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Adaptive Fault-Tolerant Control of Nonlinear Time-Delay Systems With Prescribed Performance

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ABSTRACT An adaptive fault-tolerant control method considering actuator fault is proposed for a class of strict-feedback nonlinear time-delay systems. The prescribed performance is introduced by error transformation, which guarantees the transient performance of the system. Pade approximation and intermediate variables are used to eliminate the effect of input delay on the system performance. The universal approximation nature of fuzzy logic systems is used to approximate the unknown function in the system. A general fault model is introduced to describe the partial fault and stuck fault that may occur during the operation of the systems. The controller based on backstepping can ensure that the system operates normally with actuator fault. Through the Lyapunov function, all signals in the designed closed-loop system can be proved to be semi-globally uniformly ultimately bounded, and the tracking error can quickly converge to a compact set near the origin. Compared with the non-fault-tolerant control system, the simulation results show the effectiveness of the proposed control strategy.

INDEX TERMS Adaptive control, fault-tolerant, prescribed performance, time-delay nonlinear system.

I. INTRODUCTION

The adaptive control technology of nonlinear systems has a huge impact on the industrial field, and has also obtained a lot of meaningful results [1]– [4]. The backstepping method is applied to different types of nonlinear systems to enhance the application range of adaptive control technology [5]–[7]. However, there are usually unknown items in practical systems, we can get better adaptive tracking performance through combining the approximation performance of neural networks or fuzzy logic systems [8]–[13].The calculation based on Lyapunov function ensures the stability of systems [14].

Considering the safety and reliability of the control system, there are many researches on adaptive fault-tolerant control for actuator fault [15]–[17]. In engineering systems, the actuator is an indispensable part of the system operation. The actuator is an important factor to determine whether the system operate normally or not. Because of the scale and complexity of modern systems, the occurred fault will cause incalculable loss. So it is very important to study the fault-tolerant control [18], [19]. In actual systems, there are many uncertain factors which include the time, number and type of faults. Hence, it is necessary to design a system model with unknown parameters and actuator faults [20]–[22]. Aiming at a class of nonlinear systems with unmeasurable states, the problem of fault-tolerant control is researched [23]. Reference [24] solved a problem of fault-tolerant control caused by actuator failure and interference in high-speed train traction system with unknown time-varying parameters. In [25], a fuzzy control method for uncertain time-delay active steering system with actuator fault is proposed.

The fault-tolerant control solves the problem of actuator fault. However, the signal fluctuation and the possible external interference may have a serious effect on the transient performance of the system. In order to solve this problem, the prescribed performance control method based on error transformation is proposed [26]–[28]. This method can ensure that the tracking error is always in the preset region. Meanwhile, the overshoot and the convergence speed of the system will meet the given conditions. At present, the prescribed performance has been widely used in most of nonlinear systems [29]–[31]. Because of its advantages of both the steady and transient performance of the system,

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the prescribed performance method is more indispensable in the fields of robot flexible joint control [32], aircraft attitude tracking [33] and so on. Therefore, it is necessary to preset the performance of the nonlinear system with actuator fault, which can effectively reduce the tracking error of the system and improve the system performance [34], [35]. In [36], a class of adaptive robust fault-tolerant control is proposed by combining the fault model with the prescribed performance, which can ensure the steady and transient performance of the system even if the actuator occurs a fault.

From the previous results, these methods are rarely used in nonlinear time-delay systems [37]–[40]. However, many actual systems inevitably have time-delay phenomenon. So time-delay and time-delay system are common practical problems in engineering technology, which has a great research significance [41]–[45]. Inspired by aforementioned works, this paper presents an adaptive fault-tolerant control technique for nonlinear time-delay system with prescribed performance, which solves the problem that the system can remain stable with actuator fault, and the steady and transient performance of the system are also guaranteed. The main contributions are summarized as follows.

1) Different from the previous researches [46], the problem of adaptive tracking control for time-delay nonlinear systems is investigated by combining backstepping, fault-tolerant control and prescribed performance.

2) Compared with the methods of non-fault-tolerant control system [47], [48], the experimental results show the superiority of the proposed method. Once the fault occurs, the non-fault-tolerant controller loses the control of the system after the violent fluctuate. However the fault-tolerant controller proposed in this paper recovers the control effect on the system rapidly after the short fluctuation. Therefore, it can be proved that the proposed control strategy is effective.

II. PRELIMINARIES AND PROBLEM FORMULATION

A. PROBLEM FORMULATION

Consider a class of strict-feedback nonlinear time-delay systems as follows:

$$\begin{cases} \dot{x}_i(t) = f_i(\bar{x}_i(t)) + g_i(\bar{x}_i(t))x_{i+1}(t) + d_i(\bar{x}_i(t), t) \\ \qquad (1 \le i \le n-1), \\ \dot{x}_n(t) = f_n(\bar{x}_n(t)) + g_n(\bar{x}_n(t))u(t-\tau) + d_n(\bar{x}_n(t), t), \\ \qquad y(t) = x_1(t), \end{cases} \tag{1}$$

where $\bar{x}_i = [x_1, x_2, \ldots, x_i]^T \in R^i$ $(1 \le i \le n-1)$ and $\bar{x}_n = [x_1, x_2, \ldots, x_n]^T \in R^n$ are the system states. $f_i(\cdot)$ and $g_i(\cdot)$ are smooth, bounded and unknown nonlinear functions. $d_i(\cdot)$ is unknown and bounded external disturbance. u is the system input. τ is an input time-delay which is a positive constant. y is the system output. For simplicity, $f_i(\cdot)$, $g_i(\cdot)$ and $d_i(\cdot)$ are abbreviated as f_i, g_i and d_i below.

Assumption 1: When $1 \le i \le n$, the function g_i satisfies $g_i > 0$, and there are positive constants g_m and g_M such that:

$$0 < g_m \le |g_i(\bar{x}_i)| \le g_M \quad (1 \le i \le n). \tag{2}$$

Remark 1: The unknown constants g_m and g_M in the assumption 1 are only used for analysis which are not used to design controllers.

