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Original Article

Adaptive Control for Uncertain Nonlinear Systems based on Fuzzy Logic

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Abstract *- Nowadays, robot manipulators are applied a lot in practice, it gradually replaces humans to perform boring, repetitive or life-threatening toxic environments. However, the robot is an uncertain nonlinear object, so it is difficult to model accurately, so it is not easy to control the robot to work stably. This paper presents an adaptive control method for uncertain nonlinear systems based on fuzzy logic. The controller is applied to control the robot manipulator to operate accurately, ensuring stability and good quality during the robot's work. The stability of the whole system is rigorously proven mathematically based on the Lyapunov theory. Finally, the simulation results of the robot manipulator system on Matlab-Simuink software show the effectiveness of the proposed method.*

Keywords *- Robot manipulator, Adaptive control, Fuzzy logic, Nonlinear systems, Uncertainty model.*

1. Introduction

The industrial revolution 4.0 broke out and developed more and more widely, and robots have gradually since been widely applied in most industries. Robot manipulators have contributed significantly to integrating new technologies, increasing labor efficiency, and increasing product competitiveness in the market... When robots are introduced into every stage in the production process, it will help for higher accuracy while working, helping to increase quality as well as limit defective products. For environments that are harmful to humans, such as toxic chemical environments, extreme temperatures, etc., using robots helps to solve production safety problems. Research to improve the quality of robot control will be one of the important issues for the modernization of industry and agriculture. Previously, studies often used PID controllers to control robots [1-5]. However, the parameters of the PID controller are usually fixed and do not change during system operation. Therefore, when the object has parameters or structure changes, the quality of the closed system will not be guaranteed, even unstable.

In this case, an adaptive controller is proposed [6-10] to change the robot's parameters adaptively. When the robot is affected by external disturbances, SMC is included in the study [11-16,28]. However, the disadvantage of SMC is that chattering occurs. Besides, some studies using fuzzy logic systems combined with traditional controllers have significantly improved the quality of nonlinear controllers [18-22]—for example, fuzzy, adaptive PI controllers. In addition, the fuzzy controller is also used to approximate nonlinear systems with an uncertainty model that ensures that the error is approximately within allowable limits [23-25]. We see that fuzzy control is an intelligent control method that relies on unclear information processing to issue control commands similar to human decisions. An ordinary fuzzy controller will rely on the designer's point of view, experience, and own way of thinking. The designer will convert his experiences into fuzzy composition rules to combine the fuzzy language variables together to make control decisions. Thus, the fuzzy controller is more of a trial and error than a general research method. To improve these defects, we have an adaptive fuzzy control method. The adaptive fuzzy control method is a method of designing the controller so that it can adjust its own control parameters, thereby helping the system to stabilize before changing working conditions. This self-alignment makes the fuzzy controller more flexible and reduces the limitation on the designer experience. There are many self-tuning methods of the adaptive fuzzy controller, in which the method of auto-tuning the fuzzy controller parameters is the easiest to implement. Choosing the parameter update rule requires the design system to be stable for the convergence problem, an important point of any adaptive control problem. The above analysis proposes an adaptive control method for a nonlinear system with an uncertainty model based on a fuzzy logic system. A construction controller is applied to control the robot manipulator for good response and feasibility.

The next part of the paper is presented as follows: The second part is based on the theoretical basis of the fuzzy adaptive control method of the uncertainty model nonlinear system, the third part applies the proposed controller to the robot manipulator, the results The interviews are presented in section 4, and finally section 5 is the conclusion of this paper.

2. Theoretical Basis

2.1. Description of the Problem

For a nonlinear system with a general differential equation [27]:

$$\dot{X} = \Omega(X) + Z(X)u \qquad (1)$$

where $\Omega(X)$ and $Z(X)$ are uncertain functions

The problem is to find the response of a satisfying system according to the reference value.

