1-1-2010

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Recommended Citation

Du, Haiping; Naghdy, Fazel; and Stirling, David A.: Fuzzy stability control of robotic manipulator with input delays 2010, 955-960.

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Keywords

input, stability, control, delays, robotic, manipulator, fuzzy

Disciplines

Physical Sciences and Mathematics

Publication Details

H. Du, F. Naghdy & D. Stirling, "Fuzzy stability control of robotic manipulator with input delays," in ROBIO 2010 Proceedings, 2010, pp. 955-960.

Fuzzy Stability Control of Robotic Manipulator with Input Delays

Haiping Du, Fazel Naghdy and David Stirling

Abstract—This paper studies the stabilisation control problem of a robotic manipulator with input delays. To deal with the highly nonlinear dynamics of a robotic manipulator, the model-based Takagi-Sugeno (T-S) fuzzy control strategy is applied. With representing the nonlinear robotic manipulator model as a T-S fuzzy model, sufficient conditions for designing a controller such that the system is stabilised with given decay rate are derived by constructing a less conservative Lyapunov-Krasovskii functional and using a tighter bounding technology for cross terms and the free weighting matrix approach. With appropriate derivation, all the required conditions are expressed as linear matrix inequalities (LMIs). Numerical simulations on a two-link manipulator are used to validate the effectiveness of the proposed approach. The results show that the designed controllers can stabilise a robotic manipulator with given decay rate when time delays exist in the control inputs.

I. INTRODUCTION

Many practical control systems encountered time delays when acquiring, processing, communicating, and outputting signals such that the system stability and control performance degrade. For the classical robot control problem, the significant effect of time delay on the closed-loop system stability has been highlighted in the bilateral teleoperation, where the communication delay transmitted through a network medium has been received widespread attention and different approaches have been proposed to address this problem [1]. In addition, examples like processing delays in visual systems and communication delay between different computers on a single humanoid robot are also main sources that may cause time delays in a robotic control system [2], and the issue of time delay for robotic systems has been studied through the passivity property.

In recent decades, both delay dependent and delay independent control strategies have been extensively studied for both linear and nonlinear time delay systems, see [3] and references therein. For the control of nonlinear time delay systems, model-based Takagi-Sugeno (T-S) fuzzy control [4] is regarded as one of the most effective approach because some of linear control theory can be applied directly. Conditions for designing such kinds of controllers are generally expressed as linear matrix inequalities (LMIs) which can be efficiently solved by using most available software like Matlab LMI Toolbox, or bilinear matrix inequalities (BMIs) which could be

transferred to LMIs by using algorithms like iteration algorithm or cone complementary linearisation algorithm. From the theoretical point of view, one of the current focus on the control of time delay systems is to develop less conservative approaches so that the controller can stabilise the systems or can achieve the defined control performance under bigger time delays [5], [6].

Be aware of the significance on the control of robotic systems with time delays, this paper focuses on stabilising a robotic manipulator with input delays. As a robotic manipulator is a highly nonlinear system, to design a controller so that the robotic manipulator can be stabilised with existing input time delays, the T-S fuzzy control strategy is applied. First, the nonlinear robotic manipulator model is represented by a T-S fuzzy model. Then, sufficient conditions for designing such a controller are derived with taking advantage of the recently proposed method [7] in constructing a Lyapunov-Krasovskii functional and using a tighter bounding technology for cross terms and the free weighting matrix approach to reduce the issue of conservatism. Furthermore, a decay rate constraint is added so that the designed feasible controller can stabilise the robotic manipulator with a given decay rate. With appropriate derivation, all the required conditions are expressed as LMIs. At last, simulation results on a two-link manipulator are used to validate the effectiveness of the proposed approach. The main contribution of the paper is to apply and develop an advanced technique to design a less conservative delay-dependent controller with decay rate constraint for a robotic manipulator.

