Fixed-time fault-tolerant control for constrained systems based on adaptive fuzzy

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Abstract: In view of the complexity of the operating environment of the actual industrial system, this paper considers a nonlinear system with two kinds of constrained factors (actuator faults and unknown dead-zones) and proposes a fixed-time passive fault-tolerant control (FTC) scheme based on adaptive fuzzy technique to improve the overall stability and fault tolerance of the constrained system. Firstly, a passive FTC scheme is constructed in which the adaptive fuzzy technique is used to deal with the non-dynamic influences and variations of the system induced by two constrained factors. Secondly, the design of the fixed-time controller further improves the convergence rate of the system on the basis of the finite time controller, and the introduction of the FTC scheme solves the oscillation problem caused by the fast convergence rate of the fixed-time controller and the influence of two constrained factors on the stability and tracking performance of the system. Then, based on the Lyapunov fixed-time stability theory, the feasibility of the proposed scheme is analyzed, that is, the constrained system can achieve system stability in fixed-time and the tracking error is maintained within a compact set around the to origin. Finally, the proposed strategy is verified by two simulations.

Keywords: Nonlinear system, fixed-time stability, fault-tolerant control, adaptive fuzzy technique, unknown dead-zones, actuator faults.

1. INTRODUCTION

In modern control systems, there are often actuator failures caused by component degradation, sudden environmental changes, or unknown disturbances (Yu et al., 2023). These faults may damage the system performance or lead to the instability of the whole controlled system. To address this pain point and enhance the robustness and production efficiency of industrial systems, fault-tolerant control (FTC) schemes have attracted the attention of both scholars in the control field and practitioners in industrial systems. Meanwhile, many meaningful results have been achieved. Abbaspour et al. design a new FTC strategy based on the fault types and the fault causes in a control system, which makes the controlled system more fault-tolerant (Abbaspour et al., 2020). Li et al. first use the mutual quality factor decomposition technique to solve the multiplicative faults in the system and propose a fault tolerance margin for closed-loop systems to solve the performance degradation problem caused by faults (Li et al., 2019). For spacecraft attitude control systems subject to actuator faults and fault estimation errors, Shen et al. utilize an indirect fault identification method to estimate the fault severity and reconstruct the controller based on the fault severity, such that the reconstructed controller can operate unaffected by the fault (Shen et al., 2019).

Moreover, when designing the controller, it is essential to account for the dead-zone input, which is a prevalent non-smooth nonlinear characteristic of actuators. Over the past few years, many scholars have conducted research on the control problems under dead-zone characteristics, and numerous outcomes have been produced. To mention a few examples, an adaptive two-class neural tracking control method is proposed to compensate for the effects of actuator faults and dead-zone disturbance on the nonlinear multiagent system, thus ensuring that the required system

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performance is not compromised (Cheng et al., 2023). An adaptive fault-tolerant boundary control method is developed to compensate for multiple disturbances, such as dead-zones, actuator faults, and so on, in flexible string systems (Ren et al., 2022). Guo et al. propose an improved quadratic spacing strategy with fault factor lower bounds to solve the problem of maximum acceleration variation due to actuator faults in heterogeneous vehicle formations with dead-zone nonlinearity (Guo et al., 2020) .

In addition to the above problems, another concern is the tracking accuracy and convergence rate of the controlled system. In recent years, to meet the requirements of convergence time and robustness on the system, many control methods have been proposed, such as asymptotic tracking control (Li and Tong, 2022; Zheng and Hu, 2023; Wang, 2022), finite time control (Wang et al., 2023; Lee et al., 2023), fixed-time control (Nguyen et al., 2023; Wang et al., 2024), and so on. The finite time control has the advantages of fast convergence rate, high tracking accuracy, and strong robustness compared with the asymptotic tracking control (Liu et al., 2022). However, the effectiveness of the finite time control depends on the choice of the initial conditions of the system, and when the initial conditions are far away from the equilibrium point, the control effectiveness of the system will be affected accordingly. Thus, based on finite time control, a fixed time control that can alleviate the dependence of initial conditions has been proposed (Polyakov, 2012) and has been applied in navigation and guidance, aircraft attitude tracking and other high-tech fields. For example, a fixed-time sliding mode control law based on an extended observer is proposed to solve the trajectory tracking problem of an unmanned surface vehicle in fixed time (Fan et al., 2023). Cao et al. propose a new control method based on sliding modes using a new fixed-time surface, which can achieve continuous and chattering-free attitude stabilization of flexible spacecraft with unknown inertia and disturbance (Cao et al., 2020) . A new fixed-time convergence controller based on the traditional line-of-sight guidance law is proposed, which ensures that the heading angle of an underactuated unmanned boat converges to the given bow angle at a fixed time (Liu et al., 2023). Sun et al. construct an altitude and velocity tracking controllers based the fixed-time nonsmoothing backstepping technique for air-breathing hypersonic vehicles (Sun et al., 2020).

Inspired by the above literature, this paper studies the fixed-time FTC problem for nonlinear system with two kinds of constrained factors (actuator faults and unknown dead-zones), with the following contributions:
(1) Different from single-constrained nonlinear systems (Jia and He, 2023; Song et al., 2023; Cai et al., 2024), this paper considers a nonlinear system with two constrained factors (actuator faults and unknown dead-zones) to further improve the universality of the controlled systems. In addition, the coupling of two constrained factors in the system also increases the difficulty of controller design.
(2) Compared with active FTC (Jia et al., 2024; He and Jia, 2024), this paper proposes a passive FTC scheme based on adaptive fuzzy technique to weaken the influence of external factors on the steady-state and transient performance of the system, in which the adaptive fuzzy technique is used to deal with the non-smooth nonlinear characteristics of the system induced by the two constrained factors.
(3) The fixed-time stability is introduced into the FTC scheme to develop a fixed-time fault-tolerant controller which makes the constrained system reach stability in a fixed time and makes up for the oscillation problem caused by the fast convergence rate. Unlike finite time control (Zhai, 2023; Zhao and Song, 2023), fixed-time control gets rid of the dependence on initial conditions and speeds up the convergence rate.

