

ADAPTIVE FUZZY PRESCRIBED-TIME FAULT-TOLERANT CONTROL FOR NONSTRICT-FEEDBACK NONLINEAR SYSTEM WITH INTERMITTENT ACTUATOR FAULTS

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ABSTRACT. *This paper investigates the adaptive fuzzy prescribed-time fault-tolerant control (FTC) problem for nonstrict-feedback nonlinear systems with intermittent actuator faults. Since the controlled system contains unknown nonlinear dynamics, the unknown nonlinear dynamics are approximated by using fuzzy approximation technique. Then, under the frameworks of prescribed-time stability theory and backstepping control design technique, an adaptive fuzzy prescribed-time FTC method is proposed. It is proved that the closed-loop system is prescribed-time stable and all the signals of controlled system are bounded within prescribed time interval. Finally, the proposed adaptive fuzzy prescribed-time FTC method is applied to the two-stage chemical reactor system, and the simulation results confirm its effectiveness.*

Keywords: Nonlinear systems, Fault-tolerant control, Fuzzy logic systems, Stability analysis

1. Introduction. In recent years, adaptive fuzzy or neural network (NN) control for nonlinear systems has received considerable attention, and many important results have been reported, for example, [1-5]. In [1], an adaptive fuzzy controller was designed for nonlinear systems. [2] considered a class of uncertain strict-feedback nonlinear systems and proposed a fuzzy adaptive control method by command filtering. In [3], an adaptive NN control algorithm was presented to deal with the tracking control problem for nonlinear systems. [4,5] studied the adaptive fuzzy output-feedback control problem for uncertain nonlinear systems and developed an observer-based adaptive fuzzy control scheme. Note that the above-mentioned fuzzy/NN adaptive control approaches are all for strict-feedback nonlinear systems. In fact, many practical engineering systems, such as the helicopter model, the uncertain robot systems and the aircraft sight control systems, can be expressed by nonstrict-feedback systems instead of strict-feedback ones. However, if the developed control methods for strict-feedback nonlinear systems in [1-5] are applied to nonstrict-feedback nonlinear systems, an “algebraic loop problem” will occur because the unknown nonlinear function in the nonstrict-feedback nonlinear systems includes the whole state variables of the system. To deal with this problem, several meaningful adaptive fuzzy/NN control methods were proposed for nonstrict-feedback stochastic nonlinear systems, for instance, [6,7]. In [6], an adaptive fuzzy control method was proposed for nonstrict-feedback systems by using fuzzy logic systems. [7] developed an adaptive

NN constraint control method for nonstrict-feedback nonlinear systems with state constraints. Note that intermittent actuator failures occur in many practical systems, which can reduce the control performance of the system or even destroy the stability of the system. Therefore, many results on fault-tolerant control (FTC) problem have been reported in [8-10] for nonstrict-feedback nonlinear systems with intermittent actuator faults. An adaptive NN state-feedback FTC method in [8] was proposed for nonstrict-feedback nonlinear systems, while in [9,10], fuzzy adaptive output feedback FTC strategies were proposed for nonstrict-feedback nonlinear systems with immeasurable states.

It should be noted that the above mentioned adaptive fuzzy/NN controllers are developed only to ensure the controlled systems are stable in an infinite-time interval, instead of a finite-time interval. In fact, for many practical systems, it is often more desired that their state trajectories converge to the equilibrium points within a finite time. For this purpose, the finite-time/fixed-time stable concepts were proposed in [11,12]. Based on the finite-time/fixed-time stable theories, many finite-time/fixed-time adaptive fuzzy or NN controllers have been developed for systems, for example, [13-17]. [13,14] developed adaptive fuzzy finite-time controls for nonstrict-feedback nonlinear systems with unknown dynamics. In [15], a finite-time adaptive neural tracking control method was proposed for nonlinear systems in nonstrict-feedback form. In [16], an adaptive fixed-time fuzzy controller was proposed for uncertain nonstrict-feedback systems with input saturation. [17] presented a fixed-time adaptive fuzzy tracking control method for nonstrict-feedback nonlinear systems. It should be mentioned that the least upper bound of the settling time of the above mentioned finite-time control schemes depends on the controlled system initial values, while the least upper bound of the settling time of fixed-time control methods is determined by many design parameters. In contrast, the least upper bound of the settling time of predefined-time control [18,19] can be preset irrespective of initial conditions and any other design parameters. Due to the advantages of the predefined-time control, [20] developed an adaptive predefined-time tracking control method for nonlinear systems by using command filter technology. [21] presented an adaptive fuzzy predefined-time tracking control scheme for nonstrict-feedback nonlinear systems. In [22], an adaptive fuzzy predefined-time control method was proposed for nonstrict-feedback nonlinear systems under dynamic event-triggered framework. Subsequently, to accurately specify the settling time, prescribed-time stable concept was presented in [23,24]. Based on the prescribed-time stability theory, [25] presented an event-triggered adaptive fuzzy prescribed-time tracking control strategy for nonstrict-feedback nonlinear systems. However, there has been very little research on adaptive fuzzy prescribed-time control design problem for nonstrict-feedback nonlinear systems. Furthermore, no works have been reported on adaptive fuzzy prescribed-time FTC for nonstrict-feedback nonlinear system, which motivate us for this study.

