Decentralized Adaptive Fuzzy Control for Reconfigurable Manipulators

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Abstract —**A decentralized adaptive fuzzy control scheme for reconfigurable manipulators is proposed to satisfy the concept of modular software. The dynamics of reconfigurable manipulators is represented as a set of interconnected subsystems. The fuzzy logic systems are used to model the unknown dynamics of subsystem and the interconnection term. Based on Lyapunov stability theorem, the stability of the closed-loop systems can be verified. Moreover, the proposed control scheme guarantees that variables involved are bounded and the H^{∞} tracking performance is achieved. The simulation results are presented to show the effectiveness of the proposed decentralized adaptive fuzzy control scheme.**

Keywords—**reconfigurable manipulators, decentralized control, fuzzy control, adaptive control, H^{∞} optimal control.**

I. INTRODUCTION

A reconfigurable manipulator consists of interchangeable link and joint modules with standardized connecting interfaces. It can be easily assembled and disassembled, so it can accomplish a larger number of classes of tasks through the reconfiguration of a small inventory of modules [1]. Compared with conventional manipulators with fixed configuration, reconfigurable manipulators can be adapted to diverse task requirements and take advantage of low cost, easy maintenance, convenient modification, portability and durability against system malfunctions [2].

In recent literatures, some control schemes of reconfigurable manipulators were proposed. In [3], a neurofuzzy hierarchical control architecture was proposed for modular and reconfigurable robots, which used a learning control to compensate the unmodeled system dynamics due to reconfiguration. The adaptive control parameters were updated using a skill module that was a part of the higher level of the control system hierarchy. In [4], a joystick based interactive motion control approach was presented for modular and reconfigurable manipulators. Two different control modes, velocity control mode and incremental displacement control mode, were proposed. In [5], a computing torque control based neurofuzzy compensator was developed for reconfigurable manipulators to cancel modeled and unmodeled uncertainty. All those methods have been concentrated on the centralized control. For practical purposes, a centralized controller designed on the basis of an entire system may not be applicable for a robot system due to the high computation costs, robustness, and complexities. Compared with centralized control, decentralized control scheme attempts to avoid difficulties in complexity of controller design, debugging, data gathering, and storage requirements. Due to this reason, an effort on developing advanced control schemes based on a decentralized control system structure has never been stopped [6-10].

Recently, adaptive fuzzy control system designs have been extensively discussed in the literature. Based on the approximation property of the fuzzy systems, a stable adaptive fuzzy control scheme was proposed in [11] for a class of SISO nonlinear systems with completely unknown functions. The stability problem of uncertain MIMO nonlinear systems was solved in [12] by designing corresponding adaptive fuzzy controller. A new approach combining computed torque control and fuzzy control was developed in [13] for trajectory tracking problems of robotic manipulators with structured and unstructured uncertainty. A decentralized adaptive fuzzy controller was designed in [14] for uncertain interconnected time-delay systems. In such schemes, the stability of the closed-loop system was established according to Lyapunov theory. To cope with approximation errors and external disturbances, these adaptive fuzzy controllers were augmented by a robust compensator. The major advantages in the fuzzy-based control schemes are that the developed controllers can be employed to deal with increasingly complex systems, to avoid the computation of the complicated regressor matrix, and to implement the controller without any precise knowledge of the structure of the entire dynamical model.

In this paper, a decentralized adaptive fuzzy control scheme of reconfigurable manipulators with unknown dynamics is proposed for the trajectory tracking problems. The controller of reconfigurable manipulators is considered as a decentralized computing network, in which joint modules are considered as corresponding computing nodes. Each node uses the fuzzy logic systems to approximate subsystem dynamical model and cancel the effects of interconnection term on each subsystem resulted from decomposing the overall reconfigurable manipulator system into multiple small scale mechanical systems. All adaptive algorithms in the subsystem controller are derived from the sense of Lyapunov stability analysis, so that the resulting closed-loop system is stable and the trajectory tracking performance is guaranteed. No reconfiguration parameters are modified in this control scheme, so it can be applicable to all the configurations of reconfigurable manipulators.

II. PROBLEM FORMULATION

According to the Lagrangian formulation [15], the dynamics of a reconfigurable manipulator with n degree of freedom can be written as

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

where $q \in R^n$ is the vector of joint displacements, $M(q) \in R^{n\times n}$ the inertia matrix, $C(q,\dot{q})\dot{q} \in R^n$ the Coriolis and centripetal force, $G(q) \in R^n$ the gravity term, and $u \in R^n$ the applied joint torque.

