 2, the model of the flexible joint of robot is described. In section 3, a robust modification approach is proposed. This is a main point of this paper. Experimental results are shown in section 4 and the conclusion follows.

2. MODEL OF FLEXIBLE JOINT OF A ROBOT

The flexible joint of an industrial robot as shown in Fig. 1, without loss of generality, can be represented by a two inertia system which is composed of driving motor, torsional spring and link as shown in Fig. 2 [4]. The motion of the flexible joint system can be expressed two coupled dynamics as Eq. (1) [4]. One is the motor side dynamics and the other is the robot link dynamics. In this model, the motor dynamics is actuated by the driving motor torque and the link dynamics is actuated by the motor angle through the elastic transmission.

$$\begin{aligned} \ddot{\theta}_L &= -\frac{B_L}{J_L}\dot{\theta}_L - \frac{K}{J_L}\theta_L + \frac{K}{J_L r}\theta_m \\ \ddot{\theta}_m &= -\frac{B_m}{J_m}\dot{\theta}_m - \frac{K}{J_m r^2}\theta_m + \frac{K}{J_m r}\theta_L + \frac{1}{J_m}\tau \end{aligned} \tag{1}$$

Fig. 1 Industrial robot with joint flexibility

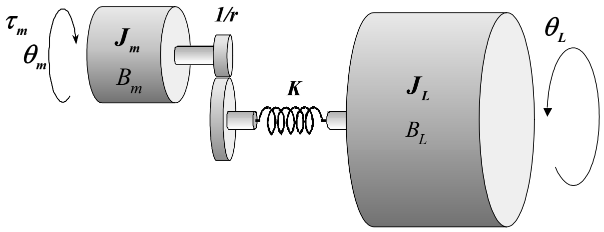

Fig. 2 Two inertia system with flexible joint

where J_m and J_L are the moments of inertia, B_m and B_L are damping coefficients, θ_m and θ_L are the angles of the motor and link respectively. K is the stiffness of the joint, r is the gear reduction ratio, and τ_m is the motor torque.

The state space equation of the flexible joint system can be represented as Eq. (2). The damping frictions are neglected for simplicity.

$$\begin{aligned} \dot{\boldsymbol{x}} &= \mathbf{A}\boldsymbol{x} + \mathbf{B}u \\ y &= \mathbf{C}\boldsymbol{x} \end{aligned} \tag{2}$$

where

$$\boldsymbol{x} = \begin{bmatrix} \omega_m \\ \theta_s \\ \omega_L \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} 0 & -\frac{1}{r}\frac{K}{J_m} & 0 \\ \frac{1}{r} & 0 & -1 \\ 0 & \frac{K}{J_L} & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \frac{1}{J_m} \\ 0 \\ 0 \end{bmatrix},$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

$$y = \omega_m, \; u = \tau_m.$$

Generally it is possible to obtain the angular velocity of motor (ω_m) from the measured angle of motor (θ_m). However, angular velocity of link (ω_L) and torsional angle (θ_s) are not available in most of industrial robots because of cost and maintenance. So from Eq. (2), a state observer which estimates the angular velocity of link and the torsional angle is constructed as

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Bu + L(y - \hat{y}) \\ \hat{y} &= C\hat{x}. \end{aligned} \tag{3}$$

The observer gain vector (L) is obtained by the pole placement method [5].

3. DESIGN OF ROBUST INPUT

The link cannot be directly controlled by the driving motor torque because of elastic interconnecting mechanism. Therefore we assume that the motor angle controls the link dynamics of Eq. (1). And we call the motor angle as the virtual control input of the link dynamics, and we design the desired virtual control input so that the link motion effectively follows the reference trajectory. By the design result, the reference input to the motor dynamics is modified and then the controlled motor angle becomes a virtual control input to link dynamics. In this paper, the virtual control input design is called as the input modification method. The previous developed feedback control [1] is used to regulate the error between the modified input and the real motor angle.