The remainder of this paper is organised as follows. Section 2 gives the system model and the relevant lemmas needed for controller design. The controller for nonlinear systems with actuator faults and unknown dead-zone is constructed in Section 3. The feasibility of the controller is analysed in Section 4. The effectiveness of the proposed scheme is verified in Section 5 by a second-order numerical system simulation and a robotic manipulator system model simulation. Finally, the whole paper is summarised in Section 6.

2. PROBLEM STATEMENT AND PRELIMINARY KNOWLEDGE

2.1 System description

Consider the following constrained systems including unknown dead-zones and actuator faults:

$$\begin{cases} \dot{x}_1 = x_2 + f_1(x) + \Delta_1(x); \\ \quad \vdots \\ \dot{x}_i = x_{i+1} + f_i(x) + \Delta_i(x); \\ \quad \vdots \\ \dot{x}_n = u + f_n(x) + \Delta_n(x) + \\ \qquad \zeta\,(t - T_0)\,\tau(x, \upsilon); \\ y = x_1. \end{cases} \tag{1}$$

where, $x = [x_1, x_2, ..., x_n]^T \in \Re^n$ and $y \in \Re$ represent the state variables and the system output, respectively; $f_i(\cdot)$ and $\Delta_i(x)$ are unknown smooth nonlinear functions and satisfy the local Lipschitz condition; $u \in \Re$ represents the control inputs; Given a reference output signal y_r, $e_1 = y - y_r$ is the corresponding tracking error. $\tau(x, \upsilon)$ and $\zeta(t - T_0)$ are the fault function and the homologous time profile at the moment t, and there are two cases:
(1) When $t < T_0$, it satisfies $\zeta(t - T_0) = 0$, and the system is in a fault-free state;
(2) When $t \geq T_0$, satisfy $\zeta(t - T_0) = 1 - e^{-\rho(t - T_0)}$, then the system is in faulty state.
where ρ is a non-negative constant that represents the corresponding evolutionary rate caused by an unknown fault. Different values of ρ, the fault type generated by the actuator is different. If ρ is a relatively small value, then the actuator's fault type is an incipient fault. If ρ tends to infinity, i.e., $\zeta(t - T_0) = 1$, the actuator's fault type is an abrupt fault.

The following reasonable assumptions are given to facilitate the subsequent handling of actuator faults.

Assumption 1: Assuming the unknown function $\bar{g}(x, \upsilon) > 0$, the inequality $|f_n(x) + \zeta\,(t - T_0)\,\tau(x, \upsilon)| \leq \bar{g}(x, \upsilon)$ holds.

Remark 1: It is clear that Assumption 1 considers the drift term $f(x)$ and the fault term $\zeta(t-T_0)\tau(x,\upsilon)$ in the system (1) as a unified whole and redefines it as a new fault function $\bar{g}(x,\upsilon)$ containing the unknown nonlinear function $f(x)$. Then, during the controller design process, the powerful approximation capability of the fuzzy logic system (FLS) is introduced to handle with $\bar{g}(x,\upsilon)$ to counteract the negative impact of failures on the system.

Choose the following asymmetric dead-zone model:

$$u = H(\upsilon)\begin{cases} \pi_r(\upsilon - d_r), \upsilon \geq d_r \\ 0, \quad -d_l < \upsilon < d_r \\ \pi_l(\upsilon + d_l), \upsilon \leq -d_l \end{cases} \tag{2}$$

where $H(\upsilon)$ is an asymmetrical dead-zone function with υ as the dead-zone input; π and d represent the slopes and breakpoints on the x-axis of the dead-zone model, respectively; the subscripts r and l refer to the left and right of the line dividing the axes origin; π_r, d_r, π_l, and d_l are positive scalars that remain unspecified.

Assumption 2 and Assumption 3 are introduced to facilitate the next step of controller design.

Assumption 2: Suppose the dead-zone input signal $\upsilon(t)$ is bounded , i.e., $|\upsilon(t)| \leq D$, where D is a non-negative constant.

Assumption 3: The coefficients π_r, d_r, π_l and d_l of the dead-zone model (2) are all uncertain positive constants and satisfy the condition $\pi_r \neq \pi_l$.

Under Assumption 2 and Assumption 3, the nonlinear function expression for the asymmetric dead-zone model (2) is displayed beneath:

$$u = \pi\upsilon + \gamma \tag{3}$$

with $\pi = \begin{cases} \pi_l, \upsilon \leq 0 \\ \pi_r, \upsilon > 0 \end{cases}$, $\gamma = \begin{cases} -\pi_r d_r, \upsilon \geq d_r \\ -\pi\upsilon, -d_l < \upsilon < d_r \\ \pi_l d_l, \upsilon \leq -d_l \end{cases}$.

Define $\Upsilon = \max\{\pi_r d_r, \pi_l d_l\}$, $\overline{\chi} = \max\{\pi_l, \pi_r\}$, $\underline{\chi} = \min\{\pi_l, \pi_r\}$, and so we get

$$\gamma \leq \Upsilon \tag{4}$$

$$\frac{\pi(t)}{\underline{\chi}} = 1 + \lambda(t), \lambda(t) \leq \frac{\bar{\chi}}{\underline{\chi}} - 1 \tag{5}$$

where $\lambda(t)$ is a bounded and segmented positive function.