For the development of the decentralized control, each joint is considered as a subsystem of the entire manipulator system interconnected by coupling torques. By separating terms depending only on local variables $(q_i, \dot{q}_i, \ddot{q}_i)$ from those terms of other joint variables, each subsystem dynamical model can be formulated in joint space as [10]

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + G_i(q_i) + Z_i(q,\dot{q},\ddot{q}) = u_i \tag{2}$$

with

$$\begin{aligned} Z_i(q,\dot{q},\ddot{q}) = & \left\{ \sum_{j=1, j\neq i}^{n} M_{ij}(q)\ddot{q}_j + [M_{ii}(q) - M_i(q_i)]\ddot{q}_i \right\} \\ & + \left\{ \sum_{j=1, j\neq i}^{n} C_{ij}(q,\dot{q})\dot{q}_j + [C_{ii}(q,\dot{q}) - C_i(q_i,\dot{q}_i)]\dot{q}_i \right\} \\ & + [\overline{G}_i(q) - G_i(q_i)] \end{aligned} \tag{3}$$

where q_i, $\dot{q}_i$, $\ddot{q}_i$, $\overline{G}_i(q)$ and u_i are the ith element of the vectors q, $\dot{q}$, $\ddot{q}$, $G(q)$ and u, respectively. $M_{ij}(q)$ and $C_{ij}(q,\dot{q})$ are the ijth element of the matrices $M(q)$ and $C(q,\dot{q})$, respectively.

Let

$$x_i = \begin{bmatrix} q_i \\ \dot{q}_i \end{bmatrix} \quad (i = 1,2,\cdots,n) \tag{4}$$

Each subsystem motion equation may be presented by the following state equation

$$S_i : \begin{cases} \dot{x}_i = A_i x_i + B_i[f_i(q_i,\dot{q}_i) + g_i(q_i)u_i + h_i(q,\dot{q},\ddot{q})] \\ y_i = C_i x_i \end{cases} \tag{5}$$

where x_i is the state vector of subsystem S_i, y_i is the output of subsystem S_i, and

$$A_i = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \quad B_i = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad C_i = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

$$f_i(q_i,\dot{q}_i) = M_i^{-1}(q_i)[-C_i(q_i,\dot{q}_i)\dot{q}_i - G_i(q_i)]$$

$$g_i(q_i) = M_i^{-1}(q_i)$$

$$h_i(q,\dot{q},\ddot{q}) = -M_i^{-1}(q_i)Z_i(q,\dot{q},\ddot{q})$$

The control objective is to design decentralized adaptive fuzzy control laws for (2) to make the reconfigurable manipulators follow a desired trajectory y_{ir}, guarantee boundedness of all variables of the closed-loop system and achieve the H^∞ tracking performance.

III. DESIGN OF DECENTRALIZED ADAPTIVE FUZZY CONTROLLER

Define the tracking error of the ith subsystem as $e_{i0} = y_i - y_{ir}$. Then, the error vector of the ith subsystem is given by $e_i = [e_{i0}, \dot{e}_{i0}]^T$, and that of the whole system is given by $e = [e_1^T, e_2^T, \cdots, e_n^T]^T$.

Assumption 1: The desired trajectories y_{ir}, $\dot{y}_{ir}$ and $\ddot{y}_{ir}$ are bounded.

The tracking error dynamics can be expressed as

$$\dot{e}_i = A_i e_i + B_i[f_i(q_i,\dot{q}_i) + g_i(q_i)u_i + h_i(q,\dot{q},\ddot{q}) - \ddot{y}_{ir}] \tag{6}$$

which can be rewritten as

$$\begin{aligned} \dot{e}_i = & \Lambda_i e_i + B_i[f_i(q_i,\dot{q}_i) + g_i(q_i)u_i \\ & + h_i(q,\dot{q},\ddot{q}) - \ddot{y}_{ir} + K_i^T e_i] \end{aligned} \tag{7}$$

where $\Lambda_i = A_i - B_i K_i^T$, $K_i^T = [k_{i1} \quad k_{i2}]$ is a gain vector of the ith subsystem.

It is clear that if $f_i(q_i,\dot{q}_i)$, $g_i(q_i)$ are available, and $h_i(q,\dot{q},\ddot{q}) = 0$, then using the feedback linearization technique leads us to obtain the following ideal control law for ith subsystem

$$u_i = [-f_i(q_i,\dot{q}_i) - K_i^T e_i + \ddot{y}_{ir}] / g_i(q_i) \tag{8}$$

Substituting (8) into (7) gives

$$\ddot{e}_{i0} + k_{i2}\dot{e}_{i0} + k_{i1}e_{i0} = 0 \tag{9}$$

If the control gain K_i is properly chosen such that the characteristic polynomial of (9) is strictly Hurwitz, that is a polynomial whose roots lie strictly in the open left half of the complex plane, it implies that $\lim_{t\to\infty} e_{i0} = 0$ meaning that the closed-loop system is asymptotically stable. However, for a reconfigurable manipulator with many possible configurations, finding the necessary dynamical model would be impractical. Therefore, the fuzzy logic systems $\hat{f}_i(q_i,\dot{q}_i,\theta_{if})$ and $\hat{g}_i(q_i,\theta_{ig})$ are proposed to approximate the unknown terms $f_i(q_i,\dot{q}_i)$ and $g_i(q_i)$.

$$\hat{f}_i(q_i,\dot{q}_i,\theta_{if}) = \theta_{if}^T \xi_{if}(q_i,\dot{q}_i) \tag{10}$$

$$\hat{g}_i(q_i,\theta_{ig}) = \theta_{ig}^T \xi_{ig}(q_i) \tag{11}$$

where θ_{if} and θ_{ig} are adjustable parameter vectors, $\xi_{if}(q_i,\dot{q}_i)$ and $\xi_{ig}(q_i)$ are fuzzy basis function vectors.

