DESIGN ADAPTIVE ROBUST FUZZY CONTROLLER FOR ROBOT MANIPULATORS

THIẾT KẾ BỘ ĐIỀU KHIỂN MỜ BỀN VỮNG THÍCH NGHI CHO TAY MÁY ROBOT

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ABSTRACT

This paper proposes an adaptive robust Fuzzy controller based on Backstepping scheme to solve with the model unknown and parameter disturbances for robot manipulator. In this research, the robust adaptive fuzzy system is combined with Backstepping design method to remove the matching condition requirement and to provide boundedness of tracking errors, even under dominant model uncertainties. Unlike previous robust adaptive fuzzy controllers of nonlinear systems, the robustness term of proposed control scheme is selected as an auxiliary controller in the control system to deal with the effects of model uncertainties and parameter adaptation errors. The adaptive turning laws of network parameters are derived using the Lyapunov stability theorem, therefore, the global stability and robustness of the entire control system are guaranteed, and the tracking errors converge to the required precision, and position is proved. Finally, the effectiveness of the proposed robust adaptive control methodology is demonstrated by comparative simulation results with the adaptive Backstepping control (BPC) and the adaptive Fuzzy control (AFC), which have done on three-joint robot manipulator.

Keywords: *Adaptive Fuzzy; robot manipulators; robust adaptive control.*

TÓM TẮT

Bài báo đề xuất thiết kế bộ điều khiển mờ bền vững thích nghi trên cơ sở phương pháp Backstepping để giải quyết bài toán có cấu trúc bất định và nhiễu loạn của các tham số cho tay máy robot. Trong nghiên cứu này, hệ thống mờ bền vững thích nghi được kết hợp với phương pháp thiết kế Backstepping để xóa các yêu cầu về điều kiện phù hợp và đưa ra giới hạn sai lệch bám, thậm chí cả tính bất định của cấu trúc. Khác với các bộ điều khiển mờ trước đó, thành phần bền vững của bộ diều khiển để xuất đóng vai trò như bộ điều khiển bù để xử lý ảnh hưởng của bất định cấu trúc và sai lệch của các tham số. Luật điều chỉnh thích nghi các tham số được đưa ra sử dụng lý thuyết ổn định Lyapunov, do vậy, sự ổn định và bền vững của hệ thống điều khiển được đảm bảo, các sai lệch hội tụ về giá trị yêu cầu và vị trí bám được cải thiện. Cuối cùng, bài báo trình bày các kết quả mô phỏng trên cơ sở so sánh với bộ điều khiển Backstepping và mờ thích nghi để thấy được hiệu quả của phương pháp điều khiển này trên tay máy robot ba bậc tự do.

Từ khóa: *Điều khiển mờ thích nghi, tay máy robot, điều khiển thích nghi bền vững.*