B. ACTUATOR FAULT

During the operation of the system, actuator fault is inevitable. It is necessary to consider actuator fault at the same time. In this section, two types of actuator fault are considered in the system model [20], [23], named lock-in-place and loss of effectiveness, which can ensure that the system operates normally even the actuator fault. This method effectively improves the security and stability of the system. The fault model is as follows:

$$\begin{cases} v_s(t) = \eta_s \bar{v}_s(t), \quad t \ge t_s,\ s \in \{1, 2, \ldots, m\} \\ \qquad \text{(loss of effectiveness)}, \\ v_k(t) = \bar{u}_k, \quad t \ge t_k,\ k \in \{1, 2, \ldots, m\} \\ \qquad \text{(lock-in-place)}. \end{cases} \tag{3}$$

There are m actuators in the system. Among them, $v_i (i = 1, \ldots, m)$ is the actual control instruction of the ith actuator; $\bar{v}_s$ is the designed value of the sth actuator; $\eta_s (0 < \eta_s < 1)$ is the effective proportion after losing partial effectiveness of the sth actuator. $\bar{u}_k$ represents the constant value after the kth actuator has a lock-in-place fault, and t_s and t_k represent the time when the actuator occurs fault.

Assumption 2: Each actuator has at most one fault during the operation of system. And once a fault occurs, the fault type will not change.

Assumption 3: At most $m-1$ actuators in the system are lock-in-place at the same time to ensure that the remaining actuators can achieve the required control target.

The actuator fault model can be described as

$$v_j(t) = \eta_j \bar{v}_j(t) + \beta_j(\bar{u}_j - \eta_j \bar{v}_j(t)), \quad j \in \{1, 2, \ldots, m\}. \tag{4}$$

In the system, $u(t) = q^T v(t)$, $q = [q_1, q_2, \ldots, q_m]^T$. q_j is known control gain. $v(t) = [v_1(t), v_2(t), \ldots, v_m(t)]^T$. When $\beta_j = 0$, the jth actuator has a lock-in-place fault. In other hand, when $\beta_j = 1$, the jth actuator loses effectiveness.

C. PRESCRIBED PERFORMANCE AND ERROR TRANSFORMATION

In this section, the tracking error z_1 of the system is limited by prescribed performance and error transformation, so that the tracking performance of the system can meet the expected performance requirements. This method can effectively improve the transient performance of the control system.

Definition 1 [27]: The continuous smooth function $\rho(t) : R_+ \to R_+$ (called a performance function) is strictly decreasing, and satisfies $\lim_{t\to\infty} \rho(t) = \rho_\infty > 0$.

Define the performance function as $\rho(t) = (\rho_0 - \rho_\infty)e^{-lt} + \rho_\infty$, and take $\triangle \in [0, 1]$, then the constraint inequalities are:

$$\begin{cases} -\triangle\rho(t) < z(t) < \rho(t), \quad z(0) > 0, \\ -\rho(t) < z(t) < \triangle\rho(t), \quad z(0) < 0. \end{cases} \tag{5}$$

For simplicity of calculation, the constraint inequalities are transformed into an unconstrained form through the error transformation function. The error transformation function is defined as

$$z(t) = \rho(t)S(\delta), \tag{6}$$

where δ is the transformed error. The error transformation formula $S(\delta)$ is smooth, invertible and strictly increasing function. And it satisfies the following conditions:

$$\begin{cases} -M < S(\delta) < 1, & z(0) > 0, \\ -1 < S(\delta) < M, & z(0) < 0. \end{cases} \tag{7}$$

$$\begin{cases} \lim\limits_{\delta\to-\infty} S(\delta) = -M, \\ \lim\limits_{\delta\to\infty} S(\delta) = 1, \\ z(0) > 0. \end{cases} \tag{8}$$

$$\begin{cases} \lim\limits_{\delta\to-\infty} S(\delta) = -1, \\ \lim\limits_{\delta\to\infty} S(\delta) = M, \\ z(0) < 0. \end{cases} \tag{9}$$

D. FUZZY LOGIC SYSTEMS

The fuzzy logic systems [49], [50] are described as follows: R^l: If x_1 is F_1^l, and x_2 is F_2^l, and …, and x_n is F_n^l,

Then y is G^l,$l = 1, 2, \ldots, N$,

where $x = [x_1, x_2, \ldots, x_n]^T$ and y are the input and output of the fuzzy logic systems. F_i^l and G^l are fuzzy sets. N is a positive constant which represents the number of fuzzy rules. By the singleton fuzzifier and the center average defuzzifier, then we get:

$$y(x) = \frac{\sum_{l=1}^{N} \bar{y}_l \prod_{i=1}^{n} \mu_{F_i^l}(x_i)}{\sum_{l=1}^{N}[\prod_{i=1}^{n} \mu_{F_i^l}(x_i)]}, \tag{10}$$

where $\bar{y}_l = \max\limits_{y_l\in R} \mu_{G^l}(y_l)$, $\mu_{F_i^l}(x_i)$ and μ_{G^l} are membership functions. The membership functions are defined as:

$$\varphi_l = \frac{\prod_{i=1}^{n} \mu_{F_i^l}(x_i)}{\sum_{l=1}^{N}[\prod_{i=1}^{n} \mu_{F_i^l}(x_i)]}. \tag{11}$$

The fuzzy logic system can be expressed as:

$$y(x) = W^T\varphi(x), \tag{12}$$

where $W^T = [\bar{y}_1, \ldots, \bar{y}_N] = [W_1, \ldots, W_N]$, $\varphi(x) = [\varphi_1(x), \ldots, \varphi_N(x)]^T$, and W is the weight.

Lemma 1 [37]: Assume a continuous function $f(x)$ is defined in a compact set, the fuzzy logic system satisfies:

$$\sup_{x\in\Omega} |f(x) - W^T\varphi(x)| \le \varepsilon, \tag{13}$$

where ε is the minimum approximation error.

