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Adaptive Fuzzy Event-Triggered Tracking Control of Flexible-Joint Robot Systems: Design and Experiment

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Abstract In this paper, the problem of adaptive fuzzy tracking control for a class of flexible-joint robot systems is investigated. For the control of flexible-joint robot systems, many control programs still need to be improved and not practically applied, while most of the control programs can not achieve the purpose of saving resources. Therefore, based on the existing research, in order to realize a more effective and flexible control of flexible-joint robot systems, while saving resources, this paper carries out the following system design. Firstly, in order to realize the high performance of the flexible-joint robot systems and reduce the uncertainties during their operations, this article adopts the adaptive tracking control strategy and backstepping technique. Secondly, a dynamic event-triggered mechanism is designed which saves resources. In addition, fuzzy logic system is utilized to approximate unknown nonlinear function. Further, with the help of backstepping technique and Lyapunov stability theorem, it is proved that all signals of the closed-loop system are bounded and Zeno behavior does not occur. Finally, this paper applied the designed control scheme to the 2-link flexible-joint robot of Quanser Company platform, and the trajectory tracking, system states, and system control outputs diagrams in the experimental results all show that the control strategy designed in this paper is effective and has practical application value.

Keywords Adaptive tracking control · Fuzzy logic system · Event-triggered strategy · Quanser platform experiments

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1 Introduction

As classical nonlinear systems, robot systems have a wide range of applications in real life, so the research on robot systems are of great value, and many excellent research results have emerged in reports [1–4]. For robot systems, there are flexible-joint robot systems and rigid-joint robot systems. With the improvement of mechanization level, the flexible-joint robots show the development trend of high precision, high speed and lightweight, and their performance are much higher than that of the rigid-joint robots [5], and the emergence of flexible-joint robot systems open up a new direction for the development of robotics technology [6]. Therefore, flexible-joint robots have received more and more attention from scholars, such as [7,8]. Accordingly, in order to make the flexible-joint robots better applied, the research on their control strategies is especially important. For the robot systems, common control strategies mainly include proportional integral derivative control, model predictive control, reinforcement learning control and deep learning control. For example, a robust control method of joint torque based on uncertainty and disturbance estimator for the flexible-joint robot was proposed in [9]. In [10], a trajectory control technique was used to rule the motion of the manipulator arm through predefined paths to ensure optimal efficiency and accuracy of the manipulator arm motion. Zhu et al. [11] overcame the "complexity explosion" problem in the traditional backstepping method by introducing instruction filtering control with error compensation, and designed an adaptive fuzzy instruction filtering control scheme based on the time-varying barrier Lyapunov function. Although many excellent control strategies have been proposed for flexible-joint robot systems, most of the control strategies only stay in numerical simulation and have not been practically applied to flexible-joint robot, which lacks the support of practical

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applications. Instead, in this paper, the designed control strategy is practically applied to a 2-link flexible-joint robot for physical experiments.

Since the flexible-joint robot system is a kind of complex system with uncertainties such as parameters uptake and external disturbances, its uncertainties will seriously affect the performance of the system. Therefore, how to realize effective control of the flexible-joint robot systems is a noteworthy issue. For nonlinear systems with uncertainties, adaptive control methods can address effectively their uncertainty problems, and many excellent research results have been given in [12–17]. For example, in [16], an adaptive integral sliding mode controller based on singular perturbation method and two state observers to achieve high performance in flexible-joint robot was proposed. Sun et al. [17] for one class of non-triangular structured stochastic switching nonlinear systems with complete state constraints, an adaptive fuzzy stochastic switching control scheme was devised and a closed-loop system was realized in which all signals were semi-globally homogeneous eventually bounded and had complete state constraints. Therefore, the adaptive control method is still an effective way to solve the tracking control of flexible-joint robots, and we design a more flexible control scheme based on the existing research results.

Moreover, the backstepping method realizes effective control of the nonlinear systems by splitting the complex nonlinear system into multiple subsystems with setting Lyapunov candidate functions and virtual controllers in [18, 19]. Then, Li et al. [20] proposed a barrier Lyapunov function backstepping control mechanism based on a compensation function observer, which was more effective than the traditional backstepping control methods. On these foundations, adaptive backstepping technique is an effective method to solve the control problems of nonlinear systems. So, many adaptive backstepping control strategies for nonlinear systems have been proposed in [21–24]. Giving an example, Zheng et al. [24] proposed an adaptive neural network backstepping control method for a class of uncertain nonlinear systems with unknown nonlinearity. Compared with the traditional control scheme, the control method in this paper can regulate the damping ratio of the system by prescribed parameter selection rules. Furthermore, the approach of fuzzy approximation plays an important role in the control of nonlinear systems. Fuzzy logic system can approximate the unknown function very well, so it can be used to deal with the nonlinear terms of nonlinear systems. And great results were obtained in [25–28]. For instance, the controller designed based on fuzzy approximation technique made the system output follow the reference input signals in [28]. Therefore, many excellent research results based on adaptive techniques, backstepping methods and fuzzy logic systems have been given for the control problem of flexible-joint robots, on the basis of which this paper improves the control scheme and designs a more flexible control scheme.

Nevertheless, for the existing control strategies for nonlinear systems, the output of the controller has been continuing in many cases, which will result in the waste of resources and communication burden. Therefore, the event-triggered control mechanism was proposed in [29], which did not require input-to-state stability assumptions. Unlike the traditional time-triggered control, under the event-triggered strategy, the controller is triggered only if the system requires it, so it can greatly save the communication burden and communication resources. As a result, the application of event-triggered control to nonlinear systems has become a popular trend in recent years, and excellent results have been given in [30–36]. To just name a few, a distributed dual adaptive observer using an event-triggered control mechanism for estimating the state of an out-of-reference system was developed in [35]. Wang et al. [36] presented an event-triggered adaptive sliding mode control scheme based on the full-motion system approach for a class of uncertain strict-feedback nonlinear systems. However, for the tracking control of flexible-joint robots, many research programs do not take into account the problem of saving resources or the design process of event-triggered strategy does not consider the actual system, while this paper incorporates the dynamic event-triggered strategy in the process of the design of the control program, so as to achieve the purpose of saving resources, and its practical application to the flexible-joint robot systems.

On the basis of the above analysis, although many excellent control results have been given in many excellent literatures, there are still many issues that need to be considered for the n-link flexible-joint robot systems.

(1) The control strategies still need to be improved for lower triangular systems due to many uncertainties of the nonlinear system that can affect the dynamics model of the flexible-joint robot systems.
(2) Many control schemes in existing literatures on flexible-joint robot systems still remain in the experimental stage of numerical simulation, and the control schemes have not yet been practically applied in production life, so how to practically apply the ideal control scheme is still a great challenge.
(3) Most of the literatures for the control strategy of flexible-joint robot systems adopt the time-triggered control strategy, which is triggered even when the system is not needed, which will result in a waste of resources. Therefore, how to design an effective event-triggered

strategy to save resources is an issue that should not be ignored.

