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Control of Robot Manipulator with Uncertain Dynamics by Adaptive Fuzzy Controller

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Abstract: To exploit the beneficial features of feedback linearization control and fuzzy control, and also to overcome their disadvantages, this paper presents a robust adaptive fuzzy control scheme combining conventional feedback linearization control and a compensator for the robust tracking control of robotic manipulators with uncertainties in forms of structured and unstructured. The proposed compensator is based on adaptive fuzzy estimation and compensation of uncertainty. The adaptive fuzzy system compensates uncertainties by modeling of the uncertainties as a nonlinear function of the joint position variables. The novelty and advantage of the proposed adaptive fuzzy system is to use a non-complicated structure and without applying all system states for estimating the uncertainty, so the number of fuzzy rules is reduced. According to Lyapunov stability theory, a tracking error limit is derived for the closed - loop control system and accordingly the convergence and stability of the control scheme is proved. A comparison between the proposed adaptive fuzzy control and conventional feedback linearization controller at presence of uncertainties is presented. The authenticity of the proposed control scheme is showcased by numerical simulations of a SCARA robot manipulator.

Keywords: Robot Manipulator, Feedback linearization control, Adaptive Control, Fuzzy Estimator and Compensator

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1. Introduction

In order to employ industrial robots in operation field, a considerable attention has been focused on the robust control of robot manipulators. These efforts try to overcome the uncertainties that degrade control systems performance [1-4]. The uncertainty includes unmodeled dynamics, parametric uncertainty, and external disturbances. Consideration of various sources of uncertainties such as modeling errors, unknown loads, and computation errors is indispensable in practical employ of control approaches.

The presence of uncertainties is a challenge for using feedback linearization as one of the popular techniques used in the control of robot manipulators [5]. To apply the feedback linearization a perfect model is required, whereas a perfect model is not available. Instead, only a nominal model is accessible while it differs from the actual system. As a result, the model inaccuracy decreases reliability of the control system. Therefore, uncertainty must be compensated by the control laws to enhance performance of the control system.

Uncertainties may have a bad effect on a controller's performance and may make instability. To exposure uncertainties, one of approaches is using adaptive control. Some researchers [6, 7] have offered several adaptive control methods. The adaptive sliding mode control is an effective and widespread tools to exposure the parameter variations and disturbances. Another paper [8] offered an adaptive fuzzy sliding mode control scheme, where the author by the fuzzy rules, effectively reduced the control signal chattering. In order to compensate the friction, [9] proposed an adaptive fuzzy control scheme based on the sliding mode control compensator. Another paper [10] presented an adaptive fuzzy sliding mode control scheme, that a fuzzy compensator is used to adjust both parts of fuzzy rules. Paper [11] accommodates the adaptation laws of the algorithm discussed in [10] and applied it to robotic manipulators. In [12] purpose to achieve robustness in presence of external disturbances, unstructured dynamics, and model uncertainty properties of muscle‐joint dynamics, the author discussed a robust control structure, that is based on the composition of a sliding mode control with an adaptive nonlinear compensator. Paper [13] proposed a fuzzy sliding mode control method based on support vector machines, where in it a fuzzy control algorithm makes adaptability to disturbance. Although the sliding mode control is useful to provide high robustness for control systems, unwanted chattering on the sliding surface along frequent switching can take down control system performances [14]. Another moot point of the sliding mode control methods is that the upper and lower bounds of uncertainties need to be in access unto the design of the controller. Therefore, if the controlled systems have many unknown parameters and disturbance, the design of the sliding mode controller can become very bothersome.

Computed‐torque control strategy is one popular and effective model‐based control method that can proffer a great diversity of advantages over model‐free methods, such as potentially higher tracking accuracy, lower feedback gains, and lower energy consumption [15]. However, it has become widely known that this method in actual operations is feeble in facing structured and unstructured uncertainties and its tracking performance may impress.

Fuzzy control is a robust model-free control approach that can be simply designed and it can be brings up as an alternative to the conventional robust control [16]. To construct a fuzzy controller, we do not require an exact knowledge of system's model. Fuzzy controller that uses fuzzy linguistic rules based on information from experts is an intelligent controller. Consequently, fuzzy control of robotic systems has possessed lots of researches to overcome uncertainty, nonlinearity, and coupling [17–20]. Fuzzy logic system has also been widely applied to generate complementary joint torques to compensate these uncertainties. Paper [21] presented an approach to improve trajectory tracking problems of robotic manipulators through incorporating computed‐torque control and fuzzy control. The fuzzy control part in the approach approximates uncertainties in robotic system; however parameters in the fuzzy control part need to be adjusted by a complex Lyapunov equation, which leads to a complex controller design. Another paper [22] combined the conventional feedback linearization computed‐torque control with a fuzzy logic system to solve trajectory tracking problems of an industrial robot. But, because of determining the fuzzy logic rules in the fuzzy control system by some experimental data and designers' experiences instead of the fuzzy adaptive control law, it is very difficult to ensure stability for the general fuzzy control systems with uncertain dynamics. And in another paper [23] the authors combined the computed‐torque control with a fuzzy logic system to estimate and compensate the uncertainties. However, number of fuzzy rules in their scheme is very much.