Lemma 2 [34]: The function $V : [0, \infty) \to R$ satisfies the inequality

$$\dot{V} \le -\Gamma V + M, \quad \forall t \ge 0, \tag{14}$$

where Γ and M are positive constants, then

$$V(t) \le V(t_0)e^{-2\Gamma(t-t_0)} + \frac{M}{\Gamma} \le V(t_0) + \frac{M}{\Gamma}, \quad \forall t \ge 0. \tag{15}$$

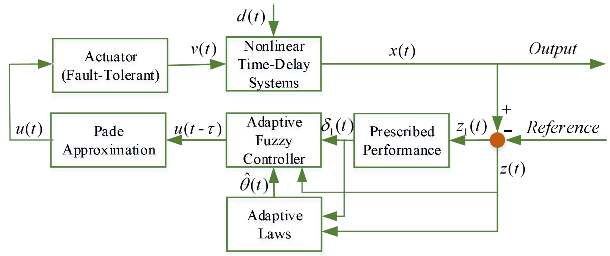


FIGURE 1. **Control method block diagram.**

III. CONTROLLER DESIGN AND STABILITY ANALYSIS

The block diagram of the proposed control method is shown in Fig.1. Firstly, the strict-feedback nonlinear time-delay system is transformed to eliminate the influence of the input delay on the system performance. The coordinate transformation and Pade approximation [51] are introduced to compensate the input delay, and the Laplace transform is applied to the system with input delay, we have

$$\mathcal{L}\{u(t-\tau)\} = e^{-\tau\varpi}\mathcal{L}(u(t)) = (e^{-\tau\varpi/2}/e^{\tau\varpi/2})\mathcal{L}(u(t)). \tag{16}$$

Based on the Pade approximation method, then

$$(e^{-\tau\varpi/2}/e^{\tau\varpi/2})\mathcal{L}(u(t)) \approx \frac{1-\tau\varpi/2}{1+\tau\varpi/2}\mathcal{L}\{u(t)\}, \tag{17}$$

where ϖ is a Laplace variable, and $\mathcal{L}\{u(t)\}$ is a Laplace transform of $u(t)$.

Remark 2: This paper solves the problem of small delay with limitation based on Pade approximation. Due to the small delay time, there is $e^{-\tau\varpi} - \frac{1-\tau\varpi/2}{1+\tau\varpi/2} \approx 0$.

The intermediate variable x_{n+1} is defined and satisfies the following equation:

$$\frac{1-\tau\varpi/2}{1+\tau\varpi/2}\mathcal{L}\{u(t)\} = \mathcal{L}\{x_{n+1}(t)\} - \mathcal{L}\{u(t)\}. \tag{18}$$

The (18) can be simplified as:

$$\mathcal{L}\{x_{n+1}(t)\} = 2\mathcal{L}\{u(t)\} - \frac{\tau\varpi}{2}\mathcal{L}\{x_{n+1}(t)\}. \tag{19}$$

The inverse Laplace transform of (19) is obtained:

$$\dot{x}_{n+1} = \frac{4}{\tau}u - \frac{2}{\tau}x_{n+1}. \tag{20}$$

Define the variable $\lambda = \frac{2}{\tau}$, we can get

$$\dot{x}_{n+1} = 2\lambda u - \lambda x_{n+1}. \tag{21}$$

In summary, the system (1) can be transformed into:

$$\begin{cases} \dot{x}_i = f_i + g_i x_{i+1} + d_i, & 1 \le i \le n-1, \\ \dot{x}_n = f_n + g_n(x_{n+1} - u(t)) + d_n, \\ \dot{x}_{n+1} = 2\lambda u - \lambda x_{n+1}, \\ y = x_1. \end{cases} \tag{22}$$

Remark 3: Different from the state vectors $x_i(i = 1, 2, \ldots, n)$, the defined x_{n+1} is not a real variable of the system. It is an intermediate variable used to eliminate the system instability caused by the unknown time delay τ in the system.

The error equations are:

$$\begin{cases} z_1 = x_1 - y_r, \\ z_i = x_i - \alpha_{i-1}, \quad (i = 2, 3, \ldots, n-1), \\ z_n = x_n - \alpha_{n-1} + g_m x_{n+1}/\lambda, \end{cases} \tag{23}$$

where α_i are virtual control variables.

Step 1: The derivative of tracking error is

$$\dot{z}_1 = \dot{x}_1 - \dot{y}_r = f_1 + g_1 x_2 + d_1 - \dot{y}_r. \tag{24}$$

According to (6), we can get

$$\delta_1 = S^{-1}(\frac{z_1}{\rho}). \tag{25}$$

Then

$$\dot{\delta}_1 = \frac{\partial S_1^{-1}}{\partial(\frac{z_1}{\rho})}\frac{1}{\rho}(\dot{z}_1 - \frac{\dot{\rho} z_1}{\rho}). \tag{26}$$

Combining (24), the result is

$$\dot{\delta}_1 = \frac{\partial S_1^{-1}}{\partial(\frac{z_1}{\rho})}\frac{1}{\rho}(f_1 + g_1 x_2 + d_1 - \dot{y}_r - \frac{\dot{\rho} z_1}{\rho}). \tag{27}$$

In summary, the derivative of the equivalent error model of the original system equation is:

$$\dot{\delta}_1 = r_1(f_1 + g_1 x_2 + d_1 - \dot{y}_r + h_1), \tag{28}$$

where $r_1 = \frac{\partial S_1^{-1}}{\partial(\frac{z_1}{\rho})}\frac{1}{\rho}$ and $r_1 > 0$; $h_1 = -\frac{\dot{\rho} z_1}{\rho}$ is a known function about state and time.

Select the Lyapunov function as

$$V_1 = \frac{1}{2r_1}\delta_1^2 + \frac{g_m}{2\gamma_1}\tilde{\theta}_1^T\tilde{\theta}_1. \tag{29}$$

The derivative of V_1 is

$$\begin{aligned} \dot{V}_1 &= \delta_1(f_1 + g_1 x_2 + d_1 - \dot{y}_r + h_1) - \frac{g_m\tilde{\theta}_1}{\gamma_1}\dot{\hat{\theta}}_1 \\ &= \delta_1(F_1 + g_1 x_2) - \frac{g_m\tilde{\theta}_1}{\gamma_1}\dot{\hat{\theta}}_1, \end{aligned} \tag{30}$$

where $F_1 = f_1 + d_1 - \dot{y}_r + h_1$. $\hat{\theta}_1$ is the estimate of θ_1, $\tilde{\theta}_1$ is the estimation error, and $\tilde{\theta}_1 = \theta_1 - \hat{\theta}_1$.