In order to solve some existing problems of the flexible-joint robot systems, a simpler adaptive tracking control strategy is designed, and an event-triggered mechanism is used in the process of system switching to achieve the purpose of saving communication resources and communication burden. The main contributions are summarized as follows.

(1) A dynamic event-triggered control mechanism is presented and the proposed scheme is more flexible compared to other articles.
(2) In order to solve the uncertainty problems in the control of the flexible-joint robot systems, this paper adopts adaptive approximate technique and backstepping control strategy to improve the performance of the flexible-joint robot systems.
(3) Simulation experiments are conducted for the control strategy of the flexible-joint robot system using the Quanser platform, which fully verify the effectiveness of the method proposed in this paper.

2 Problem Statement and Preliminaries

Dynamical model for n-link flexible-joint robot systems can be characterized as follows:

$$\begin{cases} H(q)\ddot{q} + C(q,\dot{q})\dot{q} + M(q) + F(\dot{q}) + Kq = Kq_m, \\ J\ddot{q}_m + B\dot{q}_m + K(q_m - q) = u, \end{cases} \tag{1}$$

where $q = [q_1, q_2, \ldots, q_n]^T \in \mathbb{R}^n$, $\dot{q} \in \mathbb{R}^n$, $\ddot{q} \in \mathbb{R}^n$ are on behalf of link position, link velocity and link acceleration vectors, respectively. $H(q) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $M(q) \in \mathbb{R}^n$ represents the gravity vector, and $K = \text{diag}(K_1, K_2, \ldots, K_n) \in \mathbb{R}^{n\times n}$ denotes joint flexibility positive-definite symmetric matrix. $J = \text{diag}(J_1, J_2, \ldots, J_n) \in \mathbb{R}^{n\times n}$, $B = \text{diag}(B_1, B_2, \ldots, B_n) \in \mathbb{R}^{n\times n}$, $u = [u_1, u_2]^T \in \mathbb{R}^2$ represent the actuator inertia, natural damping term and torque input vector of actuator, respectively. $C(q, \ddot{q}) \in \mathbb{R}^{n\times n}$ stands the Coriolis/centripetal force matrix. $F(\dot{q}) \in \mathbb{R}^n$ represents the friction term. $q_m = [q_{m_1}, q_{m_2}, \ldots, q_{m_n}]^T \in \mathbb{R}^n$, $\dot{q}_m \in \mathbb{R}^n$, $\ddot{q}_m \in \mathbb{R}^n$ are on behalf of rotor position, rotor velocity and rotor acceleration vectors, respectively. The 2-Link flexible-joint robot built on a platform from Quanser Corporation is employed in this experiment, as shown in Fig. 1. Besides, Fig. 2 presents a simplified structural diagram of a 2-link flexible-joint robot and its relevant parameters covered in this paper are displayed in Table 1.

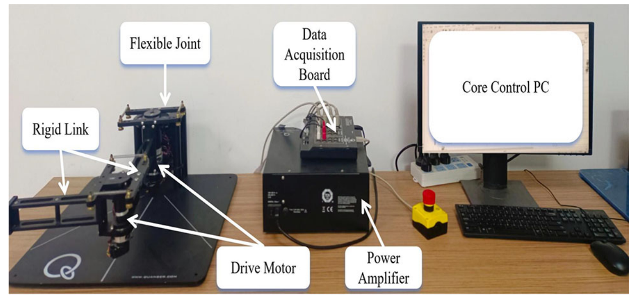

Fig. 1 The experimental platform of 2-link flexible-joint robot

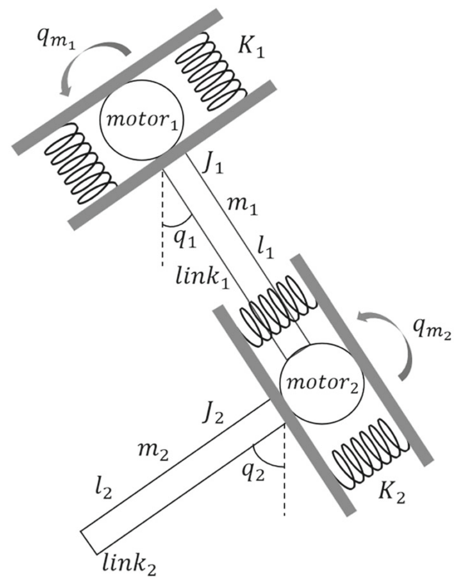

Fig. 2 A simplified structural diagram of a 2-link flexible-joint robot

Then, let the $x_1 = q$, $x_2 = \dot{q}$, $x_3 = q_m$, $x_4 = \dot{q}_m$, so (1) can be rewritten as

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = H^{-1}Kx_3 + H^{-1}[-Cx_2 - M(x_1) - F(x_1) - Kx_1], \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = J^{-1}[u - Bx_4 - K(x_3 - x_1)]. \end{cases} \tag{2}$$

The target of this paper is to develop an efficient control strategy for a 2-link flexible-joint robot system such that the system covariates q, $\dot{q}$, q_m and $\dot{q}_m$ are bounded, and the position vectors of the robotic arm linkage are able to incrementally track the ideal signals $y_d = [y_{d_1}, y_{d_2}, \ldots, y_{d_n}]^T \in \mathbb{R}^n$. In addition, the tracking error $e_1 = q - y_d$ is kept within a desirable range. To this end, the following assumption and lemmas are introduced.

Assumption 1 The reference signal y_d and $\dot{y}_d$ are continuous and bounded.

Table 1 Parameters of the 2-link flexible-joint robot

Parameters	Description	Unit
m_1	The mass of the link 1	kg
m_2	The mass of the link 2	kg
l_1	The distance of the link 1	m
l_2	The distance of the link 2	m
K_1	The stiffness	N m/rad
K_2	The stiffness	N m/rad
J_1	The joint flexibility	m/s^2
J_2	The joint flexibility	m/s^2

Lemma 1 [17] *With respect to any* $\varepsilon > 0$ *and a continue function* $f(X)$, *which is defined on a compact set* U, *so there exists a fuzzy logic system* $W^T S(X)$ *satisfying*

$$f(X) = W^T S(X) + \varepsilon(X), |\varepsilon(X)| \le \bar{\varepsilon}, \bar{\varepsilon} > 0,$$

where $W = [W_1, W_2, \ldots, W_n]^T$ *is the weight vector,* $\varepsilon(X)$ *is the approximate error,* $S(X) = [S_1, S_2, \ldots, S_n]^T$ *is the membership function.*

Lemma 2 [29] *The following inequality holds*

$$0 \le |\zeta| - \zeta \tanh\left(\frac{\zeta}{\tau}\right) \le 0.2785\tau,$$

where $\tau > 0$ *and* $\zeta \in \mathbb{R}$.