3.1 State feedback control

The previous state feedback control input was set as [1]

$$\tau_m = -\left[Kx_1 Kx_2 Kx_3 Kx_4\right] \begin{bmatrix} \varpi_m \\ \hat{\theta}_s \\ \hat{\varpi}_L \\ \xi \end{bmatrix} \tag{4}$$

where $\xi = \int(\varpi_{mr} - \varpi_m)dt$, θ_{mr} is the reference angle of motor, and Kx_1, Kx_2, Kx_3, Kx_4 are feedback control gains [1]. Fig. 3 shows the observer based state feedback control scheme for flexible joint robot. K_P is a proportional control gain in position control loop.

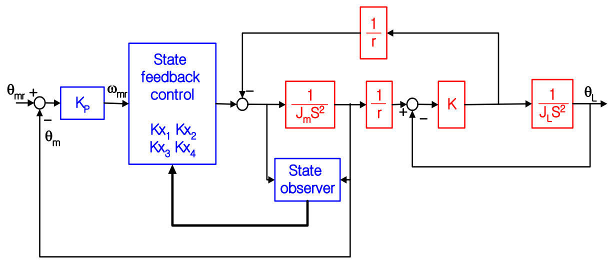

Fig. 3 State feedback control scheme for the flexible joint of a robot

3.2 Robust Input Modification Method

The main idea of the proposed input modification method is to modify an original input command of flexible joint robot to improve a control performance. The design procedure of robust modified input (θ_f) consists of two phases: at first, a model based modified input is derived from the dynamic equation to regulate the position and velocity error in link side, and then a robust modified input is designed to maintain the tracking performance under model uncertainties. The whole virtual control input is expressed as

$$\theta_f = \theta_{fm} + r\theta_{fr} \tag{5}$$

where θ_{fm} is a model based modified input term and θ_{fr} is an additional input term for robustness.

3.2.1 Model Based Modified Input

A new state s is defined as

$$s = \dot{\theta}_L - \dot{\theta}_d + \lambda(\theta_L - \theta_d) \tag{6}$$

where θ_d and $\dot{\theta}_d$ are desired position and velocity of link and λ is a gain and always positive. Eq. (6) is re-written as

$$\begin{aligned} s &= (\dot{\theta}_L - \dot{\theta}_d) + \lambda(\theta_L - \theta_d) \\ &= \dot{\theta}_L - \dot{\theta}_r \end{aligned} \tag{7}$$

where $\dot{\theta}_r = \dot{\theta}_d - \lambda(\theta_L - \theta_d)$.

Using Eqs. (1) and (7), it is possible to compute the model based modified input as

$$\theta_{fm} = \frac{r}{\hat{K}}(\hat{J}_L \ddot{\theta}_r + \hat{B}_L \dot{\theta}_r) + r\theta_L \tag{8}$$

The robust modified input will be designed by the state s.

3.2.2 Robust Modified Input

In this section, the design procedure of robust modification input (θ_{fr}) will be explained. Substituting Eqs. (5) and (8) into link dynamic equation of Eq. (1),

$$\begin{aligned} \ddot{\theta}_L &= -\frac{B_L}{J_L}\dot{\theta}_L - \frac{K}{J_L}\theta_L + \frac{K}{J_L r}\theta_f \\ &= -\frac{B_L}{J_L}\dot{\theta}_L - \frac{K}{J_L}\theta_L + \frac{K}{J_L r}(\theta_{fm} + r\theta_{fr}) \\ &= -\frac{B_L}{J_L}\dot{\theta}_L + \frac{K}{J_L}\frac{\hat{J}_L}{\hat{K}}\ddot{\theta}_r + \frac{K}{J_L}\frac{\hat{B}_L}{\hat{K}}\dot{\theta}_r + \frac{K}{J_L r} r\theta_{fr} \end{aligned} \tag{9}$$