This paper is organised as follows. In section II, the problem formulation and some preliminaries are introduced. The conditions for designing a stabilisation controller with decay rate constraint are derived in section III. In section IV, the simulation results on a nonlinear two-link robotic manipulator are discussed. Finally, conclusions are presented in section V.

The notation used throughout the paper is fairly standard. For a real symmetric matrix W , the notation of $W > 0$ ($W < 0$) is used to denote its positive- (negative-) definiteness. $\|\cdot\|$ refers to either the Euclidean vector norm or the induced matrix 2-norm. I is used to denote the identity matrix of appropriate dimensions. To simplify notation, $*$ is used to represent a block matrix which is readily inferred by symmetry.

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Fig. 1. Two-link robotic manipulator.

II. PROBLEM FORMULATION AND PRELIMINARIES

A. Manipulator System Description

To simplify the problem formulation, a two-link robot manipulator as shown in Fig. 1 is considered.

The dynamic equation of the two-link robot manipulator is expressed as [8]

$$M(q)\ddot{q} + V(q, \dot{q})\dot{q} + G(q) = u, \quad (1)$$

where

$$\begin{aligned} M(q) &= \begin{bmatrix} (m_1 + m_2)l_1^2 & m_1 l_1 l_2 (s_1 s_2 + c_1 c_2) \\ m_2 l_1 l_2 (s_1 s_2 + c_1 c_2) & m_2 l_2^2 \end{bmatrix}, \\ V(q, \dot{q}) &= m_2 l_1 l_2 (c_1 c_2 - s_1 s_2) \begin{bmatrix} 0 & -\dot{q}_2 \\ -\dot{q}_1 & 0 \end{bmatrix}, \\ G(q) &= \begin{bmatrix} -(m_1 + m_2)l_1 g s_1 \\ -m_2 l_2 g s_2 \end{bmatrix}, \end{aligned}$$

and $q = [q_1, q_2]^T$ and $u = [u_1, u_2]^T$ denote the generalised coordinates (radians) and the control torques (N-m), respectively. $M(q)$ is the moment of inertia, $V(q, \dot{q})$ is the centripetal-Coriolis matrix, and $G(q)$ is the gravitational vector. m_1 and m_2 (in kilograms) are link masses, l_1 and l_2 (in meters) are link lengths, $g = 9.8$ (m/s²) is the acceleration due to gravity, and $s_1 = \sin(q_1)$, $s_2 = \sin(q_2)$, $c_1 = \cos(q_1)$, and $c_2 = \cos(q_2)$. After defining $x_1 = q_1$, $x_2 = \dot{q}_1$, $x_3 = q_2$, and $x_4 = \dot{q}_2$, (1) can be rearranged as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f_1(x) + g_{11}(x)u_1 + g_{12}(x)u_2 \\ \dot{x}_3 &= x_4 \\ \dot{x}_4 &= f_2(x) + g_{21}(x)u_1 + g_{22}(x)u_2, \end{aligned} \quad (2)$$