Inspired by this motivation, this article investigates an adaptive fuzzy prescribed-time FTC design problem for nonstrict-feedback nonlinear systems with intermittent actuator faults. Different from the previous results, its main contributions are as follows.

1) In this paper, an adaptive fuzzy prescribed-time FTC scheme is proposed under the prescribed-time stability theory. It should be noted that, although [25] investigated adaptive fuzzy prescribed-time control problems, the developed controllers are not applicable to uncertain nonstrict-feedback nonlinear systems with intermittent actuator faults.

2) Different from the previous adaptive fuzzy/NN FTC schemes [8-10], the adaptive fuzzy prescribed-time FTC scheme in this paper ensures that the tracking errors converge within a prescribed time and the convergence time is independent of the initial value. Additionally, the algebraic loop problem is avoided by the presented control method in this paper.

The remainder of this paper is structured as follows. Section 2 gives problem formulation. In Section 3, a prescribed-time fuzzy fault-tolerant controller is developed. Simulation studies are given in Section 4. Section 5 concludes the paper.

2. Problem Statement and Preliminaries.

2.1. System model.

$$\begin{aligned}\dot{\chi}_m &= \chi_{m+1} + g_m(\bar{\chi}_n), \quad m = 1, \dots, n-1 \\ \dot{\chi}_n &= bu + g_n(\bar{\chi}_n) \\ y &= \chi_1\end{aligned}\tag{1}$$

where $\bar{\chi}_n = [\chi_1, \dots, \chi_n]^T$ is the state vector; u and y are the control input and output; $g_m(\bar{\chi}_n)$ is an unknown smooth nonlinear function with $g_m(0) = 0$; b represents a known constant.

According to [10], an intermittent fault model is described in this article as

$$u(t) = \rho(t)u_c(t) + u_f(t)\tag{2}$$

where $\rho(t) = \rho_q$, $t \in [t_q, t_{q+1})$, $\forall q \in \mathbb{Z}^+$, $0 < \rho^* \leq \rho_q \leq 1$ with ρ^* and ρ_q being unknown constants. $u_f(t)$ is the bounded function.

Assumption 2.1. [10] *There exists a positive constant u_M , such that $|u_f(t)| \leq u_M$.*

The control objective of this work is to design a fuzzy adaptive prescribed-time event-triggered controller for nonlinear system (1) such that the system output y can be steered to a given reference signal $r(t)$ at a prescribed time T_f .

Assumption 2.2. [17] *The reference signal $r(t)$ is $(n-1)$ th-order differentiable and its derivatives are bounded.*

2.2. Prescribed-time stability. Consider a nonlinear system as follows:

$$\dot{\chi}(t) = f(\chi(t))\tag{3}$$

where $\chi(t)$ is the system state vector and f is a locally Lipschitz continuous nonlinear function and satisfies $f(0) = 0$. Assume that $\chi = 0$ is the equilibrium point of system (1).

Denoting by T_f the given prescribed convergence time, the prescribed-time function ω is given as follows:

$$\omega = \begin{cases} \left(\frac{T_f}{T_f + t_0 - t} \right)^p & t \in [t_0, t_0 + T_f) \\ 1 & t \in [t_0 + T_f, +\infty) \end{cases}\tag{4}$$

where $t_0 \geq 0$ and $p \geq 2$ is an integer.

Lemma 2.1. [23] *For the nonlinear system (1), if there exists a function $U(\chi)$ that satisfies*

$$\dot{U}(\chi) \leq -2\kappa\omega U(\chi) + \frac{\omega\Phi^2(t)}{4v}\tag{5}$$

where κ and v are positive constants and $\Phi^2(t)$ denotes an unknown disturbance, then $U(\chi)$ remains bounded within $[t_0, t_0 + T_f)$.

2.3. Fuzzy logic systems. The knowledge base of a fuzzy logic system (FLS) comprises a set of fuzzy if-then rules in the following form.

R^j : if χ_1 is F_1^j , if χ_2 is F_2^j , ..., if χ_n is F_n^j , then g is G^j , $j = 1, 2, \dots, N$ where N is the fuzzy rule number, $\chi = [\chi_1, \chi_2, \dots, \chi_n]^T$ and g are the FLS input and output, respectively. F_i^j and G^j are fuzzy sets with their respective membership functions $\mu_{F_i^j}(\chi_i)$ and $\mu_{G^j}(g)$.

Through center average defuzzification, the FLS can be described as

$$g(\chi) = \frac{\sum_{j=1}^N \bar{w}_j \prod_{k=1}^2 \mu_{F_k^j}(\chi_k)}{\sum_{j=1}^N \prod_{k=1}^2 \mu_{F_k^j}(\chi_k)} \quad (6)$$

where $\bar{w}_j = \max_{g \in R} \mu_{G^j}(g)$.