And then, Eq. (9) is re-expressed by the state s as

$$\dot{s} = As + B_1 w + B_2\theta_{fr} \tag{10}$$

where $A = -\frac{B_L}{J_L},\ B_1 = \frac{K}{J_L},\ B_2 = \frac{K}{J_L}$, and w is a uncertainty vector expressed as

$$w = \left(\frac{\hat{J}_L}{\hat{K}} - \frac{J_L}{K}\right)\ddot{\theta}_r + \left(\frac{\hat{B}_L}{\hat{K}} - \frac{B_L}{K}\right)\dot{\theta}_r \tag{11}$$

A new state variable z, which represents the performance of the system, is introduced to design the robust input according to H_∞ control theory [6].

$$z = Hs + D\theta_{fr},\ \ H^T D = 0,\ \ D^T D > 0 \tag{12}$$

The design of robust input for the system is described in the Theorem 1 [6].

Theorem 1 : Given $\gamma > 0$, suppose that there exists a semi-positive definite matrix P satisfying

$$\begin{aligned} &P^T A + AP + (1/\gamma^2)P^T B_1 B_1^T P \\ &\qquad - P^T B_2 (D^T D)^{-1} B_2^T P + H^T H \le 0 \end{aligned} \tag{13}$$

and there exists a nonnegative energy storage function $E \ge 0$ such that $\frac{\partial E}{\partial s} = 2s^T P^T$. Then the robust input satisfying L_2-gain $\le \gamma$ is

$$\theta_{fr} = -(D^T D)^{-1} B_2^T Ps \tag{14}$$

where P is called a robust gain of the modified input. And the derivative of energy storage function satisfies [7]

$$\dot{E} \le \gamma \|w\|^2 - \|z\|^2 \tag{15}$$

Proof : Derivative of energy storage function E is given as

$$\begin{aligned} \dot{E} &= \frac{\partial E}{\partial s}\dot{s} \\ &= 2s^T P^T (As + B_1 w + B_2\theta_{fr}) \\ &= s^T (P^T A + AP)s + 2s^T P^T (B_1 w + B_2 \theta_{fr}) \end{aligned} \tag{16}$$

Introducing $\gamma\|w\|^2 - \|z\|^2$ into Eq. (16) to find the modified input, we obtain that

$$\begin{aligned} \dot{E} &= \gamma^2\|w\|^2 - \|z\|^2 + s^T(P^T A + AP)s \\ &\quad + (1/\gamma^2)s^T P^T B_1 B_1^T Ps - \gamma^2\left\|w - (1/\gamma^2)B_1^T Ps\right\|^2 \\ &\quad + 2s^T P^T B_2 \theta_{fr} + s^T H^T Hs \\ &\quad + \theta_{fr}^T D^T D\theta_{fr} + 2s^T H^T D\theta_{fr} \\ &= \gamma^2\|w\|^2 - \|z\|^2 - \gamma^2\left\|w - (1/\gamma^2)B_1^T Ps\right\|^2 \\ &\quad + \left\|D\theta_{fr} + D^{-T}B_2^T Ps\right\|^2 + s^T[P^T A + AP \\ &\quad + (1/\gamma^2)P^T B_1 B_1^T P - P^T B_2 (D^T D)^{-1} B_2^T P + H^T H]s \\ &\quad + 2s^T H^T D\theta_{fr}. \qquad (H^T D = 0) \\ &\le \gamma^2\|w\|^2 - \|z\|^2 \qquad \textit{by Eqs.}\ (13)\ \textit{and}\ (14) \end{aligned} \tag{17}$$

Thus the input $\theta_{fr} = -(D^T D)^{-1} B_2^T Ps$ yields a closed loop with L_2-gain less than or equal to γ [6]. ■

To obtain the solution to the Eq. (13), pre-multiply and post-multiply the inequality by positive definite matrices P^{-T} and P^{-1}, respectively. And then it is transformed into a LMI (Linear Matrix Inequality) [8] by the Schur complement as

$$\begin{bmatrix} AQ + Q^T A^T + (1/\gamma^2)B_1 B_1^T - B_2(D^T D)^{-1} B_2 & Q^T \\ Q & -H^T H \end{bmatrix} \le 0 \tag{18}$$

where $Q = P^{-1}$. The LMI can be solved by an efficient convex optimization algorithm.