where

$$\begin{aligned} f_1(x) &= \frac{(s_1 c_2 - c_1 s_2)}{l_1 l_2 [(m_1 + m_2) - m_2 (s_1 s_2 + c_1 c_2)^2]} \\ &\quad \times [m_2 l_1 l_2 (s_1 s_2 + c_1 c_2) x_2^2 - m_2 l_2^2 x_4^2] \\ &\quad + \frac{1}{l_1 l_2 [(m_1 + m_2) - m_2 (s_1 s_2 + c_1 c_2)^2]} \\ &\quad \times [(m_1 + m_2) l_2 g s_1 - m_2 l_2 g s_2 (s_1 s_2 + c_1 c_2)], \\ f_2(x) &= \frac{(s_1 c_2 - c_1 s_2)}{l_1 l_2 [(m_1 + m_2) - m_2 (s_1 s_2 + c_1 c_2)^2]} \\ &\quad \times [-(m_1 + m_2) l_1^2 x_2^2 + m_2 l_1 l_2 (s_1 s_2 + c_1 c_2) x_4^2] \\ &\quad + \frac{1}{l_1 l_2 [(m_1 + m_2) - m_2 (s_1 s_2 + c_1 c_2)^2]} \\ &\quad \times [-(m_1 + m_2) l_1 g s_1 (s_1 s_2 + c_1 c_2) \\ &\quad + (m_1 + m_2) l_1 g s_2], \\ g_{11}(x) &= \frac{m_2 l_2^2}{m_2 l_1^2 l_2^2 [(m_1 + m_2) - m_2 (s_1 s_2 + c_1 c_2)^2]}, \\ g_{12}(x) &= \frac{-m_2 l_1 l_2 (s_1 s_2 + c_1 c_2)}{m_2 l_1^2 l_2^2 [(m_1 + m_2) - m_2 (s_1 s_2 + c_1 c_2)^2]}, \\ g_{21}(x) &= \frac{-m_2 l_1 l_2 (s_1 s_2 + c_1 c_2)}{m_2 l_1^2 l_2^2 [(m_1 + m_2) - m_2 (s_1 s_2 + c_1 c_2)^2]}, \\ g_{22}(x) &= \frac{(m_1 + m_2) l_1^2}{m_2 l_1^2 l_2^2 [(m_1 + m_2) - m_2 (s_1 s_2 + c_1 c_2)^2]}. \end{aligned}$$

Note that the time variable t is omitted in the above equations for brevity.

B. Fuzzy Model

The above described robotic manipulator is a nonlinear system. To deal with the controller design problem for the nonlinear system, the Takagi-Sugeno (T-S) fuzzy model is employed to represent the nonlinear system with input delay as follows:

Plant rule i

IF $\theta_1(t)$ is $N_{i1} \dots \theta_p(t)$ is N_{ip} THEN

$$\dot{x}(t) = A_i x(t) + B_i u(t - \tau),$$

$$x(0) = x_0, u(t) = \varphi(t), t \in [-\bar{\tau}, 0], i = 1, 2, \dots, k \quad (3)$$

where N_{ij} is a fuzzy set, $\theta = [\theta_1(t), \dots, \theta_p(t)]^T$ are the premise variables, $x(t) \in \mathbf{R}^n$ is the state vector, and $u(t) \in \mathbf{R}^m$ is the control input, $A_i \in \mathbf{R}^{n \times n}$ and $B_i \in \mathbf{R}^{n \times m}$ are constant matrices. Scalar k is the number of IF-THEN rules. It is assumed that the premise control variables do not depend on the input $u(t)$. The input delay τ is an unknown constant time-delay, and the constant $\bar{\tau} > 0$ is an upper bound of τ .

Given a pair of $(x(t), u(t))$, the final output of the fuzzy system is inferred as follows

$$\dot{x}(t) = \sum_{i=1}^k h_i(\theta(t)) (A_i x(t) + B_i u(t - \tau)), \quad (4)$$

$$x(0) = x_0, u(t) = \varphi(t), t \in [-\bar{\tau}, 0],$$

where

$$h_i(\theta(t)) = \frac{\mu_i(\theta(t))}{\sum_{i=1}^k \mu_i(\theta(t))}, \mu_i(\theta_j(t)) = \prod_{j=1}^p N_{ij}(\theta_j(t))$$

and $N_{ij}(\theta_j(t))$ is the degree of the membership of $\theta_j(t)$ in N_{ij} . In this paper, we assume that $\mu_i(\theta_j(t)) \geq 0$ for $i = 1, 2, \dots, k$ and $\sum_{i=1}^k \mu_i(\theta(t)) > 0$ for all t . Therefore, $h_i(\theta(t)) \geq 0$ for $i = 1, 2, \dots, k$ and $\sum_{i=1}^k h_i(\theta(t)) = 1$.

