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Backstepping Adaptive Fuzzy Scheme for SCARA GRB400 Robot

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Abstract

In order to achieve the accurate trajectory tracking of 2 degree-of –freedom robot, a backstepping adaptive fuzzy control scheme based on Lyapunov method, is presented for the SCARA (Selective Compliance Assembly Robot Arm) robot system. The control strategy consists of the traditional backstepping control and adaptive fuzzy control to cope with the model unknown and parameter disturbances. The system is modeled using the MATLAB-SIMULINK toolbox. The simulation is presented to verify the effectiveness of the proposed control scheme. From the simulation results, fast response, strong robustness, good disturbance rejection capability and good angle tracking capability can be obtained. The output tracking error between the actual position output and the desired position output can asymptotically converge to zero. It is also revealed from simulation results that the proposed control strategy is valid and effective for the SCARA robot system.

Keywords: *backstepping adaptive fuzzy control, SCARA robot, MATLAB simulation*

1. Introduction

In recent decades, the robot research has been paid great attention. Robotic is a vast research field, mainly because of the many potential applications. The basic problem in controlling robot is to make manipulator to perform preplanned trajectory. Therefore, it must be controlled properly to track some trajectory because there exist the uncertainties, nonlinear, strong coupling and time-varied of the robot system, and external disturbances. In order to achieve these goals, many schemes which were PID (Proportion Integration Differentiation) control, optimal control, sliding mode control (SMC), adaptive control, fuzzy control and so on, have long been presented and applied [1]. Among these several control schemes, PID control is the most popularly adopted for controlling the robots in the industry due to its simplicity and computational efficiency.

Although the first robot invented by Japan has beenmore than forty years up to now, the SCARA (Selective Compliance Assembly Robot Arm) robot is still considered as the indispensable element in the automatic manufacture. SCARA is widely accepted by user in all kinds of automatic mechanical arm. Because of its speed, cost efficiency, reliability and small track under work, The SCARA is still considered as the best robot for a lot of work. In this paper, the SCARA GRB-400 robot (Figure 1) manufactured by Googol Technology is selected as object of study, which is consisted of base, horizontal arm, lifting joint and end actuator. SCARA robot has two parallel rotary joint, and the rotary motion of robot arm is in the plane, so the SCARA robot is also called horizontal robot. SCARA robot has a compact and simple structure, has higher motion speed and accuracy, especially is used for assembling work in the electronics industry, so SCARA robot is also called as assembly robot.

In this paper, based on Lyapunov method, an adaptive fuzzy control scheme combining backstepping is presented for the SCARA GRB-400 robot system which has two rotational joints on a horizontal plane and one translational joint on the vertical axis. The SCARA robot is commonly used as an assembly robot in the industry to perform some task repeatedly. It is proved that the closed-loop system is globally stable in the Lyapunov sense. If all the signals are bounded, the system output can track the desired reference output asymptotically with uncertainties and disturbances [2-3].

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Figure 1. SCARA GRB-400 robot

The paper is organized as follows. Section 2 will concern the mathematical model of the SCARA GRA-400 robot. The Backstepping Adaptive Fuzzy Control algorithm is proposed and proofed in section 3. The simulation results will be shown in section 4. Finally, the conclusion is drawn in Section 5.

2. Model of Scara Robot

2.1. Model Description

In Engineering, robots not only can improve productivity but also can achieve high-strength, highly difficult and hazardous jobs. Manipulators are the usual plants in robotics. Using the lagrangian formulation, the dynamic equation of a planner n degrees of freedom rigid manipulator can be expressed as follows.

$$M\left(q_k(t)\right)\ddot{q}_k(t)+C\left(q_k(t),\dot{q}_k(t)\right)\dot{q}_k(t)+G\left(q_k(t)\right)=\tau_k(t)+d_k(t) \quad (1)$$

Where $M\left(q_k(t)\right)\in R^{n\times n}$ is the inertia matrix. $q_k(t)\in R^n$ is the angle vector, $\dot{q}_k(t)\in R^n$ is the velocity vector, also the $\ddot{q}_k(t)\in R^n$ is acceleration vector. t denotes the time and is the nonnegative integer. $k\in Z_+$ denotes the operation or iteration times. $C\left(q_k(t),\dot{q}_k(t)\right)\in R^n$ is a vector resulting from the centrifugal and coriolis forces. $G\left(q_k(t)\right)$ is the gravity. $\tau_K(t)\in R^n$ is the control moment applied to the joints, and $d_k(t)\in R^n$ is the vector containing the unmodeled dynamics and other unknown external disturbances.