Therefore the robust modified input of Eq. (5) is finally re-written as

$$\theta_f = \frac{r}{\hat{K}}(\hat{J}_L \ddot{\theta}_r + B_L \dot{\theta}_r) + r\theta_L - (D^T D)^{-1} B_2^T P s. \qquad (19)$$

The overall control scheme is shown in Fig. 4. The robust input modification module is added in the conventional state feedback control.

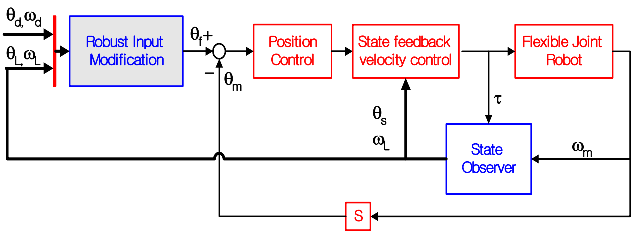

Fig. 4 Block diagram of overall control scheme

4. EXPERIMENTS

Experiments are conducted on a 6-axis articulated industrial robot with parallelogram linkage. The payload of the robot is 165kg.

The robust gain (P) is obtained taking into account 20 percent uncertainty of load inertia and joint stiffness of Eq. (11). The load inertia moment of robot varies drastically according to robot pose as shown in Fig. 5. When value of the inertia moment at pose (iii) is normalized as 1, it changes from 0.2 to 2 according to robot pose. To maintain the performance, the robust gain (P) of the input modification method should be adequately adjusted along its time-varying nature of load inertia moment because the elements of Eq. (17) vary according to robot pose. One possible approach is to solve the LMI each control period. However, it is a time-consuming process. Therefore a gain-scheduling method is adopted to obtain the robust gain in accordance with variation of load inertia as shown in Fig. 6. The dotted line of Fig. 6 shows the gain obtained from convex optimization of LMI and the solid line shows the one obtained from scheduling.

4.1 Experiments for Joint Command Following

To evaluate a joint tracking performance, the robot operating command is set as follows: Only axis 1 is commanded to move from 0° to -10° with the maximum acceleration and deceleration in each robot pose of Fig. 5. The experimental results are compared with those obtained from the conventional state feedback control in each robot pose. The angle tracking control results for the motion of axis 1 are shown in Figs. 7 and 8. The proposed method shows improved performance while the conventional state feedback controller shows large servo delay and settling time, as shown in Figs 7 and 8. The servo delay is reduced by around 60%. The position settling time is also greatly reduced at the end of motion.

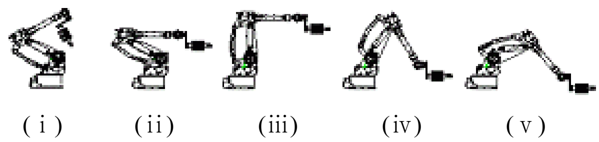

Fig. 5 Robot pose

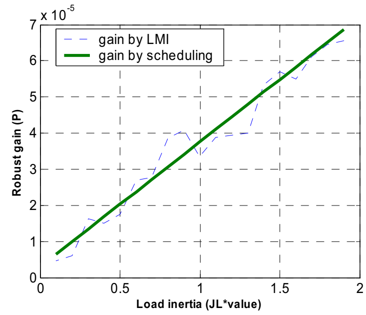

Fig. 6 Robust gain by solving LMI and scheduling according to load inertia variation