Next, the fuzzy logic system $\hat{p}_i(|e_i^T P_i B_i|, \theta_{ip})$ is proposed to compensate the interconnection term. The fuzzy system $\hat{p}_i(|e_i^T P_i B_i|, \theta_{ip})$ can be expressed as

$$\hat{p}_i(|e_i^T P_i B_i|, \theta_{ip}) = \theta_{ip}^T \xi_{ip}(|e_i^T P_i B_i|) \tag{12}$$

where θ_{ip} is adjustable parameter vector, $\xi_{ip}(|e_i^T P_i B_i|)$ is fuzzy basis function vector, and matrix $P_i = P_i^T > 0$ will be defined later.

Assumption 2: The interconnection term $h_i(q,\dot{q},\ddot{q})$ is bounded by

$$\left|h_i(q,\dot{q},\ddot{q})\right| \le \sum_{j=1}^{n} d_{ij}E_j \tag{13}$$

where $d_{ij} \ge 0$, $E_j = 1+\left|e_j^T P_j B_j\right| + \left|e_j^T P_j B_j\right|^2$.

The decentralized controller is now designed as

$$\begin{aligned} u_i = [&-\mathrm{sgn}(e_i^T P_i B_i)\hat{p}_i(\left|e_i^T P_i B_i\right|,\theta_{ip}) \\ &-\hat{f}_i(q_i,\dot{q}_i,\theta_{if}) - K_i^T e_i + \ddot{y}_{ir} + u_{ia}]/\hat{g}_i(q_i,\theta_{ig}) \end{aligned} \tag{14}$$

Our design objective involves specifying the control term u_{ia} and adaptive laws for θ_{if}, θ_{ig} and θ_{ip} so that the H^∞ tracking performance is achieved. In meantime the interconnection term and the fuzzy approximation error are compensated.

Substituting (14) into (7), adding $\hat{g}_i(q_i,\theta_{ig})u_i$ and then subtracting $\hat{g}_i(q_i,\theta_{ig})u_i$ on the right-hand side of (7), one can obtain the following error equation

$$\begin{aligned} \dot{e}_i = \Lambda_i e_i + B_i \{&[f_i(q_i,\dot{q}_i) - \hat{f}_i(q_i,\dot{q}_i,\theta_{if})] \\ &+ [g_i(q_i) - \hat{g}_i(q_i,\theta_{ig})]u_i + h_i(q,\dot{q},\ddot{q}) \\ &- \mathrm{sgn}(e_i^T P_i B_i)\hat{p}_i(\left|e_i^T P_i B_i\right|,\theta_{ip}) + u_{ia}\} \end{aligned} \tag{15}$$

Define the optimal parameter vectors as

$$\theta_{if}^* = \arg\min_{\theta_{if}\in\Omega_{if}} \left\{ \sup_{x_i\in U_{if}} |\hat{f}_i(q_i,\dot{q}_i,\theta_{if}) - f_i(q_i,\dot{q}_i)| \right\} \tag{16}$$

$$\theta_{ig}^* = \arg\min_{\theta_{ig}\in\Omega_{ig}} \left\{ \sup_{q_i\in U_{ig}} |\hat{g}_i(q_i,\theta_{ig}) - g_i(q_i)| \right\} \tag{17}$$

$$\theta_{ip}^* = \arg\min_{\theta_{ip}\in\Omega_{ip}} \left\{ \sup_{e_i\in U_{ip}} |\hat{p}_i(\left|e_i^T P_i B_i\right|,\theta_{ip}) - p_i(\left|e_i^T P_i B_i\right|)| \right\} \tag{18}$$

where $p_i(\left|e_i^T P_i B_i\right|) = n\max_{ij}\{d_{ij}\}E_i$ depends on the interconnection strength, Ω_{if}, Ω_{ig}, Ω_{ip}, U_{if}, U_{ig}, and U_{ip} denote the sets of suitable bounds on θ_{if}, θ_{ig}, θ_{ip}, x_i, q_i, and e_i respectively. Assume that θ_{if}, θ_{ig}, θ_{ip}, x_i, q_i, and e_i never reach the boundary of Ω_{if}, Ω_{ig}, Ω_{ip}, U_{if}, U_{ig}, and U_{ip}. Also the minimum approximation errors are defined as

$$w_{i1} = [f_i(q_i,\dot{q}_i) - \hat{f}_i(q_i,\dot{q}_i,\theta_{if}^*)] + [g_i(q_i) - \hat{g}_i(q_i,\theta_{ig}^*)]u_i \tag{19}$$

$$w_{i2} = p_i(\left|e_i^T P_i B_i\right|) - \hat{p}_i(\left|e_i^T P_i B_i\right|,\theta_{ip}^*) \tag{20}$$