3 System Description and Preliminaries

First of all, define the following coordinate transformations

$$\begin{cases} e_1 = x_1 - y_d, \\ e_2 = x_2 - \alpha_1, \\ e_3 = x_3 - \alpha_2, \\ e_4 = x_4 - \alpha_3, \end{cases} \tag{3}$$

where α_1, α_2 and α_3 are the virtual control signals.

Step 1: The derivative with respect to e_1 yields

$$\begin{aligned} \dot{e}_1 &= \dot{x}_1 - \dot{y}_d \\ &= e_2 + \alpha_1 - \dot{y}_d. \end{aligned} \tag{4}$$

Choose the Lyapunov function as

$$V_1 = \frac{1}{2} e_1^T e_1. \tag{5}$$

Then, we can get

$$\begin{aligned} \dot{V}_1 &= e_1^T \dot{e}_1 \\ &= e_1^T (e_2 + \alpha_1 - \dot{y}_d). \end{aligned} \tag{6}$$

Constructing the virtual controller α_1 is

$$\alpha_1 = -c_1 e_1 + \dot{y}_d, \tag{7}$$

where c_1 is a positive design parameter.

Thus, we have

$$\dot{V}_1 = e_1^T e_2 - c_1 e_1^T e_1. \tag{8}$$

Step 2: The derivative with respect to e_2 yields

$$\begin{aligned} \dot{e}_2 &= \dot{x}_2 - \dot{\alpha}_1 \\ &= H^{-1} K x_3 \\ &\quad + H^{-1} [-C x_2 - M(x_1) - F(x_2) - K x_1] - \dot{\alpha}_1. \end{aligned} \tag{9}$$

From (3), it can get

$$\begin{aligned} \dot{e}_2 &= H^{-1} K e_3 + H^{-1} K \alpha_2 \\ &\quad + H^{-1} [-C x_2 - M(x_1) - F(x_2) - K x_1] - \dot{\alpha}_1. \end{aligned} \tag{10}$$

Define the Lyapunov function as

$$V_2 = V_1 + \frac{1}{2} e_2^T e_2 + \frac{1}{2 r_2} \tilde{\theta}_2^2, \tag{11}$$

with a known constant $r_2 > 0$, and the adaptive parameter error $\tilde{\theta}_2 = \theta_2 - \hat{\theta}_2$ in which $\hat{\theta}_2$ is the estimation of θ_2.

Then, the derivation of V_2 yields

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + e_2^T \dot{e}_2 + \frac{1}{r_2} \tilde{\theta}_2 \dot{\tilde{\theta}}_2 \\ &= -c_1 e_1^T e_1 - \frac{1}{r_2} \tilde{\theta}_2 \dot{\hat{\theta}}_2 - \frac{e_2^T e_2}{2} \\ &\quad + e_2^T [H^{-1} K (e_3 + \alpha_2) + f_2], \end{aligned} \tag{12}$$

where $f_2 = H^{-1}[-C x_2 - M(x_1) - F(x_2) - K x_1] - \dot{\alpha}_1 + e_1 + \frac{e_2}{2}$.

Based on Lemma 1, $\|f_2\|$ can be estimated by following fuzzy logic system. For any $\bar{\varepsilon}_2 > 0$

$$\|f_2\| = W_2^T S_2 + \varepsilon_2, |\varepsilon_2| \le \bar{\varepsilon}_2, \bar{\varepsilon}_2 > 0, \tag{13}$$

in which ε_2 is the approximation error, and $\bar{\varepsilon}_2$ is an arbitrary positive constant. As the square is completed, the following equation can be obtained

$$e_2^T f_2 \le \left\| e_2^T \right\| \|f_2\|$$

$$\leq \frac{\theta_2 e_2^T e_2 S_2^T S_2}{2a_2^2} + \frac{e_2^T e_2}{2} + \frac{a_2^2}{2} + \frac{\bar{\varepsilon}_2^2}{2}, \tag{14}$$

where $a_2 > 0$ is a constant, and $\theta_2 = \|W_2\|^2$. Constructing the virtual controller α_2 is

$$\alpha_2 = K^{-1} H \left(-c_2 e_2 - \frac{\hat{\theta}_2 e_2 S_2^T S_2}{2a_2^2} \right), \tag{15}$$

where $c_2 > 0$ is a design parameter.

Substituting (14) and (15) into (12) produces

$$\dot{V}_2 \leq -c_1 e_1^T e_1 + e_2^T \left[H^{-1} K e_3 - c_2 e_2 - \frac{\hat{\theta}_2 e_2 S_2^T S_2}{2a_2^2} \right] + \frac{\theta_2 e_2^T e_2 S_2^T S_2}{2a_2^2} + \frac{a_2^2}{2} + \frac{\bar{\varepsilon}_2^2}{2} - \frac{1}{r_2}\tilde{\theta}_2 \dot{\hat{\theta}}_2. \tag{16}$$

Choose the adaptive law as

$$\dot{\hat{\theta}}_2 = \frac{r_2 e_2^T e_2 S_2^T S_2}{2a_2^2} - \varsigma_2 \hat{\theta}_2, \tag{17}$$

with $\varsigma_2 > 0$ is a constant. Then, we can get

$$\dot{V}_2 \leq -c_1 e_1^T e_1 + H^{-1} K e_2^T e_3 - c_2 e_2^T e_2 + \frac{a_2^2}{2} + \frac{\bar{\varepsilon}_2^2}{2} + \frac{\varsigma_2}{r_2}\tilde{\theta}_2 \hat{\theta}_2. \tag{18}$$

By means of Young's inequality, we get

$$\dot{V}_2 \leq -c_1 e_1^T e_1 + H^{-1} K e_2^T e_3 - c_2 e_2^T e_2 + \frac{a_2^2}{2} + \frac{\bar{\varepsilon}_2^2}{2} + \frac{\varsigma_2}{2r_2}\theta_2^2 - \frac{\varsigma_2}{2r_2}\tilde{\theta}_2^2. \tag{19}$$

Step 3: The derivative with respect to e_3 yields

$$\begin{aligned} \dot{e}_3 &= \dot{x}_3 - \dot{\alpha}_2 \\ &= x_4 - \dot{\alpha}_2 \\ &= e_4 + \alpha_3 - \dot{\alpha}_2. \end{aligned} \tag{20}$$

Define the Lyapunov function as

$$V_3 = V_2 + \frac{1}{2} e_3^T e_3 + \frac{1}{2r_3}\tilde{\theta}_3^2, \tag{21}$$

with a known constant $r_3 > 0$, and $\tilde{\theta}_3 = \theta_3 - \hat{\theta}_3$, in which $\hat{\theta}_3$ is the estimation of θ_3.