To defeat these disadvantages and employ the beneficial features of conventional feedback linearization control and fuzzy control, this paper presents a novel robust adaptive fuzzy control scheme. This scheme is designed based on combining conventional feedback linearization control and a compensator for the robust tracking control of robotic manipulators with uncertainties based on adaptive fuzzy estimation and compensation of uncertainty. This proposed adaptive fuzzy system can compensate the uncertainties by modeling of the uncertainties as a nonlinear function of the joint position variables. The advantage of the proposed adaptive fuzzy system is that it is benefited from a non-complicated structure, which has a considerable feature for actual systems. Also the proposed scheme does not use all system states for estimating the uncertainty, so the number of fuzzy rules is reduced. The stability of the tracking error is guaranteed by using the Lyapunov method. Numerical simulations are employed to specify the performance of the proposed adaptive controller that controls a three link SCARA robotic manipulator.

This paper is organized as follows. Section 2 explains model of the robotic system. Section 3 develops the proposed control law and depicts the adaptive fuzzy scheme that can estimate and compensate the uncertainties. Section 4 discusses the stability analysis. Section 5 via illustrating simulation results, describes performance evaluation of the control system. Finally, Section 6 concludes the paper.

2. Model of System

The dynamic equation of an n degree - of - freedom manipulator in joint space coordinates is given by:

$$D_{(q)}\ddot{q} + H_{(q,\dot{q})} + F = \tau \quad (1)$$

where the vectors $q, \dot{q}$, $\ddot{q}$ are the joint angle, the angular velocity, and the angular acceleration, respectively; $D_{(q)}$ is the n×n symmetrical positive definite inertia matrix; $H_{(q,\dot{q})}$ is the n×1 vector of Coriolis, centrifugal torques and gravitational torque; F is uncertainty including friction terms and external disturbances, and so on; and τ is the n×1 vector of actuator joint torques.

3. Proposed Control Law

The robot dynamic Eq. (1) represents a highly nonlinear and coupled system. In most practical cases, the model is not exactly accessible. Thus, only nominal estimations of the model are available for controller design. Feedback linearization based on torque control is the most effective approach for robot motion control when a nominal robot dynamic model is available. The feedback linearization control law can be written as

$$\tau = \widehat{D}_{(q)}\left(\ddot{q}_d + k_d\dot{e} + k_p e\right) + \widehat{H}_{(q,\dot{q})} \quad (2)$$

where $\widehat{D}_{(q)}$, $\widehat{H}_{(q,\dot{q})}$ are estimations of $D_{(q)}$ and $H_{(q,\dot{q})}$, respectively; k_d and k_p are $n×n$ symmetrical positive definite gain matrices; q_d is the desired joint trajectory; $e = q_d - q$ is defined as trajectory tracking error vectors.

Substituting Eq.(2) into Eq.(1) yields the following closed loop tracking error dynamic equation in the statespace form:

$$\dot{X} = AX + Bw \quad (3)$$

where $= (e, \dot{e})^T$, $A = \begin{bmatrix} 0_{n\times n} & I_{n\times n} \\ -k_{p_{n\times n}} & -k_{d_{n\times n}} \end{bmatrix}$, $B = \begin{bmatrix} 0_{n\times n} \\ I_{n\times n} \end{bmatrix}$ and $w = \widehat{D}_{(q)}^{\ -1}(\left(D_{(q)} - \widehat{D}_{(q)}\right)\ddot{q} + \left(H_{(q,\dot{q})} - \widehat{H}_{(q,\dot{q})}\right) + F)$

Since there are always uncertainties in the robot dynamic model, the ideal error response cannot be achieved in general. The actual system performance is governed by Eq.(3), which will result in the feedback linearization control not being robust in practice. To improve robustness, we introduce a fuzzy logic controller as a compensator for the uncertainties due to friction, disturbance, or payload variation. In this paper, the final output result of a fuzzy system is expressed by the following.

3.1. Fuzzy System Structure

A multi-input and multi-output fuzzy logic system performs a mapping from fuzzy sets in $U \in R^I$ to fuzzy sets in $\in R^m$, based on the fuzzy IF-THEN rules. The output of Mamdani type fuzzy logic system with center-average defuzzifier, product inference engine and singleton fuzzifier takes the following form [16]:

$$f_j = \frac{\sum_{l=1}^{L} \bar{y}_j^l (\prod_{i=1}^{l} \mu_{A_i^l(x_i)})}{\sum_{l=1}^{L} \prod_{i=1}^{l} \mu_{A_i^l(x_i)}} \quad , \quad j=1,2,\ldots,m \qquad (4)$$

where $\bar{y}_j^l$ is the point in Vj at which fuzzy membership function $\mu_{B_j^l}$ achieves its maximum value, which is assumed to be 1; A_i^l and B_j^l are the linguistic variables of the fuzzy sets in the subspace U_i and V_j , described by their membership functions $\mu_{A_i^l(x_i)}$ and $\mu_{B_j^l(y_j)}$; L is the number of fuzzy rules.