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ABBREVIATIONS

BPC: Backstepping control

AFC: adaptive Fuzzy control

1. INTRODUCTION

In recent years, interest in designing robust tracking control for robot manipulator system has been ever increasing, and many significant research attentions have been attracted. However, robotics are nonlinear systems and they suffer from various uncertainties in their dynamics, which deteriorate the system performance and stability, such as external disturbance, nonlinear friction, high time varying and payload variation. Therefore, achieving high performance in trajectory tracking is a very challenging task. To overcome these problems, many powerful methodologies have been proposed, including adaptive control, intelligent control, sliding mode control and variable structure control, etc.[1-4]. Recently, Backstepping technique has been widely applied to design adaptive controller for nonlinear system. Investigations base on Backstepping control method are provided a systematic framework for the design of tracking and regulation strategies, suitable for a large class of state feedback linearizable nonlinear systems [5-8]. However, there are some problems in the Backstepping design method. A major constraint is that certain functions must be "linear in the unknown parameters", which may not be satisfied in practice. Furthermore, some very tedious analysis is needed to determine "regression matrices", and the problem of determining and computing the regression matrices becomes even more acute. In general, the application of fuzzy logic theory to control problems provides an alternative to the traditional modeling and design of control systems when system knowledge and dynamics models are uncertain and time-varying. The fuzzy systems are used to uniform approximate the unstructured uncertain functions in the designed system by using the universal approximation properties of the uncertain class of fuzzy systems, and several stable adaptive fuzzy controllers that ensure the stability of the overall system are developed by [9-16]. However, in the aforementioned schemes, a lot of parameters are needed to be tuned in the learning laws when there are many state variables in the designed system and many rules bases have to be used in the fuzzy system for approximating the nonlinear uncertain functions, so that the learning times tend to become unacceptably large for the systems or higher order and time-consuming process is un avoidable when the fuzzy logic controllers are implemented. In this paper, we proposes a robust adaptive control method by combining adaptive fuzzy system with backstepping design technique for the three-joint robot manipulator to achieve the high precision position tracking under various environments. An adaptive fuzzy system is used as a universal approximator, and the robust adaptive control by backstepping design is used to guarantee uniform boundedness of tracking errors. So that, the research does not require the matching condition imposed in the control system, and the boundedness of tracking errors, even with poor parameter adaptation are also provided. In addition, the robust term is also selected to limit the sizes of the parameter adaptation errors, and it can provide better tracking performance and robustness at the cost of expensive control inputs. Therefore, the tracking performance and robustness of the proposed control method can be guaranteed at all costs, even though the target system is effected by dominant unknown nonlinearities or disturbances.

This paper is organized as follows. The problem formulation and preliminaries are presented in section 2. Section 3 presents control design and stability analysis of the system. The boundedness of the tracking error is guaranteed and proven. In section 4, the simulation results on the three-joint robot manipulators are presented. The final section is a conclusion of the paper.

2. PROBLEM FORMULATION AND PRELIMINARIES

2.1. Dynamic of Robot manipulators

Consider the dynamics equation of an n- link robot manipulators with external disturbances as follows:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{D}_e = \boldsymbol{\tau} \tag{1}$$

where $(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}}) \in \boldsymbol{R}^{n\times 1}$ are the vectors of joint position, velocity and acceleration, respectively. $\boldsymbol{M}(\boldsymbol{q}) \in \boldsymbol{R}^{n\times n}$ is the symmetric inertial Matrix. $\boldsymbol{C}(\boldsymbol{q},\dot{\mathbf{q}}) \in \mathbf{R}^{n\times n}$ is the vector of Coriolis and Centripetal forces. $\boldsymbol{D}_e \in \boldsymbol{R}^{n\times 1}$ is the bounded unknown disturbances input and the unmodeled dynamics vector, and $\boldsymbol{\tau} \in \boldsymbol{R}^{n\times 1}$ is the joints torque input vector.

For the purpose of designing controller, there are some properties.

Property 1: The inertial matrix ***M (q)*** is a symmetric and bounded positive matrix:

$$M(q) \le m_0 I, \tag{2}$$

where $m_0 > 0$ and $m_0 \in R$

Property 2: $\dot{\boldsymbol{M}}(\boldsymbol{q}) - 2\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is skew symmetric matrix, for any vector x:

$$x^T\left[\dot{M}(q) - 2C(q,\dot{q})\right]x = 0 \tag{3}$$

Property 3: $C(q,\dot{q})\dot{q}$, $F(\dot{q})$ *is* bounded as follows:

$$\|C(q,\dot{q})\dot{q}\| \le C_k\|\dot{q}\|^2 \tag{4}$$

where C_k is positive constants.

Property 4: $D_e > 0$; $D_e \in R^{n\times 1}$ is the unknown disturbance and bounded as:

$$\|D_e\| \le d_e \tag{5}$$

where d_e is known positive constants.