Define approximation error

$$w_i = \left|w_{i1}\right| + \left|w_{i2}\right| \tag{21}$$

Assumption 3: The approximation error $w_i \in L_{2T}$, i.e. $\int_0^T w_i^2\,dt < \infty$.

Define the parameter error vectors of fuzzy systems as

$$\tilde{\theta}_{if} = \theta_{if}^* - \theta_{if} \tag{22}$$

$$\tilde{\theta}_{ig} = \theta_{ig}^* - \theta_{ig} \tag{23}$$

$$\tilde{\theta}_{ip} = \theta_{ip}^* - \theta_{ip} \tag{24}$$

Then the tracking error dynamics can be written as

$$\begin{aligned} \dot{e}_i = \Lambda_i e_i + B_i[&\tilde{\theta}_{if}^T\xi_{if}(q_i,\dot{q}_i) + \tilde{\theta}_{ig}^T\xi_{ig}(q_i)u_i + h_i(q,\dot{q},\ddot{q}) \\ &- \mathrm{sgn}(e_i^T P_i B_i)\hat{p}_i(\left|e_i^T P_i B_i\right|,\theta_{ip}) + u_{ia} + w_{i1}] \end{aligned} \tag{25}$$

Theorem: *Consider the subsystem* (2) *with assumptions 1-3, the decentralized adaptive fuzzy control is designed as* (14) *guarantees that all the variables of the closed-loop system are bounded and the* H^∞ *tracking performance is achieved provided that the auxiliary control part is given by*

$$u_{ia} = -B_i^T P_i e_i / r_i \tag{26}$$

With the adaptive laws

$$\dot{\theta}_{if} = \eta_{if} e_i^T P_i B_i \xi_{if}(q_i,\dot{q}_i) \tag{27}$$

$$\dot{\theta}_{ig} = \eta_{ig} e_i^T P_i B_i \xi_{ig}(q_i)u_i \tag{28}$$

$$\dot{\theta}_{ip} = \eta_{ip}\left|e_i^T P_i B_i\right|\xi_{ip}(\left|e_i^T P_i B_i\right|) \tag{29}$$

where η_{if}, η_{ig} *and* η_{ip} *are positive constants, and the matrix* $P_i = P_i^T > 0$ *is the solution of the following Riccati-like equation*

$$\Lambda_i^T P_i + P_i\Lambda_i - P_i B_i(2/r_i - 1/\rho^2)B_i^T P_i + Q_i = 0 \tag{30}$$

where $Q_i \in R^{2\times 2}$ *is an arbitrary positive definite matrix,* $\rho > 0$ *denotes a prescribed attenuation level of the approximation error,* $r_i > 0$ *is a weighting factor chosen such that* $r_i \le 2\rho^2$.

Proof: Consider the following Lyapunov function candidate $V = \sum_{i=1}^{n} V_i$.

where

$$V_i = e_i^T P_i e_i/2 + \tilde{\theta}_{if}^T\tilde{\theta}_{if}/(2\eta_{if}) + \tilde{\theta}_{ig}^T\tilde{\theta}_{ig}/(2\eta_{ig}) + \tilde{\theta}_{ip}^T\tilde{\theta}_{ip}/(2\eta_{ip}) \tag{31}$$

Differentiating (31) with respect to time, we get

$$\begin{aligned} \dot{V}_i = &\dot{e}_i^T P_i e_i/2 + e_i^T P_i \dot{e}_i/2 \\ &+ \tilde{\theta}_{if}^T\dot{\tilde{\theta}}_{if}/\eta_{if} + \tilde{\theta}_{ig}^T\dot{\tilde{\theta}}_{ig}/\eta_{ig} + \tilde{\theta}_{ip}^T\dot{\tilde{\theta}}_{ip}/\eta_{ip} \end{aligned} \tag{32}$$

Substituting (25) into (32), one can obtained

$$\begin{aligned} \dot{V}_i = [&e_i^T(\Lambda_i^T P_i + P_i\Lambda_i)e_i/2 + e_i^T P_i B_i u_{ia} + e_i^T P_i B_i w_{i1} \\ &+ \tilde{\theta}_{if}^T(e_i^T P_i B_i \xi_{if}(q_i,\dot{q}_i) - \dot{\theta}_{if}/\eta_{if}) \\ &+ \tilde{\theta}_{ig}^T(e_i^T P_i B_i \xi_{ig}(q_i)u_i - \dot{\theta}_{ig}/\eta_{ig}) + e_i^T P_i B_i h_i(q,\dot{q},\ddot{q}) \\ &- \left|e_i^T P_i B_i\right|\theta_{ip}^T\xi_{ip}(\left|e_i^T P_i B_i\right|) - \tilde{\theta}_{ip}^T\dot{\theta}_{ip}/\eta_{ip}] \end{aligned} \tag{33}$$