The characteristics of the kinetic model of a robot arm [4]:

1. Kinetic mode contains more number of items: The number of items included in the equation increases with the increase in the number of robot joint.
2. Highly nonlinearity: Each item of the equations contains non-linear factors such as sine and consine, et al.
3. High degree of coupling.
4. Model uncertainty and time-variant: Because the objects are not similar, the load will vary when the robot moves the objects. Also the joint friction torque will also change over time.

Suppose that the parameters of the system are unknown, and the following properties are written as:

Property 1

$M\left(q_k(t)\right)\in R^{n\times n}$ is a positive-definite symmetric, and bounded matrix. There exists positive constant, $\sigma_0>0,\sigma_0\in R,0<M\left(q_k(t)\right)\le\sigma_0 I$

Property 2
$C\left(q_k(t), \dot{q}_k(t)\right)$ is bounded. There exists known $C_b(q)$ such that $\left|C\left(q_k(t), \dot{q}_k(t)\right)\right| \le C_b(q)\left\|\dot{q}_k(t)\right\|$

Property 3
Matrix $\dot{M}\left(q_k(t)\right) - 2C\left(q_k(t), \dot{q}_k(t)\right)$ is a symmetric matrix, and:

$$X^T\left(\dot{M}\left(q_k(t)\right) - 2C\left(q_k(t), \dot{q}_k(t)\right)\right)X = 0 \tag{2}$$

Where X is a vector.
Property 4
The known disturbance is satisfied with $\left\|d_k\right\| \le d_m$, where d_m is a known positive constant.

2.2. Mathematical Model
The SCARA GRB-400 robot generally has two revolute joints and prismatic joint. The schematic diagram of the SCARA GRB-400 robot is shown in Figure 1. The robots transport a load horizontally by actuating the two revolute joints. The robots transport a load vertically by actuating the prismatic joint [5].

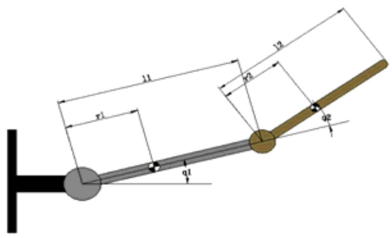

Figure 2. The Schematic Diagram of the SCARA GRB-400 Robot

The dynamic equation of the model for SCARA GRB-400 robot manipulator can be expressed as follows:

$$\begin{aligned} &M\left(q_k(t)\right)\ddot{q}_k(t) + C\left(q_k(t), \dot{q}_k(t)\right)\dot{q}_k(t) + d_k(t) = \tau_K(t) \\ &y = q_k(t) \end{aligned} \tag{3}$$

According to Lagrangian method, the inertia matrix $M\left(q_k(t)\right)$ can be written as:

$$M\left(q_k(t)\right) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{4}$$

Where:

$$M_{11} = J_1 + J_2 + 2m_2 r_2 l_1 \cos\theta_2, \quad M_{12} = J_2 + m_2 r_2 l_1 \cos\theta_2,$$
$$M_{21} = J_2 + m_2 r_2 l_1 \cos\theta_2, \quad M_{22} = J_2,$$
$$J_1 = \frac{4}{3} m_1 r^2{}_1 + m_2 l^2{}_1, \quad J_2 = \frac{4}{3} m_2 r^2{}_2.$$

Also the $C\left(q_k\left(t\right),\dot{q}_k\left(t\right)\right)$ is given by:

$$C\left(q_k\left(t\right),\dot{q}_k\left(t\right)\right) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \quad (5)$$

Where:

$$C_{11} = -2m_2r_2l_1\dot{\theta}_2\sin\theta_2, \quad C_{12} = -m_2r_2l_1\dot{\theta}_2\sin\theta_2,$$
$$C_{21} = m_2r_2l_1\dot{\theta}_2\sin\theta_2, \quad C_{22} = 0,$$
$$q = \begin{bmatrix}\theta_1 & \theta_2\end{bmatrix}^T, \quad \tau = \begin{bmatrix}\tau_1 & \tau_2\end{bmatrix}^T$$

Where m_1 is the mass of the 1th link, m_2 is the mass of the 2th link, l_1 and l_2 are the length of each link. r_1 and r_2 are distances between the gravity center position and rotational position of the each links. θ_1 and θ_2 are the angle of each links. J_1 and J_2 are the inertia matrix of two links. In addition, $G\left(q_k\left(t\right)\right)$ terms are ignored in this paper because the absence of the $G\left(q_k\left(t\right)\right)$ terms in the equation of motion could be interpreted as assuming the robot is statically balanced. On the other hand, the absence of gravity is interpreted by simply assuming that the robot is working in outer space.