2.2. Adaptive fuzzy system

A fuzzy logic system includes four parts: the knowledge base, the fuzzifier, the fuzzy inference engine working on fuzzy rules, and the defuzzifier. The knowledge base of the fuzzy logic system is a collection of fuzzy IF-THEN rules of the following form:

R^l: IF x_1 is F_1^l and x_2 is F_2^l and … and x_n is F_n^l, THEN y is $G^l, l = 1,2,\dots,N$

where $x = (x_1,\dots,x_n)^T$ and y are the fuzzy logic system input and output, respectively. F_i^l, G^l are associated with the fuzzy membership functions $\mu_{F_i^l}(x_i)$ and $\mu_{G^l}(y)$, respectively. *N* is the number of rules.

The output of the fuzzy system can be expressed as:

$$y(x) = \frac{\sum_{l=1}^N \delta_l \prod_{i=1}^n \mu_{F_i^l}(x_i)}{\sum_{l=1}^N\left[\prod_{i=1}^n \mu_{F_i^l}(x_i)\right]} \tag{6}$$

where $\delta_l = \max_{y\in R}\mu_{G^l}(y)$, and $\delta = [\delta_1,\delta_2,\dots,\delta_N]^T$

Define the fuzzy basis function as follows

$$\sigma_l = \frac{\prod_{i=1}^n \mu_{F_i^l}(x_i)}{\sum_{l=1}^N\left[\prod_{i=1}^n \mu_{F_i^l}(x_i)\right]}$$

$$\text{where } \sigma = [\sigma_1(x),\sigma_2(x),\dots,\sigma_N(x)]^T \tag{7}$$

Then the output of the fuzzy system (6) can be rewritten as

$$y(x) = \sigma^T(x)\delta \tag{8}$$

Let $f(x)$ be a continuous function defined on a compact set Φ, then for any small constant $\omega > 0$, there exists a fuzzy logic system such that

$$\|f(x_i) - \sigma^T(x_i)\delta_i^*\| \le \omega \tag{9}$$

where δ_i^* is the optimal approximate constant, and define $\tilde{\delta} = \delta^* - \delta$

3. CONTROL DESIGN AND STABILITY ANALYSIS

In this section, we proposed an intelligent controller which combines adaptive fuzzy control [14] and Backstepping technique to suppress the effects of the uncertainties and approximation errors. Thus, the unknown functions of robot manipulator control system is estimated, and the stability of control system can be guaranteed. The block diagram of the adaptive control system is presented in Fig.1.

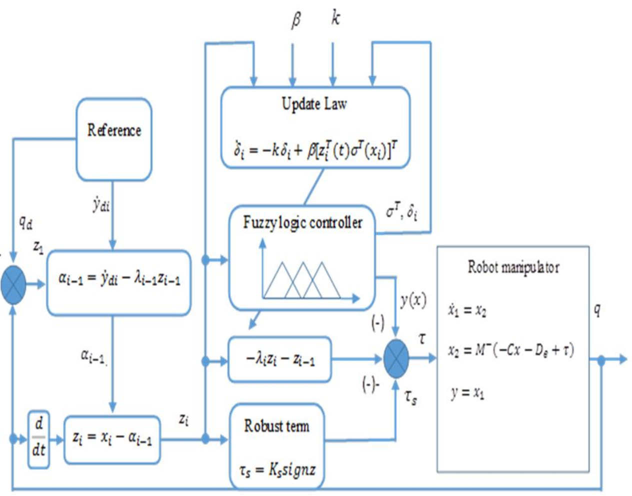

Figure 1. The block diagram of the adaptive control system

The adaptive Backstepping method will be applied to solve the approximator of the system (1). The *n* step adaptive fuzzy backstepping design is based on the change of coordinates