From (27) and (28), yields

$$\begin{aligned} \dot{V} \le &\sum_{i=1}^{n}[e_i^T(\Lambda_i^T P_i + P_i\Lambda_i)e_i/2 + e_i^T P_i B_i u_{ia} \\ &+ e_i^T P_i B_i w_{i1} + \left|e_i^T P_i B_i\right|\sum_{j=1}^{n} d_{ij}E_j \\ &- \left|e_i^T P_i B_i\right|\theta_{ip}^T\xi_{ip}(\left|e_i^T P_i B_i\right|) - \tilde{\theta}_{ip}^T\dot{\theta}_{ip}/\eta_{ip}] \\ \le &\sum_{i=1}^{n}[e_i^T(\Lambda_i^T P_i + P_i\Lambda_i)e_i/2 + e_i^T P_i B_i u_{ia} \\ &+ e_i^T P_i B_i w_{i1} - \left|e_i^T P_i B_i\right|\theta_{ip}^T\xi_{ip}(\left|e_i^T P_i B_i\right|) \\ &- \tilde{\theta}_{ip}^T\dot{\theta}_{ip}/\eta_{ip}] + \max_{ij}\{d_{ij}\}\sum_{i=1}^{n}\left|e_i^T P_i B_i\right|\sum_{j=1}^{n} E_j \end{aligned} \tag{34}$$

Notice that $\left|e_i^T P_i B_i\right| \le \left|e_j^T P_j B_j\right| \Leftrightarrow E_i \le E_j$, using Chebyshev inequality, one can obtain that

$$\sum_{i=1}^n \left|e_i^T P_i B_i\right| \sum_{j=1}^n E_j \le n \sum_{i=1}^n \left|e_i^T P_i B_i\right| E_i \tag{35}$$

Combining (34) and (35), we get

$$\begin{aligned} \dot V \le & \sum_{i=1}^n [e_i^T(\Lambda_i^T P_i + P_i\Lambda_i)e_i/2 + e_i^T P_i B_i u_{ia} \\ & - \left|e_i^T P_i B_i\right| \theta_{ip}^T \xi_{ip}(\left|e_i^T P_i B_i\right|) + e_i^T P_i B_i w_{i1} \\ & - \tilde\theta_{ip}^T \dot\theta_{ip}/\eta_{ip} + \left|e_i^T P_i B_i\right| n \max_{ij}\{d_{ij}\} E_i] \\ = & \sum_{i=1}^n [e_i^T(\Lambda_i^T P_i + P_i\Lambda_i)e_i/2 + e_i^T P_i B_i u_{ia} \\ & - \left|e_i^T P_i B_i\right| \theta_{ip}^T \xi_{ip}(\left|e_i^T P_i B_i\right|) + e_i^T P_i B_i w_{i1} \\ & - \tilde\theta_{ip}^T \dot\theta_{ip}/\eta_{ip} + \left|e_i^T P_i B_i\right| p_i(\left|e_i^T P_i B_i\right|)] \end{aligned} \tag{36}$$

Form (20) and (24), (36) becomes

$$\begin{aligned} \dot V \le & \sum_{i=1}^n [e_i^T(\Lambda_i^T P_i + P_i\Lambda_i)e_i/2 + e_i^T P_i B_i u_{ia} \\ & + e_i^T P_i B_i w_{i1} + \left|e_i^T P_i B_i\right| w_{i2} \\ & + \tilde\theta_{ip}^T(\left|e_i^T P_i B_i\right| \xi_{ip}(\left|e_i^T P_i B_i\right|) - \dot\theta_{ip}/\eta_{ip})] \end{aligned} \tag{37}$$

Using (21) and (29), yields

$$\begin{aligned} \dot V \le & \sum_{i=1}^n [e_i^T(\Lambda_i^T P_i + P_i\Lambda_i)e_i/2 + e_i^T P_i B_i u_{ia} \\ & + \left|e_i^T P_i B_i\right| \left|w_{i1}\right| + \left|e_i^T P_i B_i\right| \left|w_{i2}\right|] \\ = & \sum_{i=1}^n [e_i^T(\Lambda_i^T P_i + P_i\Lambda_i)e_i/2 + e_i^T P_i B_i u_{ia} \\ & + \left|e_i^T P_i B_i\right| w_i] \end{aligned} \tag{38}$$