Combining (3) and (5) generates the following new expression:

$$u = \underline{\chi}(1 + \lambda(t))\upsilon(t) + \gamma(t) \tag{6}$$

2.2 Relevant Lemmas

To fulfil the control task of this paper, which is to develop a fault-tolerant control in the sense of fixed-time stabilisation for constrained systems with triangular structure, the following Lemmas are necessary.

Lemma 1 (Tian et al., 2023): Suppose that $V(x)$ is a positive definite function. If the inequality $\dot{V}(x) \leq -rV(x)^q - tV(x)^p + W$ is satisfied, then accordingly the semi-global fixed-time stability of the controlled system can be guaranteed, where the scalars r, t, p, q, and W are all positive real numbers with $0 < q < 1$ and $p > 1$. In addition, for $0 < \eta < 1$, the setting-time upper bound function as $T \leq T_{\max} := \frac{1}{r\eta(q-1)} + \frac{1}{t\eta(1-p)}$.

Lemma 2 (Shao and Ye, 2022): For arbitrary $x \in \Re$, $y \in \Re$, scalar parameters $a > 0$, $b_1 > 1$, $b_2 > 1$, and b_1, b_2 satisfy $\frac{1}{b_1} + \frac{1}{b_2} = 1$, there is always the inequality $|x||y| \leq \frac{a^{b_1}}{b_1}|x|^{b_1} + \frac{1}{b_2 a^{b_2}}|y|^{b_2}$ holds.

Lemma 3 (Sui et al., 2023): If $a \in (0,1)$, $b \in (1,\infty)$, $m_i \in \Re$, the following inequalities hold:

$$\left(\sum_{i=1}^{n} m_i\right)^a \leq \sum_{i=1}^{n} m_i^a \tag{7}$$

$$n^{1-b}\left(\sum_{i=1}^{n} m_i\right)^b \leq \sum_{i=1}^{n} m_i^b \tag{8}$$

where $i = 1, ..., n$.

Lemma 4 (Liu et al., 2023): In the system (1), the function $f(x)$ is a nonlinear function that is unknown with all system state variables. More importantly, due to the smooth and continuous characteristic throughout of $f(x)$, it can be approximated and fitted by FLS $R^T\phi(x)$, i.e., $\sup_{x\in U}\left|f(x) - R^T\phi(x)\right| \leq \varepsilon$, where ε is the approximation error and $|\varepsilon|$ is not greater than a bounded positive constant δ, $R = [R_1, R_2, ..., R_n]^T$ is the ideal weight vector, $\phi(x)$ is the fuzzy basis function vector, whose expression can be written as

$$\phi(x) = \frac{[s_1(x), s_2(x), \ldots, s_n(x)]^T}{\sum_{i=1}^{n} s_i(x)} \tag{9}$$

In (9), i and $s_i(x)$ represent the number of fuzzy rules and the membership function satisfying the Gaussian function condition respectively, i.e. $s_i(x) = \exp\left[\frac{-(x-\mu_i)^T(x-\mu_i)}{\eta_i^2}\right]$, $i = 1, 2, ..., n$, where $\mu_i = [\mu_{i1}, \mu_{i2}, \ldots, \mu_{in}]$ is the centre vector and η_i is the width of the Gaussian function.

In a FLS, assume that $\vartheta = \|R\|^2$, $\hat{\vartheta}$ is the optimal estimate of ϑ, and hence the estimation error is $\tilde{\vartheta} = \vartheta - \hat{\vartheta}$.

3. DESIGN OF FIXED-TIME FAULT-TOLERANT CONTROLLER

The ultimate goal of this section is to construct a fault-tolerant controller adapted to the constrained system in the sense of fixed-time stability using backstepping method as the design framework. The backstepping method is a recursive design method that requires n iterations before obtaining the final desired controller. Unlike the traditional backstepping method, in this paper, a set of coordinate transformations are introduced as follows:

$$e_1 = x_1 - y_r, e_i = x_i - \alpha_{i-1}, i = 2, \ldots, n \tag{10}$$

where α_{i-1} is the virtual control protocol for the corresponding subsystem of the n-order constrained system.

Step 1: Considering the first order subsystem of the constrained system (1) and the first transformation of the coordinate transformation (10), the first order derivative $\dot{e}_1$ of e_1 can be obtained as follows:

$$\dot{e}_1 = e_2 + \alpha_1 + f_1(x) + \Delta_1(x) - \dot{y}_r \tag{11}$$

Construct the Lyapunov candidate function $V_1 = \frac{1}{2}e_1^2 + \frac{1}{2m_1}\tilde{\vartheta}_1^2$, where $m_1 > 0$ is a constant. Finding the time derivative $\dot{V}_1$ of V_1 and combining it with (11), we get

$$\dot{V}_1 = e_1\big(e_2 + \alpha_1 + h_1(x) - \frac{1}{2}e_1 - \dot{y}_r\big) - \frac{1}{m_1}\tilde{\vartheta}_1^T\dot{\hat{\vartheta}}_1 \quad (12)$$

where $h_1(x) = f_1(x) + \Delta_1(x) + \frac{1}{2}e_1$.