First, we use fuzzy logic to approximate $\Omega(X)$ and $Z(X)$.

$$\begin{aligned} \hat{\Omega}(X) &= \vartheta_{\Omega}^{T}\sigma(X) \\ \hat{Z}(X) &= \vartheta_{Z}^{T}\varsigma(X) \end{aligned} \qquad (2)$$

Where: ϑ_{Ω}^{T}, ϑ_{Z}^{T} are the parameter vectors at the output of the fuzzy system; $\sigma(X)$, $\varsigma(X)$ are vectors of basis functions. Then the adaptive fuzzy controller

$$u = \frac{1}{\hat{Z}(X)}\left(-\hat{\Omega}(X) + y^{\cdot}{}_{ref} + \kappa^{T}\Theta\right) \qquad (3)$$

With the adaptive law is as follows:

$$\begin{aligned} \dot{\vartheta}_{\Omega} &= -\eta_{1}\Theta^{T}H\Phi\sigma(X) \\ \dot{\vartheta}_{Z} &= -\eta_{2}\Theta^{T}H\Phi\varsigma(X)\,u \end{aligned} \qquad (4)$$

where y_{ref} is the reference output of the system; $\Theta$is the tracking error;$H$is a positively definite symmetric matrix satisfying the Lyapunov equation.

κ satisfies the equation:

$$\Theta^{n} + \kappa_{n}\Theta^{n-1} + \kappa_{n-1}\Theta^{n-2} + \ldots + \kappa_{1}\Theta = 0 \qquad (5)$$

Thus (5) is stable if the following polynomial is Hurwitz:

$$\begin{aligned} B(s) = s^{n} + \kappa_{n}s^{n-1} + \kappa_{n-1}s^{n-2} + \ldots + \kappa_{1}s \\ = 0 \end{aligned} \qquad (6)$$

2.2. Proof of Stability

Define the Lyapunov function as

$$\begin{aligned} V &= \frac{\Theta^{T}\mathrm{H}\Theta}{2} \\ &+ \frac{1}{2\eta_{1}}\left(\vartheta_{\Omega} - \vartheta_{\Omega}^{*}\right)^{T}\left(\vartheta_{\Omega} - \vartheta_{\Omega}^{*}\right) \\ &+ \frac{1}{2\eta_{2}}\left(\vartheta_{Z} - \vartheta_{Z}^{*}\right)^{T}\left(\vartheta_{Z} - \vartheta_{Z}^{*}\right) \end{aligned} \qquad (7)$$

Substitute (3) into equation (1) and transform we have:

$$\begin{aligned} \Theta^{n} &= -\kappa^{T}\Theta + \left(\Omega(X) - \hat{\Omega}(X)\right) \\ &+ \left(Z(X) - \hat{Z}(X)\right)u \end{aligned} \qquad (8)$$

$$\dot{\Theta} = \lambda\Theta + \Phi\begin{pmatrix} \left(\Omega(X) - \hat{\Omega}(X)\right) \\ +\left(Z(X) - \hat{Z}(X)\right)u \end{pmatrix} \qquad (9)$$

Where

$$\lambda = \begin{bmatrix} 0 & 1 & 0 & \ldots & 0 \\ 0 & 0 & 1 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ -\kappa_{1} & -\kappa_{2} & -\kappa_{3} & \ldots & -\kappa_{n} \end{bmatrix} \qquad (10)$$

$$\Phi = [0 \quad 0 \quad \ldots \quad 1]^{T} \qquad (11)$$

The symbols ϑ_{F}^{*} and ϑ_{G}^{*} are the optimal parameters of the fuzzy system. Then we can rewrite equation (9) as:

$$\begin{aligned} \dot{\Theta} &= \lambda\Theta + \Phi\begin{pmatrix} \left(\hat{\Omega}(X,\vartheta_{\Omega}^{*}) - \hat{\Omega}(X)\right) \\ +\left(\hat{Z}(X,\vartheta_{Z}^{*}) - \hat{Z}(X)\right)u \end{pmatrix} \\ &+\Phi\begin{pmatrix} \left(\Omega(X) - \hat{\Omega}(X,\vartheta_{\Omega}^{*})\right) \\ +\left(Z(X) - \hat{Z}(X,\vartheta_{Z}^{*})\right)u \end{pmatrix} \\ &= \lambda\Theta + \Phi\begin{pmatrix} \left(\hat{\Omega}(X,\vartheta_{\Omega}^{*}) - \hat{\Omega}(X)\right) \\ +\left(\hat{Z}(X,\vartheta_{Z}^{*}) - \hat{Z}(X)\right)u \end{pmatrix} + \Phi\Gamma \\ &= \lambda\Theta + \Phi\left(\begin{pmatrix} \left(\hat{\Omega}(X,\vartheta_{\Omega}^{*}) - \hat{\Omega}(X)\right) \\ +\left(\hat{Z}(X,\vartheta_{Z}^{*}) - \hat{Z}(X)\right)u \end{pmatrix} + \Gamma\right) \end{aligned} \qquad (12)$$

For Hsatisfying the Lyapunov equation:

$$\lambda^{T}H + H\lambda = -K \qquad (13)$$

Where: K is a positive definite symmetric matrix. Derivative of equation (7), we have:

$$\begin{aligned} \dot{V} &= \frac{1}{2}\Theta^{T}\mathrm{K}\Theta + \Theta^{T}\mathrm{H}\Phi\Gamma \\ &+ \frac{1}{\eta_{1}}\left(\vartheta_{\Omega} - \vartheta_{\Omega}^{*}\right)^{T}\left(\dot{\vartheta}_{\Omega} + \eta_{1}\Theta^{T}\mathrm{H}\Phi\sigma(\mathrm{X})\right) \\ &+ \frac{1}{\eta_{2}}\left(\vartheta_{Z} - \vartheta_{Z}^{*}\right)^{T}\left(\dot{\vartheta}_{Z} + \eta_{2}\Theta^{T}\mathrm{H}\Phi\varsigma(\mathrm{X})u\right) \end{aligned} \qquad (14)$$

With the adaptive law (4) and controller (3), then $\dot{V} < 0$. Therefore the system will be stable according to Lyapunov's theory.

2.3. Simulation Example

The dynamic equation of the robot manipulator is [25]

$$M(q)\ddot{q} + C(q,\dot{q}) + D(q) + E(q,\dot{q},\ddot{q}) = \tau \qquad (15)$$

where $E(q,\dot{q},\ddot{q})$ unknown.

Figure 1 is the robot manipulator.

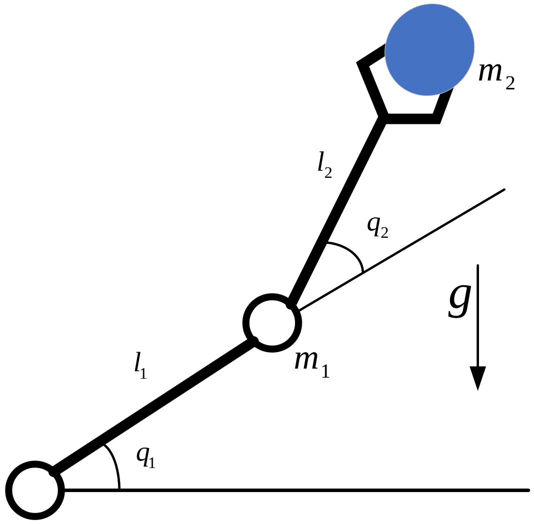

Fig. 1 A Two-joint robot manipulator

where $q = [q_1 \quad q_2]^T$; $M(q) \in R^{n\times n}$ is the inertial matrix; $C(q,\dot{q}) \in R^n$ is radial torque and Coriolis torque; $D(q) \in R^n$ is gravitational torque, $E(q,\dot{q},\ddot{q}) \in R^n$ is friction torque, and $\tau \in R^n$ joint torques.