It can be concluded that

$$\dot{V}_3 = \dot{V}_2 + e_3^T (e_4 + \alpha_3 - \dot{\alpha}_2) - \frac{1}{r_3}\tilde{\theta}_3 \dot{\hat{\theta}}_3. \tag{22}$$

By using (19), one has

$$\dot{V}_3 \leq -c_1 e_1^T e_1 - c_2 e_2^T e_2 + \frac{a_2^2}{2} + \frac{\bar{\varepsilon}_2^2}{2} + \frac{\varsigma_2}{2r_2}\theta_2^2 - \frac{\varsigma_2}{2r_2}\tilde{\theta}_2^2 + e_3^T (e_4 + \alpha_3) + e_3^T f_3 - \frac{e_3^T e_3}{2} - \frac{1}{r_3}\tilde{\theta}_3 \dot{\hat{\theta}}_3, \tag{23}$$

where $f_3 = -\dot{\alpha}_2 + H^{-1} K e_2 + \frac{e_3}{2}$.

Based on Lemma 1, $\|f_3\|$ can be estimated by following fuzzy logic system. For any $\bar{\varepsilon}_3 > 0$

$$\begin{aligned} e_3^T f_3 &\leq \|e_3^T\| \|f_3\| \\ &\leq \frac{\theta_3 e_3^T e_3 S_3^T S_3}{2a_3^2} + \frac{e_3^T e_3}{2} + \frac{a_3^2}{2} + \frac{\bar{\varepsilon}_3^2}{2}, \end{aligned} \tag{24}$$

where $a_3 > 0$ is a constant, and $\theta_3 = \|W_3\|^2$.

Constructing the virtual controller α_3 is

$$\alpha_3 = -c_3 e_3 - \frac{\hat{\theta}_3 e_3 S_3^T S_3}{2{a_3}^2}, \tag{25}$$

where $c_3 > 0$ is a design parameter.

Substituting (24) and (25) into (23), we can get

$$\dot{V}_3 \leq -c_1 e_1^T e_1 - c_2 e_2^T e_2 + \frac{a_2^2}{2} + \frac{\bar{\varepsilon}_2^2}{2} + \frac{\varsigma_2}{2r_2}\theta_2^2 - \frac{\varsigma_2}{2r_2}\tilde{\theta}_2^2 + e_3^T \left(e_4 - c_3 e_3 - \frac{\hat{\theta}_3 e_3 S_3^T S_3}{2{a_3}^2} \right) + \frac{\theta_3 e_3^T e_3 S_3^T S_3}{2a_3^2} + \frac{a_3^2}{2} + \frac{\bar{\varepsilon}_3^2}{2} - \frac{1}{r_3}\tilde{\theta}_3 \dot{\hat{\theta}}_3. \tag{26}$$

Choose the adaptive law as

$$\dot{\hat{\theta}}_3 = \frac{r_3 e_3^T e_3 S_3^T S_3}{2a_3^2} - \varsigma_3 \hat{\theta}_3, \tag{27}$$

with $\varsigma_3 > 0$ is a constant.

Thus, we have

$$\dot{V}_3 \leq -c_1 e_1^T e_1 - c_2 e_2^T e_2 - c_3 e_3^T e_3 + e_3^T e_4 + \frac{\varsigma_2}{2r_2}\theta_2^2 - \frac{\varsigma_2}{2r_2}\tilde{\theta}_2^2 + \frac{\varsigma_3}{r_3}\tilde{\theta}_3 \hat{\theta}_3 + \frac{a_2^2}{2} + \frac{a_3^2}{2} + \frac{\bar{\varepsilon}_2^2}{2} + \frac{\bar{\varepsilon}_3^2}{2}. \tag{28}$$

By means of Young's inequality, we can get

$$\dot{V}_3 \leq \sum_{i=1}^{3} (-c_i e_i^T e_i) + \sum_{i=2}^{3} \left(\frac{a_i^2}{2} + \frac{\bar{\varepsilon}_i^2}{2} + \frac{\varsigma_i}{2r_i}\theta_i^2 - \frac{\varsigma_i}{2r_i}\tilde{\theta}_i^2 \right) + e_3^T e_4. \tag{29}$$

Step 4: The derivative with respect to e_4 yields

$$\dot{e}_4 = \dot{x}_4 - \dot{\alpha}_3 = J^{-1}[u - Bx_4 - K(x_3 - x_1)] - \dot{\alpha}_3. \tag{30}$$

In order to save resources, the actual controller and the event-triggered conditions for the n-link flexible-joint robot system is designed as follows:

$$\omega(t) = -(1+\eta(t))\left(\alpha_n \tanh\frac{e_4^T J^{-1}\alpha_n}{\rho}\right. \tag{31}$$

$$\left. + o_1 \tanh\frac{e_4^T J^{-1} o_1}{\rho}\right), \tag{32}$$

$$u_j(t) = \omega_j(t_{j,k}), \forall t \in [t_{j,k}, t_{j,k+1}), \tag{33}$$

$$t_{j,k+1} = \inf\{t \in R \| \|\beta_j(t)| \geq \eta(t)\left|u_j(t)\right| + d_j\}, \tag{34}$$

$$\dot{\eta}(t) = -c\eta^2(t), \tag{35}$$

in which $\beta(t) = u(t) - \omega(t)$. $c \geq 0$, $d_j > 0$, $\rho > 0$, $o_{j,1} > \frac{d_j}{1-\eta(0)}$ are design parameters, $j = 1, \ldots, n$ and $t_{j,k}$ denotes the trigger moment of the system. For any initial value $0 < \eta(0) < 1$, for $\forall t > 0$ one has $\eta(t) \in (0, 1)$.

Remark 1 Among the advantages of the designed event-triggered mechanism in (33) is that the threshold parameter $\eta(t)$ can be dynamically adjusted and will not be continuously fixed. If $c = 0$, $d_j \neq 0$ and $\eta(0) = 0$, the (33) can be written as $t_{j,k+1} = \inf\{t \in \mathbb{R} \left| \left|\beta_j(t)\right| \geq d_j\right\}$. Furthermore, if $c = 0$, $d_j \neq 0$ and $\eta(0) \neq 0$, (33) can be reduced to (32). Thus, compared to other event-triggered mechanisms, the event-triggered mechanism devised in this paper is more flexible.

Therefore, on the basis of equation (33), we can obtain $\omega(t) = (1 + \xi_1(t)\eta(t))u(t) + \xi_2(t)d$ for $t \in [t_{j,k}, t_{j,k+1})$, where $\xi_1(t), \xi_2(t) \in [-1, 1]$. Then we can get

$$u = \frac{\omega(t)}{1+\xi_1\eta} - \frac{\xi_2 d}{1+\xi_1\eta}. \tag{36}$$

Then, define the Lyapunov function as

$$V_4 = V_3 + \frac{1}{2}e_4^T e_4 + \frac{1}{2r_4}\tilde{\theta}_4^2, \tag{37}$$

with a known constant $r_4 > 0$, and $\tilde{\theta}_4 = \theta_4 - \hat{\theta}_4$, in which $\hat{\theta}_4$ is the estimation of θ_4.