Denote $w = [\bar{w}_1, \bar{w}_2, \dots, \bar{w}_N]^T$, $\psi(\chi) = [\psi_1(\chi), \dots, \psi_N(\chi)]^T$ and define the fuzzy basis functions ψ_j as

$$\psi_j(\chi) = \frac{\prod_{k=1}^2 \mu_{F_k^j}(\chi_k)}{\sum_{j=1}^N \prod_{k=1}^2 \mu_{F_k^j}(\chi_k)} \quad (7)$$

Then, the FLS (4) can be rewritten as

$$g(\chi) = w^T \psi(\chi) \quad (8)$$

According to [1], fuzzy logic systems can be employed to approximate the continuous function. Its main property is displayed by Lemma 2.2.

Lemma 2.2. [1] Assume that $g(\chi)$ is a continuous function over a compact set Γ_χ , for any constant $\varsigma > 0$, there exists a fuzzy logic system $w^T \psi(\chi)$ such that

$$g(\chi) = w^T \psi(\chi) + \varsigma$$

where $\psi(\chi) = [\psi_1(\chi), \dots, \psi_N(\chi)]^T$ denotes the fuzzy basis function, and w represents the ideal weight. N is the fuzzy rule number.

3. Prescribed-Time Fuzzy Fault-Tolerant Controller. Define the following coordinates transformation as

$$\begin{aligned} z_1 &= \chi_1 - r(t) \\ z_q &= \chi_q - \beta_{q-1}, \quad q = 2, \dots, n \end{aligned} \quad (9)$$

where β_{q-1} denotes the virtual controller. t will be omitted in the following.

By using (9), the n -step backstepping design process is presented as follows.

Step 1. From (9), one has

$$\dot{z}_1 = g_1(\bar{\chi}_n) + z_2 + \beta_1 - \dot{r} \quad (10)$$

With the help of Lemma 2.2, we have $g_1(\bar{\chi}_n) = \vartheta_1^{*T} \gamma_1(\bar{\chi}_n) + \delta_1$, $|\delta_1| \leq \bar{\delta}$, where ϑ_1^* denotes the ideal weight, δ_1 represents the approximation error and $\bar{\delta}$ is a positive constant.

From (9) and (10), we have

$$\dot{z}_1 = \vartheta_1^{*T} \gamma_1(\bar{\chi}_n) + \delta_1 + z_2 + \beta_1 - \dot{r} \quad (11)$$

Denote by $\eta_s = \omega z_s$ with $s = 1, 2, \dots, n$, and then we get

$$\dot{\eta}_1 = \omega (\vartheta_1^{*T} \gamma_1(\bar{\chi}_n) + \delta_1 - \dot{r}) + \eta_2 + \omega \beta_1 + \dot{\omega} \omega^{-1} \eta_1 \quad (12)$$

Select the Lyapunov function candidate as

$$U_1 = \frac{1}{2} \eta_1^2 + \frac{\omega}{2d_1} \tilde{\vartheta}_1^T \tilde{\vartheta}_1 \quad (13)$$

where $d_1 > 0$ is a constant, and $\tilde{\vartheta}_1 = \vartheta_1^* - \vartheta_1$ with ϑ_1 being the estimation of ϑ_1^* .

Using (12) and (13), one has

$$\begin{aligned} \dot{U}_1 &= \eta_1 (\omega (\vartheta_1^{*T} \gamma_1(\bar{\chi}_n) - \vartheta_1^{*T} \gamma_1(\chi_1) + \vartheta_1^{*T} \gamma_1(\chi_1) + \delta_1 - \dot{r}) + \eta_2 + \omega \beta_1 + \dot{\omega} \omega^{-1} \eta_1) \\ &\quad - \frac{\omega}{d_1} \tilde{\vartheta}_1^T \dot{\vartheta}_1 + \frac{\dot{\omega}}{2d_1} \tilde{\vartheta}_1^T \tilde{\vartheta}_1 \end{aligned} \quad (14)$$

By applying Young's inequality, one has

$$\omega\eta_1 (\vartheta_1^{*T}\gamma_1(\bar{\chi}_n) - \vartheta_1^{*T}\gamma_1(\chi_1) + \delta_1) \leq 3v\omega\eta_1^2 + \frac{2\omega\|\vartheta_1^*\|^2 + \omega\bar{\delta}^2}{4v} \quad (15)$$

where $v > 0$ is a constant.