For (4), based on the parallel distributed compensation (PDC) strategy, the following fuzzy control law is employed to deal with the problem of stability control via state feedback

Control rule i

IF $\theta_1(t)$ is $N_{i1} \dots \theta_p(t)$ is N_{ip} THEN

$$u(t) = K_i x(t), i = 1, 2, \dots, k, \quad (5)$$

Hence, the overall fuzzy control law is represented by

$$u(t) = \sum_{i=1}^k h_i(\theta(t)) K_i x(t),$$

where K_i , $i = 1, 2, \dots, k$, are the local control gains. When there exists an input delay τ , we have that $u(t - \tau) = \sum_{i=1}^k h_i(\theta(t - \tau)) K_i x(t - \tau)$, so, it is natural and necessary to make an assumption that the functions $h_i(\theta(t))$, $i = 1, 2, \dots, k$, are well defined for all $t \in [-\tau, 0]$, and satisfy the following properties $h_i(\theta(t - \tau)) \geq 0$ for $i = 1, 2, \dots, k$ and $\sum_{i=1}^k h_i(\theta(t - \tau)) = 1$. For convenience, let $h_i = h_i(\theta(t))$, $h_i(\tau) = h_i(\theta(t - \tau))$, $x(\tau) = x(t - \tau)$, and $u(\tau) = u(t - \tau)$.

The objective of the fuzzy controller design is to determine the feedback gains K_i ($i = 1, 2, \dots, k$) such that the resulting closed-loop system is asymptotically stable with the decay rate $\alpha > 0$. With the control law (5), the overall closed-loop system can be expressed as follows

$$\dot{x}(t) = \sum_{i,j=1}^k h_i h_j(\tau) (A_i x + B_i K_j x(\tau)). \quad (6)$$

To derive the conditions for designing such a controller, the following lemma will be used.

Lemma 1: [7] For any constant matrices $S_{11} \geq 0$, $S_{22} \geq 0$, S_{12} , $\begin{bmatrix} S_{11} & S_{12} \\ * & S_{22} \end{bmatrix} \geq 0$, scalar $\tau \leq \bar{\tau}$, and vector function $\dot{x}: [-\bar{\tau}, 0] \rightarrow \mathbb{R}^n$ such that the following integration is well defined, then

$$\begin{aligned} & -\bar{\tau} \int_{t-\bar{\tau}}^t [x^T(s), \dot{x}^T(s)] \begin{bmatrix} S_{11} & S_{12} \\ * & S_{22} \end{bmatrix} \begin{bmatrix} x(s) \\ \dot{x}(s) \end{bmatrix} ds \\ & \leq \begin{bmatrix} x \\ x(\tau) \\ \int_{t-\bar{\tau}}^t x(s) ds \end{bmatrix}^T \begin{bmatrix} -S_{22} & S_{22} & -S_{12}^T \\ S_{22} & -S_{22} & S_{12}^T \\ -S_{12} & S_{12} & -S_{11} \end{bmatrix} \\ & \begin{bmatrix} x \\ x(\tau) \\ \int_{t-\bar{\tau}}^t x(s) ds \end{bmatrix}. \end{aligned}$$

III. STABILITY CONTROLLER DESIGN

Choose a delay-dependent Lyapunov-Krasovskii functional candidate as

$$V = x^T P x + \bar{\tau} \int_{t-\bar{\tau}}^t e^{2\alpha(s-t)} (s - (t - \bar{\tau})) \eta^T(s) S \eta(s) ds,$$

where $\eta(s) = \begin{bmatrix} x^T(s) & \dot{x}^T(s) \end{bmatrix}^T$, $P > 0$, $S = \begin{bmatrix} S_{11} & S_{12} \\ * & S_{22} \end{bmatrix}$, $S_{11} > 0$, $S_{22} > 0$, $\begin{bmatrix} S_{11} & S_{12} \\ * & S_{22} \end{bmatrix} > 0$.