Property 1: Matrix $M(q)$ is satisfied $m_1 I \le M(q) \le m_2 I$;
Property 2:

$$x^T\left(\dot{M} - 2C\right)x = 0 \tag{16}$$

Select the sliding surface as:

$$s = \dot{\tilde{q}} + \gamma\tilde{q} \tag{17}$$

Where γ is a positive definite matrix;
$\tilde{q} = q - q_d$ is the tracking error;
and q_d is the ideal angle.
Define

$$\dot{q}_r = \dot{q}_d - \gamma\tilde{q} \tag{18}$$

$E(q,\dot{q},\ddot{q})$ is approximated by the fuzzy system $\hat{E}(q,\dot{q},\ddot{q})$

$$\hat{E}(q,\dot{q},\ddot{q}) = \begin{bmatrix} \hat{E}_1(q,\dot{q},\ddot{q}) \\ \hat{E}_2(q,\dot{q},\ddot{q}) \\ \dots \\ \hat{E}_n(q,\dot{q},\ddot{q}) \end{bmatrix} \tag{19}$$

$$\hat{E}(q,\dot{q},\ddot{q}) = \begin{bmatrix} \Theta_1^T\sigma(q,\dot{q},\ddot{q}) \\ \Theta_2^T\sigma(q,\dot{q},\ddot{q}) \\ \dots \\ \Theta_n^T\sigma(q,\dot{q},\ddot{q}) \end{bmatrix} \tag{20}$$

2.3.1. Simulation Results

The parameters of the robot manipulator kinematics model are as follows

$$M(q) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

Where

$$M_{11} = (m_1 + m_2)r_1^2 + m_2 r_2^2 + 2m_2 r_1 r_2 \cos(q_2)$$
$$M_{12} = M_{21} = m_2 r_2^2 + m_2 r_1 r_2 \cos(q_2)$$
$$M_{22} = m_2 r_2^2$$

Let $y = [q_1 \quad q_2]^T$, $\tau = [\tau_1 \quad \tau_2]^T$, $q = [q_1 \quad \dot{q}_1 \quad q_2 \quad \dot{q}_2]^T$

The parameters of the robot manipulator model are given in Table 1.

Table 1. Parameters of robot manipulator

Symbol	Meaning	Value	Unit
m_1	Mass of link 1	1	kg
m_2	Mass of link 2	1.5	kg
l_1	Length of link 1	1	m
l_2	Length of link 2	0.8	m

Choose $\kappa = [5 \quad 10]^T$
The reference trajectory is $y_{ref} = 0.05 \sin t$

$$\lambda = \begin{bmatrix} 0 & 1 \\ -5 & -10 \end{bmatrix}, H = \begin{bmatrix} 100 & 50 \\ 50 & 30 \end{bmatrix}, K = \begin{bmatrix} 115 & 50 \\ 50 & 26 \end{bmatrix}$$
$\eta_1 = 50, \eta_2 = 1$

Fuzzy sets for input x_1:

$$\begin{cases} x\text{gaussmf}(x_1, [0.1885; -\pi/3])_{1-\inf} \\ x_{1zero} = \text{gaussmf}(x_1, [0.1885; 0]) \\ x\text{gaussmf}(x_1, [0.1885; \pi/3])_{1\inf} \end{cases} \tag{21}$$

Fuzzy sets for input x_2:

$$\begin{cases} x\text{gaussmf}(x_2, [0.0568; -0.1])_{2-inf} \\ x_{2zero} = \text{gaussmf}(x_2, [0.0568; 0]) \\ x\text{gaussmf}(x_2, [0.0568; 0.1])_{2inf} \end{cases} \tag{22}$$

The basis function vector $\varsigma(x)$ is:

$$\varsigma(x) = \begin{bmatrix} x_{1-inf} \\ x_{1zero} \\ x_{1inf} \end{bmatrix} \tag{23}$$