Design the virtual controller and the adaptive law as

$$\beta_1 = -\left(c_1\eta_1 - \frac{z_1}{2} + 3v\omega\eta_1 + \dot{\omega}\omega^{-1}\eta_1 - \dot{r} + \vartheta_1^T\gamma_1(\chi_1)\right) \quad (16)$$

$$\dot{\vartheta}_1 = d_1(\eta_1\gamma_1(\chi_1) - \sigma_1\vartheta_1) \quad (17)$$

where c_1 and σ_1 are design constants.

$$\dot{U}_1 \leq -c_1\omega\eta_1^2 + \eta_1\eta_2 - \frac{1}{2}\eta_1^2 + \omega\sigma_1\vartheta_1\tilde{\vartheta}_1 + \frac{\dot{\omega}}{2d_1}\|\tilde{\vartheta}_1\|^2 + \frac{2\omega\|\vartheta_1^*\|^2 + \omega\bar{\delta}^2}{4v} \quad (18)$$

Step s ($s = 2, \dots, n-1$). From (9), one has

$$\dot{z}_s = g_s(\bar{\chi}_n) + z_{s+1} + \beta_s - \dot{\beta}_{s-1} \quad (19)$$

Let $\bar{g}_s(\bar{\chi}_n) = g_s(\bar{\chi}_n) - \dot{\beta}_{s-1}$, and then with the help of Lemma 2.2, we have $\bar{g}_s(\bar{\chi}_n) = \vartheta_s^T\gamma_s(\bar{\chi}_n) + \delta_s$, $|\delta_s| \leq \bar{\delta}$, where ϑ_s^* denotes the ideal weight, δ_s represents the approximation error and $\bar{\delta}$ is a positive constant.

$$\dot{\eta}_s \leq \omega(\vartheta_s^{*T}\gamma_1(\bar{\chi}_n) + \bar{\delta}) + \eta_{s+1} + \omega\beta_s + \dot{\omega}\omega^{-1}\eta_s \quad (20)$$

Select the Lyapunov function candidate as

$$U_s = \frac{1}{2}\eta_s^2 + \frac{\omega}{2d_s}\tilde{\vartheta}_s^T\tilde{\vartheta}_s + U_{s-1} \quad (21)$$

where $d_s > 0$ is a constant, and $\tilde{\vartheta}_s = \vartheta_s^* - \vartheta_s$ with ϑ_s being the estimation of ϑ_s^* .

Using (12) and (13), one has

$$\begin{aligned} \dot{U}_s &= \eta_s\omega(\vartheta_s^{*T}\gamma_s(\bar{\chi}_n) - \vartheta_s^{*T}\gamma_s(\bar{\chi}_s) + \vartheta_s^{*T}\gamma_s(\bar{\chi}_s) + \bar{\delta}) + \eta_s\eta_{s+1} + \eta_s\omega\beta_s \\ &\quad + \dot{\omega}\omega^{-1}\eta_s - \frac{\omega}{d_s}\tilde{\vartheta}_s^T\dot{\vartheta}_s + \dot{U}_{s-1} \end{aligned} \quad (22)$$

By applying Young's inequality, one has

$$\omega\eta_s(\vartheta_s^{*T}\gamma_s(\bar{\chi}_n) - \vartheta_s^{*T}\gamma_s(\bar{\chi}_s) + \bar{\delta}) \leq 3v\omega\eta_s^2 + \frac{2\omega\|\vartheta_s^*\|^2 + \omega\bar{\delta}^2}{4v} \quad (23)$$

Design the virtual controller and the adaptive law as

$$\beta_s = -\left(c_s\eta_s - \frac{z_s}{2} + 3v\omega\eta_s + \dot{\omega}\omega^{-1}\eta_s + \vartheta_s^T\gamma_s(\bar{\chi}_s)\right) \quad (24)$$

$$\dot{\vartheta}_s = d_s(\eta_s\gamma_s(\bar{\chi}_s) - \sigma_s\vartheta_s) \quad (25)$$

where c_s and σ_s are design constants.

$$\dot{U}_s \leq -c_s\omega\eta_s^2 + \eta_s\eta_{s+1} - \frac{1}{2}\eta_s^2 + \frac{2\omega\|\vartheta_s^*\|^2 + \omega\bar{\delta}^2}{4v} + \omega\sigma_s\vartheta_s\tilde{\vartheta}_s + \dot{U}_{s-1} \quad (26)$$

Step n . From (9), one has

$$\dot{z}_n = g_n(\bar{\chi}_n) + v - \dot{\beta}_{n-1} \quad (27)$$

With the help of Lemma 2.2, we have $g_n(\bar{\chi}_n) = \vartheta_n^T\gamma_n(\bar{\chi}_n) + \delta_n$, $|\delta_n| \leq \bar{\delta}$, where ϑ_n^* denotes the ideal weight, δ_n represents the approximation error and $\bar{\delta}$ is a positive constant.

$$\dot{\eta}_n \leq \omega(\vartheta_n^{*T}\gamma_n(\bar{\chi}_n) + \bar{\delta}) + \omega v + \dot{\omega}\omega^{-1}\eta_n \quad (28)$$

Select the Lyapunov function candidate as

$$U_n = \frac{1}{2}\eta_n^2 + \frac{\omega}{2d_n}\tilde{\vartheta}_n^T\tilde{\vartheta}_n + \frac{b\rho}{2\gamma}\tilde{\varpi}^2 + U_{n-1} \quad (29)$$

where $d_n > 0$ and $\gamma > 0$ are constants, and $\tilde{\vartheta}_n = \vartheta_n^* - \vartheta_n$ with ϑ_n being the estimation of ϑ_n^* . $\tilde{\varpi} = \varpi^* - \hat{\varpi}$, $\hat{\varpi}$ is the estimation of $\varpi^* = 1/|b|\rho$.