Because f_1 and d_1 in the system are unknown, the designed virtual controller α_1 cannot be constructed with F_1. Using the approximation characteristic of the fuzzy logic system to approximate F_1, we can get:

$$F_1 = W_1^{*T}\varphi_1 + \varepsilon_1, \tag{31}$$

where $\varepsilon_1 > 0$ is the fuzzy approximation error. $z_2 = x_2 - \alpha_1$ is substituted into (30), then

$$\dot{V}_1 = \delta_1(W_1^{*T}\varphi_1 + \varepsilon_1 + g_1 z_2 + g_1\alpha_1) - \frac{g_m\tilde{\theta}_1}{\gamma_1}\dot{\hat{\theta}}_1. \tag{32}$$

According to the Young inequality, there are:

$$\delta_1 W_1^{*T}\varphi_1 \le \frac{1}{2}\delta_1^2 \| W_1\|^2\varphi_1^T\varphi_1 + \frac{1}{2}. \tag{33}$$

$$\delta_1\varepsilon_1 \le \frac{g_m}{2}\delta_1^2 + \frac{1}{2g_m}\varepsilon_1^2. \tag{34}$$

Let $\theta_1 = \| W_1\|^2/g_m$, then

$$\delta_1 W_1^{*T}\varphi_1 \le \frac{g_m\theta_1}{2}\delta_1^2\varphi_1^T\varphi_1 + \frac{1}{2}. \tag{35}$$

Combining the above formulas, we can get

$$\begin{aligned} \dot{V}_1 \le \delta_1 g_m(\frac{\hat{\theta}_1}{2}\delta_1\varphi_1^T\varphi_1 + \frac{1}{2}\delta_1 + \alpha_1) + \frac{g_m\tilde{\theta}_1}{\gamma_1}(\frac{\gamma_1}{2}\delta_1^2\varphi_1^T\varphi_1 - \dot{\hat{\theta}}_1) \\ + g_m\delta_1 z_2 + \chi_1. \end{aligned} \tag{36}$$

where $\chi_1 = \frac{1}{2g_m}\varepsilon_1^2 + \frac{1}{2}$. The virtual control law is designed as:

$$\alpha_1 = -\frac{\hat{\theta}_1}{2}\delta_1\varphi_1^T\varphi_1 - \frac{1}{2}\delta_1 - c_1\delta_1. \tag{37}$$

The adaptive law is

$$\dot{\hat{\theta}}_1 = \frac{\gamma_1}{2}\delta_1^2\varphi_1^T\varphi_1 - \sigma_1\hat{\theta}_1, \tag{38}$$

where c_1,σ_1 are positive design parameters, we can get

$$\dot{V}_1 \le -c_1 g_m\delta_1^2 + \frac{\sigma_1 g_m}{\gamma_1}\tilde{\theta}_1\hat{\theta}_1 + \delta_1 z_2 g_m + \chi_1. \tag{39}$$

Step i: The derivative of z_i is

$$\dot{z}_i = f_i + g_i x_{i+1} + d_i - \dot{\alpha}_{i-1}. \tag{40}$$

Select the Lyapunov function as

$$V_i = V_{i-1} + \frac{1}{2}z_i^2 + \frac{g_m}{2\gamma_i}\tilde{\theta}_i^T\tilde{\theta}_i. \tag{41}$$

where $\hat{\theta}_i$ is the estimate of θ_i, $\tilde{\theta}_i$ is the estimation error, and $\tilde{\theta}_i = \theta_i - \hat{\theta}_i$. The definition of θ_i is given below. The derivative of V_i is

$$\dot{V}_i = \dot{V}_{i-1} + z_i(f_i + g_i x_{i+1} + d_i - \dot{\alpha}_{i-1}) - \frac{g_m\tilde{\theta}_i}{\gamma_i}\dot{\hat{\theta}}_i. \tag{42}$$

Then

$$\begin{aligned} \dot{V}_i \le \sum_{j=1}^{i-1}(-c_j g_m\iota_j^2 + \chi_j + \frac{\sigma_j g_m}{\gamma_j}\tilde{\theta}_j\hat{\theta}_j) \\ + z_i(F_i + g_m z_{i+1} + g_m\alpha_i) - \frac{g_m\tilde{\theta}_i}{\gamma_i}\dot{\hat{\theta}}_i, \end{aligned} \tag{43}$$

where $\iota_1 = \delta_1$, $\iota_j = z_j (2 \le j \le i-1)$, $\chi_j = \frac{1}{2g_m}\varepsilon_j^2 + \frac{1}{2}(1 \le j \le i-1)$, $F_i = g_m z_{i-1} + f_i + d_i - \dot{\alpha}_{i-1}$. $\hat{\theta}_i$ is the estimate of θ_i, $\tilde{\theta}_i$ is the estimation error, and $\tilde{\theta}_i = \theta_i - \hat{\theta}_i$.

Using the approximation characteristic of the fuzzy logic system to approximate F_i, we can get that

$$F_i = W_i^{*T}\varphi_i + \varepsilon_i, \tag{44}$$

where $\varepsilon_i > 0$ is the fuzzy approximation error. According to the Young inequality, there are

$$z_i W_i^{*T}\varphi_i \le \frac{1}{2}z_i^2 \| W_i\|^2\varphi_i^T\varphi_i + \frac{1}{2}. \tag{45}$$

$$z_i\varepsilon_i \le \frac{g_m}{2}z_i^2 + \frac{1}{2g_m}\varepsilon_i^2. \tag{46}$$

Let $\theta_i =\| W_i\|^2/g_m$, then

$$z_i W_i^{*T}\varphi_i \leq \frac{g_m\theta_i}{2} z_i^2 \varphi_i^T\varphi_i + \frac{1}{2}. \tag{47}$$

We have

$$\begin{aligned}\dot{V}_i \leq& \sum_{j=1}^{i-1}(-c_j g_m \iota_j^2 + \chi_j + \frac{\sigma_j g_m}{\gamma_j}\tilde{\theta}_j\hat{\theta}_j) + \frac{g_m\theta_i}{2} z_i^2\varphi_i^T\varphi_i + \frac{1}{2} \\ &+ \frac{g_m}{2} z_i^2 + \frac{1}{2g_m}\varepsilon_i^2 + z_i z_{i+1} g_m + z_i g_m \alpha_i - \frac{g_m\tilde{\theta}_i}{\gamma_i}\dot{\hat{\theta}}_i.\end{aligned} \tag{48}$$

Simplify the equation (48), we can obtain

$$\begin{aligned}\dot{V}_i \leq& \sum_{j=1}^{i-1}(-c_j g_m \iota_j^2 + \chi_j + \frac{\sigma_j g_m}{\gamma_j}\tilde{\theta}_j\hat{\theta}_j) \\ &+ z_i g_m(\frac{\hat{\theta}_i}{2} z_i\varphi_i^T\varphi_i + \frac{1}{2}z_i + \alpha_i) \\ &+ \frac{g_m\tilde{\theta}_i}{\gamma_i}(\frac{\gamma_i}{2} z_i^2\varphi_i^T\varphi_i - \dot{\hat{\theta}}_i) + z_i z_{i+1} g_m + \chi_i.\end{aligned} \tag{49}$$