Substituting (26) into (38), we have

$$\begin{aligned} \dot V \le & \sum_{i=1}^n [e_i^T(\Lambda_i^T P_i + P_i\Lambda_i - 2P_i B_i B_i^T P_i/r_i)e_i/2 \\ & + \left|e_i^T P_i B_i\right| w_i] \end{aligned} \tag{39}$$

From the Riccati-like equation (30), we get

$$\begin{aligned} \dot V \le & \sum_{i=1}^n [-e_i^T Q_i e_i/2 - e_i^T P_i B_i B_i^T P_i e_i/(2\rho^2) + \left|e_i^T P_i B_i\right| w_i] \\ = & \sum_{i=1}^n [-e_i^T Q_i e_i/2 - (\left|e_i^T P_i B_i\right|/\rho - \rho w_i)^2/2 + \rho^2 w_i^2/2] \\ \le & \sum_{i=1}^n [-e_i^T Q_i e_i/2 + \rho^2 w_i^2/2] \end{aligned} \tag{40}$$

Denoting $Q = diag(Q_1, Q_2, \cdots, Q_n)$, $w = [w_1, w_2, \cdots, w_n]^T$, yields

$$\dot V \le -e^T Q e/2 + \rho^2 w^T w/2 \tag{41}$$

This may be written as

$$\dot V \le -\lambda_{\min}(Q)\|e\|^2/2 + \rho^2\|w\|^2/2 \tag{42}$$

where $\lambda_{\min}(Q)$ is the real part of the eigenvalue of Q with the minimum magnitude. It is clear that the time derivative of V is negative outside a compact set Ω_e defined by

$$\Omega_e = \left\{e : 0 \le \|e\| \le \sqrt{1/\lambda_{\min}(Q)}\rho\|w\|\right\} \tag{43}$$

So, all the variables are bounded.

Integrating (42) from t=0 to t=T yields

$$2V(T) + \int_0^T e^T Q e dt \le 2V(0) + \rho^2 \int_0^T \|w\|^2 dt \tag{44}$$

Equation (44) indicates that the H^∞ tracking performance is achieved.

IV. Simulation Results

In order to verify the effectiveness and reliability of proposed decentralized adaptive fuzzy control scheme, two different configurations of two degree of freedom reconfigurable manipulators shown in Fig. 1 are simulated, whose dynamical model can be described by (1).

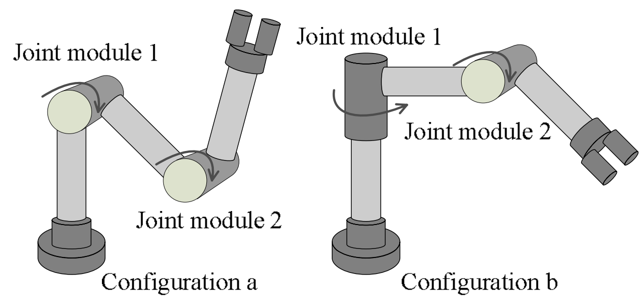

Fig. 1 Configurations for simulation

Configuration a:

The dynamical model of the configuration a is defined by

$$M(q) = \begin{bmatrix} 0.36\cos(q_2) + 0.6066 & 0.18\cos(q_2) + 0.1233 \\ 0.18\cos(q_2) + 0.1233 & 0.1233 \end{bmatrix}$$

$$C(q,\dot q) = \begin{bmatrix} -0.36\sin(q_2)\dot q_2 & -0.18\sin(q_2)\dot q_2 \\ 0.18\sin(q_2)(\dot q_1 - \dot q_2) & 0.18\sin(q_2)\dot q_1 \end{bmatrix}$$

$$G(q) = \begin{bmatrix} -5.88\sin(q_1+q_2) - 17.64\sin(q_1) \\ -5.88\sin(q_1+q_2) \end{bmatrix}$$

The desired trajectories of joints are $q^d = [q_1^d, q_2^d]^T$ with $q_1^d = 0.5\cos(t) + 0.2\sin(3t)$ and $q_2^d = 0.3\cos(3t) - 0.5\sin(2t)$. The initial positions of joints are $q_1(0) = q_2(0) = 2$, and initial velocities of joints are zeros.

For each subsystem, the variables q_i , $\dot q_i$, and $\left|e_i^T P_i B_i\right|$ are fuzzified using seven fuzzy sets as depicted in Fig. 2. Then, the corresponding fuzzy system rule bases are designed as follows

$f_i(q_i, \dot q_i)$: if q_i is F_{i1}^l and $\dot q_i$ is F_{i2}^l then $\hat f_i(q_i, \dot q_i)$ is Y_{if}^l for $l = 1, \cdots, 7$.

$g_i(q_i)$: if q_i is F_{i1}^l then $\hat g_i(q_i)$ is Y_{ig}^l for $l = 1, \cdots, 7$.