Using (12) and (13), one has

$$\dot{U}_n = \eta_n\omega(\vartheta_n^{*T}\gamma_n(\bar{\chi}_n) + \bar{\delta}) + \eta_n\omega v + \dot{\omega}\omega^{-1}\eta_n - \frac{\omega}{d_n}\tilde{\vartheta}_n^T\dot{\vartheta}_n + \frac{b\rho}{2\gamma}\tilde{\varpi}\dot{\tilde{\varpi}} + \dot{U}_{n-1} \quad (30)$$

By applying Young's inequality, one has

$$\omega\eta_n\bar{\delta} \leq v\omega\eta_n^2 + \frac{\omega\bar{\delta}^2}{4v} \quad (31)$$

Design the virtual controller and the adaptive law as

$$\beta_n = -\left(c_n\eta_n - \frac{z_n}{2} + \eta_n + v\omega\eta_n + \dot{\omega}\omega^{-1}\eta_n + \vartheta_n^T\gamma_n(\bar{\chi}_n)\right) \quad (32)$$

$$\dot{\vartheta}_n = d_n(\eta_n\gamma_n(\bar{\chi}_n) - \sigma_n\vartheta_n) \quad (33)$$

where c_n and σ_n are design constants.

Design the following final controller u_c and the adaptive law of parameter $\hat{\varpi}$ as

$$u_c = -\text{sgn}(b)\frac{z_n\hat{\varpi}^2\beta_n^2}{\sqrt{z_n^2\hat{\varpi}^2\beta_n^2 + \bar{\eta}^2}} \quad (34)$$

$$\dot{\hat{\varpi}} = z_n\gamma u_c - \bar{c}\hat{\varpi} \quad (35)$$

where $\bar{\eta}$ and $\bar{c}$ are design constants.

Theorem 3.1. *If nonlinear system (7) satisfies Assumption 2.1, then the designed fault-tolerant controller (34) with adaptive laws (17), (25), (33) and (35) can ensure that the controlled system is prescribed-time stable and the tracking error z_1 can converge to a small neighborhood of zero within the predefined time T_f .*

Proof: According to [10] and designed control law (34), we have

$$z_nb\rho u_c \leq -|b|\rho\frac{z_n^2\hat{\varpi}^2\beta_n^2}{\sqrt{z_n^2\hat{\varpi}^2\beta_n^2 + \bar{\eta}^2}} \leq |b|\rho\bar{\eta} - z_n|b|\rho\hat{\varpi}\beta_n \quad (36)$$

$$z_n\beta_n - |b|\rho z_n\hat{\varpi}\beta_n - |b|\rho z_n\tilde{\varpi}\beta_n = 0 \quad (37)$$

By applying Young's inequality, one has

$$\vartheta_s^T\tilde{\vartheta}_s = \tilde{\vartheta}_s^T(\vartheta_s^* - \tilde{\vartheta}_s) \leq -\frac{1}{2}\|\tilde{\vartheta}_s\|^2 + \frac{1}{2}\|\vartheta_s^*\|^2 \quad (38)$$

$$\tilde{\varpi}\hat{\varpi} \leq \frac{1}{2}\varpi^{*2} - \frac{1}{2}\tilde{\varpi}^2 \quad (39)$$

Then, substituting (34), (35), (36), (37), (38) and (39) into (30) yields

$$\begin{aligned} \dot{U}_n \leq & -\sum_{p=1}^n c_p\omega\eta_p^2 + \omega\sum_{p=1}^n \frac{2\|\vartheta_p^*\|^2 + \bar{\delta}^2 + 2v\|\vartheta_p^*\|^2}{4v} - \sum_{p=1}^n \left(\frac{1}{2} - \frac{1}{d_p}\right)\omega\|\tilde{\vartheta}_p\|^2 \\ & + \frac{1}{2}b^2u_M^2 + \frac{\bar{c}b\rho}{2\gamma}\varpi^{*2} \end{aligned} \quad (40)$$

Choose $\kappa = \min\{c_p, d/2 - 1\}$. Thus, one can obtain

$$\dot{U}_n \leq -2\kappa\omega U_n + \omega\zeta + \frac{1}{2}b^2u_M^2 + \frac{\bar{c}b\rho}{2\gamma}\varpi^{*2} + |b|\rho\bar{\eta} \quad (41)$$

where $\zeta = \sum_{p=1}^n \frac{2\|\vartheta_p^*\|^2 + \bar{\delta}^2 + 2v\|\vartheta_p^*\|^2}{4v}$. Therefore, by Lemma 2.1, it is concluded that all signals of the controlled system (7) are bounded, and the tracking error z_1 can converge to a small neighborhood of zero within $[t_0, t_0 + T_f]$.

The parameter selection guideline for the prescribed-time fuzzy fault-tolerant controller design is given as follows.

1) Choose the design constants so that $T_f > 0$, $p \geq 2$, $c_s > 0$ and $v > 0$ can determine the prescribed-time function ω and the virtual controller β_s .