Design the virtual control law as

$$\alpha_i = -\frac{\hat{\theta}_i}{2} z_i\varphi_i^T\varphi_i - \frac{1}{2}z_i - c_i z_i. \tag{50}$$

The adaptive law is

$$\dot{\hat{\theta}}_i = \frac{\gamma_i}{2} z_i^2\varphi_i^T\varphi_i - \sigma_i\hat{\theta}_i, \tag{51}$$

where c_i,σ_i are positive design parameters. we can get

$$\dot{V}_i \leq \sum_{j=1}^{i}(-c_j g_m \iota_j^2 + \chi_j + \frac{\sigma_j g_m}{\gamma_j}\tilde{\theta}_j\hat{\theta}_j) + z_i z_{i+1} g_i. \tag{52}$$

Step n: The derivative of z_n is

$$\begin{aligned}\dot{z}_n &= f_n + g_n(x_{n+1} - u) + d_n - \dot{\alpha}_{n-1} - g_m x_{n+1} + 2g_m u \\ &\leq f_n + g_m u + d_n - \dot{\alpha}_{n-1}.\end{aligned} \tag{53}$$

Select the Lyapunov function as

$$V_n = V_{n-1} + \frac{1}{2}z_n^2 + \frac{g_m}{2\gamma_n}\tilde{\theta}_n^T\tilde{\theta}_n + \sum_{j\notin K}\frac{\eta_j}{2\gamma}\tilde{\kappa}^T\tilde{\kappa}, \tag{54}$$

where $\hat{\theta}_n$ is the estimate of θ_n, $\hat{\kappa}$ is the estimate of κ, and $\tilde{\theta}_n = \theta_n - \hat{\theta}_n$, $\tilde{\kappa}_n = \kappa_n - \hat{\kappa}_n$. K is the set of actuators with lock-in-place faults, that is, when $j \in K(j = 1, 2, \ldots, m)$, the ith actuator has lock-in-place fault. The derivative can be obtained as

$$\begin{aligned}\dot{V}_n \leq& \sum_{j=1}^{n-1}(-c_j g_m \iota_j^2 + \chi_j + \frac{\sigma_j g_m}{\gamma_j}\tilde{\theta}_j\hat{\theta}_j) + z_n(F_n + g_m u) \\ &- \frac{g_m\tilde{\theta}_n}{\gamma_n}\dot{\hat{\theta}}_n - \sum_{j\notin K}\frac{\eta_j}{\gamma}\tilde{\kappa}\dot{\hat{\kappa}},\end{aligned} \tag{55}$$

where $F_n = g_m z_{n-1} + f_n + d_n - \dot{\alpha}_{n-1}$.

Using the approximation characteristic of the fuzzy logic system to approximate F_n, we can get that

$$F_n = W_n^{*T}\varphi_n + \varepsilon_n, \tag{56}$$

where $\varepsilon_n > 0$ is the fuzzy approximation error. According to the Young inequality, we can get

$$z_n W_n^{*T}\varphi_n \leq \frac{1}{2}z_n^2\| W_n\|^2\varphi_n^T\varphi_n + \frac{1}{2}. \tag{57}$$

$$z_n\varepsilon_n \leq \frac{g_m}{2}z_n^2 + \frac{1}{2g_m}\varepsilon_n^2. \tag{58}$$

Let $\theta_n =\| W_n \|^2/g_m$, where θ_n is an unknown constant, we have

$$z_n W_n^{*T}\varphi_n \leq \frac{g_m\theta_n}{2} z_n^2\varphi_n^T\varphi_n + \frac{1}{2}. \tag{59}$$

The fault control laws can be designed as:

$$v_j = \kappa^T\zeta \quad (j = 1, \ldots, m), \tag{60}$$

where $\kappa = [\kappa_1, \kappa_2, \kappa_3]^T$, $\zeta = [u, q^T]^T$. And it should satisfy

$$u = \sum_{j\notin K}(\eta_j\kappa^T\zeta) + \sum_{j\in K}\bar{u}_j, \quad j \in \{1, 2, \ldots, m\}. \tag{61}$$

So

$$\begin{aligned}\dot{V}_n \leq& \sum_{j=1}^{n-1}(-c_j g_m \iota_j^2 + \chi_j + \frac{g_m\sigma_j}{\gamma_j}\tilde{\theta}_j\hat{\theta}_j) + \frac{g_m\theta_n}{2} z_n^2\varphi_n^T\varphi_n + \frac{1}{2} \\ &+ \frac{g_m}{2}z_n^2 + \frac{1}{2g_m}\varepsilon_n^2 + z_n g_m(\sum_{j\notin K}(\eta_j\kappa^T\zeta) + \sum_{j\in K}\bar{u}_j) \\ &- \frac{g_m\tilde{\theta}_n}{\gamma_n}\dot{\hat{\theta}}_n + \sum_{j\notin K}\frac{\eta_j}{\gamma}\tilde{\kappa}(\frac{\gamma}{2}z_n^2\zeta - \dot{\hat{\kappa}}).\end{aligned} \tag{62}$$

Design the control law as

$$u = -\frac{\hat{\theta}_n}{2} z_n\varphi_n^T\varphi_n - \frac{1}{2}z_n - c_n z_n. \tag{63}$$

Adaptive law:

$$\dot{\hat{\theta}}_n = \frac{\gamma_n}{2} z_n^2\varphi_n^T\varphi_n - \sigma_n\hat{\theta}_n. \tag{64}$$

Fault adaptive law:

$$\dot{\hat{\kappa}} = \frac{\gamma}{2}z_n^2\zeta - \sigma\hat{\kappa}, \tag{65}$$

where γ_n, γ, σ_n, σ are positive design parameters.