The derivative of V along the trajectory of (6) satisfies that

$$\begin{aligned} \dot{V} &= 2x^T P \dot{x} + \bar{\tau}^2 \eta^T S \eta \\ &\quad - \bar{\tau} \int_{t-\bar{\tau}}^t e^{2\alpha(s-t)} \eta^T(s) S \eta(s) ds \\ &\quad - 2\alpha \bar{\tau} \int_{t-\bar{\tau}}^t e^{2\alpha(s-t)} (s - (t - \bar{\tau})) \eta^T(s) S \eta(s) ds \\ &= -2\alpha(V - x^T P x) + 2x^T P \dot{x} + \bar{\tau}^2 \eta^T S \eta \\ &\quad - \bar{\tau} \int_{t-\bar{\tau}}^t e^{2\alpha(s-t)} \eta^T(s) S \eta(s) ds \\ &\leq -2\alpha(V - x^T P x) + 2x^T P \dot{x} + \bar{\tau}^2 \eta^T S \eta \\ &\quad - \bar{\tau} e^{-2\alpha\bar{\tau}} \int_{t-\bar{\tau}}^t \eta^T(s) S \eta(s) ds. \end{aligned}$$

If follows from (6) that

$$0 = 2 \left[x^T T_1 + x^T(\tau) T_2 + \dot{x}^T T_3 \right] \left(\sum_{i,j=1}^k h_i h_j(\tau) (A_i x + B_i K_j x(\tau)) - \dot{x} \right)$$

i.e.,

$$\begin{aligned} 0 &= 2 \sum_{i,j=1}^k h_i h_j(\tau) \begin{bmatrix} x^T & x^T(\tau) & \dot{x}^T \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \\ &\quad \begin{bmatrix} A_i & B_i K_j & -I \end{bmatrix} \begin{bmatrix} x \\ x(\tau) \\ \dot{x} \end{bmatrix} \\ &= \sum_{i,j=1}^k h_i h_j(\tau) \begin{bmatrix} x^T & x^T(\tau) & \dot{x}^T \end{bmatrix} \\ &\quad \left(\begin{bmatrix} T_1 A_i & T_1 B_i K_j & -T_1 \\ T_2 A_i & T_2 B_i K_j & -T_2 \\ T_3 A_i & T_3 B_i K_j & -T_3 \end{bmatrix} + \begin{bmatrix} T_1 A_i & T_1 B_i K_j & -T_1 \\ T_2 A_i & T_2 B_i K_j & -T_2 \\ T_3 A_i & T_3 B_i K_j & -T_3 \end{bmatrix}^T \right) \begin{bmatrix} x \\ x(\tau) \\ \dot{x} \end{bmatrix} \\ &= \sum_{i,j=1}^k h_i h_j(\tau) \begin{bmatrix} x^T & x^T(\tau) & \dot{x}^T \end{bmatrix} \end{aligned}$$

$$\begin{bmatrix} T_1 A_i & T_1 B_i K_j & -T_1 \\ +A_i^T T_1^T & +A_i^T T_2^T & +A_i^T T_3^T \\ T_2 A_i & T_2 B_i K_j & -T_2 \\ +K_j^T B_i^T T_1^T & +K_j^T B_i^T T_2^T & +K_j^T B_i^T T_3^T \\ T_3 A_i & T_3 B_i K_j & -T_3 \\ -T_1^T & -T_2^T & -T_3^T \end{bmatrix} \begin{bmatrix} x \\ x(\tau) \\ \dot{x} \end{bmatrix},$$

where the property $\sum_{i,j=1}^k h_i h_j(\tau) = 1$ is applied.