2) Choose the design constants so that $d_s > 0$, $\sigma_s > 0$, $\gamma > 0$ and $\bar{c} > 0$ can determine the adaptive laws of parameters $\hat{\vartheta}_s$ and $\hat{\varpi}$.

3) Choose the design constant so that $\bar{\eta} > 0$ can determine the prescribed-time controller $u_c(t)$.

Remark 3.1. From (41), we know that the convergence rate variables in the system (7) are related to c_s , d_s , σ_s , $\bar{c}$, $\bar{\eta}$, γ , and p . Therefore, we can conclude that increasing these design parameters makes the convergence of the variables in system (7) faster. However, note that a higher convergence rate will result in larger control input. Therefore, a careful consideration of the trade-off between convergence speed and control input is required in practical systems.

4. Numerical Simulation. In this section, we take the two-stage chemical reactor system as an example to verify the effectiveness of the proposed prescribed-time adaptive fuzzy fault-tolerant tracking control method. The dynamics of the chemical reactor system are described as [20]

$$\begin{cases} \dot{C}_A = \frac{1 - R_B}{V_A} C_B - \left(\frac{1}{\Xi_A} + K_A \right) C_A \\ \dot{C}_B = v(t) + \frac{R_A}{V_B} C_A - \left(\frac{1}{\Xi_B} + K_B \right) C_B \end{cases} \quad (42)$$

where $v(t)$ is the control input, C_A and C_B are compositions, R_A and R_B are recycle flow rates, K_A and K_B are the reaction constants, V_A and V_B are reactor volumes, and Ξ_A and Ξ_B are the reactor residence times. The parameters of system (42) are listed in Table 1.

TABLE 1. The system parameters of system (42)

Parameters	Values
R_A, R_B	0.25, 0.35
K_A, K_B	0.75, 0.5
V_A, V_B	1, 1.5
Ξ_A, Ξ_B	4, 4.5

Let $\chi_1 = C_A$, $\chi_2 = C_B$, $g_1(\bar{\chi}_2) = -\left(\frac{1}{\Xi_A} + K_A\right)\chi_1 + \frac{1-R_B-V_A}{V_A}\chi_2$ and $g_2(\bar{\chi}_2) = \frac{R_A}{V_B}\chi_1 - \left(\frac{1}{\Xi_B} + K_B\right)\chi_2$. Then, the above chemical reactor system can be rewritten as

$$\begin{cases} \dot{\chi}_1 = \chi_2 + g_1(\bar{\chi}_2) \\ \dot{\chi}_2 = u(t) + g_2(\bar{\chi}_2) \end{cases} \quad (43)$$

The intermittent fault model is defined as follows

$$u(t) = \rho(t)u_c(t) + u_f(t) \quad (44)$$

where $\rho(t) = \rho_q = 0.5$, $t \in [3q, 3q+1)$, $\rho(t) = 1$, $t \notin [3q, 3q+1)$, $q \in \mathbb{Z}^+$ and $u_f(t) = 2\sin(t)$.

Select IF-THEN rules as R^j : if χ_1 is F_1^j , if χ_2 is F_2^j , then g is G^j .

The membership functions of fuzzy sets F_k^j are chosen as $\mu_{F_k^j}(\chi_k) = \exp [-(\chi_k + 3 - j)^2 / 200]$, $k = 1, 2$, $j = 1, 2, 3, 4, 5$.

The fuzzy basis functions γ_1^j and γ_2^j are constructed as

$$\gamma_1^j(\bar{\chi}_2) = \gamma_2^j(\bar{\chi}_2) = \frac{\prod_{k=1}^2 \mu_{F_k^j}(\chi_k)}{\sum_{j=1}^5 \prod_{k=1}^2 \mu_{F_k^j}(\chi_k)}$$

Then fuzzy basis function vectors $\gamma_1(\bar{\chi}_2)$ and $\gamma_2(\bar{\chi}_2)$ are as follows:

$$\gamma_1(\bar{\chi}_2) = [\gamma_1^1, \gamma_1^2, \gamma_1^3, \gamma_1^4, \gamma_1^5]^T \in \mathbb{R}^{5 \times 1}, \quad \gamma_2(\bar{\chi}_2) = [\gamma_2^1, \gamma_2^2, \gamma_2^3, \gamma_2^4, \gamma_2^5]^T \in \mathbb{R}^{5 \times 1}$$

Construct the FLS $\vartheta_1^T \gamma_1(\bar{\chi}_2)$, $\vartheta_2^T \gamma_2(\bar{\chi}_2)$ to approximate $g_1(\bar{\chi}_2)$ and $\bar{g}_2(\bar{\chi}_2)$. The reference signal $r(t)$ is chosen as $r(t) = 1.5 \sin(t)$. Then, the design parameters for the virtual controller (16), (32) and intermittent fault-tolerant controller (34) with adaptive laws (17), (33) and (35) are listed in Table 2.