Define

$$\begin{cases} x_1(t) = q(t) \\ z_1(t) = y(t) - y_d(t) \\ y(t) = x_1(t) \\ z_i(t) = x_i(t) - \alpha_{i-1} \;; i = 2, \ldots, n-1 \end{cases} \tag{10}$$

where $y_d(t)$ is the expected angle and has second order derivative, $x_i(t) = \dot{x}_{i-1}(t)$, α_{i-1} is an intermediate control and selected as:

$$\alpha_{i-1} = \dot{y}_{di}(t) - \lambda_{i-1}z_{i-1}(t); (\lambda_{i-1} > 0) \tag{11}$$

Step 1: By choosing the appropriate α_{i-1}, leading to $z_i(t) \to 0$, and from (10), the derivative of $z_1(t)$ can be obtained:

$$\dot{z}_1(t) = z_i + \alpha_{i-1} - \dot{y}_d \tag{12}$$

Consider the following Lyapunov function candidate L_1 as:

$$L_1 = \frac{1}{2}z_1^T z_1 \tag{13}$$

The time derivative of the Lyapunov function L_1 is:

$$\dot{L}_1 = z_1^T \dot{z}_1$$

By using equations (10-12), one has

$$\dot{L}_1 = z_1^T z_i - \lambda_1 z_1^T z_1 \tag{14}$$

Step i, (2 ≤ i ≤ n-1): The dynamics equation (1) of an n-link robot manipulators can be rewritten as follows:

$$\dot{x}_i(t) = -M^{-1}Cx_i(t) - M^{-1}D_e + M^{-1}\tau \tag{15}$$

From (15), and by using $z_i(t) = x_i(t) - \alpha_{i-1}$, we can obtain:

$$\dot{z}_i(t) = -M^{-1}Cx_i(t) - M^{-1}D_e + M^{-1}\tau - \dot{\alpha}_{i-1} \tag{16}$$

To continue our design, the adaptive control law is proposed as:

$$\tau = -z_{i-1}(t) - \lambda_i z_i(t) - y(x) - \tau_s \tag{17}$$

where τ_s is a robust term that is used to suppress the effects of uncertainties and approximation errors.

The robust compensator τ_s is designed by:

$$\tau_s = -K_s sgn(z) \tag{18}$$

where K_s is selected as: $K_s \leq d_e$

Consider the Lyapunov function candidate as

$$L_i = L_{i-1} + \frac{1}{2}z_i^T(t)Mz_i(t) \tag{19}$$

The time derivative of L_i is

$$\dot{L}_i = \dot{L}_{i-1} + \frac{1}{2}\dot{z}_i^T(t)Mz_i(t) + \frac{1}{2}z_i^T(t)\dot{M}z_i(t) + \frac{1}{2}z_i^T(t)M\dot{z}_i(t) \tag{20}$$

From equations (10), (14), (16) and using property 3, we have

$$\dot{L}_i = z_{i-1}^T(t)z_i(t) - \lambda_{i-1}z_{i-1}^T(t)z_{i-1}(t) + z_i^T(t)(-C\alpha_{i-1} - M\dot{\alpha}_{i-1} - \lambda_i z_i(t) - z_{i-1}(t) - \sigma^T(x_i)\delta_i) + z_i^T(t)K_s sgn(z_i) - z_i^T(t)D_e \tag{21}$$

By defining $f(x_i) = -C\alpha_{i-1} - M\dot{\alpha}_{i-1}$, now (21) becomes

$$\begin{aligned}\dot{L}_i = &-\lambda_{i-1}z_{i-1}^T(t)z_{i-1}(t) - \lambda_i z_i^T(t)z_i(t) \\ &+ z_i^T(t)(f(x_i) - \sigma^T(x_i)\delta_i^*) \\ &+ z_i^T(t)\sigma^T(x_i)\tilde{\delta}_i + z_i^T(t)K_s sgn(z_i) \\ &- z_i^T(t)D_e\end{aligned}$$

$$\begin{aligned}\dot{L}_i \leq &-\lambda_{i-1}z_{i-1}^T(t)z_{i-1}(t) - \lambda_i z_i^T(t)z_i(t) \\ &+ \|z_i^T(t)\|\|(f(x_i) - \sigma^T(x_i)\delta_i^*)\| \\ &+ z_i^T(t)\sigma^T(x_i)\tilde{\delta}_i\end{aligned} \tag{22}$$