Thus, the derivative of V_4 is

$$\dot{V}_4 = \dot{V}_3 + e_4^T \dot{e}_4 + \frac{1}{r_4}\tilde{\theta}_4\dot{\tilde{\theta}}_4 = \dot{V}_3 + e_4^T[J^{-1}[u - Bx_4 - K(x_3 - x_1)] - \dot{\alpha}_3] - \frac{1}{r_4}\tilde{\theta}_4\dot{\hat{\theta}}_4. \tag{38}$$

From Eq. (35), one has

$$\dot{V}_4 = \dot{V}_3 + e_4^T\left[J^{-1}\left[\frac{\omega(t)}{1+\xi_1\eta} - \frac{\xi_2 d}{1+\xi_1\eta} - Bx_4 - K(x_3 - x_1)\right] - \dot{\alpha}_3\right] - \frac{1}{r_4}\tilde{\theta}_4\dot{\hat{\theta}}_4. \tag{39}$$

Substituting (29) into (38), we can get

$$\dot{V}_4 \leq \sum_{i=1}^{3}(-c_i e_i^T e_i) + \sum_{i=2}^{3}\left(\frac{a_i^2}{2} + \frac{\bar{\varepsilon}_i^2}{2} + \frac{\varsigma_i}{2r_i}\theta_i^2 - \frac{\varsigma_i}{2r_i}\tilde{\theta}_i^2\right) + e_4^T\left[J^{-1}\frac{\omega(t) - \xi_2 d}{1+\xi_1\eta} + f_4\right] - \frac{1}{r_4}\tilde{\theta}_4\dot{\hat{\theta}}_4 - \frac{1}{2}e_4^T e_4, \tag{40}$$

where $f_4 = -\dot{\alpha}_3 + e_3 + \frac{1}{2}e_4 - J^{-1}(Bx_4 + Kx_3 - Kx_1)$.

In a similar way to Eq. (13), the following equation can be obtained

$$\|f_4\| = W_4^T S_4 + \varepsilon_4, |\varepsilon_4| \leq \bar{\varepsilon}_4, \bar{\varepsilon}_4 > 0, \tag{41}$$

in which ε_4 is the approximation error, and $\bar{\varepsilon}_4$ is an arbitrary positive constant.

By using fuzzy logic system, one can obtain

$$e_4^T f_4 \leq \frac{\theta_4 e_4^T e_4 S_4^T S_4}{2a_4^2} + \frac{1}{2}a_4^2 + \frac{1}{2}e_4^T e_4 + \frac{1}{2}\bar{\varepsilon}_4^2, \tag{42}$$

where $a_4 > 0$ is a constant, and $\theta_4 = \|W_4\|^2$.

Since $\frac{e_4^T J^{-1}\omega}{1+\xi_1\eta} \leq \frac{e_4^T J^{-1}\omega}{1+\eta}$ and $\left|\frac{e_4^T J^{-1}\xi_2 d}{1+\xi_1\eta}\right| \leq \frac{e_4^T J^{-1} d}{1-\eta}$, at the same time substituting (41) into (39), we obtain

$$\dot{V}_4 \leq \sum_{i=1}^{3}(-c_i e_i^T e_i) + \sum_{i=2}^{3}\left(\frac{a_i^2}{2} + \frac{\bar{\varepsilon}_i^2}{2} + \frac{\varsigma_i}{2r_i}\theta_i^2 - \frac{\varsigma_i}{2r_i}\tilde{\theta}_i^2\right) + \frac{e_4^T J^{-1}\omega}{1+\eta} + \left|\frac{e_4^T J^{-1} d}{1-\eta}\right| + \frac{\theta_4 e_4^T e_4 S_4^T S_4}{2a_4^2} + \frac{1}{2}a_4^2 + \frac{1}{2}\bar{\varepsilon}_4^2 - \frac{1}{r_4}\tilde{\theta}_4\dot{\hat{\theta}}_4. \tag{43}$$

According to Eq. (31) and Lemma 2, we have

$$\dot{V}_4 \leq \sum_{i=1}^{3}(-c_i e_i^T e_i) + \sum_{i=2}^{3}\left(\frac{a_i^2}{2} + \frac{\bar{\varepsilon}_i^2}{2} + \frac{\varsigma_i}{2r_i}\theta_i^2 - \frac{\varsigma_i}{2r_i}\tilde{\theta}_i^2\right) + e_4^T J^{-1}\alpha_4 - \left|e_4^T J^{-1} o_1\right| + \left|\frac{e_4^T J^{-1} d}{1-\eta}\right| - \frac{1}{r_4}\tilde{\theta}_4\dot{\hat{\theta}}_4$$

$$+\frac{\theta_4 e_4^T e_4 S_4^T S_4}{2a_4^2}+\frac{1}{2}a_4^2+\frac{1}{2}\bar{\varepsilon}_4^2+0.557\tau. \tag{44}$$

Construct the virtual control signal α_4 as follows

$$\alpha_4 = J\left(-c_4 e_4 - \frac{\hat{\theta}_4 e_4 S_4^T S_4}{2a_4^2}\right), \tag{45}$$

where $c_4 > 0$ is a design parameter.

Thus, we have

$$\begin{aligned}\dot{V}_4 \le& \sum_{i=1}^{3}(-c_i e_i^T e_i)+\sum_{i=2}^{3}\left(\frac{a_i^2}{2}+\frac{\bar{\varepsilon}_i^2}{2}+\frac{\varsigma_i}{2r_i}\theta_i^2-\frac{\varsigma_i}{2r_i}\tilde{\theta}_i^2\right)\\ &- c_4 e_4^T e_4 - \frac{\hat{\theta}_4 e_4^T e_4 S_4^T S_4}{2a_4^2} - \left|e_4^T J^{-1} o_1\right| + \left|\frac{e_4^T J^{-1} d}{1-\eta}\right|\\ &+\frac{\theta_4 e_4^T e_4 S_4^T S_4}{2a_4^2}+\frac{1}{2}a_4^2+\frac{1}{2}\bar{\varepsilon}_4^2+0.557\tau-\frac{1}{r_4}\tilde{\theta}_4\dot{\hat{\theta}}_4.\end{aligned} \tag{46}$$

Choose the adaptation law as

$$\dot{\hat{\theta}}_4 = \frac{r_4 e_4^T e_4 S_4^T S_4}{2a_4^2} - \varsigma_4 \hat{\theta}_4, \tag{47}$$

with $\varsigma_4 > 0$ is a constant.