3. Backstepping Adaptive Fuzzy Control Algorithm [11]

In order to apply Backstepping method, define $x_1 = q_k(t), x_2 = \dot{q}_k(t)$. Using (1), we can obtain:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= M^{-1}(x_1)\tau - M^{-1}(x_1)C(x_1,x_2)x_2 - M^{-1}(x_1)d \\ y &= x_1 \end{aligned} \quad (6)$$

Step 1:

Assuming y_d is the expected angle and has second order derivative. Define $z_1 = y - y_d$. α_1 is the estimation of the x_2. Define $z_2 = x_2 - \alpha_1$. According to selecting the appropriate α_1, making $z_2 \to 0$, we can obtain $\dot{z}_1$ following as:

$$\dot{z}_1 = \dot{x}_1 - \dot{y}_d = z_2 + \alpha_1 - \dot{y}_d \quad (7)$$

Select the virtual control item as:

$$\alpha_1 = -\lambda_1 z_1 + \dot{y}_d \left(\lambda_1 > 0\right) \quad (8)$$

Select the Lyapunov function for the first subsystem as :

$$V_1 = \frac{1}{2}z_1^T z_1 \quad (9)$$

There:

$$\dot{V}_1 = z_1^T \dot{z}_1 = z^T{}_1(\dot{y} - \dot{y}_d) = z^T{}_1(z_2 + \alpha_1 - \dot{y}_d) = -\lambda_1 z^T{}_1 z_1 + z^T{}_1 z_2 \quad (10)$$

If z_2 is zero, the first subsystem is stable.

Step 2:
Using (3) (5), we can obtain :

$$\dot{z}_2 = \dot{x}_2 - \dot{\alpha}_1 = -M^{-1}Cx_2 - M^{-1}d + M^{-1}\tau - \dot{\alpha}_1 \quad (11)$$

Select the control rule as following:

$$\tau = -\lambda_2 z_2 - z_1 - \phi \quad (12)$$

Select the Lyapunov function for the second subsystem:

$$V_2 = V_1 + \frac{1}{2} z^T{}_2 M z_2 \quad (13)$$

Therefore:

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 + \frac{1}{2}\dot{z}_2^T M z_2 + \frac{1}{2} z^T{}_2 \dot{M} z_2 + \frac{1}{2} z^T{}_2 M \dot{z}_2 = -\lambda_1 z^T{}_1 z_1 + z^T{}_1 z_2 + z^T{}_2 M(\dot{x}_2 - \dot{\alpha}_1) + \frac{1}{2} z^T{}_2 \dot{M} z_2 \\ &= -\lambda_1 z^T{}_1 z_1 + z^T{}_1 z_2 + z^T{}_2 M(-M^{-1}Cx_2 - M^{-1}d + M^{-1}\tau - \dot{\alpha}_1) + z^T{}_2 C z_2 \\ &= -\lambda_1 z^T{}_1 z_1 + z^T{}_1 z_2 + z^T{}_2(f - \lambda_2 z_2 - z_1 - \phi) - z^T{}_2 d \\ &= -\lambda_1 z^T{}_1 z + -\lambda_2 z^T{}_2 z_2 + z^T{}_2(f - \phi)\end{aligned} \quad (14)$$

Where $f = -C\alpha_1 - M\dot{\alpha}_1$

From the expression of the f, we can obtain the modeling information of robotics system. In order to realize the control without model information, we make fuzzy system approximate the f. If ϕ is used to approximate the fuzzy system of the nonlinear function f, the single value fuzzification, the product inference engine and the center average defuzzifier are adopted [3, 6, 7, 8].