To deal with the new unknown function $h_1(x)$, firstly, Lemma 4 is used to obtain $h_1(x) = R_1^T\phi_1(x) + \varepsilon_1$, and secondly, Lemma 2 is used to deal with $e_1h_1(x)$. Thus, for $a_1 > 0$, $\delta_1 > 0$, it follows

$$e_1h_1(x) \le \frac{1}{2a_1^2}e_1^2\vartheta_1\phi_1(x)^T\phi_1(x) + \frac{1}{2}a_1^2 + \frac{1}{2}e_1^2 + \frac{1}{2}\delta_1^2 \quad (13)$$

Substituting (13) into (12) yields

$$\begin{aligned}\dot{V}_1 \le & e_1\big(e_2 + \alpha_1 + \frac{1}{2a_1^2}e_1\vartheta_1\phi_1(x)^T\phi_1(x) - \dot{y}_r\big)\\ & + \frac{1}{2}a_1^2 + \frac{1}{2}\delta_1^2 - \frac{1}{m_1}\tilde{\vartheta}_1^T\dot{\hat{\vartheta}}_1 \end{aligned} \quad (14)$$

Virtual controller α_1 and adaptive law $\dot{\hat{\vartheta}}_1$ are selected as

$$\begin{aligned}\alpha_1 = & -M_{1,1}e_1^{2p-1} - M_{2,1}e_1^{2q-1} + \dot{y}_r\\ & - \frac{1}{2a_1^2}e_1\hat{\vartheta}_1\phi_1(x)^T\phi_1(x)\end{aligned} \quad (15)$$

$$\dot{\hat{\vartheta}}_1 = \frac{m_1}{2a_1^2}e_1^2\phi_1(x)^T\phi_1(x) - \lambda_1\hat{\vartheta}_1 - \kappa_1\hat{\vartheta}_1^{2p-1} \quad (16)$$

where $M_{1,1} > 0$, $M_{2,1} > 0$, $\lambda_1 > 0$, $\kappa_1 > 0$, $p > 1$, $0 < q < 1$.

With the above results (15) and (16), $\dot{V}_1$ can be finally written as

$$\begin{aligned}\dot{V}_1 \le & -M_{1,1}e_1^{2p} - M_{2,1}e_1^{2q} + e_1e_2 + \frac{1}{2}a_1^2 +\\ & \frac{1}{2}\delta_1^2 + \frac{\lambda_1}{m_1}\tilde{\vartheta}_1^T\hat{\vartheta}_1 + \frac{\kappa_1}{m_1}\tilde{\vartheta}_1^T\hat{\vartheta}_1^{2p-1}\end{aligned} \quad (17)$$

Step i **(**$2 \le i \le n-1$**):** Considering the ith-order subsystem of the constrained system (1) and the ith transformation of the coordinate transformation (10), the first order derivative $\dot{e}_i$ of e_i can be obtained as follows:

$$\dot{e}_i = e_{i+1} + \alpha_i + f_i(x) + \Delta_i(x) - \dot{\alpha}_{i-1} \quad (18)$$

Construct the positive definite Lyapunov function V_i corresponding to the ith-order constrained subsystem with the expression $V_i = V_{i-1} + \frac{1}{2}e_i^2 + \frac{1}{2m_i}\tilde{\vartheta}_i^2$, where $m_i > 0$ is an adjustable parameter. Define a new composite unknown nonlinear function $h_i(x) = e_{i-1} + f_i(x) + \Delta_i(x) + \frac{1}{2}e_i - \dot{\alpha}_{i-1}$, so that the first-order derivatives $\dot{V}_i$ of V_i can be expressed as

$$\begin{aligned}\dot{V}_i = & \dot{V}_{i-1} - e_{i-1}e_i + e_i\big(e_{i+1} + \alpha_i\\ & + h_i(x) - \frac{1}{2}e_i\big) - \frac{1}{m_i}\tilde{\vartheta}_i^T\dot{\hat{\vartheta}}_i\end{aligned} \quad (19)$$

Let $h_i(x) = R_i^T\phi_i(x) + \varepsilon_i$, and using Lemma 2, we get

$$e_ih_i(x) \le \frac{1}{2a_i^2}e_i^2\vartheta_i\phi_i(x)^T\phi_i(x) + \frac{1}{2}a_i^2 + \frac{1}{2}e_i^2 + \frac{1}{2}\delta_i^2 \quad (20)$$

where $a_i > 0$, $\delta_i > 0$.

Thus,

$$\begin{aligned}\dot{V}_i \le & \dot{V}_{i-1} + e_i\big(e_{i+1} + \alpha_i + \frac{1}{2a_i^2}e_i\vartheta_i\phi_i(x)^T\phi_i(x)\big)\\ & + \frac{1}{2}a_i^2 + \frac{1}{2}\delta_i^2 - \frac{1}{m_i}\tilde{\vartheta}_i^T\dot{\hat{\vartheta}}_i - e_{i-1}e_i\end{aligned} \quad (21)$$

Select the following virtual controller α_i and adaptive law $\dot{\hat{\vartheta}}_i$ as follows:

$$\begin{aligned}\alpha_i = & -M_{1,i}e_i^{2p-1} - M_{2,i}e_i^{2q-1}\\ & - \frac{1}{2a_i^2}e_i\hat{\vartheta}_i\phi_i(x)^T\phi_i(x)\end{aligned} \quad (22)$$

$$\dot{\hat{\vartheta}}_i = \frac{m_i}{2a_i^2}e_i^2\phi_i(x)^T\phi_i(x) - \lambda_i\hat{\vartheta}_i - \kappa_i\hat{\vartheta}_i^{2p-1} \quad (23)$$

where $M_{1,i}$, $M_{2,i}$, λ_i, κ_i are positive constants.