Then, the in Eq. (45) can be rewritten as

$$\begin{aligned}\dot{V}_4 \le& \sum_{i=1}^{3}(-c_i e_i^T e_i)+\sum_{i=2}^{3}\left(\frac{a_i^2}{2}+\frac{\bar{\varepsilon}_i^2}{2}+\frac{\varsigma_i}{2r_i}\theta_i^2-\frac{\varsigma_i}{2r_i}\tilde{\theta}_i^2\right)\\ &- c_4 e_4^T e_4 - \left|e_4^T J^{-1} o_1\right| + \left|\frac{e_4^T J^{-1} d}{1-\eta}\right|\\ &+\frac{1}{2}a_4^2+\frac{1}{2}\bar{\varepsilon}_4^2+0.557\tau+\frac{\varsigma_4}{r_4}\tilde{\theta}_4\hat{\theta}_4.\end{aligned} \tag{48}$$

By means of Young's inequality, we can get

$$\begin{aligned}\dot{V}_4 \le& \sum_{i=1}^{4}(-c_i e_i^T e_i)+\sum_{i=2}^{4}\left(\frac{a_i^2}{2}+\frac{\bar{\varepsilon}_i^2}{2}+\frac{\varsigma_i}{2r_i}\theta_i^2-\frac{\varsigma_i}{2r_i}\tilde{\theta}_i^2\right)\\ &+0.557\tau - \left|e_4^T J^{-1} o_1\right| + \left|\frac{e_4^T J^{-1} d}{1-\eta}\right|.\end{aligned} \tag{49}$$

Thus, according to $o_{j,1} > \frac{d_j}{1-\eta(0)}$, we can get

$$\begin{aligned}\dot{V}_4 \le& \sum_{i=1}^{4}(-c_i e_i^T e_i)+\sum_{i=2}^{4}\left(\frac{a_i^2}{2}+\frac{\bar{\varepsilon}_i^2}{2}+\frac{\varsigma_i}{2r_i}\theta_i^2-\frac{\varsigma_i}{2r_i}\tilde{\theta}_i^2\right)\\ &+0.557\tau.\end{aligned} \tag{50}$$

The in Eq. (49) can be rewritten as

$$\dot{V}_4 \le \sum_{i=1}^{4}(-c_i e_i^T e_i)-\sum_{i=2}^{4}\left(\frac{\varsigma_i}{2r_i}\tilde{\theta}_i^2\right)+\tilde{\gamma}_4, \tag{51}$$

where $\tilde{\gamma}_4 = \sum_{i=2}^{4}\left(\frac{a_i^2}{2}+\frac{\bar{\varepsilon}_i^2}{2}+\frac{\varsigma_i}{2r_i}\theta_i^2\right)+0.557\tau$.

Theorem 1 *Assuming that the nonlinear system (1) satisfies Assumption 1, the actual controller (32), and the adaptation laws in (17), (27) and (46) are constructed. Thus, not only all signals of the closed-loop resulting system are ultimately consistently bounded, but also the Zeno phenomenon can be avoided.*

Proof The following constant variables are defined:

$$a = \min\{2c_1, 2c_2, 2c_3, 2c_4, \varsigma_2, \varsigma_3, \varsigma_4\}, \tag{52}$$

$$b = \tilde{\gamma}_4. \tag{53}$$

Choosing $V = V_4$ as the Lyapunov function candidate, the following inequality can be obtained

$$\dot{V} \le -aV + b. \tag{54}$$

And then, according to Eq. (53), we can obtain $V(t) \le [V(0)-(b/a)]e^{-at}+(b/a)$, which suggests that $\tilde{\theta}_i$ and $\hat{\theta}_i$ are bounded. Because $e_i = x_i - \alpha_i$, so x_i is bounded and e_i must be bounded. Hence, α_i is bounded as a function of e_i and $\hat{\theta}_i$. Therefore, all signals of the closed-loop system are bounded.

At the same time, the Zeno phenomenon is precluded by proving the existence of $t_j^* > 0$ resulting in $t_{j,k+1} - t_{j,k} \ge t_j^*$, $k \in z^+$. Because for $\forall t \in [t_{j,k}, t_{j,k+1})$, $j = 1, \ldots, n$, $\beta_j(t) = u_j(t) - \omega_j(t)$, it yields

$$\frac{d}{dt}\left|\beta_j\right| = \frac{d}{dt}(\beta_j \cdot \beta_j)^{\frac{1}{2}} = sign(\beta_j)\dot{\beta}_j \le \left|\dot{u}_j\right|. \tag{55}$$

From (31), it can be concluded that u_j is differentiable and $\dot{u}_j$ is a continuous function. Consequently, one has a positive constant u^* such that $\left|\dot{u}_j\right| \le u^*$ holds. By combining $\beta_j(t_{j,k}) = 0$ and $\lim_{t \to t_{j,k+1}} \beta_j = \eta(t)\left|\omega_j(t_{j,k})\right| + d_j$, we can obtain $t_j^* \ge \frac{d_j}{u^*} > 0$. The Zeno behavior is prevented. In a word, the proof is completed.

Remark 2 This paper realizes the tracking control of flexible-joint robot systems through a 4-step system design, in which in the process of the system design, this paper adopts the dynamic event-triggered strategy so that the system will be triggered only when it is needed, which achieves the purpose of saving resources. Incorporating the dynamic event-triggered strategy into the control process of flexible-joint robot systems is one of the main tasks of this paper.

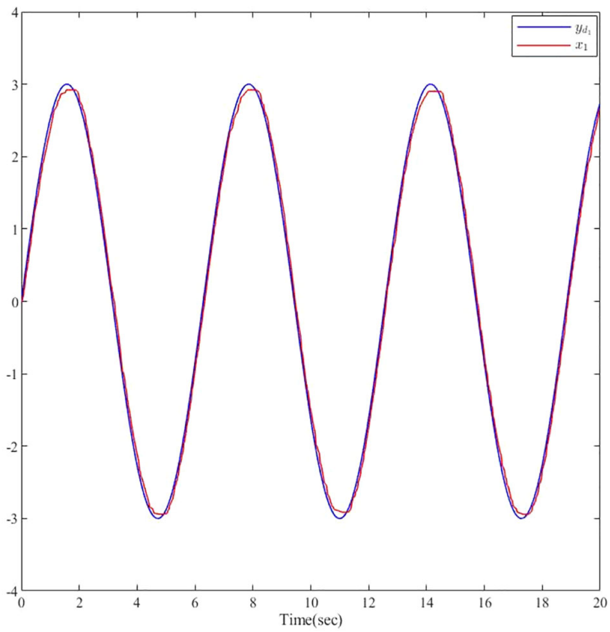

Fig. 3 Simulation: tracking trajectories between x_1 and y_{d_1}

Remark 3 The main contributions of this paper in terms of adaptive learning can be summarized as: (i) Most existing research results mainly consider the control of general systems, while this paper focuses on the adaptive tracking control of flexible-joint robot systems. (ii) In the control of flexible-joint robot systems, the control schemes designed by using adaptive fuzzy control and event-triggered techniques can be considered. Thus, the application of adaptive learning theory is expanded.