If fuzzy system is consisted of N fuzzy rules, the ith fuzzy rule is expressed as:

R^i :IF x_1 is $\mu^k{}_1$ and...and x_n is $\mu^k{}_n$, then y is B^k (k =1,2, …N) ,Where $\mu^k{}_i$ is the membership function of the x_i (i =1,2, …n).

The output of fuzzy system is written as:

$$y = \frac{\sum_{k=1}^{N} \theta_K \prod_{i=1}^{n} \mu^k{}_i(x_i)}{\sum_{k=1}^{N} \prod_{i=1}^{n} \mu^k{}_i(x_i)} = \xi^T \theta \quad (15)$$

Where:

$$\xi = [\xi_1(x), \xi_2(x), \xi_3(x), ..., \xi_N(x)], \quad \xi_K(x) = \frac{\prod_{i=1}^{n} \mu^k{}_i(x_i)}{\sum_{k=1}^{N} \prod_{i=1}^{n} \mu^k{}_i(x_i)}, \quad (16)$$

$$\theta = \left[\theta_1, \theta_2, \theta_3, \ldots, \theta_N\right]^T.$$

Based on the fuzzy approximation of the f the fuzzy system for $f(1)$ and $f(2)$ is designed as:

$$\phi_1(x) = \frac{\sum_{k=1}^{N} \theta_{1K} \prod_{i=1}^{n} \mu^k{}_i(x_i)}{\sum_{k=1}^{N}\left[\prod_{i=1}^{n} \mu^k{}_i(x_i)\right]} = \xi_1^T \theta_1$$
$$\phi_1(x) = \frac{\sum_{k=1}^{N} \theta_{2K} \prod_{i=1}^{n} \mu^k{}_i(x_i)}{\sum_{k=1}^{N}\left[\prod_{i=1}^{n} \mu^k{}_i(x_i)\right]} = \xi_2^T \theta_2 \tag{17}$$

Define:

$$\Phi = \left[\phi_1, \phi_2\right]^T = \begin{bmatrix} \xi_1^T & 0 \\ 0 & \xi_2^T \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \xi^T \theta \tag{18}$$

θ^* is defined the optimal approximative constant. The following inequality is established for a given any small constant $\varepsilon(\varepsilon > 0)$ [9, 10].

$\left\|f - \Phi^*\right\| \le \varepsilon$. and $\tilde{\theta} = \theta^* - \theta$.

The self-adaptive control law is designed as:

$$\dot{\theta} = \gamma(z_2^T \xi^T(x))^T - 2k\theta \tag{19}$$

Step 3:

The Lyapunov function is selected for the whole system:

$$V = \frac{1}{2} z_1^T z_1 + \frac{1}{2} z_2^T M z_2 + \frac{1}{2\gamma} \tilde{\theta}^T \tilde{\theta} (\gamma > 0) \tag{20}$$

Therefore:

$$\begin{aligned} \dot{V} &= -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + z_2^T(f - \xi(x)\theta) - z_2^T - \frac{1}{\gamma} \tilde{\theta}^T \dot{\theta} \\ &= -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + z_2^T(f - \xi(x)\theta^*) + z_2^T(\xi(x)\theta^* - \xi(x)\theta) - z_2^T d - \frac{1}{\gamma} \tilde{\theta}^T \dot{\theta} \end{aligned} \tag{21}$$

Then:

$$\begin{aligned} \dot{V} &\le -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + \left\|z_2^T\right\| \left\|(f - \xi(x)\theta^*)\right\| + z_2^T(\xi(x)\tilde{\theta}) + \left\|z_2^T\right\| \left\|d\right\| - \frac{1}{\gamma} \tilde{\theta}^T \dot{\theta} \\ &\le -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + \frac{1}{2}\left\|z_2^T\right\|^2 + \frac{1}{2}\varepsilon^2 + \frac{1}{2}\left\|z_2^T\right\|^2 \\ &\quad + \frac{1}{2}\left\|d\right\|^2 + \tilde{\theta}^T \left[(z_2^T \xi(x))^T - \frac{1}{\gamma}\dot{\theta}\right] \end{aligned} \tag{22}$$

Because of $\dot{\theta} = \gamma(z_2^T \xi^T(x))^T - 2k\theta$, we can obtain:

$$\dot{V} \le -\lambda_1 z_1^T z_1 - (\lambda_2 - 1) z_1^T z_2 + \frac{k}{\gamma}(2\theta^{*T}\theta - 2\theta^T\theta) + \frac{\varepsilon^2}{2} + \frac{1}{2} d^T d \tag{23}$$