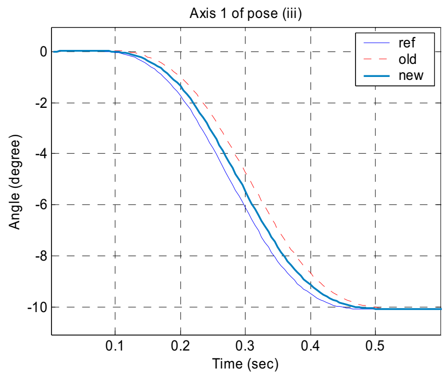

Fig. 7 Angle tracking control of axis 1 of pose (iii)

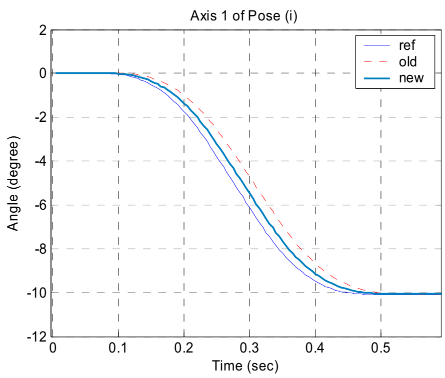

Fig. 8 Angle tracking control of axis 1 of pose (i)

4.2 Experiments for Trajectory Following

After all axes of robot are tuned up, the trajectory tracking experiments are carried out. The experiments are executed along the reference path of solid thin line of Fig. 9 at full speed according to the path planning algorithm of the controller. Path tracking performance is improved in accordance with reduction of servo delay of each axis.

Fig 9 shows the trajectory following results. And the magnification figures of Fig. 9 are shown in Fig. 10. Path errors of the proposed scheme are substantially smaller than those of the conventional state feedback control as shown in Figs. 9 and 10.

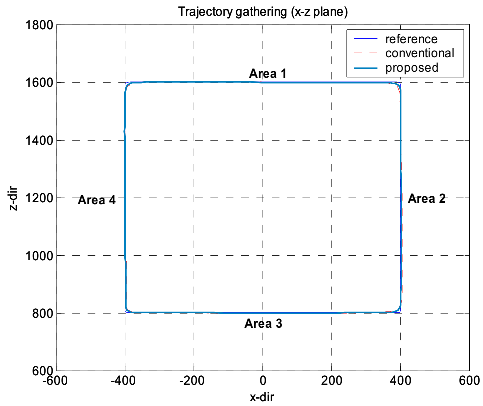

Fig. 9 Trajectory tracking control result

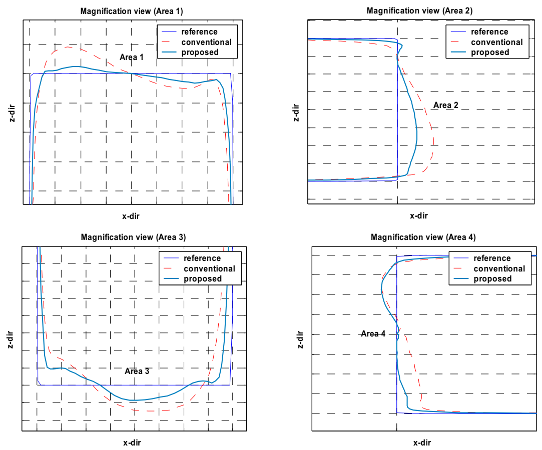

Fig. 10 Magnification view of Fig. 9

5. CONCLUSIONS

In this study we presented a robust input modification method for an industrial robot with flexible joints. The advantage of the proposed method is that it is able to improve the control performance and be applied to most kinds of feedback control for a flexible joint system without changes of control structure. To evaluate the control performance, experiments were conducted on the heavy payload industrial robot. The effectiveness of the proposed method was shown through experiments. For the future works, it is necessary to study on advanced feedback control scheme to accurately regulate the error between the modified input and the real motor angle.

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