Substituting (22) and (23) into (21), $\dot{V}_i$ can be written as

$$\begin{aligned}\dot{V}_i \le & -\sum_{j=1}^{i}M_{1,j}e_j^{2p} - \sum_{j=1}^{i}M_{2,j}e_j^{2q} + \frac{1}{2}\sum_{j=1}^{i}\big(a_j^2 + \delta_j^2\big)\\ & + \sum_{j=1}^{i}\frac{\lambda_j}{m_j}\tilde{\vartheta}_j^T\hat{\vartheta}_j + \sum_{j=1}^{i}\frac{\kappa_j}{m_j}\tilde{\vartheta}_j^T\hat{\vartheta}_j^{2p-1} + e_ie_{i+1}\end{aligned} \quad (24)$$

Step n**:** According to the nth-order subsystem of the constrained system (1) and the nth transformation of the coordinate transformation (10), the first order derivative $\dot{e}_n$ of e_n can be obtained as follows:

$$\begin{aligned}\dot{V}_n = & \dot{V}_{n-1} - e_{n-1}e_n + e_n\big(e_{n-1} + f_n(x)\\ & + \Delta_n(x) + u + \frac{1}{2}e_n - \frac{1}{2}e_n - \dot{\alpha}_{n-1}\\ & + \zeta(t-T_0)\tau(x,v)\big) - \frac{1}{m_n}\tilde{\vartheta}_n^T\dot{\hat{\vartheta}}_n\end{aligned} \quad (25)$$

where $m_n > 0$ is a design constant.

According to Assumption 1 and FLS, the following inequality holds:

$$\begin{aligned}e_n(f_n(x) + \zeta(t-T_0)\tau(x,v)) \le & |e_n||\bar{g}(x,v)|\\ \le & \frac{1}{2b}e_n^2\bar{g}^2(x,v) + \frac{1}{2}b\\ = & e_ng(x,v) + \frac{1}{2}b\end{aligned} \quad (26)$$

where $g(x,v) = \frac{1}{2b}e_n\bar{g}^2(x,v)$, $b > 0$ is an adjustable parameter.

From Assumption 2 and (4)-(6), the ideal fault-tolerant controller u can be constructed as

$$u = \underline{\chi}v + (\overline{\chi} - \underline{\chi})D + \Upsilon \quad (27)$$

Substituting (26) and (27) into (25), we get

$$\begin{aligned}\dot{V}_n \le & \dot{V}_{n-1} - e_{n-1}e_n + e_n\big(e_{n-1} + \Upsilon + \frac{1}{2}e_n\\ & + \underline{\chi}v + (\overline{\chi} - \underline{\chi})D + \Delta_n(x) + g(x,v)\\ & - \frac{1}{2}e_n - \dot{\alpha}_{n-1}\big) + \frac{1}{2}b - \frac{1}{m_n}\tilde{\vartheta}_n^T\dot{\hat{\vartheta}}_n\end{aligned} \quad (28)$$

Defining $h_n(x) = e_{n-1} + g(x,v) + \Delta_n(x) + \frac{1}{2}e_n - \dot{\alpha}_{n-1}$ as a new function, (28) can be written as

$$\begin{aligned}\dot{V}_n \le & \dot{V}_{n-1} - e_{n-1}e_n + e_n\big(-\frac{1}{2}e_n + h_n(x) + \underline{\chi}v\\ & + (\overline{\chi} - \underline{\chi})D + \Upsilon\big) - \frac{1}{m_n}\tilde{\vartheta}_n^T\dot{\hat{\vartheta}}_n + \frac{1}{2}b\end{aligned} \quad (29)$$

The FLS is utilized to handle the function $h_n(x)$, i.e., for two parameters $a_n > 0$ and $\delta_n > 0$, the inequality $e_n h_n(x) \leq \frac{1}{2a_n^2} e_n^2 \vartheta_n \phi_n(x)^T \phi_n(x) + \frac{1}{2} a_n^2 + \frac{1}{2} e_n^2 + \frac{1}{2} \delta_n^2$ holds.

Therefore,

$$\begin{aligned} \dot{V}_n \leq & \dot{V}_{n-1} - e_{n-1} e_n + e_n \big(\underline{\chi} \upsilon + (\overline{\chi} - \underline{\chi}) D \\ & + \frac{1}{2a_n^2} e_n \vartheta_n \phi_n(x)^T \phi_n(x) + \Upsilon \big) + \frac{1}{2} b \\ & + \frac{1}{2} a_n^2 + \frac{1}{2} \delta_n^2 - \frac{1}{m_n} \tilde{\vartheta}_n^T \dot{\hat{\vartheta}}_n \end{aligned} \tag{30}$$

Choose the following actual control protocol υ and adaptive law $\dot{\hat{\vartheta}}_n$:

$$\begin{aligned} \upsilon = & \frac{1}{\underline{\chi}} \big(- M_{2,n} e_n^{2q-1} - M_{1,n} e_n^{2p-1} - (\overline{\chi} - \underline{\chi}) D \\ & - \frac{1}{2a_n^2} e_n \hat{\vartheta}_n \phi_n(x)^T \phi_n(x) - \Upsilon \big) \end{aligned} \tag{31}$$

$$\dot{\hat{\vartheta}}_n = \frac{m_n}{2a_n^2} e_n^2 \phi_n(x)^T \phi_n(x) - \kappa_n \hat{\vartheta}_n^{2p-1} - \lambda_n \hat{\vartheta}_n \tag{32}$$

where $M_{1,n} > 0$, $M_{2,n} > 0$, $\lambda_n > 0$, $\kappa_n > 0$.

Thus, the final form of $\dot{V}_n$ can be obtained with the expression

$$\begin{aligned} \dot{V}_n \leq & - \sum_{j=1}^{n} M_{1,j} e_j^{2p} - \sum_{j=1}^{n} M_{2,j} e_j^{2q} + \sum_{j=1}^{n} \frac{\lambda_j}{m_j} \tilde{\vartheta}_j^T \hat{\vartheta}_j \\ & + \sum_{j=1}^{n} \frac{\kappa_j}{m_j} \tilde{\vartheta}_j^T \hat{\vartheta}_j^{2p-1} + \frac{1}{2} \sum_{j=1}^{n} \big(a_j^2 + \delta_j^2 \big) + \frac{1}{2} b \end{aligned} \tag{33}$$

At this point, the controller design is complete.