The fuzzy basis function can be defined as

$$\zeta_{(x)}{}^{l} = \frac{\prod_{i=1}^{l} \mu_{A_i^l(x_i)}}{\sum_{l=1}^{L} \prod_{i=1}^{l} \mu_{A_i^l(x_i)}} \quad , \quad l=1,2,\ldots,L \qquad (5)$$

where x_i shows the inputs of fuzzy system. Thus, Eq.(4) can be rewritten as follow:

$$f_j = \sum_{l=1}^{L} \bar{y}_j^l \zeta_{(x)} = \theta_j^T \zeta_{j(x)} \quad , \quad j=1,2,\ldots,m \qquad (6)$$

where $\zeta_{j(x)} = [\zeta_{(x)}{}^{1}, \ldots, \zeta_{(x)}{}^{L}]^T$ is the fuzzy basis function vector, and $\theta_j = [\bar{y}_j^1, \ldots, \bar{y}_j^L]^T$ is the parameter vector.

Then, the overall output of a multi-input and multi-output fuzzy logic system can be rewritten as

$$f = \theta^T \zeta_{(x)} \qquad (7)$$

where θ is an $(L\times m)$ matrix consist of the centers of output membership functions of fuzzy logic system, θ_j denotes the $(L\times 1)$ *jth* column of the matrix θ and x is vector of fuzzy system inputs. In this paper we use joint angles as inputs of system. As it is evident, the proposed adaptive fuzzy system does not use all system states for estimating the uncertainty, so the number of fuzzy rules is reduced.

3.2. Adaptive Control Scheme

In this section, an adaptive control scheme that is combined of feedback linearization controller and fuzzy compensators is designed to compensate the uncertainties. The configuration of the proposed adaptive control scheme is shown in Fig. 1. In order to make the joint motions of the robotic system follow the desired trajectories, the feedback linearization controller τ_0 in Fig.1 is connected to the compensator τ_f to generate a controller signal τ for the robot manipulator. That is, the control law is given by

$$\tau = \tau_0 + \tau_f \qquad (8)$$

where τ_0 , the output torque of the feedback linearization controller, defined as Eq.(2), and τ_f is the output torque of the fuzzy compensator that will be defined in Eq. (14).

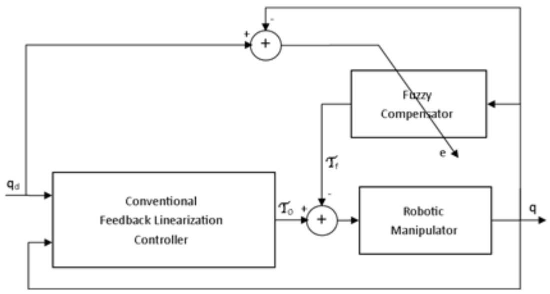

Fig. 1. Proposed adaptive control scheme

The feedback linearization part of controller takes the actual commands and position variables of joints as the input, variables of joints constitute fuzzy rules, and the error is used to tune parameters of the fuzzy compensator. The output τ_f of the fuzzy compensator omits the uncertainties caused by external disturbance and inaccurate dynamic model.

The following torque equation is used to represent the control scheme:

$$\tau = \widehat{D}_{(q)}\left(\ddot{q}_d + k_d \dot{e} + k_p e + f\right) + \widehat{H}_{(q,\dot{q})} \qquad (9)$$

Thus, the corresponding closed loop tracking error dynamic equation is

$$\ddot{e} + k_d \dot{e} + k_p e =$$

$$\widehat{D}^{-1}\left(\left(D - \widehat{D}\right)\ddot{q} + \left(H - \widehat{H}\right) + F\right) - f = \omega \qquad (10)$$

Since the control objective is to generate joint torques (f) to reduce the error signal ω in Eq. (9), clearly minimizing the error signal ω by the use of fuzzy compensator allows us to achieve ideal control directly.

The f in Eq. (9) is defined by an ideal fuzzy logic system as

$$f = \theta^{*T} \zeta_{(x)} + \varepsilon \qquad (11)$$

where ε is the minimum possible fuzzy approximation error; $\zeta_{(x)} = [\zeta_{(x)}{}^{1}, \zeta_{(x)}{}^{2}, \ldots, \zeta_{N(x)}{}^{N}]^T$ is the fuzzy basis function vector, and $\zeta_{(x)}{}^{l}$ corresponds to Eq.(5); $x = q^T$ is the input vectors of the fuzzy system. $\theta^* \in R^{N\times N}$ is a weight matrix that makes optimal estimate of uncertainties and is defined as follow [16]:

$$\theta^* = \arg min_{\theta\in\Omega_\theta} \left\{sup_{x\in\theta_x}\left|\hat{f}\left(x\middle|\hat{\theta}\right) - f(x|\theta)\right\}\right. \qquad (12)$$

where Ω_θ, θ_x denote the sets of suitable bounds on θ and x , respectively, and $\hat{f}(x|\hat{\theta})$ is an estimation of $f(x|\theta)$, which can be defined as follow:

$$\hat{f}(x|\hat{\theta}) = \hat{\theta}^T\zeta_{(x)} \quad (13)$$

Thus, the fuzzy compensator control law τ_f in Eq. (8) can be defined as follow:

$$\tau_f = \hat{D}_{(q)}\hat{f}(x|\hat{\theta}) \quad (14)$$

From Eq. (10) and Eq. (14), the tracking error dynamic Eq. (9) can be rewritten as

$$\dot{X} = AX + B\hat{\omega} \quad (15)$$

where $\hat{\omega} = \zeta_{(x)}(\theta^{*T} - \hat{\theta}^T) + \varepsilon$.