Using (9) and *property 4*, we can obtain:

$$\dot{L}_i \leq -\lambda_{i-1}z_{i-1}^T(t)z_{i-1}(t) - (\lambda_i - \frac{1}{2})z_i^T(t)z_i(t) + \frac{1}{2}\omega^2 + z_i^T(t)\sigma^T(x_i)\tilde{\delta}_i \tag{23}$$

Step n: In the final step, choose the following Lyapunov function candidate:

$$L_n = L_{n-1} + \frac{1}{2\beta}\tilde{\delta}_n^T\tilde{\delta}_n \qquad (\beta > 0) \tag{24}$$

The time derivative of L_n is

$$\dot{L}_n = \dot{L}_{n-1} - \frac{1}{\beta}\tilde{\delta}_n^T\dot{\delta}_n \tag{25}$$

Similar to the derivations in *Step i*, once has

$$\begin{aligned}\dot{L}_n \leq &-\lambda_{n-1}z_{n-1}^T(t)z_{n-1}(t) - (\lambda_n - \frac{1}{2})z_n^T(t)z_n(t) \\ &+ \frac{1}{2}\omega^2 + z_n^T(t)\sigma^T(x_n)\tilde{\delta}_n - \frac{1}{\beta}\tilde{\delta}_n^T\dot{\delta}_n\end{aligned}$$

$$\begin{aligned}\dot{L}_n \leq &-\lambda_{n-1}z_{n-1}^T(t)z_{n-1}(t) \\ &-\left(\lambda_n - \frac{1}{2}\right)z_n^T(t)MM^{-1}z_n(t) \\ &+ z_n^T(t)\sigma^T(x_n)\tilde{\delta}_n - \frac{1}{\beta}\tilde{\delta}_n^T\dot{\delta}_n + \frac{1}{2}\omega^2\end{aligned} \tag{26}$$

Choosing the adaptive law for δ is:

$$\dot{\delta}_i = -k\delta_i + \beta[z_i^T(t)\sigma^T(x_i)]^T \tag{27}$$

From *property 1* and the adaptive law (27), now (26) becomes

$$\dot{L}_n \le -\lambda_{n-1} z_{n-1}^T(t) z_{n-1}(t) - \left(\lambda_n - \frac{1}{2}\right)\frac{1}{m_0} z_n^T(t) M z_n(t) + \frac{k}{2\beta}\left(-\delta^{*T}_n\delta_n^* - \delta_n^T\delta_n\right) + \frac{k}{\beta}\delta^{*T}_n\delta_n^* + \frac{1}{2}\omega^2 \quad (28)$$

Since $-\delta^{*T}_n\delta_n^* - \delta_n^T\delta_n \le -\frac{1}{2}\tilde{\delta}_n^T\tilde{\delta}_n$, now (28) becomes

$$\dot{L}_n \le -\lambda_{n-1} z_{n-1}^T(t) z_{n-1}(t) - \left(\lambda_n - \frac{1}{2}\right)\frac{1}{m_0} z_n^T(t) M z_n(t) - \frac{k}{2\beta}\left(\frac{1}{2}\tilde{\delta}_n^T\tilde{\delta}_n\right) + \frac{k}{\beta}\delta^{*T}_n\delta_n^* + \frac{1}{2}\omega^2 \quad (29)$$