Along with (60) (63) and (64), (65) becomes

$$\dot{V}_n \leq \sum_{j=1}^{n}(-c_j g_m \iota_j^2 + \chi_j + \frac{g_m\sigma_j}{\gamma_j}\tilde{\theta}_j\hat{\theta}_j) + \sum_{i\notin K}\frac{\eta_j\sigma}{\gamma}\tilde{\kappa}\hat{\kappa}, \tag{66}$$

where $\chi_j = \frac{1}{2g_m}\varepsilon_j^2 + \frac{1}{2}(1 \leq j \leq n)$.

$$\tilde{\kappa}_j\hat{\kappa}_j = \tilde{\kappa}_j(\kappa_j - \tilde{\kappa}_j) \leq \frac{1}{2}\kappa_j^2 - \frac{1}{2}\tilde{\kappa}_j^2, \tag{67}$$

In the same way:

$$\tilde{\theta}_j\hat{\theta}_j \leq \frac{1}{2}\theta_j^2 - \frac{1}{2}\tilde{\theta}_j^2 \tag{68}$$

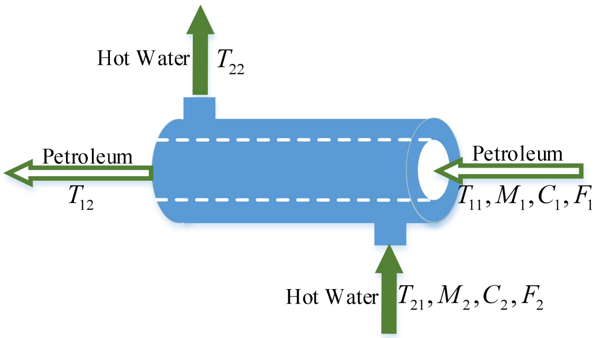


FIGURE 2. **Schematic diagram of tubular heat exchanger.**

Substituting (67) and (68) into (66) results in

$$\dot{V}_n \leq -\sum_{j=1}^{n}(c_j g_m \iota_j^2 + \frac{g_m \sigma_j}{2\gamma_j}\tilde{\theta}_j^2) - \sum_{j \notin K}\frac{\eta_j \sigma}{2\gamma}\tilde{\kappa}^2 + \sum_{j=1}^{n}(\chi_j + \frac{g_m \sigma_j}{2\gamma_j}\theta_j^2) + \sum_{j \notin K}\frac{\eta_j \sigma}{2\gamma}\kappa^2, \quad (69)$$

where $\iota_1 = \delta_1$, $\iota_j = z_j (j = 2, \ldots, n)$.

Choose $\Gamma_0 = \min_{1 \leq j \leq n}\{c_j g_m, \frac{g_m \sigma_j}{2\gamma_i}, \frac{\eta_j \sigma}{2\gamma}\}$, $M_0 = \sum_{j=1}^{n}(\chi_j + \frac{g_m \sigma_j}{2\gamma_j}\theta_j^2) + \sum_{j \notin K}\frac{\eta_j \sigma}{2\gamma}\kappa^2$, then equation (69) is equivalent to:

$$\dot{V}_n \leq -\Gamma_0 V_n + M_0. \quad (70)$$

According to Lemma 2, there are

$$V_n(t) \leq V_n(t_0) + \frac{M_0}{\Gamma_0}. \quad (71)$$

When actuators have fault, a change of κ causes a change of V_n. Since the actuators can only have limited faults during operation, κ and V_n changed value are finite. So V_n is always bounded. It can be concluded that initial conditions and all signals in the closed-loop system are always bounded. The designed controller can ensure tracking performance and tracking error converge to a compact set of the origin.

IV. ANALYSIS OF SIMULATION RESULTS

Take the heat exchange process of tubular heat exchanger for kerosene [52] as an example. The schematic diagram of tubular heat exchanger is shown in Fig.2. Assume that there is no heat loss during the process of heat exchange, and the flow rate of fluid always keeps constant. The model of heat exchanger systems with flow delay are established as:

$$\begin{cases} M_1 C_1 \dot{T}_{12} = F_1 C_1 (T_{11} - T_{12}) + K_{12} A (T_{22} - T_{12}), \\ M_2 C_2 \dot{T}_{22} = F_2 C_2 (T_{21} - T_{22}) - K_{12} A (T_{22} - T_{12}), \end{cases} \quad (72)$$

where M_i is the fluid mass in the tube, C_i is the fluid heat capacity, T_i is the temperature and F_i is the flow rate. A is the average heat conduction area.The thermal conductivity is K_{12}. The control variable is the flow rate F_2 of hot water through the heat exchanger. The controlled variable is the temperature T_{12} of kerosene at the outlet of the heat exchanger. Then the derivative can be obtained as

$$\begin{cases} \dot{T}_{12} = -(\frac{F_1}{M_1} + \frac{K_{12}A}{M_1 C_1})T_{12} + \frac{K_{12}A}{M_1 C_1}T_{22} + \frac{F_1}{M_1}T_{11}, \\ \dot{T}_{22} = \frac{K_{12}A}{M_2 C_2}T_{12} - (\frac{F_2}{M_2} + \frac{K_{12}A}{M_2 C_2})T_{22} + \frac{F_2}{M_2}T_{21}. \end{cases} \quad (73)$$

The transfer function of the control system is:

$$G(s) = \frac{T_{12}(s)}{F_2(s)} = \frac{a_2 b_2}{(s - a_1)(s - a_2) - a_2 b_1}, \quad (74)$$

where $a_1 = -(\frac{F_1}{M_1} + \frac{K_{12}A}{M_1 C_1})$, $a_2 = \frac{K_{12}A}{M_1 C_1}$, $b_1 = \frac{K_{12}A}{M_2 C_2}$, $b_2 = \frac{T_{21} - T_{22}}{M_2}$.Due to the delay of heat transfer, the third-order inertia delay heat exchanger is obtained by improving the system order to shorten the delay:

$$G(s) = \frac{K}{(Ts + 1)^3}e^{-\tau s} = \frac{a_2 b_2}{(s - a_1)(s - a_2) - a_2 b_1}, \quad (75)$$

where K is the system gain, T is the time constant and τ is the delay time. After Laplace Inverse Transformation, the systems equation are:

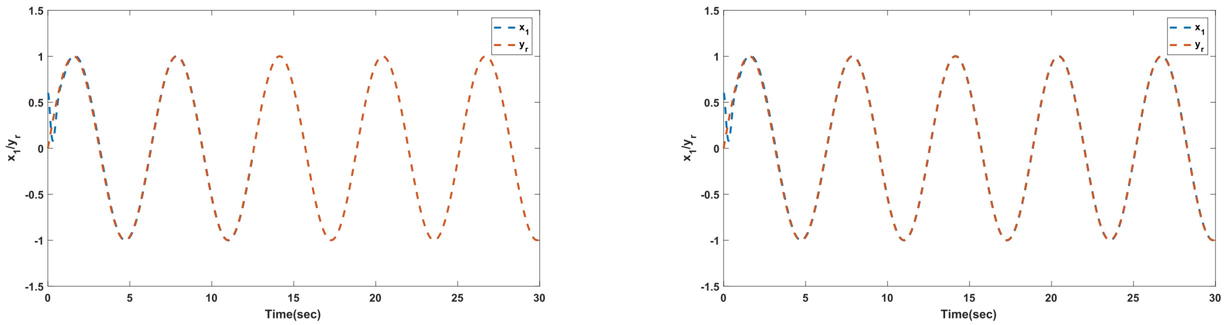
$$\begin{cases} \dot{x}_1(t) = x_2(t), \\ \dot{x}_2(t) = x_3(t), \\ \dot{x}_3(t) = f(\overline{x}) + bu(t - \tau), \\ y(t) = x_1(t), \end{cases} \quad (76)$$

where $f(\overline{x}) = -\frac{3}{T}x_3 - \frac{3}{T^2}x_2 - \frac{3}{T^3}x_1$, $b = \frac{K}{T^3}$, $T = 15$, $K = 3.734 * 10^4$, $\tau = 0.001$. $\overline{x} = [x_1, x_2, x_3]$ is system state vector.

The fuzzy membership functions are defined as: $\mu_{F_i^1}(x_i) = \exp[-(x_i+2)^2/4]$, $\mu_{F_i^2}(x_i) = \exp[-(x_i+1)^2/4]$, $\mu_{F_i^3}(x_i) = \exp[-x_i^2/4]$, $\mu_{F_i^4}(x_i) = \exp[-(x_i - 1)^2/4]$, $\mu_{F_i^5}(x_i) = \exp[-(x_i - 2)^2/4]$, $i = 1, 2, 3$.

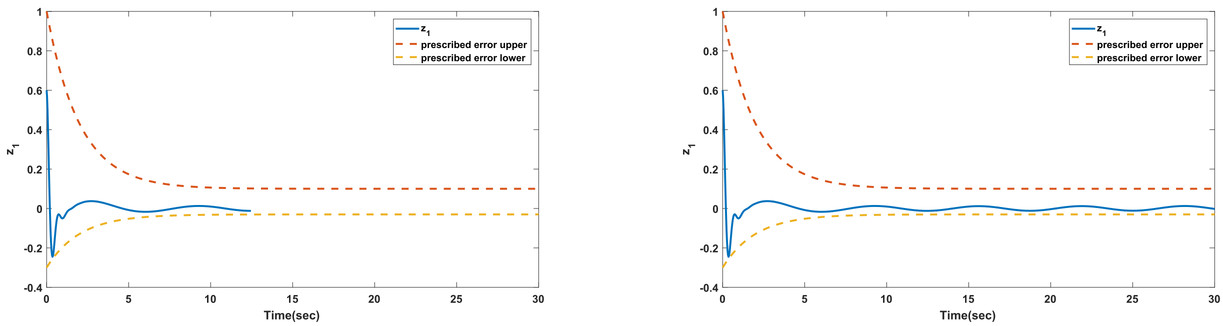
The initial conditions are $[x_1(0), x_2(0), x_3(0)]^T = [0.6, 0, 0]^T$, $\hat{\theta}_1(0) = \hat{\theta}_2(0) = \hat{\theta}_3(0) = 0.2$, and the reference signal is $y_r = \sin(t)$. The performance function is $\rho(t) = (1 - 10^{-1})e^{-0.5t} + 10^{-1}$. The system parameters are: $\gamma_1 = \gamma_2 = \gamma_3 = 0.02$, $\gamma = 0.2$, $c_1 = c_2 = c_3 = 8$, $\sigma_1 = \sigma_2 = \sigma_3 = \sigma = 0.2$. Assume that the actuator 1 has the loss of effectiveness fault when $t = 10s$, and the fault parameter is $\eta_1 = 0.6$. Actuator 2 has a lock-in-place fault when $t = 15s$, and the fault parameter is $\overline{u}_2 = 10$. The two control gains are $q_1 = 0.5$ and $q_2 = 0.5$ respectively.

Compared with the proposed method in [53], the effectiveness of the proposed method in this paper is verified. The simulation results are shown in Fig.3-Fig.8. Fig.3 shows the tracking of the system output. The solid line in Fig.4 is the tracking error, the dashed lines are the preset error limits. Fig.5 shows the system state vectors. Fig.6 is the adaptive laws, and Fig.7 is the input control. Fig.8 is the control signals of two actuators. Wherein, Fig.(a) is the simulation results of non-fault-tolerant system(NFT) of nonlinear time-delay systems with prescribed performance, and Fig.(b) is the simulation results of adaptive fault-tolerant control(FT) of nonlinear



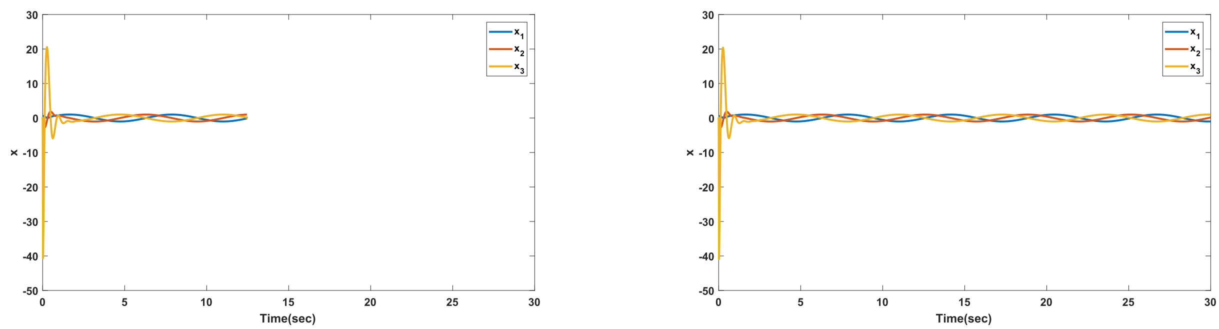
(a)(NFT) (b)(FT)

FIGURE 3. State variable x_1 and reference output y_r.