3.3. Adaption Law

Definition 1. The trace of a square matrix $A = [a_{ij}]_{n\times n}$, denoted by $tr(A)$, is defined as the sum of diagonal elements of the matrix A. The trace function has the following properties: (1) $tr(A^T) = tr(A)$; (2) for any $n\times k$ matrix A and $k\times n$ matrix B, $tr(AB) = tr(BA)$; (3) for any scalar a and square matrix A , $tr(a.A) = a.tr(A)$.

On the basis of the above discussions, by Lyapunov stability theory we can get the following result. We define the following function for energy of system as Lyapunov function candidate:

$$V = \tfrac{1}{2}X^TPX + \tfrac{1}{2\gamma}tr\left((\theta^* - \hat{\theta})^T(\theta^* - \hat{\theta})\right) \quad (16)$$

Where P is a unique $n\times n$ positive definite symmetrical matrix, which can be earned by the Lyapunov equation [24]:

$$A^TP + PA = -Q \quad (17)$$

The derivative of V with respect to time is given by:

$$\dot{V} = \tfrac{1}{2}\dot{X}^TPX + \tfrac{1}{2}X^TP\dot{X} - \tfrac{1}{2\gamma}tr\left(\dot{\hat{\theta}}^T(\theta^* - \hat{\theta}) + (\theta^* - \hat{\theta})^T\dot{\hat{\theta}}\right) \quad (18)$$

By substituting Eq. (15) and (17) into Eq. (18) we will have the following equation:

$$\dot{V} = -\tfrac{1}{2}X^TQX + X^TPB\left(\zeta_{(x)}(\theta^{*T} - \hat{\theta}^T) + \varepsilon\right) - \tfrac{1}{\gamma}tr\left(\dot{\hat{\theta}}(\theta^* - \hat{\theta})^T\right) \quad (19)$$

With the help of mathematical rules of matrix we can extract the following adaption law for the adaptive fuzzy compensator in control torque Eq. (8).

$$\dot{\hat{\theta}} = \gamma X^TPB\zeta_{(x)} \quad (20)$$

4. Stability Analysis

Theorem 1. Rayleigh-Ritz theorem [25]**:** Let A be a real, symmetrical $n\times n$ positive-definite matrix. Let λ_{min} be the minimum eigenvalue and λ_{max} be the maximum eigenvalue of A . Then, for $X \in R^n$, $\lambda_{\min(A)}\|X\|^2 \le X^TAX \le \lambda_{\max(A)}\|X\|^2$.

From the adaptive control law Eq.(20) and Lyapunov Eq.(17), we can get

$$\dot{V} = -\tfrac{1}{2}X^TQX + X^TPB\varepsilon \quad (21)$$

Based on theorem 1 (Rayleigh-Ritz), we will have:

$$\begin{cases} -\tfrac{1}{2}X^TQX \le -\tfrac{1}{2}\lambda_{\min(Q)}\|X\|^2 \\ X^TPB\varepsilon \le \|\varepsilon_0\|\|P\|\|X\| \le \|\varepsilon_0\|\lambda_{\max(P)}\|X\| \end{cases} \quad (22)$$

Thus we reach the following inequality:

$$\dot{V} \le -\tfrac{1}{2}\lambda_{\min(Q)}\|X\|^2 + \|\varepsilon_0\|\lambda_{\max(P)}\|X\| = -\tfrac{1}{2}\|X\|\left[\lambda_{\min(Q)}\|X\| - 2\|\varepsilon_0\|\lambda_{\max(P)}\right] \quad (23)$$

As long as the term in the brace is positive then the $\dot{V}$ is negative, which connotes

$$\|X\| > \frac{2\|\varepsilon_0\|\lambda_{\max(P)}}{\lambda_{\min(Q)}} \quad (24)$$

The negative semi-definiteness of $\dot{V}$ outside the compact set $\left\{\|X\| < \frac{2\|\varepsilon_0\|\lambda_{\max(P)}}{\lambda_{\min(Q)}} < \infty\right\}$ implies the boundedness of V and X . Thus as long as the inequality (24) is satisfied, inequality (23) is guaranteed and the error will be reduced. In other words the error signal will move into a spherical space with radius $2\|\varepsilon_0\|\lambda_{\max(P)}/\lambda_{\min(Q)}$ and by assuming a good system design with sufficiently small fuzzy approximation error, according to Lyapunov stability theory, the system is stable and the error would be limited. Therefore, the stability of the closed-loop system is guaranteed using the control adaption law Eq. (20).

5. Simulation Results and Discussions

In this section, we examine the performance of the proposed adaptive fuzzy controller through simulations on applying the proposed control law to control an SCARA robot manipulator with a symbolic picture in Fig. 2. We also make a comparison between the proposed controller and conventional feedback linearization controller.