Using (22) and $\left(\theta - \theta^*\right)^T \left(\theta - \theta^*\right) \geq 0$, we can obtain:

$$\dot{V} \leq -\lambda_1 z_1^T z_1 - (\lambda_2 - 1) z_2^T z_2 + \frac{k}{\gamma}(-\theta^{*T}\theta^* - \theta^T\theta) + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d \tag{24}$$

Due to $\left(\theta + \theta^*\right)^T \left(\theta + \theta^*\right) \geq 0$, Then:

$$\tilde{\theta}^T\tilde{\theta} = (\theta^{*T} - \theta^T)(\theta^* - \theta) \leq 2\theta^{*T}\theta^* + 2\theta^T\theta - \theta^T\theta - \theta^{*T}\theta^* \leq -\frac{1}{2}\tilde{\theta}^T\tilde{\theta} \tag{25}$$

Namely:

$$\dot{V} \leq -\lambda_1 z_1^T z_1 - (\lambda_2 - 1) z_2^T M^{-1} M z_2 - \frac{k}{2\gamma}\tilde{\theta}^T\tilde{\theta} + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d \tag{26}$$

The optimal parameter is defined as: $\lambda_2 > 1$,

$$M \leq \sigma_0 I,\ -M^{-1} \leq -\frac{1}{\sigma_0} I \tag{27}$$

We can obtain:

$$\dot{V} \leq -\lambda_1 z_1^T z_1 - (\lambda_2 - 1)\frac{1}{\sigma_0} z_2^T M z_2 - \frac{k}{2\gamma}\tilde{\theta}^T\tilde{\theta} + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d \tag{28}$$

Define:

$$\frac{c_0}{2} = \min\left\{\lambda_1, (\lambda_2 - 1)\frac{1}{\sigma_0}, \frac{k}{2}\right\} \tag{29}$$

Then:

$$\begin{aligned}\dot{V} &\leq -c_0\left(\frac{1}{2}z_1^T z_1 + \frac{1}{2}z_2^T M z_2 + \frac{1}{2\gamma}\tilde{\theta}^T\tilde{\theta}\right) + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d \\ &\leq -c_0 V + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d\end{aligned} \tag{30}$$

Because the interference $d \in R^n$ is bounded, then there exists the $D > 0$ and meets the $d^T d \leq D$.
Then:

$$\dot{V} \leq -c_0 V + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{D}{2} = -c_0 V + c_{V\max} \tag{31}$$

Where $c_{V\max} = \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{D}{2}$
By solving the inequality (30), we can obtain:

$$V(t) \leq V(0)\exp(-c_0 t) + \frac{c_{V\max}}{c_0}\left[1 - \exp(-c_0 t)\right] \leq V(0) + \frac{c_{V\max}}{c_0}, (t \geq 0) \tag{32}$$

Where $V(0)$ is the initial value of the V. Defining the compact set, $\Omega_0 = \left\{X V(X) \leq V(0) + \frac{c_{V\max}}{c_0}\right\}$.

4. Simulation

In order to verify the effectiveness of the Backstepping Adaptive Fuzzy scheme, MATLAB is used to make simulation for the SCARA GRB-400 robot. The parameters for simulation are shown in Table 1.

Table 1. Parameters for Simulation

Description	Parameter
m_1	0.2kg
m_2	0.2kg
l_1	0.3m
l_2	0.3m
r_1	0.15
r_2	0.15

The initial state value of system is as: $x(0)=\begin{bmatrix}1 & 1 & 0 & 0\end{bmatrix}^T$

The external disturbance is selected as: $d = \begin{bmatrix}0.5\sin t & 0.5\cos t\end{bmatrix}$

Design parameter are selected as:

$$\lambda_1 = 10, \lambda_2 = 15, k = 1.5, \gamma = 2, \quad \lambda_1 = 2, \lambda_2 = 2.5, k = 1.5, \gamma = 2,$$

Desired trajectory is as: $y_d = \sin(2\pi t)$.

The membership function is seclected as:

$$\mu_{F_i}{}^1 = \exp[-0.5((x_i + 1.25)/0.6)^2];$$

$$\mu_{F_i}{}^2 = \exp[-0.5((x_i)/0.6)^2];$$

$$\mu_{F_i}{}^3 = \exp[-0.5((x_i - 1.25)/0.6)^2];$$

Simulation results are shown from Figure 3 to Figure 9.