4 Simulation

In this section, this paper applied the control strategy to a 2-link flexible-joint robot system on the existing Quanser platform. The 2-link flexible-joint robot system that has no friction term can be depicted as follows:

$$\begin{cases} H(q)\ddot{q} + C(q,\dot{q})\dot{q} + M(q) + Kq = Kq_m, \\ J\ddot{q}_m + B\dot{q}_m + K(q_m - q) = u, \end{cases} \tag{56}$$

in which $H(q) = \begin{bmatrix} (m_1+m_2)l_1^2 & m_1l_1l_2D \\ m_1l_1l_2D & m_2l_2^2 \end{bmatrix}\text{kg}\cdot\text{m}^2$, $C(q,\dot{q}) = m_2l_1l_2(a_1b_2 - b_1a_2)\begin{bmatrix} 0 & -\dot{q}_2 \\ -\dot{q}_1 & 0 \end{bmatrix}\text{Nm}\cdot/\text{rad}$, $M(q) = \begin{bmatrix} -(m_1+m_2)l_1gb_1 \\ -m_2l_2gb_2 \end{bmatrix}\text{N}$, $J = \begin{bmatrix} J_1 & 0 \\ 0 & J_2 \end{bmatrix}\text{kg}\cdot\text{m}^2$, $B = \begin{bmatrix} B_1 & 0 \\ 0 & B_2 \end{bmatrix}\text{Nm}\cdot/\text{rad}$, $K = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix}\text{Nm}\cdot/\text{rad}$, with $a_1 = \cos(q_1)$, $a_2 = \cos(q_2)$, $b_1 = \sin(q_1)$, $b_2 = \sin(q_2)$, $D = a_1a_2 + b_1b_2$ and $g = 9.8\text{m/s}$ being the constant of gravity. The parameters relevant for 2-link flexible robot are $J_1 = J_2 = 0.004$, $K_1 = K_2 = 120$, $B_1 = 0.5$, $B_2 = 0.8$, $m_1 = 1.5$, $m_2 = 2$, $l_1 = 0.6$ and $l_2 = 0.8$. In the experiment, the ideal trajectories are selected as $q_{d_1}(t) = q_{d_2}(t) = 3\sin t$. The other parameters used in the experiment are $c_1 = 25$, $c_2 = 15$, $c_3 = 15$, $c_4 = 55$, $r_2 = r_3 = r_4 = 5$, $\varsigma_2 = \varsigma_3 = 1$, $\varsigma_4 = 0.5$, $\eta(0) = 0.5$, $d = [1; 2]$, $o = [10; 10]$.