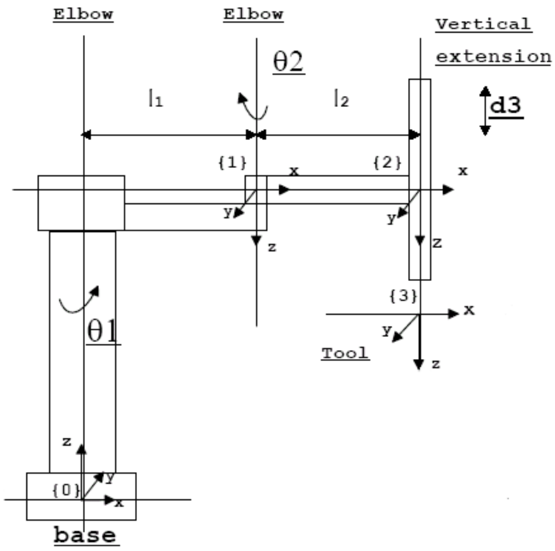

Fig. 2. The structure of three link SCARA robot manipulator

Table 1. The Denavit-Hartenberg parameters

$Joint$	l	α	d	θ
1	l_1	0	0	θ_1
2	l_2	2π	0	θ_2
3	0	0	d_3	0

The Denavit–Hartenberg (DH) parameters of the SCARA robot are given in Table 1, where the parameters θ_i , d_i , α_i and l_i are called the joint angle, link offset, link twist, and link length, respectively. Using the conventional Euler-Lagrangian approach, we can derive the robot dynamic equation of the three-link SCARA robot manipulator as follows [26]:

$$D_{(q)_{3\times3}}\ddot{q} + C_{(q,\dot{q})_{3\times3}}\dot{q} + G_{(q)_{3\times1}} = \tau \qquad (25)$$

where

$$D_{11} = \left(\frac{m_1}{3} + m_2 + m_3\right) {l_1}^2 + \left(\frac{m_2}{3} + m_3\right) {l_2}^2 + (m_2 + 2m_3) l_1 l_2 Cosq_2 + I_1 + I_2 + I_3$$

$$D_{12} = -\left(\frac{m_2}{2} + m_3\right) {l_2}^2 - \left(\frac{m_2}{3} + m_3\right) l_1 l_2 Cosq_2 + I_2 + I_3$$

$$D_{22} = -\left(\frac{m_2}{3} + m_3\right) {l_2}^2 + I_2 + I_3$$

$$D_{33} = m_3 \quad , \quad D_{21} = D_{12} \quad , \quad D_{13} = D_{23} = D_{31} = D_{32} = 0$$

$$C_{11} = -l_1 l_2 (\frac{m_2}{2} + m_3)\dot{q}_2 Sinq_2$$

$$C_{12} = -l_1 l_2 (\frac{m_2}{2} + m_3)\dot{q}_2 Sinq_2 - l_1 l_2 (\frac{m_2}{2} + m_3)\dot{q}_1 Sinq_2$$

$$C_{21} = l_1 l_2 (\frac{m_2}{2} + m_3)\dot{q}_1 Sinq_2$$

$$C_{13} = C_{22} = C_{23} = C_{31} = C_{32} = C_{33} = 0$$

$$G_1 = G_2 = 0 \quad , \quad G_3 = -9.81 m_3$$

and l_i , I_i and m_i are the length, moment of inertia and mass of the i-th link respectively. The actual parameter values used for the simulation study are given in table 2.

Table 2. Actual parameters of links

$link$	$length$	$mass$	$moment\ of\ inertia$
1	$l_1 = 0.4\,m$	$m_1 = 10\,kg$	$I_1 = 0.88\,kgm^2$
2	$l_2 = 0.4\,m$	$m_2 = 10\,kg$	$I_2 = 0.58\,kgm^2$
3	$l_3 = 0.3\,m$	$m_3 = 3.9\,kg$	$I_3 = 0.15\,kgm^2$

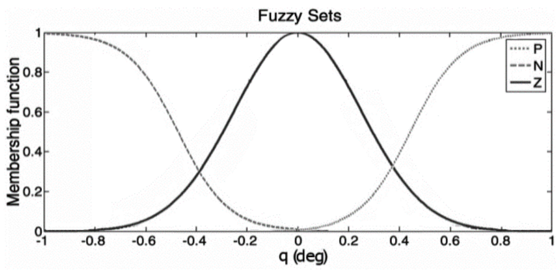

Fig. 3. Membership functions of each input

In order to consider the structured uncertainties, all parameters are assumed to be 90% of their real values. Moreover, friction force is added to each joint. In the simulation, the initial values of the SCARA robot are set as $q_{i(0)} = 0\ and\ \dot{q}_{i(0)} = 0\ (i = 1,2,3)$. The input vector of the fuzzy controller is given as $x = \{q_1, q_2, q_3\}$. The fuzzy linguistic rules are submitted in the form of Mamdani type

$$Rule^l :\ If\ x_1\ is\ {A_1}^l\ and\ \ x_2\ is\ {A_2}^l\ and\ \ x_3\ is\ {A_3}^l, \quad Then\ f\ is\ B^l$$

where l _the number of fuzzy rule_ for three inputs will be $l = 1, \ldots, 27$. In the lth rule, ${A_i}^l\ (i = 1,2,3)$ and B^l are membership functions of the fuzzy variables. Three Gaussian membership functions, $\mu_{A^l(x_i)}$, named as Positive (P), Zero (Z), and Negative (N) as shown as in Fig. (3) are defined for each input.

To simulate the control scheme of the three-link SCARA robot manipulator, the kinematics and dynamic models obtained from Eq. (25) are implemented within the MATLAB environment, and Matlab/Simulink software is used as the simulation tool.