Denote

$\xi_m = \mathrm{Min}\left\{2\lambda_{n-1}, (2\lambda_n - 1)\frac{1}{m_0}, \frac{k}{2}\right\}$;

and $\xi_0 = \frac{k}{\beta}\delta^{*T}_n\delta_n^* + \frac{1}{2}\omega^2$

We have

$$\dot{L}_n \le -\xi_m\left(\frac{1}{2} z_{n-1}^T(t) z_{n-1}(t) + \frac{1}{2} z_n^T(t) M z_n(t) + \frac{1}{2\beta}\tilde{\delta}_n^T\tilde{\delta}_n\right) + \xi_0$$

$$\dot{L}_n \le -\xi_m L_n + \xi_0 \quad (30)$$

Integrating $\dot{L}_n$ with respect to time as follows:

$\int_0^t \dot{L}_n(t)dt \le -\int_0^t(-\xi_m L_n + \xi_0)dt = L_n(0)e^{-\xi_m t} + \frac{\xi_0}{\xi_m}\left[1 - e^{-\xi_m t}\right] \quad (\forall t \ge 0)$

Then $\quad L_n(t) \le L_n(0) + \frac{\xi_0}{\xi_m} \quad (31)$

Moreover, by (31), we can further obtain

$$\frac{1}{2}z_1^2(t) = \frac{1}{2}\left(y(t) - y_d(t)\right)^2 \le L_n(t) \le L_n(0) + \frac{\xi_0}{\xi_m} \quad (32)$$

Equation (30) implies that there exists T which for all $t > T$, the tracking error z_1 satisfies

$$|z_1| \le \sqrt{\frac{\xi_0}{\xi_m}} \quad (33)$$

Following the above design procedures and stable analysis, guarantees that all the signals in the closed-loop system are bounded in mean square. Furthermore, the tracking error can be made arbitrarily small by choosing the appropriate design parameters.

4. SIMULATION RESULTS

In this section, a three-link robot manipulators is applied to verify the validity of the proposed control scheme for illustrative purposes. The detailed system parameters of the three-link robot manipulators model are given as follows [4]:

$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}; C = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

$$M_{11} = (m_1 + m_2 + m_3)l_1^2 + (m_2 + m_3)l_2^2 + m_3 l_3^2 + 2(m_2 + m_3)l_1 l_2\cos(q_2) + 2m_3 l_1 l_3\cos(q_2 + q_3) + 2m_3 l_2 l_3\cos(q_3)$$

$$M_{12} = (m_2 + m_3)l_2^2 + m_3 l_3^2 + (m_2 + m_3)l_1 l_2\cos(q_2) + m_3 l_1 l_3\cos(q_2 + q_3) + 2m_3 l_2 l_3\cos(q_3)$$

$M_{13} = m_3 l_3^2 + m_3 l_1 l_3\cos(q_2 + q_3) + m_3 l_2 l_3\cos(q_3)$;

$M_{21} = M_{12}$;

$M_{22} = (m_2 + m_3)l_2^2 + m_3 l_3^2 + 2m_3 l_2 l_3\cos(q_3)$;

$M_{23} = m_3 l_3^2 + m_3 l_2 l_3\cos(q_3)$;

$M_{31} = m_3 l_3^2 + m_3 l_1 l_3\cos(q_2 + q_3) + m_3 l_2 l_3\cos(q_3)$;

$M_{32} = M_{23}$; $M_{33} = m_3 l_3^2$

$$C_{11} = -2(m_2 + m_3)l_1 l_2\sin(q_2)\dot{q}_2 - 2m_3 l_1 l_3\sin(q_2 + q_3)(\dot{q}_2 + \dot{q}_3) - 2m_3 l_2 l_3\sin(q_3)\dot{q}_3$$

$$C_{12} = -(m_2 + m_3)l_1 l_2\sin(q_2)\dot{q}_2 - m_3 l_1 l_3\sin(q_2 + q_3)(\dot{q}_2) - 2m_3 l_2 l_3\sin(q_3)\dot{q}_3 - 2m_3 l_1 l_3\sin(q_2 + q_3)\dot{q}_3$$

$$C_{13} = -m_3 l_2 l_3\sin(q_3)\dot{q}_3 - m_3 l_1 l_3\sin(q_2 + q_3)\dot{q}_3$$