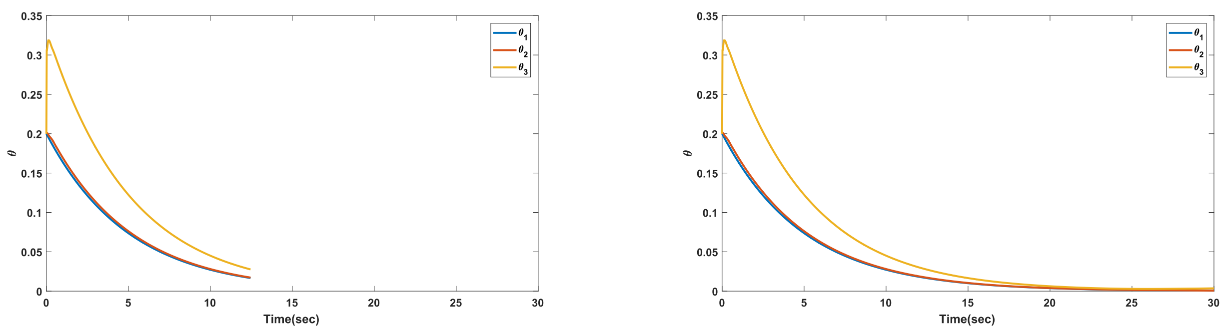
(a)(NFT) (b)(FT)

FIGURE 4. Tracking error z_1 and performance function $\rho(t)$.



(a)(NFT) (b)(FT)

FIGURE 5. State variables x_1, x_2 and x_3.

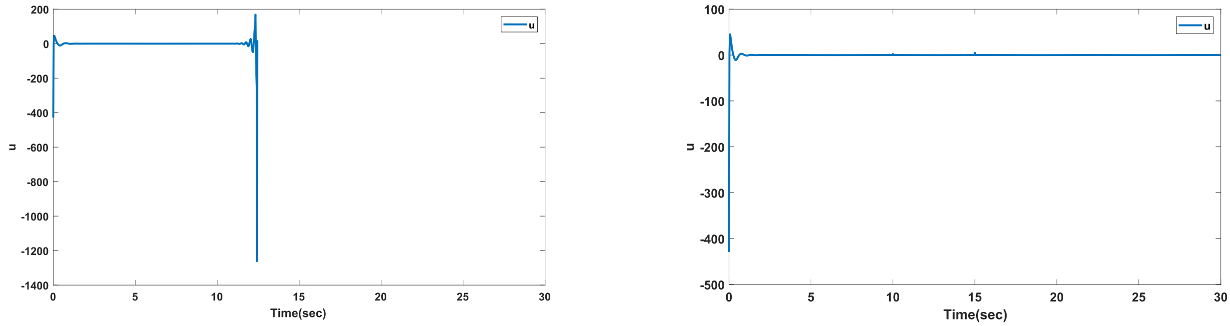


(a)(NFT) (b)(FT)

FIGURE 6. Adaptive laws θ_1, θ_2 and θ_3.

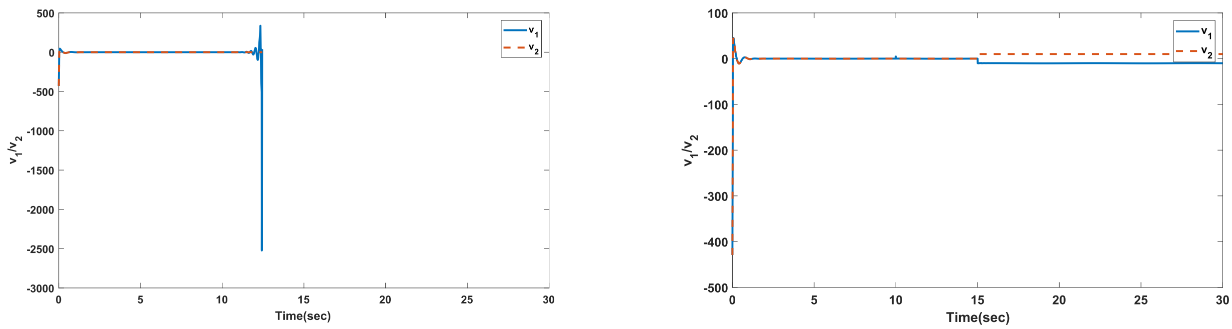
time-delay systems with prescribed performance proposed in this paper.

Actuator 1 experiences the loss of effectiveness fault at $t = 10s$. At this time, the signal of the non-fault-tolerant



(a)(NFT) (b)(FT)

FIGURE 7. System input u.



(a)(NFT) (b)(FT)

FIGURE 8. Actuator inputs v_1 and v_2.

system in Fig.(a) fluctuates violently, which causes the tracking error to exceed the preset range, so that the system loses control. The fault-tolerant system can adjust quickly and restore the stability of the system, which can be seen in Fig.(b). Actuator 2 has a lock-in-place fault at $t = 15s$. Meanwhile, the non-fault-tolerant system Fig.(a) is still out of control, while the fault-tolerant system Fig.(b) continues to track the reference signal stably after the small fluctuation, and the tracking error remains within the preset range.

V. CONCLUSION

In this paper, an adaptive fuzzy fault-tolerant control method backstepping-based is proposed for the strict-feedback nonlinear time-delay control system with prescribed performance, which can ensure the system operates normally with actuator fault. This method also greatly improves the stability and safety of the system, and can be more widely used in the actual system. It is proved that the adaptive fuzzy fault-tolerant controller can guarantee the steady performance and the transient performance of the system in the case of actuator fault. At the same time, variables in the closed-loop system are bounded. What's more, the tracking error converges to a compact set of the origin. Finally, compared with the non-fault-tolerant system, the simulation results show that the fault-tolerant control system can adjust quickly after the actuator suddenly breaks down in the operation process, so that the system can quickly return to normal after a short fluctuation. Furthermore, the range of fluctuation is slight and does not affect the actual production quality, which proves that the method has better control performance.The method proposed in this paper is only applied to the time-delay systems with constant and small delay. So this method still has some limitations. In practical systems, there are many time-varying delay systems in addition to the time-delay systems. Due to the complexity and diversity of time-varying delay systems, there are still a lot of gaps and problems in this field. In the future, we will continue to study the transient and steady performance of time-varying delay systems with fault-tolerant.

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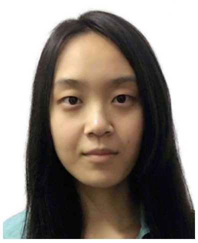

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