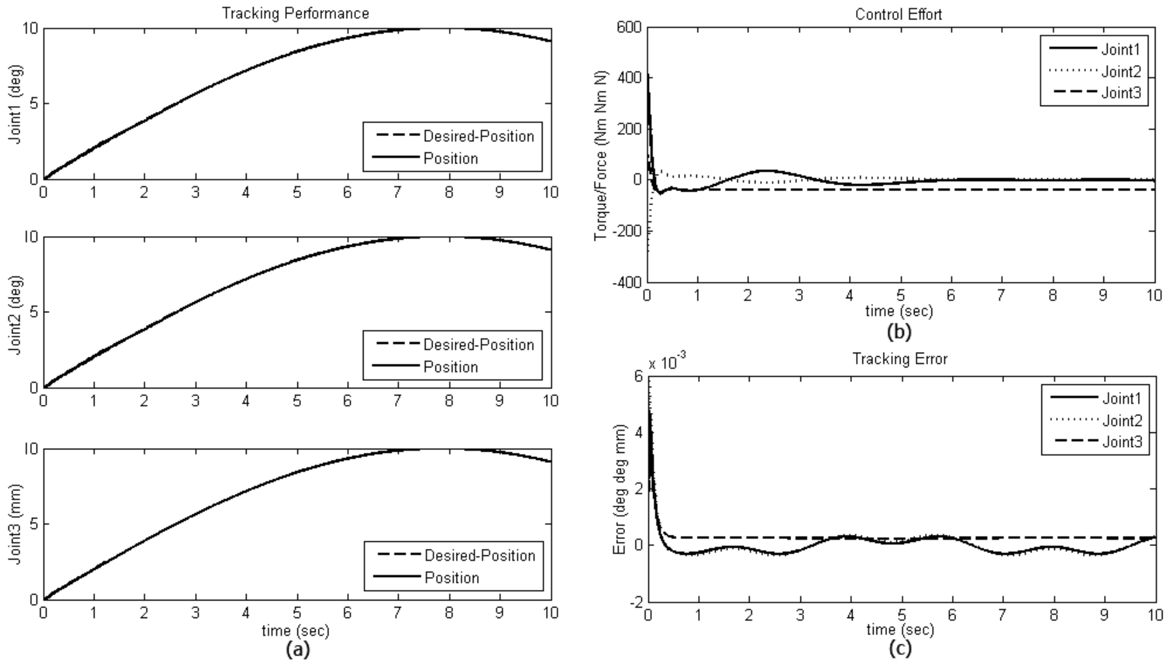

Fig. 4 Performance of the controller Eq. (2) without uncertainties:
(a) Tracking performance of first, second and third joint; (b) Input torques for three joints; (c) Tracking error of three joints.

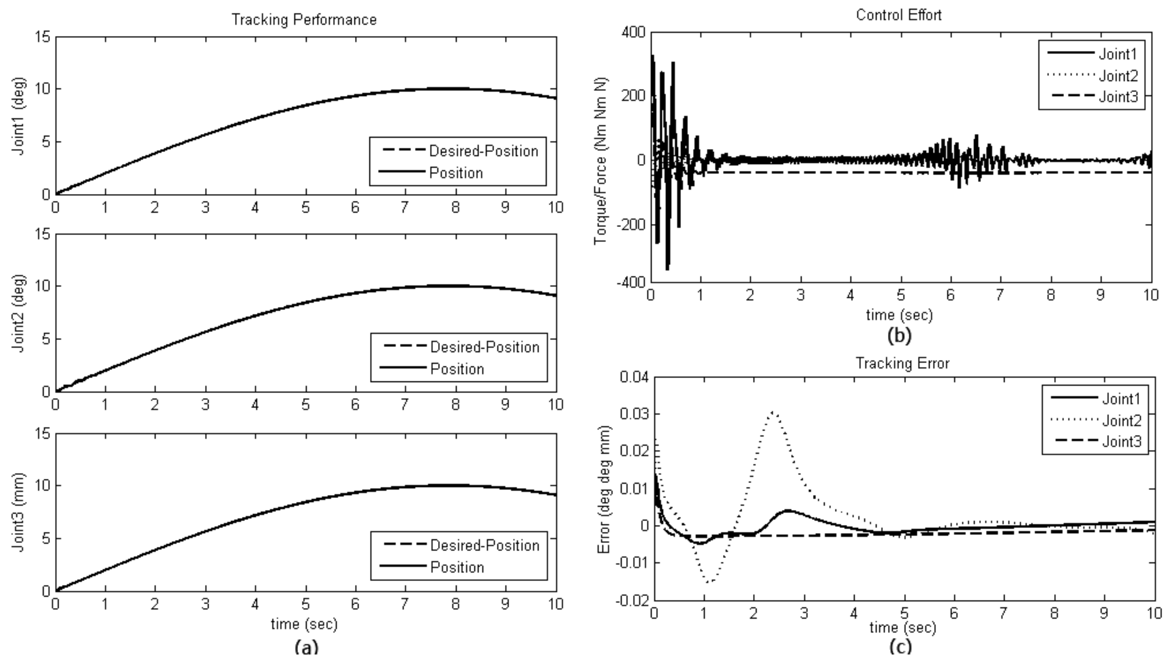

Fig. 5. Performance of the controller Eq. (2) in presence of uncertainties:
(a) Tracking performance of first, second and third joint; (b) Input torques for three joints; (c) Tracking error of three joints.