By the above equality and Lemma 1, it is obtained that

$$\begin{aligned} \dot{V} &\leq -2\alpha(V - x^T P x) + 2x^T P \dot{x} \\ &+ \bar{\tau}^2 \begin{bmatrix} x^T & \dot{x}^T \end{bmatrix} \begin{bmatrix} S_{11} & S_{12} \\ * & S_{22} \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} \\ &+ e^{-2\alpha\bar{\tau}} \begin{bmatrix} x \\ x(\tau) \\ \int_{t-\bar{\tau}}^t x(s) ds \end{bmatrix}^T \begin{bmatrix} -S_{22} & S_{22} & -S_{12}^T \\ S_{22} & -S_{22} & S_{12}^T \\ -S_{12} & S_{12} & -S_{11} \end{bmatrix} \begin{bmatrix} x \\ x(\tau) \\ \int_{t-\bar{\tau}}^t x(s) ds \end{bmatrix} \\ &+ 2 \sum_{i,j=1}^k h_i h_j(\tau) \begin{bmatrix} x^T & x^T(\tau) & \dot{x}^T \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \\ &\begin{bmatrix} A_i & B_i K_j & -I \end{bmatrix} \begin{bmatrix} x \\ x(\tau) \\ \dot{x} \end{bmatrix} \\ &= -2\alpha V + \sum_{i,j=1}^k h_i h_j(\tau) \xi^T \Sigma_{ij} \xi, \end{aligned}$$

where $\xi^T = \begin{bmatrix} x^T & x^T(\tau) & (\int_{t-\bar{\tau}}^t x(s) ds)^T & \dot{x}^T \end{bmatrix}$ and

$$\Sigma_{ij} = \begin{bmatrix} \bar{\tau}^2 \hat{S}_{11} & \hat{S}_{22} & P+ & \bar{\tau}^2 \hat{S}_{12} \\ -\hat{S}_{22} & \hat{S}_{22} & -T_1 + & -T_1 + \\ +T_1 A_i & +T_1 B_i K_j & -S_{12}^T & A_i^T T_3^T \\ +A_i^T T_1^T & +A_i^T T_2^T & A_i^T T_3^T & \\ +2\alpha P & & & \\ * & -\hat{S}_{22} + & \hat{S}_{12}^T & K_j^T B_i^T T_3^T \\ & T_2 B_i K_j + & -T_2 & \\ & K_j^T B_i^T T_2^T & -S_{11} & 0 \\ * & * & -S_{11} & \bar{\tau}^2 \hat{S}_{22} \\ * & * & * & -T_3^T \\ & & & -T_3 \end{bmatrix} \quad (8)$$

where $\hat{S}_{11} = e^{-2\alpha\bar{\tau}} S_{11}$, $\hat{S}_{12} = e^{-2\alpha\bar{\tau}} S_{12}$, $\hat{S}_{22} = e^{-2\alpha\bar{\tau}} S_{22}$. It can be seen that if $\Sigma_{ij} < 0$, then $\dot{V} + 2\alpha V < 0$ can be deduced from (7) and $V(x) < V(x_0)e^{-2\alpha t}$ can be established. Therefore, the closed-loop system (6) is asymptotically stable with decay rate α .

By denoting $T_2 = d_2 T_1$, $T_3 = d_3 T_1$, where d_2 and d_3 are given constants, pre and post-multiplying both side of (8)

with $\text{diag}[Q \ Q \ Q \ Q]$ and their transpose, defining new variables $Q = T_1^{-1}$, $\bar{S}_{11} = Q \hat{S}_{11} Q^T$, $\bar{S}_{12} = Q \hat{S}_{12} Q^T$, $\bar{S}_{22} = Q \hat{S}_{22} Q^T$, $\bar{P} = Q P Q^T$, and $\bar{K}_j = K_j Q^T$, $\Sigma_{ij} < 0$ is equivalent to $\Xi_{ij} < 0$ where

$$\Xi_{ij} = \begin{bmatrix} \bar{\tau}^2 \bar{S}_{11} & \bar{S}_{22} + & \bar{P} + & \bar{\tau}^2 \bar{S}_{12} \\ -\bar{S}_{22} & \bar{S}_{22} + & -\bar{S}_{12}^T & -Q^T + \\ +A_i Q^T & B_i \bar{K}_j + & d_2 Q A_i^T & d_2 Q A_i^T \\ +2\alpha P & d_2 Q A_i^T & d_2 Q A_i^T & \\ * & -\bar{S}_{22} + & \bar{S}_{12}^T & d_3 \bar{K}_j^T B_i^T \\ & d_2 B_i \bar{K}_j + & -\bar{S}_{11} & 0 \\ * & d_2 K_j^T B_i^T & * & \bar{\tau}^2 \bar{S}_{22} \\ * & * & * & -d_3 Q \\ & & & -d_3 Q^T \end{bmatrix}$$