The basis function vector $\sigma(x)$ is:

$$\sigma(x) = \begin{bmatrix} x_{1-\inf} x_{2-\inf} \\ x_{1-\inf} x_{2zero} \\ x_{1-\inf} x_{2\inf} \\ x_{1zero} x_{2-\inf} \\ x_{1zero} x_{2zero} \\ x_{1zero} x_{2\inf} \\ x_{1\inf} x_{2-\inf} \\ x_{1\inf} x_{2zero} \\ x_{1\inf} x_{2\inf} \end{bmatrix} \tag{24}$$

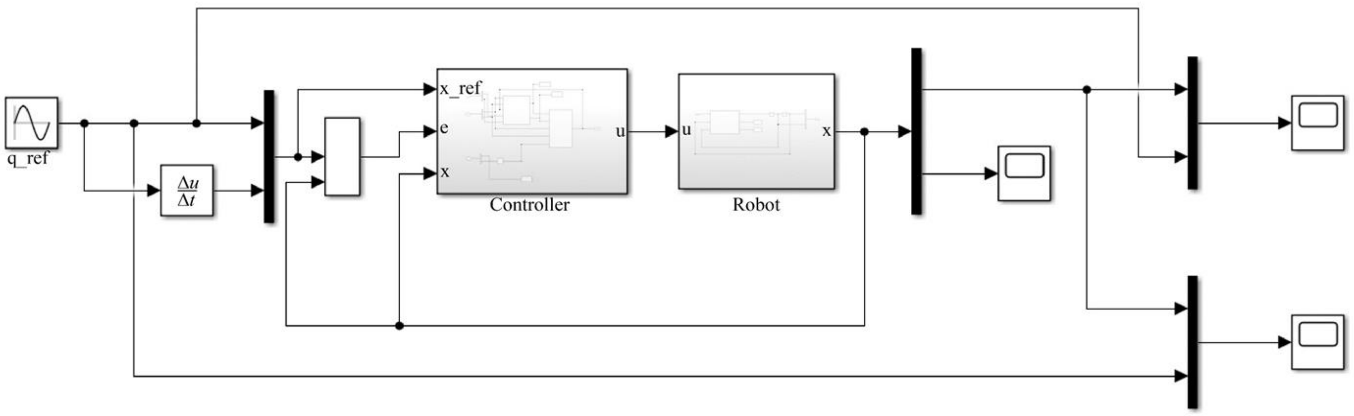

Fig. 2 System simulation diagram in Matlab-Simulink

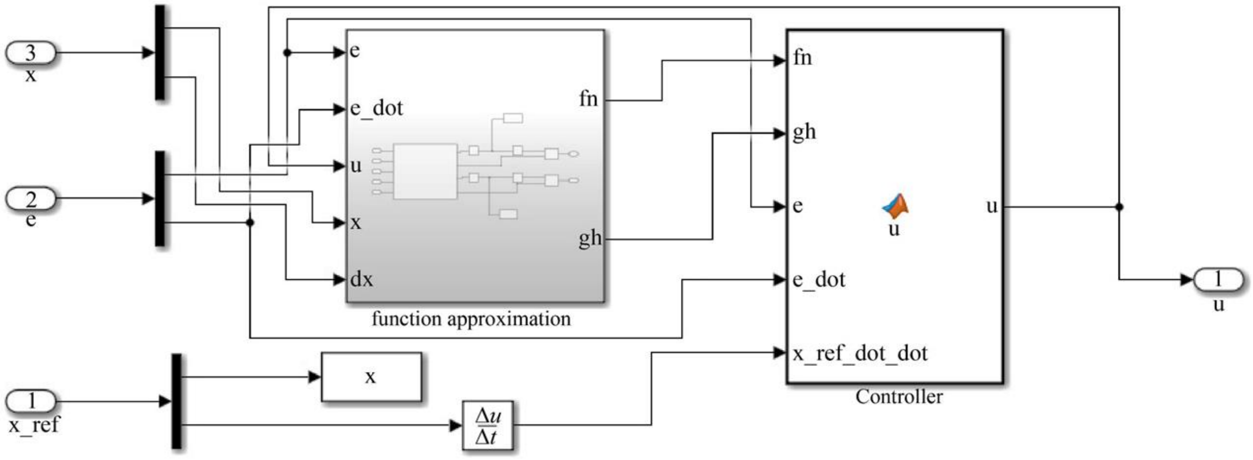

Fig. 3 Modeling the controller in Matlab-Simulink

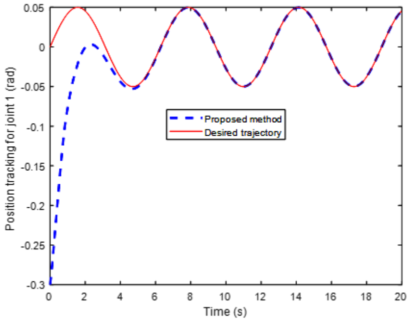

Fig. 4 Position tracking for joint 1 of robot manipulator

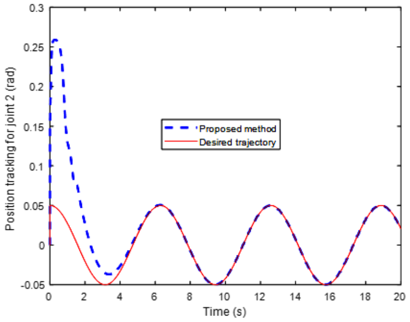

Fig. 5 Position tracking for joint 2 of robot manipulator

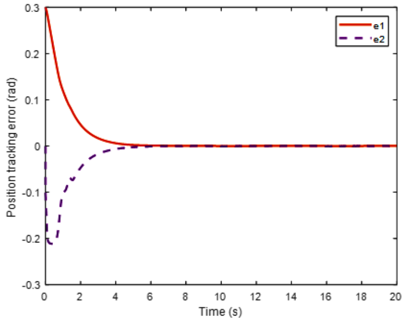

Fig. 6 Position and velocity error of robot manipulator

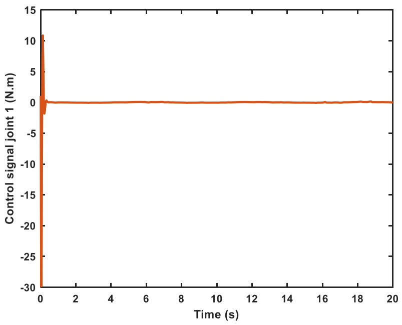

Fig. 7 Control signal joint 1

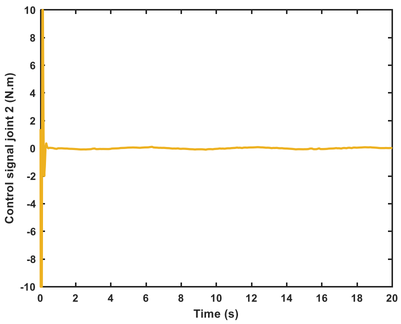

Fig. 8 Control signal joint 2

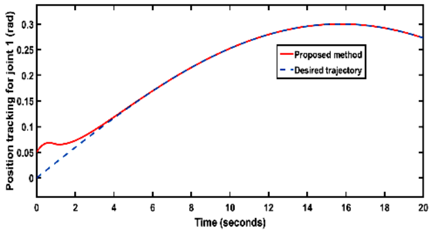

Fig. 9 Position tracking for joint 1 of robot manipulator

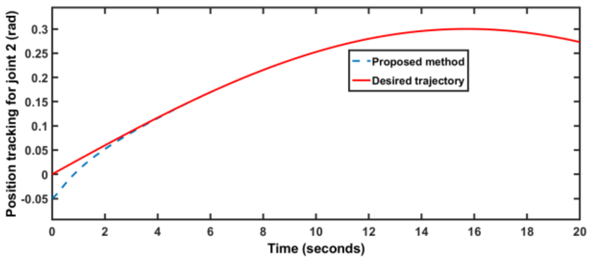

Fig. 10 Position tracking for joint 2 of robot manipulator

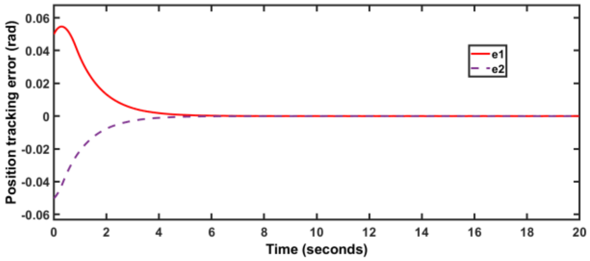

Fig. 11 Position tracking error of robot manipulator

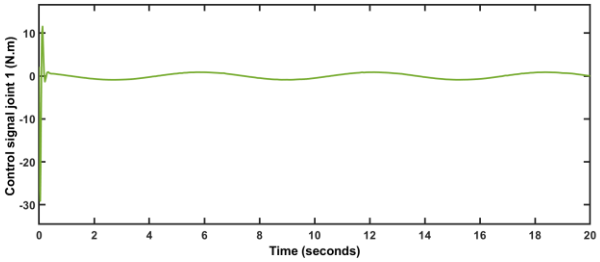

Fig. 12 Control signal joint 1

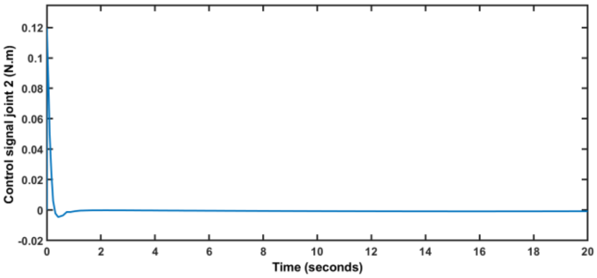

Fig. 13 Control signal joint 2