Simulation 1 . We set the feedback linearization control law (2) with $K_p = diag(200,200,200)$ and $K_d = diag(20,20,20)$. The performance of the controller and computed torques are shown in Fig. 4 (a) and Fig. 4 (b) and error signal in Fig. 4 (c). In this case the feedback linearization Controller is based on precise dynamical knowledge of robotic manipulators without uncertainties. As can be observed from Fig. 4, the tracking error goes under 1×10^{-3} deg/deg/mm and the input torques applied to the three joints shows smooth control performances. However, because of uncertainty in dynamics of model in industrial field, this feedback linearization control is unattractive to industry.

Simulation 2 . The set of tracking performance of the feedback linearization controller (2) in presence of uncertain dynamics is illustrated in Fig. 5.

In this case the control scheme is designed according to nominal parameters in case simulation 1, it's while the actual parameters are different from nominal parameters and viscous type friction force with constant diagonal coefficient matrix $f = 0.2$ is added to joints. In compared with the first case, from Fig. 5 (a, c) is evident that the tracking performance cannot be acceptable and the tracking error goes above 0.03 deg in joint 2. Thus the control scheme (2) cannot be useful with uncertain dynamics.

Simulation 3 . In order to decrease the tracking error in case simulation 2, the proposed adaptive fuzzy controller in Eq. (9) is used to control the manipulator with uncertain dynamics _same as simulation 2_ and an external disturbance with sudden changes in uncertainty, given by a square pulse with amplitude=1Nm and period=5secs. In this case the part of feedback linearization control law adjusted with the same coefficients of case simulation 1 and the adaptive fuzzy compensator's parameters are given by $x_c = 5$, $\sigma = 1$, $\gamma = 8000$ and $Q = I_{6\times6}$.

Fig. 6 displays the tracking performances in third case.

As depicted in Fig. 6, the tracking errors are clearly reduced compared with simulation 2, and is under 1×10^{-2} .

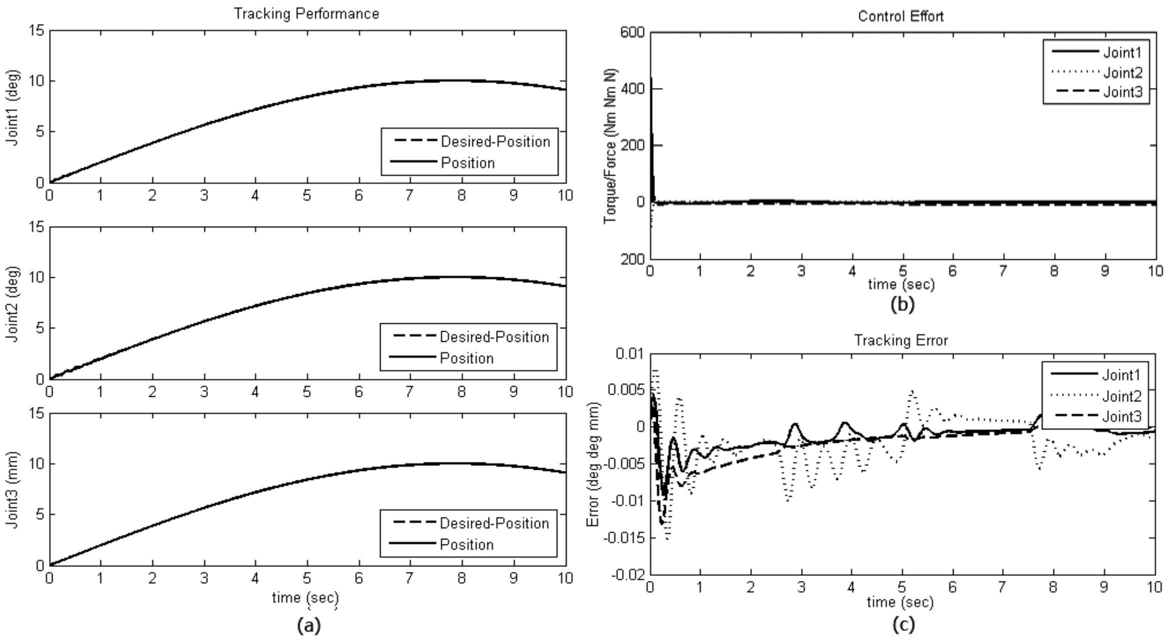

Fig. 6. Performance of the controller in presence of uncertainties and external disturbance:
(a) Tracking performance of first, second and third joint; (b) Input torques for three joints; (c) Tracking error of three joints.

Therefore, these simulations showcase that the proposed feedback linearization controller combined with the fuzzy compensator can obtain better performances in presence of uncertainties and external disturbance in comparison to conventional feedback linearization controller.

6. Conclusion

This paper has developed an adaptive control scheme, that fuzzy compensator is used to compensate uncertainties in dynamic model and external disturbance. We have used a fuzzy system to estimate and compensate uncertainty. Comparisons of its performance with conventional feedback linearization torque controller under the condition of these uncertainties are carried out. Comparative results demonstrate that the adaptive control scheme is effective in improving control performances in presence of modeling uncertainties and external disturbances. The convergence and stability of the control scheme is proved by using the Lyapunov method. The stability analysis verifies that the system states will be bounded. Computer simulation of a three-link SCARA robot manipulator is carried out. Simulation results have corroborated the effectiveness of the method. The control approach is robust with a very good tracking performance.