In summary, given $\bar{\tau}$, d_2 , and d_3 , the closed-loop system (6) is asymptotically stable for any $0 \leq \tau \leq \bar{\tau}$ with decay rate α via PDC technique if there exist $\bar{P} > 0$, $\bar{S}_{11} > 0$, $\bar{S}_{22} > 0$ and real matrices Q , $\bar{S}_{12}$, $\bar{K}_j$ ($j=1, \dots, r$) satisfying LMIs

$$\Xi_{ii} < 0, \quad (9)$$

$$\Xi_{ij} + \Xi_{ji} < 0, \quad (10)$$

$$\begin{bmatrix} \bar{S}_{11} & \bar{S}_{12} \\ * & \bar{S}_{22} \end{bmatrix} \geq 0. \quad (11)$$

Moreover, the control gain matrix is given by

$$K_j = \bar{K}_j (Q^T)^{-1}.$$

IV. NUMERICAL SIMULATIONS

(7) Take two-link robotic manipulator as an example, the T-S fuzzy model with nine rules can be used to represent the original nonlinear system with acceptable accuracy when link mass $m_1 = m_2 = 1$ (kg), link length $l_1 = l_2 = 1$ (m), and angular position are constrained within $[-\pi/2, \pi/2]$. Triangle type membership functions are used for all the rules. For more details on the T-S fuzzy model, readers can refer to [8] for details.

In the reference [9], to reduce the complexity caused by the number of fuzzy rules, a region based rule reduction approach was proposed and the simplest case was obtained with one rule, which is regarded as a robust controller and the design result for a decay rate 0.5 was given as

$$K = \begin{bmatrix} -115.6439 & -49.9782 & -13.4219 & -3.7453 \\ 14.6547 & -3.4203 & -62.7788 & -22.1846 \end{bmatrix} \quad (12)$$

For comparison purpose, we call this controller as controller I. The simulation results for the nonlinear model (2) with initial condition $x(0) = [1.2, 0, -1.2, 0]^T$ and controller I without input delays are shown in Fig. 2.

It can be seen from Fig. 2 that all the state variables converge to equilibrium states from initial conditions quickly. We now introduce input delays to the two control inputs. As an example, input delays for both control

Fig. 2. State responses for controller I without input delays.

inputs are given as 24 ms. The simulation results for all state variables are shown in Fig. 3.

It is observed that the state variables do not converge to equilibrium states in this case and controller I is not able to stabilise the system when input time delays are given as 24 ms.

We now design a fuzzy controller using the proposed approach. For given $\bar{\tau} = 30$ ms, $d_2 = 0.1$, $d_3 = 0.1$, and $\alpha = 3.5$, the LMIs are feasible to find a solution, and the controller gain matrices for nine rules are given as

$$K_{fr1} = \begin{bmatrix} -67.4380 & -18.2681 & -30.4026 & -8.7744 \\ -29.4171 & -8.9634 & -32.9427 & -9.2487 \end{bmatrix}$$

$$K_{fr2} = \begin{bmatrix} -87.0516 & -23.3088 & -1.4633 & -0.5275 \\ -0.9148 & -0.3282 & -47.8832 & -13.5136 \end{bmatrix}$$

$$K_{fr3} = \begin{bmatrix} -69.1222 & -18.0397 & 30.5473 & 8.6986 \\ 31.2782 & 8.9476 & -30.1957 & -8.9625 \end{bmatrix}$$

$$K_{fr4} = \begin{bmatrix} -90.4670 & -23.5990 & -1.8147 & -0.3720 \\ 3.0053 & -0.1332 & -49.6101 & -13.6206 \end{bmatrix}$$