TABLE 2. The design parameters in (16), (17), (32), (33), (34), (35)

Parameters	Values
t_0, p, T_f	0, 2, 3.5
$d_1, d_2, \sigma_1, \sigma_2$	3, 3, 2, 2
$\bar{\eta}, \bar{c}, \gamma$	1, 0.01, 0.005
c_1, c_2	2, 2 (when $t \in [0, T_f]$)
c_1, c_2	150, 150 (when $t \in [T_f, +\infty)$)

In the simulation, the initial conditions are selected as $\chi_1(0) = 1$, $\chi_2 = -1$, $\vartheta_1(0) = [0.5705, 0.2683, 0.6053, 0.0849, 0.9737]^T$, $\vartheta_2(0) = [0.5163, 0.8890, 0.0974, 0.0891, 0.0184]^T$ and $\varpi(0) = 0.45$.

Figures 1-4 show the simulation results. The curves of the system output $\chi_1(t)$ and reference signal $r(t)$ are shown in Figure 1. From Figure 1, it can be seen that the system

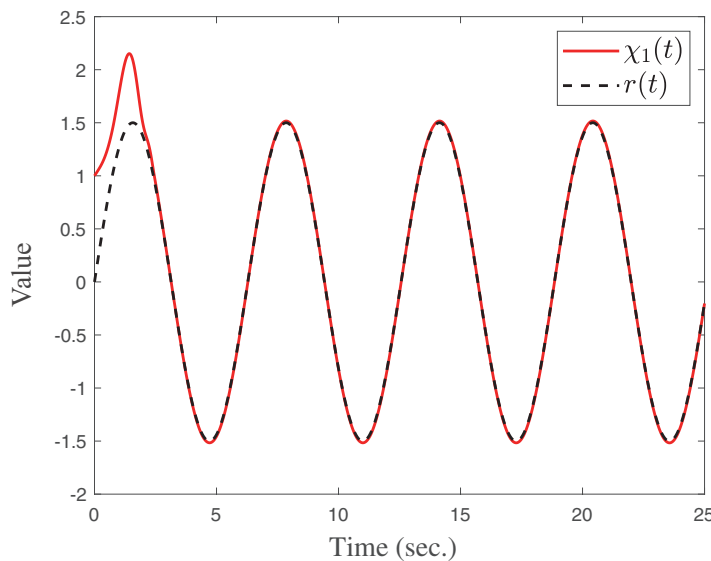
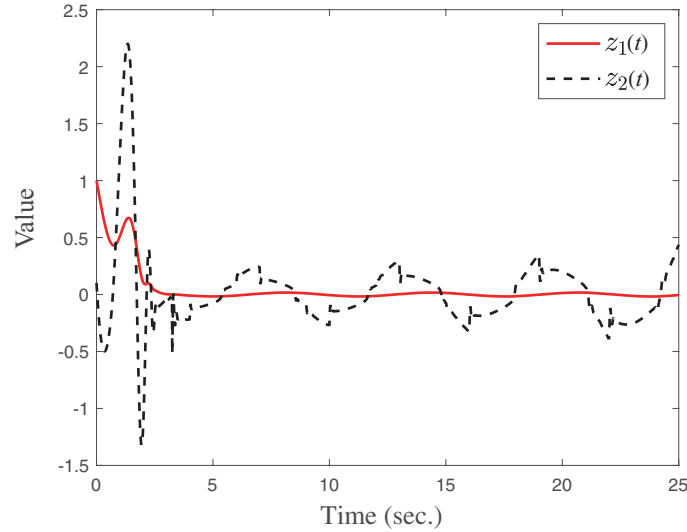
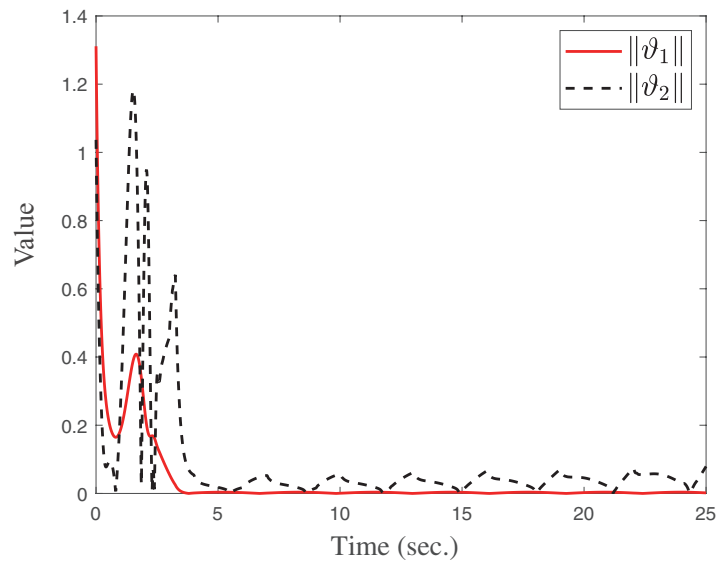


FIGURE 1. The curves of the system output $\chi_1(t)$ and reference signal $r(t)$