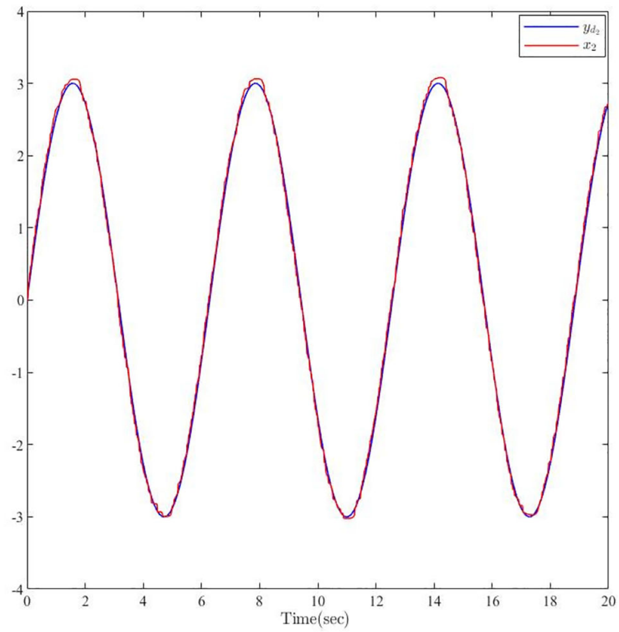

Fig. 4 Simulation: tracking trajectories between x_2 and y_{d_2}

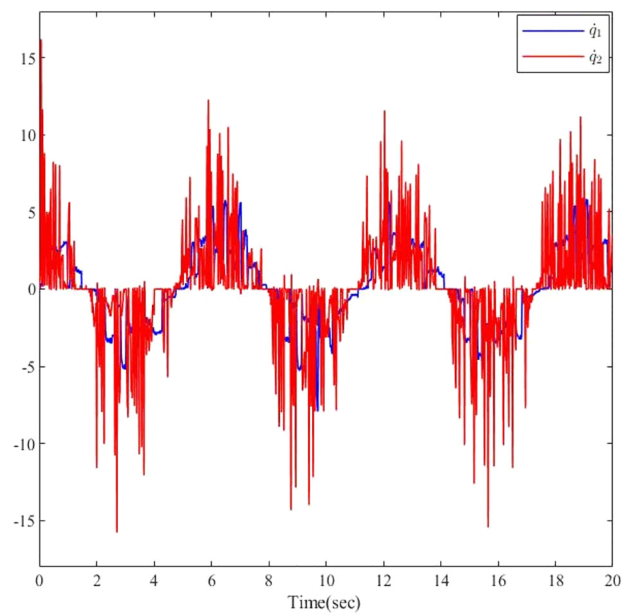

Fig. 5 Simulation: system states $\dot{q}_1$ and $\dot{q}_2$

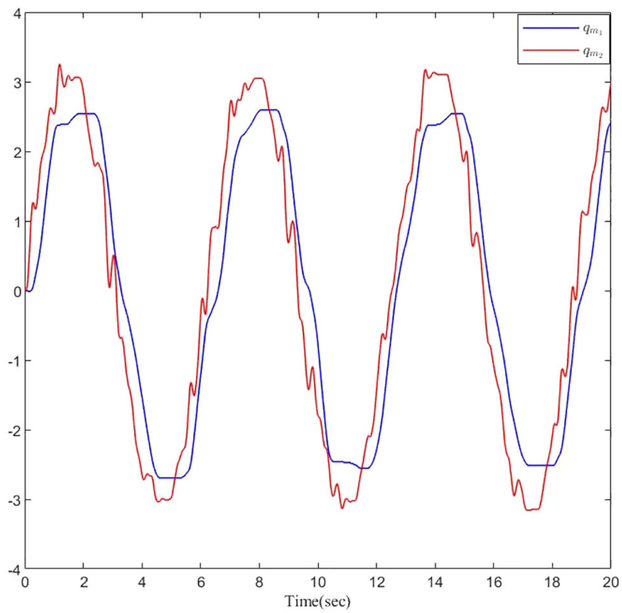

Fig. 6 Simulation: system states q_{m_1} and q_{m_2}

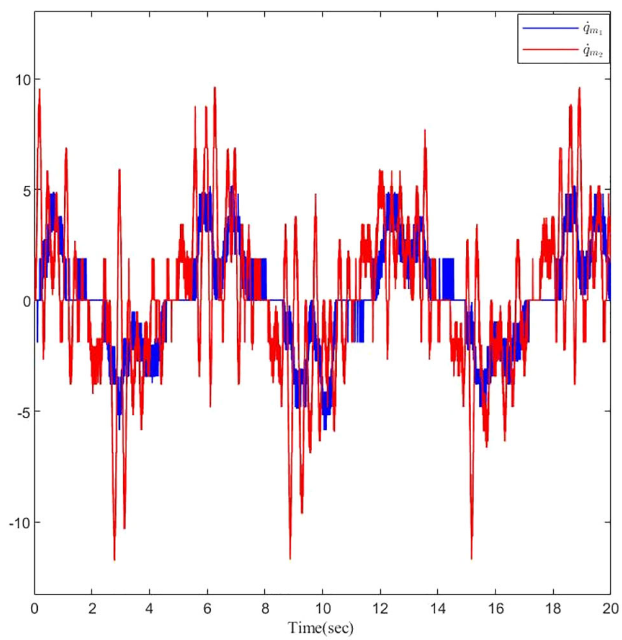

Fig. 7 Simulation: system states $\dot{q}_{m_1}$ and $\dot{q}_{m_2}$

The initial set of values for all states and the adaptive values of the parameters are chosen to be zero. Figures 3, 4, 5, 6, 7, 8, 9 and 10 illustrate the simulation results gained by the designed virtual control signals (7), (15), (25) and (44) as well as adaptive laws (17), (27) and (46). Figure 3 plots the trajectories of x_1 and y_{d_1}. Figure 4 plots the trajectories of x_2 and y_{d_2}. The system states are shown in Figs. 5, 6 and 7. The adaptive laws are shown in Fig. 8. The system outputs are shown in Figs. 9 and 10. Referring to the experimental results

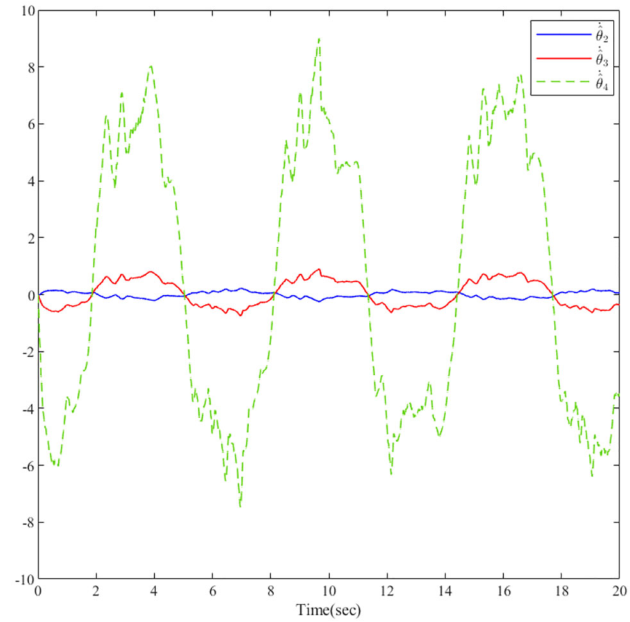

Fig. 8 Simulation: adaptive parameters $\dot{\hat{\theta}}_2$, $\dot{\hat{\theta}}_3$ and $\dot{\hat{\theta}}_4$

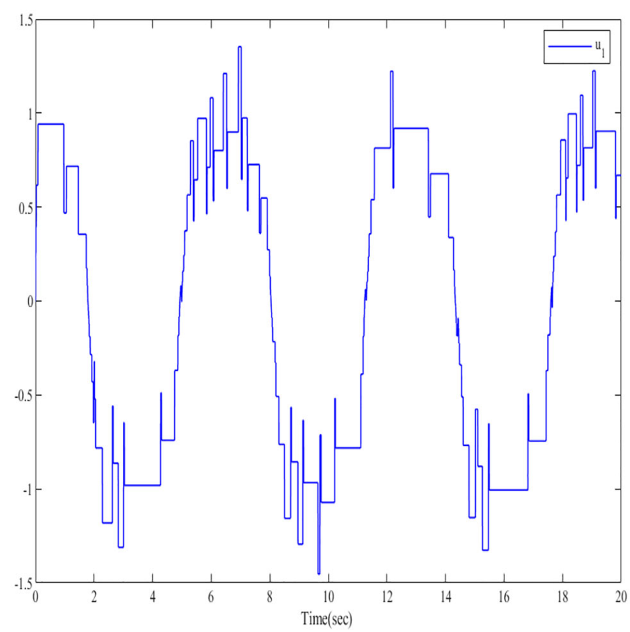

Fig. 9 Simulation: system control inputs u_1

of existing research results, such as [11], the experimental results in this paper show that the control scheme proposed in this paper can realize the effective control of the 2-link flexible-joint robot systems.

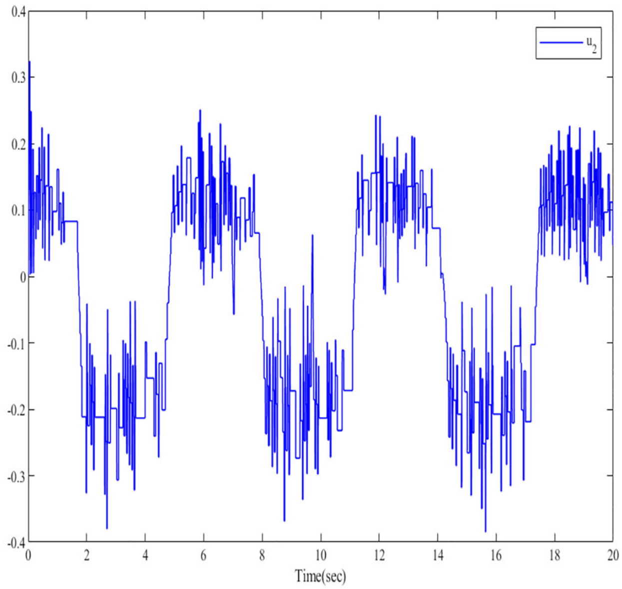

Fig. 10 Simulation: system control inputs u_2

5 Conclusion

This article focuses on the adaptive fuzzy tracking control problem of the flexible-joint robot systems. Firstly, for the flexible-joint robot systems, this paper utilizes the adaptive backstepping method for system design on the basis of system error transformation and coordinate transformation, so as to estimate the uncertain parameters of the system and adjust the control coefficients in time to realize the stable control of the system. Secondly, the fuzzy logic system is used to approximate the unknown nonlinear function, and the appropriate Lyapunov candidate function and adaptive law are selected to realize the high performance of the flexible-joint robot systems and to reduce the uncertainty during its operation. Subsequently, this paper designs an appropriate dynamic event-triggered mechanism to realize triggering the system when needed to achieve the purpose of saving resources.

Finally, this paper carries out simulation experiments using a 2-link flexible-joint robot on the Quanser platform, which show that all signals in the closed-loop systems are bounded and that the position vectors of the flexible-joint robot linkage can keep track of the desired trajectory within a small error. In conclusion, the simulation experiments verify the effectiveness of the control strategy designed in this paper for the flexible-joint robot systems, referring to the experimental results of existing research results, such as [25].

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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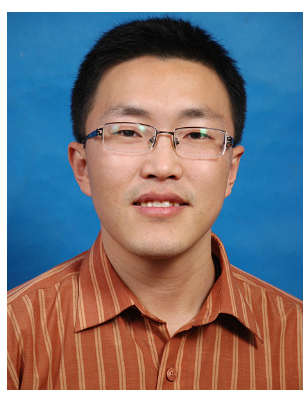

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