The controller model is built in Figure 2. The simulation diagram of the robot manipulator control system is built on Matlab-Simulink software, described in Figure 3. In which the input of the robot receives control signals. From the proposed controller design, with an adaptive mechanism built upon its response.

Select $x_0 = [-0.3 \quad 0]^T$. The simulation results are shown in Figure (4). The angle set here is sinusoidal with amplitude 0.05 with period 2π as a solid red line, and the arm rotation angle is the blue dotted line. We see that after about 5 seconds, the tilt angle follows the set value.

Remark results: The simulation results show that the actual trajectory of the robot manipulator has followed the reference value. The controller has good grip quality and can adapt to the change in model uncertainty parameters. In addition, the lack of prior knowledge of the object model is also one of the advantages of the controller. While the robot manipulator works, the mass and moment of inertia change, but the controller still ensures that the tracking error reaches zero. This control technique is increasingly applied in practice in different fields, such as industrial and civil. These developments strongly promote the use of adaptive fuzzy control in identifying and controlling uncertain nonlinear systems. The proposed control method needs extensive research attention in its application for control purposes as an alternative to traditional control methods.

3. Conclusion

This paper presents a method of designing adaptive controllers based on fuzzy logic systems for uncertain nonlinear systems. Components that are difficult to model in the object model accurately are friction, external disturbances, and other uncertainties approximated by a fuzzy logic system. With the adaptive law applied, the control law is flexible enough to adapt to the parameter variation of the unstable and stable nonlinear system, according to Lyapunov's theory. The robotic manipulator model is used to illustrate the design approach.

The simulation results on Matlab/Simulink software show that the fuzzy adaptive controller is perfectly suitable for controlling the robot manipulator. The robot's response does not appear to overshoot, the settling time is short, and the setting error is negligible.

The adaptive fuzzy controller gives good control quality when the system has time-varying parameters, contains uncertain factors, etc. So to improve the control quality without intervention. PID controllers are available, and in line with industrial requirements, we need to apply adaptive fuzzy control techniques combined with traditional control methods. The author will install the proposed control method to apply the application model in practice in the coming time.

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