Remark 2: Actuator fault and dead-zone input are two common constrained factors in systems. The actuator fault is usually caused by the limitation of the actuator material itself, while the dead-zone input is the non-smooth nonlinear characteristic caused by the complexity of the system working environment. The existence of actuator fault and dead-zone input can impair system performance and even cause system crash in severe cases. Therefore, it is very important to choose the appropriate processing method to eliminate the influence of dead-zone input on system performance and develop the corresponding fault-tolerant control scheme to deal with actuator faults. This is one of the motives of this paper.

4. STABILITY ANALYSIS

In the previous section, the detailed design process of the controller is revealed. The task of this section is to analyse the fixed-time stability and tracking accuracy of the fault-tolerant controller constructed for the constrained system in the previous section. The relevant results are summarised in Theorem 1.

Theorem 1: Consider the nonlinear system with the triangular structure and two kinds of constrained factors (actuator faults and unknown dead-zones. Under Assumptions 1-3, by utilizing backstepping method and Lyapunov fixed-time stability theory, the desired actual control signal (31), virtual controllers (15) and (22), adaptive laws (16), (23), and (32) can be obtained to guarantee the stability of the constrained system (1) in a fixed-time sense, with the following properties:
(1) All involved signals are bounded;
(2) The tracking error converges to within a compact set centred at the origin.

Proof: It follows from Lemma 2:

$$\begin{aligned} \sum_{j=1}^{n} \frac{\kappa_j}{m_j} \tilde{\vartheta}_j^T \hat{\vartheta}_j^{2p-1} \leq & \frac{2p-1}{2p} \sum_{j=1}^{n} \frac{\kappa_j}{m_j} \vartheta_j^{2p} \\ & - \frac{2p-1}{2p} \sum_{j=1}^{n} \frac{\kappa_j}{m_j} \tilde{\vartheta}_j^{2p} \end{aligned} \tag{34}$$

$$\sum_{j=1}^{n} \frac{\lambda_j}{m_j} \tilde{\vartheta}_j^T \hat{\vartheta}_j \leq \sum_{j=1}^{n} \frac{\lambda_j}{2m_j} \vartheta_j^2 - \sum_{j=1}^{n} \frac{\lambda_j}{2m_j} \tilde{\vartheta}_j^2 \tag{35}$$

Substituting (35) and (34) into (33), we get

$$\begin{aligned} \dot{V}_n \leq & - \sum_{j=1}^{n} \frac{M_{1,j}}{2^p} \left(\frac{e_j^2}{2} \right)^p - \frac{2p-1}{p} \sum_{j=1}^{n} \frac{\kappa_j}{2m_j} \tilde{\vartheta}_j^{2p} \\ & - \sum_{j=1}^{n} \frac{\lambda_j}{2m_j} \tilde{\vartheta}_j^2 - \sum_{j=1}^{n} \frac{M_{2,j}}{2^q} \left(\frac{e_j^2}{2} \right)^q + W_1 \\ \leq & -r \sum_{j=1}^{n} \left(\frac{e_j^2}{2} \right)^p - r \sum_{j=1}^{n} \left(\frac{e_j^2}{2} \right)^q - r \sum_{j=1}^{n} \frac{\tilde{\vartheta}_j^2}{2m_j} \\ & - r \sum_{j=1}^{n} \left(\frac{1}{2m_j} \tilde{\vartheta}_j^2 \right)^p + W_1 \end{aligned} \tag{36}$$

where $W_1 = \sum\limits_{j=1}^{n} \frac{\lambda_j}{2m_j} \vartheta_j^2 + \frac{2p-1}{2p} \sum\limits_{j=1}^{n} \frac{\kappa_j}{m_j} \vartheta_j^{2p} + \frac{1}{2} \sum\limits_{j=1}^{n} \big(a_j^2 + \delta_j^2 \big) + \frac{1}{2} b$, $r = \min\left\{ \frac{M_{1,j}}{2^p}, \frac{M_{2,j}}{2^q}, \lambda_j, \frac{2p-1}{p} \kappa_j 2^p m_j^p, j = 1, 2, \ldots, n \right\}$, and W_1 is a bounded constant.

Since $\left(\sum\limits_{j=1}^{n} \frac{1}{2m_j} \tilde{\vartheta}_j^2 \right)^q \leq \sum\limits_{j=1}^{n} \frac{1}{2m_j} \tilde{\vartheta}_j^2 + (1-q) q^{\frac{q}{1-q}}$, by Lemma 3, we have

$$\begin{aligned} \dot{V}_n \leq & -r n^{1-p} \left(\sum_{j=1}^{n} \frac{e_j^2}{2} \right)^p - r n^{1-p} \sum_{j=1}^{n} \left(\frac{1}{2m_j} \tilde{\vartheta}_j^2 \right)^p \\ & - r \left(\sum_{j=1}^{n} \frac{e_j^2}{2} \right)^q - r \sum_{j=1}^{n} \left(\frac{1}{2m_j} \tilde{\vartheta}_j^2 \right)^q + W_1 \\ & + r(1-q) q^{\frac{q}{1-q}} \\ \leq & -r n^{1-p} 2^{1-p} \left(\sum_{j=1}^{n} \frac{e_j^2}{2} + \frac{1}{2m_j} \tilde{\vartheta}_j^2 \right)^p + W_1 \\ & - y \left(\sum_{j=1}^{n} \frac{e_j^2}{2} + \frac{1}{2m_j} \tilde{\vartheta}_j^2 \right)^q + r(1-q) q^{\frac{q}{1-q}} \\ \leq & -t V^p - r V^q + W \end{aligned} \tag{37}$$

where $t = r n^{1-p} 2^{1-p}$, $W = W_1 + r(1-q) q^{\frac{q}{1-q}}$.