$$C_{21} = -(m_2 + m_3)l_1 l_2\sin(q_2)\dot{q}_2 - m_3 l_1 l_3\sin(q_2 + q_3)(\dot{q}_2 + \dot{q}_3) - 2m_3 l_2 l_3\sin(q_3)\dot{q}_3 + (m_2 + m_3)l_1 l_2\sin(q_2)(\dot{q}_2 + \dot{q}_1) + m_3 l_1 l_3\sin(q_2 + q_3)(\dot{q}_2 + \dot{q}_1 + \dot{q}_3)$$

$C_{22} = -2m_3 l_2 l_3\sin(q_3)\dot{q}_3$; $C_{23} = -m_3 l_2 l_3\sin(q_3)\dot{q}_3$

$$C_{31} = -m_3 l_1 l_3\sin(q_2 + q_3)(\dot{q}_2 + \dot{q}_3) - m_3 l_2 l_3\sin(q_3)\dot{q}_3 + m_3 l_1 l_3\sin(q_2 + q_3)(\dot{q}_2 + \dot{q}_1 + \dot{q}_3) + m_3 l_2 l_3\sin(q_2 + q_3)(2\dot{q}_2 + \dot{q}_1 + \dot{q}_3)$$

$C_{32} = m_3 l_2 l_3\sin(q_3)\dot{q}_2$; $C_{33} = 0$;

where m_1, m_2, m_3 are links masses; l_1, l_2, l_3 are links lengths; $g = 10(m/s^2)$ is acceleration of gravity.

The parameters of three link industrial robot manipulator are given as follows:

$m_1 = 1.1\ (kg), m_2 = 1.1\ (kg), m_3 = 0.5\ (kg)$;

$l_1 = 0.3\ (m), l_2 = 0.3\ (m), l_3 = 0.1\ (m)$

The object is to design control input in order to force joint variables $q = [q_1 \quad q_2 \quad q_3]^T$ to track desired trajectories as time goes to infinity. Here, the desired position trajectories of the three link industrial robot manipulator are chosen by $q_d = [q_{d1} \quad q_{d2} \quad q_{d3}]^T = [0.5\sin(2\pi t) \quad 0.5\sin(2\pi t) \quad 0.5\sin(2\pi t)]^T$;

The parameter values used in the adaptive control system are chosen for the convenience of simulations as follows:

$\lambda_1 = 2; \lambda_2 = 5; k = 1.5; \beta = 2; K_s = diag[0.1\ 0.1\ 0.1]$;

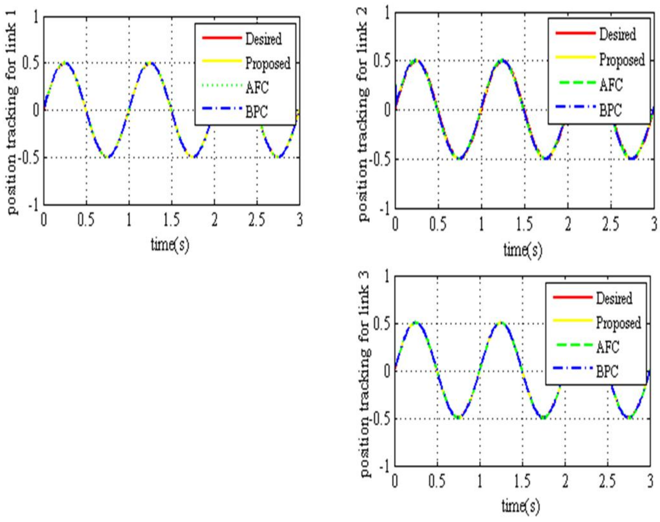

Figure 2. Simulated positions tracking of the proposed control system, AFC and BPC