$p_i(\left|e_i^T P_i B_i\right|)$: if $\left|e_i^T P_i B_i\right|$ is F_{ie}^l then $\hat p_i(\left|e_i^T P_i B_i\right|)$ is Y_{ip}^l for $l = 1, \cdots, 7$.

where F_{i1}^l , F_{i2}^l and F_{ie}^l are the fuzzy sets with the membership functions depicted in Fig. 2, Y_{if}^l , Y_{ig}^l and Y_{ip}^l are fuzzy singletons for $\hat f_i(q_i, \dot q_i)$, $\hat g_i(q_i)$ and $\hat p_i(\left|e_i^T P_i B_i\right|)$, respectively.

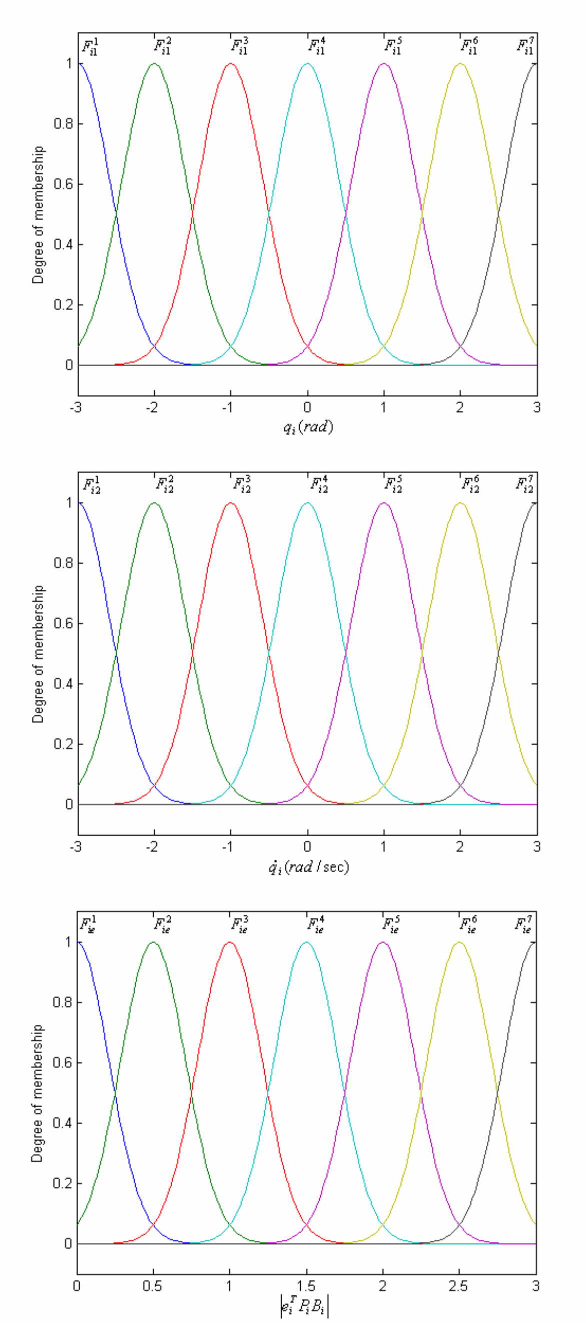

Fig. 2 Fuzzy controller membership functions

The proposed decentralized control is used as follows:

$$u_i = [-\theta_{if}^T \xi_{if}(q_i, \dot{q}_i) + \ddot{y}_{ir} - K_i^T e_i - \operatorname{sgn}(e_i^T P_i B_i)\theta_{ip}^T \xi_{ip}(\left|e_i^T P_i B_i\right|) + u_{ia}] / (\theta_{ig}^T \xi_{ig}(q_i))$$

with $u_{ia} = -B_i^T P_i e_i / r_i$.

The θ_{if}, θ_{ig} and θ_{ip} are updated by (27), (28) and (29), their initial states are simply set to ones. The controller parameters are taken as $K_i^T = [4 \quad 10]$, $\rho = 0.05$, $r_i = 2\rho^2$, $Q_i = diag(10,10)$, $\eta_{if} = 5$, $\eta_{ig} = 0.05$, and $\eta_{ip} = 100$. The tracking performances of two joints are shown in Fig. 3. The dotted lines indicate the desired trajectories and the solid lines display the actual trajectories. As shown in Fig. 3, the tracking errors of two joints appear at the beginning of the process due to the lack of knowledge about the dynamical model of subsystem. After a few seconds, the actual trajectories and the desired trajectories almost overlap with one another. Thus, the proposed decentralized control scheme exhibits satisfactory tracking performances.