By the definition of Lyapunov function and Lemma 1, the conclusion holds and the proof is closed. $\square$

5. SIMULATION STUDY

This section focuses on verifying the reasonableness of the FTC scheme proposed in the previous section in terms of fixed-time tracking by adopting the form of simulation. Regarding the asymmetric dead-zone disturbance suffered by the nonlinear system (1) during the control process, the model is shown in (2), whose parameters are chosen as $\pi_r = 2.1$, $\pi_l = 2$, $\mathrm{d}_r = 5$, and $\mathrm{d}_l = -5$. For the actuator faults, a non-affine nonlinear fault is chosen. The fault function is $\tau(x, v) = 2\left(x_1x_2 + \sin(v)\right) + 50$, and the fault is assumed to occur at the 10th second, considering the incipient fault $\zeta\left(t - T_0\right) = 1 - e^{-8(t-10)}$ at $\rho = 8$ and the abrupt fault $\zeta\left(t - T_0\right) = 1$ at $\rho = \infty$. In this paper, the same dead-zone model and fault models as above are chosen for both Example 1 and Example 2.

Example 1: Focuses on the following dynamic model of a second-order constrained system with the triangular structure and constrained factors including actuator fault and unknown dead-zone

$$\begin{cases} \dot{x}_1 = x_2 + 0.1x_1^3 + 0.5\cos(x_1) + \Delta_1(x) \\ \dot{x}_2 = u - 0.1x_1x_2 - 0.2x_1 + \Delta_2(x) \\ \qquad + \zeta(t-10)\tau(x, v) \\ \ y = x_1 \end{cases} \tag{38}$$

where x_1 and x_2 represent the state variables of the nonlinear system; $\Delta_1(x_1) = 0.01\cos(x_1)$ and $\Delta_2(x_1) = 0.5\cos(10x_1)$ are the external uncertain disturbance; u and y are the system input suffering from dead-zone nonlinearity and the system output, respectively; $\zeta\left(t - T_0\right)$ and $\tau(x, v)$ are the homologous time profile where the fault occurs and the fault function, respectively.

Assuming that the reference signal is introduced, the expression is $y_r = 0.5\sin(t)$. The purpose of Example 1 is to authenticate the stability and tracking ability of the FTC protocol proposed in this paper in a second-order constrained system.

Following the design process described in the previous section, the following controllers and adaptive laws corresponding to the first order subsystem and the second section subsystem are obtained

$$\begin{aligned} \alpha_1 &= -M_{1,1}e_1^{2p-1} - M_{2,1}e_1^{2q-1} + \dot{y}_r \\ &\quad - \frac{1}{2a_1^2}e_1\hat{\vartheta}_1\phi_1(x)^T\phi_1(x) \\ v &= \frac{1}{\chi}\big(- M_{1,2}e_2^{2p-1} - M_{2,2}e_2^{2q-1} - (\bar{\chi} - \underline{\chi})D \\ &\quad - \frac{1}{2a_2^2}e_2\hat{\vartheta}_2\phi_2(x)^T\phi_2(x) - \Upsilon\big) \\ \dot{\hat{\vartheta}}_1 &= \frac{m_1}{2a_1^2}e_1^2\phi_1(x)^T\phi_1(x) - \lambda_1\hat{\vartheta}_1 - \kappa_1\hat{\vartheta}_1^{2p-1} \\ \dot{\hat{\vartheta}}_2 &= \frac{m_2}{2a_2^2}e_2^2\phi_2(x)^T\phi_2(x) - \lambda_2\hat{\vartheta}_2 - \kappa_2\hat{\vartheta}_2^{2p-1} \end{aligned} \tag{39}$$

Before numerical simulation verification, the initial conditions of the second-order nonlinear system can be selected as $\hat{\vartheta}_1(0) = [0, 0, 0, 0, 0]^T$, $\hat{\vartheta}_2(0) = [0, 0, 0, 0, 0]^T$, $x(0) = [0.1, -0.5]$ and the relevant parameters involved in the controllers and adaptive laws can be chosen as $M_{1,1} = 1$, $M_{1,2} = 0.5$, $p = 1.4$, $q = 0.8$, $\lambda_1 = 0.02$, $\lambda_2 = 0.01$, $\kappa_1 = 0.2$, $\kappa_2 = 0.1$, $m_1 = 1$, $m_2 = 2$, $a_1 = 0.05$, $a_2 = 0.1$, $D = 100$, $M_{2,1} = 20$, $M_{2,2} = 1$.

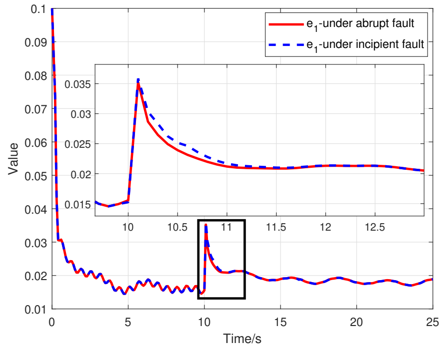

Fig. 1. Tracking error trajectories.