FIGURE 2. The curves of $z_1(t)$ and $z_2(t)$ FIGURE 3. The curves of the FLS weights norms $\|\vartheta_1\|$ and $\|\vartheta_2\|$

output $\chi_1(t)$ can track the reference signal $r(t)$. Figure 2 shows the curves of $z_1(t)$ and $z_2(t)$. Figure 3 shows the curves of the FLS norms $\|\vartheta_1\|$ and $\|\vartheta_2\|$. Figures 2 and 3 show that the reactor system is stable and the fuzzy logic system can effectively estimate the unknown nonlinear function. Figure 4 shows the curves of the control input $u(t)$ and the actuator input $u_c(t)$. Under actuator fault conditions, the control input $u(t)$ derived from the actual actuator input $u_c(t)$ can guarantee system stability. Figures 1-4 indicate that the proposed adaptive fuzzy prescribed-time fault-tolerant tracking control method can guarantee that the chemical reactor system is stable, the tracking error $z_1(t)$ converges to a small neighborhood of zero and all system signals are bounded within the time interval $[t_0, t_0 + T_f)$. To further demonstrate the advantages of the adaptive FTC control method proposed in this paper, we apply the fuzzy adaptive prescribed-time tracking control method [25] to the system (42). In the simulation, choose the same initial conditions of the system. Simulation comparison results are shown in Figure 5. It can be seen from

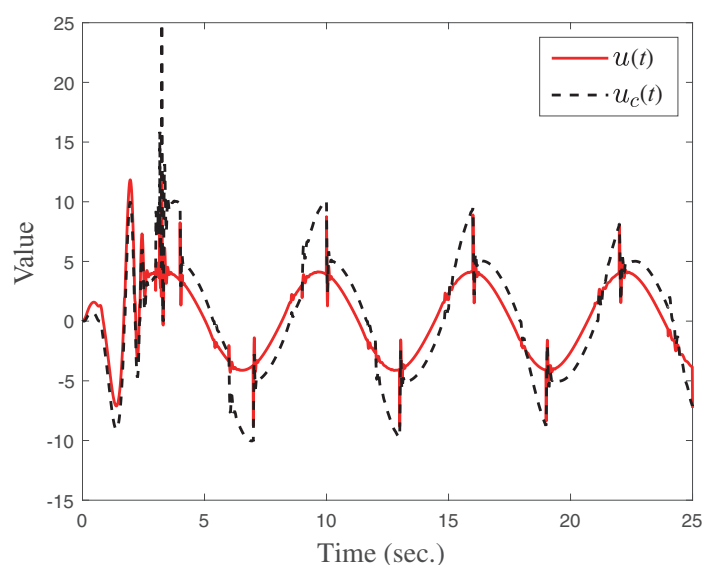


FIGURE 4. The curves of control input $u(t)$ and the actuator input $u_c(t)$

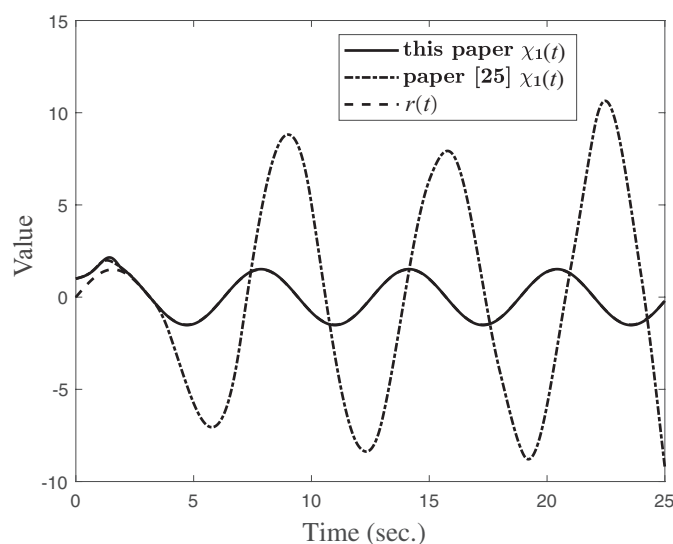


FIGURE 5. Comparison with [25]

Figure 5 that the adaptive control method [25] cannot guarantee the system output $\chi_1(t)$ tracking the reference signal $r(t)$.

5. Conclusion. This paper has investigated the adaptive fuzzy prescribed-time FTC problem for nonstrict-feedback nonlinear systems with intermittent actuator faults. Fuzzy logic systems have been employed to approximate the unknown nonlinear functions. Subsequently, under the prescribed-time stability theory and the backstepping design technique, an adaptive fuzzy prescribed-time FTC scheme has been developed. It has been proved that the proposed control method not only guarantees that the controlled system is prescribed-time stable, but also ensures that all system signals are bounded within a prescribed time interval. Finally, the simulation results indicate the effectiveness of the presented control method. It is noted that the prescribed-time fuzzy controller developed in this article did not take account of the optimization control issue and also required

that the system states are measurable. Therefore, future work will focus on addressing output-feedback optimization FTC problem for nonstrict-feedback nonlinear systems.

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