References

[1] M. M. Fateh, S. Khorashadizadeh: Robust control of electrically driven robots by adaptive fuzzy estimation of uncertainty, Nonlinear Dynamics, **69**(3), 1465-1477, (2012).

[2] M.M. Fateh, M.R. Soltanpour: Robust task-space control of robot manipulators under imperfect transformation of control space, Int. J. Innov. Comput. Inf. Control **5**(11A), 3949–3960 (2009)

[3] Y. Chen, G. Ma, S. Lin, and J. Gao: Adaptive Fuzzy Computed-Torque Control for Robot Manipulator with Uncertain Dynamics, Int. J. Advanced Robotic Systems, **9**, 237–246 (2012)

[4] H.G. Sage, M.F. De-Mathelin, E. Ostertag: Robust control of robot manipulators: a survey, Int. J. Control **72**(16), 1498–1522 (1999)

[5] M.M. Fateh: Robust control of electrical manipulators by joint acceleration, Int. J. Innov. Comput. Inf. Control **6**(12), 5501–5510 (2010)

[6] R. Yan, K. Tee, H.Z. Li: Adaptive learning tracking control of robotic manipulators with uncertainties, Journal of Control Theory and Applications, **8**(2), 160 - 165 (2010).

[7] Q. Zheng and F. Wu: Adaptive control design for uncertain polynomial nonlinear systems with parametric uncertainties, Int. J. Adaptive Control and Signal Processing, **25**(6), 502 - 518 (2011).

[8] T.C. Kuo: Trajectory Control of a Robotic Manipulator Utilizing an Adaptive Fuzzy Sliding Mode, World Academy of Science, Engineering and Technology, **65**, 913 - 917, (2010).

[9] J. Ohri, L. Dewan, M.K. Soni: Fuzzy adaptive dynamic friction compensator for robot, Int. J. Systems Applications, Engineering & Development, **2**(4), 157 - 161 (2008).

[10] C.M. Lin and C.F. Hsu: Adaptive fuzzy sliding mode control for induction servo motor systems, IEEE Transactions on Energy Conversion, **19**(2), 362 - 368, (2004).

[11] X.S. Lu, H.M. Schwartz: A revised adaptive fuzzy sliding mode controller for robotic manipulators, Int. J. Modeling, Identification and Control, **4**(2), 127 - 133 (2008).

[12] H.R. Kobravi and A. Erfanian: Decentralized adaptive robust control based on sliding mode and nonlinear compensator for the control of ankle movement using functional electrical stimulation of agonist–antagonist muscles, Journal of Neural Engineering, **6**(4), 1-10 (2009).

[13] D.H. Zeng: Fuzzy Sliding Mode Control for 6 - DOF Parallel Robot Based on Support Vector Machines, Key Engineering Materials, **467 - 469**, 645 - 651 (2011).

[14] D.Q. Zhu, T. Mei, L. Sun: Fuzzy Support Vector Machines Control for 6 - DOF Parallel Robot, Journal of Computers, **6**(9), 1926 - 1934 (2011).

[15] W. Peng, Z. Lin, J. Su: Computed torque control based composite nonlinear feedback controller for robot manipulators with bounded torques, IET Control Theory & Application, **3**(6), 701 - 711 (2009).

[16] L.X. Wang: A Course in Fuzzy Systems and Control, Prentice-Hall, New York , 1996.

[17] J.P. Hwang, E. Kim: Robust tracking control of an electrically driven robot, adaptive fuzzy logic approach. IEEE Trans. Fuzzy Syst. **14**(2), 232–247 (2006)

[18] M.M. Fateh: Robust fuzzy control of electrical manipulators, J. Intell. Robot. Syst. **60**(3–4), 415–434 (2010).

[19] M.M. Fateh: Fuzzy task-space control of a welding robot, Int. J. Robot. Autom. **25**(4), 372–378 (2010).

[20] M.M. Fateh, S. Shahrabi-Frahani, , A. Khatamianfar: Task space control of a welding robot using a fuzzy coordinator, Int. J. Control. Autom. Syst. **8**(3), 574–582 (2010).

[21] Z.S. Song, J.Q. Yi, D.B. Zhao, X.C. Li: A computed torque controller for uncertain robotic manipulator systems, Fuzzy approach, Fuzzy Sets and Systems, **154**(2), 208 - 226 (2005).

[22] W.W. Chen, J.K. Mills, J.X. Chu, D. Sun: A Fuzzy Compensator for Uncertainty of Industrial Robots, IEEE International Conference on Robotics & Automation, Seoul, Korea, 2968 - 2973 (2001).

[23] Y. Chen, G. Ma, S. Lin, and J. Gao: Adaptive Fuzzy Computed-Torque Control for Robot

Manipulator with Uncertain Dynamics, Int. J. Advanced Robotic Systems, **9**, 237-245, (2012)

[24] J. J. E. Slotine and W. Li: Applied Nonlinear Control, Prentice - Hall, New Jersey, 1991.

[25] L.L. Frank, M.D. Darren, T.A. Chaouki; Robot Manipulator Control: Theory and Practice. Marcel Dekker, New York, 2006.

[26] R.J. Schilling: Fundamentals of Robotics Analysis and Control. New Delhi: Prentice-Hall of India, 1990.