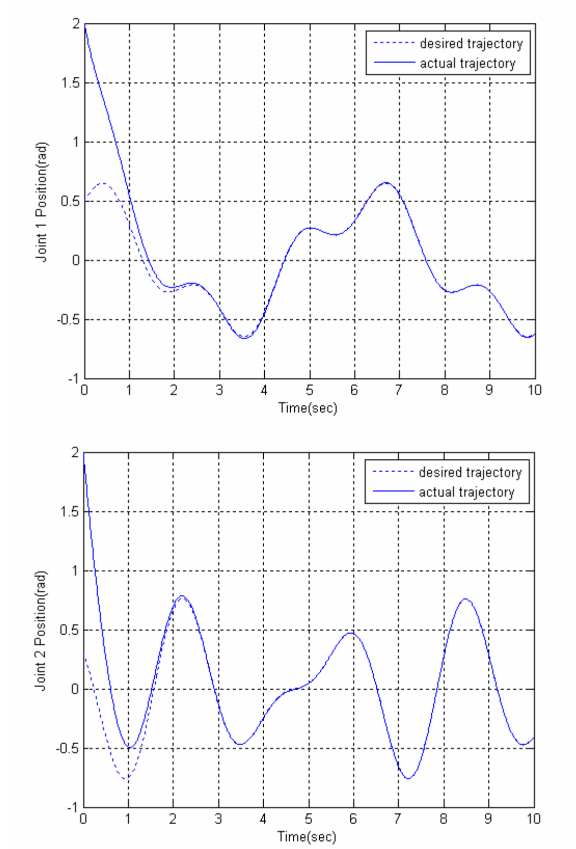

Fig. 3 Tracking performances of configuration a

Configuration b:

To further test the effectiveness of the proposed decentralized control scheme under different configurations, the same control law is also applied to the configuration b. The dynamical model of the configuration b is defined by

$$M(q) = \begin{bmatrix} 0.17 - 0.1166\cos^2(q_2) & -0.06\cos(q_2) \\ -0.06\cos(q_2) & 0.1233 \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} 0.1166\sin(2q_2)\dot{q}_2 & 0.06\sin(q_2)\dot{q}_2 \\ 0.06\sin(q_2)\dot{q}_2 - 0.0583\sin(2q_2)\dot{q}_1 & -0.06\sin(q_2)\dot{q}_1 \end{bmatrix}$$

$$G(q) = \begin{bmatrix} -5.88\cos(q_1)\sin(q_2) + 3.92\sin(q_1) \\ -5.88\sin(q_1)\cos(q_2) \end{bmatrix}$$

The desired trajectories of joints are $q^d = [q_1^d, q_2^d]^T$ with $q_1^d = 0.2\sin(3t) + 0.1\cos(4t)$ and $q_2^d = 0.3\sin(2t) + 0.2\cos(t)$.

The initial positions of joints are also $q_1(0) = q_2(0) = 2$, and initial velocities of joints are zeros. The tracking performances of the configuration b are shown in Fig. 4. The simulation results illustrate the proposed decentralized control scheme can be applicable to different configurations of reconfigurable manipulator without modifying any control parameters.

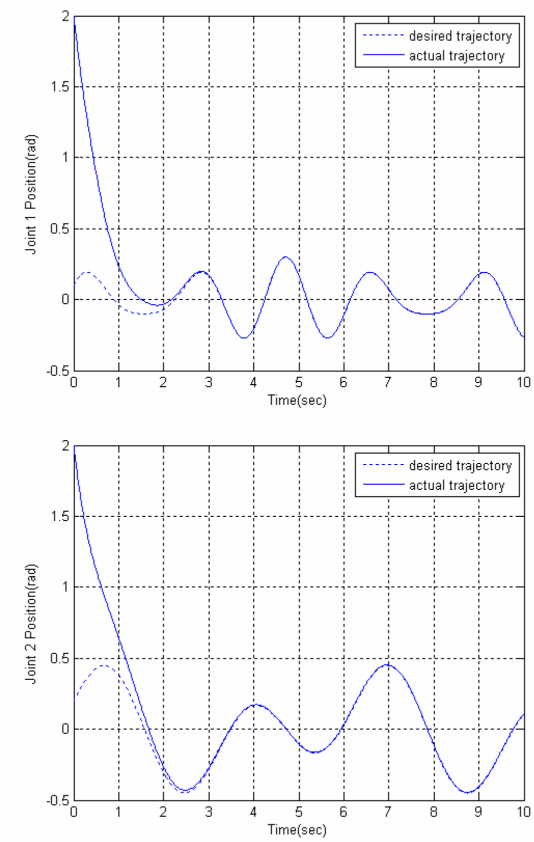

Fig. 4 Tracking performances of configuration b

V. CONCLUSIONS

In this paper, stable decentralized adaptive fuzzy control schemes which can be applicable to all the configurations of reconfigurable manipulators are presented. The control scheme does not require the reconfigurable manipulator dynamics to be known. All adaptive algorithms are derived from the sense of Lyapunov stability analysis, so that stability and trajectory tracking performance of the overall control system can be guaranteed. Two different configurations of reconfigurable manipulators are used to demonstrate the feasibility of the proposed decentralized adaptive fuzzy control scheme.

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