$$K_{fr5} = \begin{bmatrix} -73.1466 & -18.5434 & -29.1527 & -8.5766 \\ -28.4457 & -8.7684 & -36.0507 & -9.3679 \end{bmatrix}$$

$$K_{fr6} = \begin{bmatrix} -89.9913 & -23.5249 & -2.3335 & -0.4322 \\ 2.4136 & -0.2087 & -49.1740 & -13.5866 \end{bmatrix}$$

$$K_{fr7} = \begin{bmatrix} -69.0524 & -18.0351 & 30.4202 & 8.7214 \\ 31.4674 & 8.9693 & -30.2271 & -8.9684 \end{bmatrix}$$

Fig. 3. State responses for controller I with input delays as 24 ms.

$$K_{fr8} = \begin{bmatrix} -87.5553 & -23.3314 & -1.3496 & -0.5150 \\ -0.3352 & -0.2884 & -48.1256 & -13.5236 \end{bmatrix}$$

$$K_{fr9} = \begin{bmatrix} -68.1110 & -18.3855 & -30.1155 & -8.6420 \\ -28.8416 & -8.8628 & -33.3088 & -9.3470 \end{bmatrix}$$

For simplicity, we denote this controller as controller II. The simulation results for the nonlinear model (2) with controller II with input delays as 30 ms under the same initial condition are shown in Fig. 4.

It can be seen from Fig. 4 that all the state variables can quickly converge to equilibrium states from their initial conditions even when the input time delays (30 ms) exist. In fact, from numerical simulations, it can observe that when input delays are larger than the designed 30 ms to some extent, controller II can also stabilise the system responses. It shows that the presented approach still has space to further reduce its conservativeness, this, however, is beyond the scope of this paper.

The above designed controller II is a nine rules fuzzy controller. Although it can stabilise the system with a bigger input delays, its complexity in implementation can also be observed. To reduce this complexity, reference [9] proposed a region based controller design concept. Following the similar idea, a robust controller which uses only one rule and considers the fuzzy model as a polytopic uncertain model can also be designed using the presented conditions (9)-(11). For given $\bar{\tau} = 30$ ms,

Fig. 4. State responses for controller II with input delays as 30 ms.

$d_2 = 0.06$, $d_3 = 0.04$, and $\alpha = 2$, the LMIs (9)-(11) are feasible to find a solution, and the controller gain matrix is given as

$$K_f = \begin{bmatrix} -51.6925 & -17.9993 & -2.7943 & -0.6520 \\ 1.6673 & -0.4347 & -26.2372 & -9.5655 \end{bmatrix}$$

For simplicity, this controller is called controller III and the simulation results are shown in Fig. 5 when input delays are given as 30 ms. It is seen that all the state variables converge to equilibrium states. Similarly, controller III can stabilise the system responses even when input delays are larger than 30 ms to some extent in spite of its simplicity in structure. Both controller II and controller III prove that the proposed controller design approach is effective in designing a controller for robotic manipulator with bigger input delays.

V. CONCLUSIONS

A delay-dependent fuzzy controller with decay rate constraint is designed for a robotic manipulator. Based on the recently proposed techniques in constructing a Lyapunov-Krasovskii functional and using a tighter bounding technology for cross terms and the free weighting matrix approach, the conservatism in deriving the conditions is reduced. Numerical simulations on a two-link robotic manipulator is used to validate the effectiveness of the proposed approach. It can be seen that for some given parameters, the presented LMIs conditions

Fig. 5. State responses for controller III with input delays as 30 ms.

are feasible in finding a controller such that the system is stable under given input delays. In addition, the presented conditions can be used to design both a fuzzy controller with full rules and a so-called robust controller with only one rule.

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2010 IEEE International Conference on Robotics and Biomimetics

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**December 14-18, 2010
Tianjin, China**

IEEE Catalog Number: CFP10581-CDR
ISBN: 978-1-4244-9317-3

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