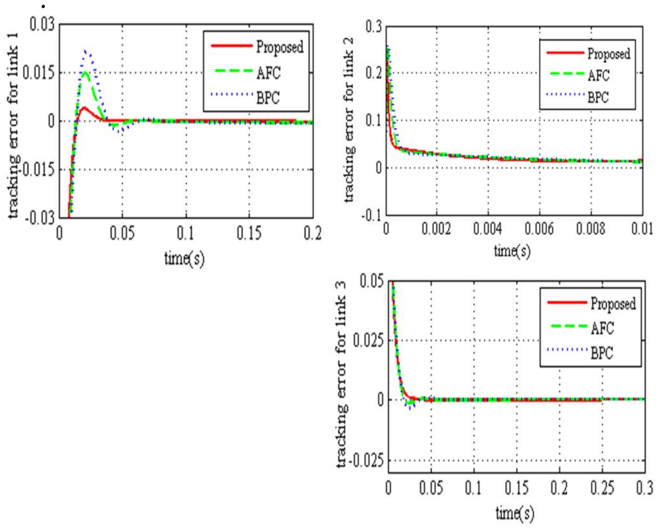

Figure 3. Simulated tracking errors of the proposed control system, AFC and BPC

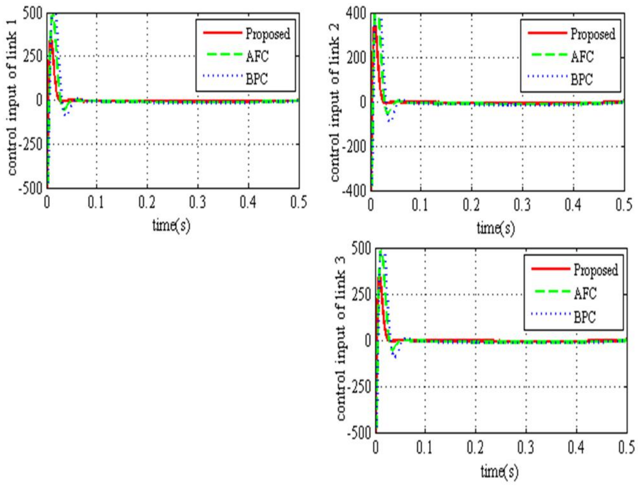

Figure 4. Simulated control efforts of the proposed control system, AFC and BPC

In the following passage, our proposed control scheme is applied to the robot manipulators in comparison with the adaptive Backstepping control (BPC) [7] and the adaptive Fuzzy control (AFC) [9]. The simulation results of joint position responses, tracking errors and control torques in following the desired trajectories for joint 1, joint 2 and joint 3 are shown in Figures (2-4), when the external disturbance is selected as: $d_e = [0.25\sin(t) \quad 0.25\sin(t) \quad 0.25\sin(t)]^T$. From these simulation results, we can see that the proposed control system converges to the desired trajectory more quickly and achieves tracking performance better than both the cases with BPC and AFC. Therefore, the use of proposed control scheme with adaptation weights can effectively improve the performance of the closed- loop system compared with the existing results. It seems that the robust tracking performance of the proposed control scheme is more excellent and effective than the BPC and AFC in [7] and [9], respectively.

5. CONCLUSION

In this paper, a robust adaptive control method that combines adaptive fuzzy system with backstepping design technique is proposed for the three-joint robot manipulators to solve the uncertain plant problems. Based on the above control algorithm, the presented control laws can guarantee the tracking errors converge to a small residual set and all the involved signals remain in a bounded set without needing an accurate robot model. Simulation results were presented on a three link robot manipulators and comparisons were made with the performance of BPC and AFC. Finally, as demonstrated in the illustrated simulation results, the proposed control scheme in this approach is not only reduce the chattering phenomenon, but also can achieve the high precision position tracking and good robustness in the trajectory tracking control of three link robot manipulators under various environments over the existing results. Thus our proposed controller can be effectively applied for the three link robot manipulator.

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