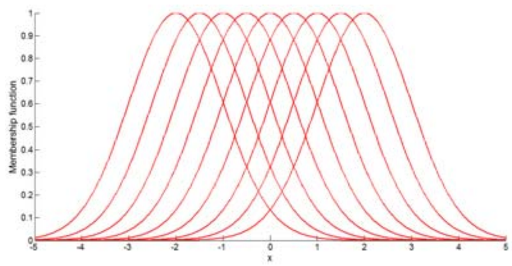

Figure 3. The Member Function of xi

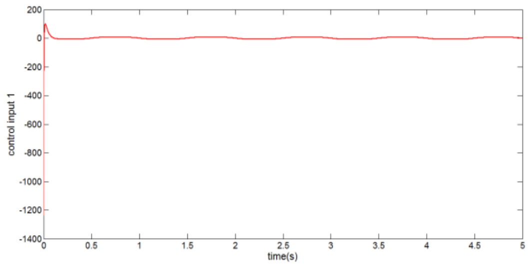

Figure 4. Control Input of 1th Link

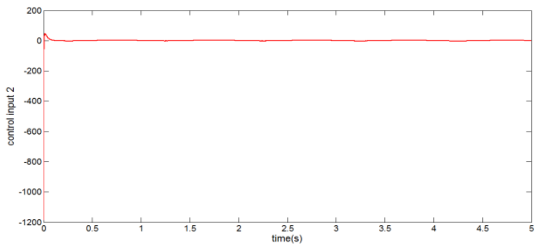

Figure 5. Control Input of 2th Link

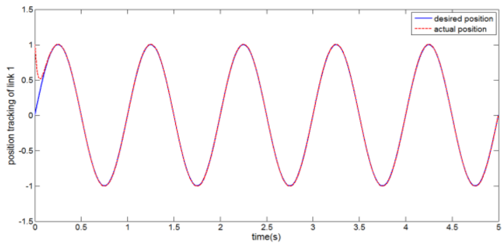

Figure 6. Response of the Angle q1

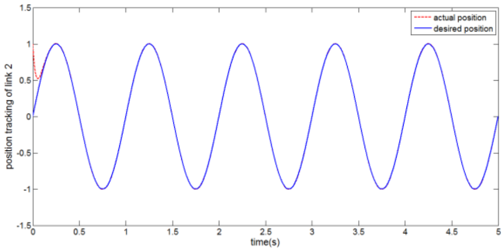

Figure 7. Response of the Angle q2

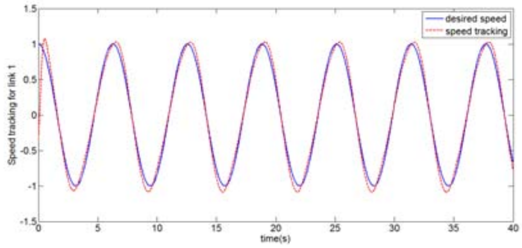

Figure 8. Speed Response of 1th Link

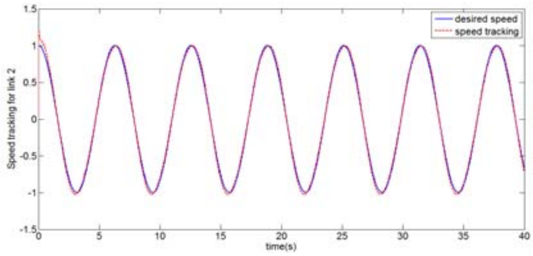

Figure 9. Speed Response of 2th Link

5. Conclusion

Pointing on uncertainties and instability in the robot system, an adaptive fuzzy control algorithm combining backstepping control algorithm is proposed for the SCARA GRB-400 robot in this paper. Based on the above control algorithm, the robust tracking performance of the SCARA GRB-400 robot can be guaranteed without needing an accurate robot model. The simulation results show that the adaptive controller can achieve desired performance and the algorithm is suitable for an inaccurate robot system. Simulation results also show the precise angle control, which is obtained in spite of disturbance and uncertainties in the system. These results also prove that the proposed control schemes are effective for the SCARA GRB-400 robot and the stability and control quality of SCARA GRB-400 robot are improved.

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