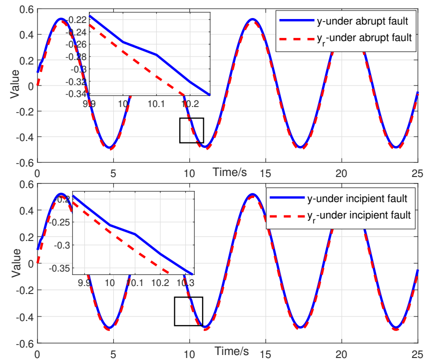

Fig. 2. Trajectories of the system output and the reference output.

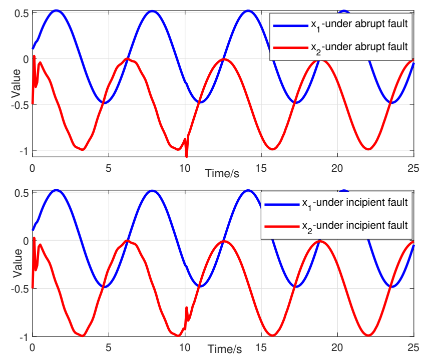

Fig. 3. Trajectories of the system state variables.

For the system (38), under the action of (39), the simulation results Figs. 1-4 are obtained. Fig. 1 illustrates the tracking error affected by the abrupt fault and asymmetric unknown dead-zone, as well as the tracking error affected by the incipient fault and asymmetric unknown dead-zone. Fig. 2 shows the tracking situation corresponding to the tracking error elaborated in Fig. 1. Fig. 3 and Fig. 4 display the trajectories of the system state variables and control signals, respectively. According to Figs. 1-4, we can easily see that under the control scheme of this paper, the tracking performance, stability and boundedness of the system in the fixed-time can be guaranteed and are not affected by the two types of constrained factors.

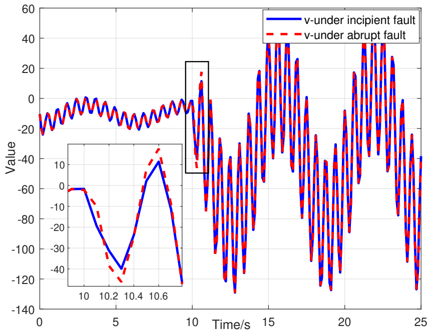

Fig. 4. Actual control signal of the system.

Example 2: A robotic manipulator system (Fig. 5) is used as the object of this model simulation to assess the reasonableness of the suggested FTC strategy in practical applications, and it is known that the system conforms to the following second-order Lagrangian equations:

$$J\ddot{q} + B\dot{q} + Mgl\sin(q) = u(t) \tag{40}$$

where the physical meanings of the symbols q, $\dot{q}$, B, J, M, l, and g refer to the the angle, the angular velocity, the damping coefficient, the total rotation inertia, the mass, the distance from the joint axis to the mass centre, and the acceleration of gravity, respectively. Assigning values to the above physical parameters: $J = 1Kg \cdot m^2$, $B = 2N/(m/s)$, $Mgl = 10J$. According to the system studied in this paper, introducing two types of disturbances, dead-zone input and actuator faults, based on the robotic manipulator model, equation (40) can be rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = u - 2x_2 - 10\sin(x_1) + \\ \qquad \zeta(t-10)\tau(x,v) \\ y = x_1 \end{cases} \tag{41}$$

where x_1 and x_2 correspond to q and $\dot{q}$ in (40), respectively. Assuming that the reference trajectory of the robotic manipulator is $y_r = 0.5\sin(t) + \sin(0.5t)$, the adjustable parameters involved in the controllers and adaptive laws in the simulation can be chosen as $M_{1,1} = 1$, $M_{2,1} = 100$, $M_{1,2} = 0.5$, $p = 1.1$, $q = 0.9$, $\lambda_2 = 0.05$, $\kappa_2 = 0.1$, $m_2 = 0.5$, $a_2 = 0.5$, $D = 100$, $M_{2,2} = 20$ and initial values are $x_2(0) = -0.1$, $\hat{\vartheta}(0) = [0,0,0,0,0]^T$, $x_1(0) = 0.3$.

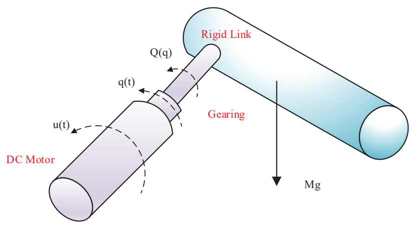

Fig. 5. The robotic manipulator system.

The purpose of Example 2 is to analyse whether the actual motion path of the robotic manipulator with the dual influence of actuator fault and unknown dead-zone can follow the prescribed reference path under the fixed-time FTC scheme. The simulation results are shown in Figs. 6-9. Fig. 6 illustrates the situation that the actual motion path tracks the reference path for the robotic manipulator with the dual influence of actuator fault and unknown dead-zone, where Fig. 7 displays the tracking errors corresponding to Fig. 6. Fig. 6 and Fig. 7 demonstrate the possibility of applying the fixed-time control strategy combined with FTC in the constrained actual system. Up until the tenth second, the plant is solely influenced by the unknown dead-zone. It is evident that the tracking performance remains unaffected and still rapidly stabilises during the initial stages of the controller's action. At the tenth second, an actuator fault is introduced into the system, and accordingly, the tracking performance shifts for a short period of time and then quickly stabilises. At this point, the system suffers from both the unknown dead-zone and the actuator fault as constrained factors. Compared to the tracking performance before ten seconds, which was only influenced by the unknown dead-zone, the tracking performance after ten seconds is slightly degraded due to both the unknown dead-zone and the actuator fault. However, this degradation is subtle and does not impair the overall control of the system. Fig. 8 and Fig. 9 show the trajectories of the system state variables and the controller control signal, respectively.

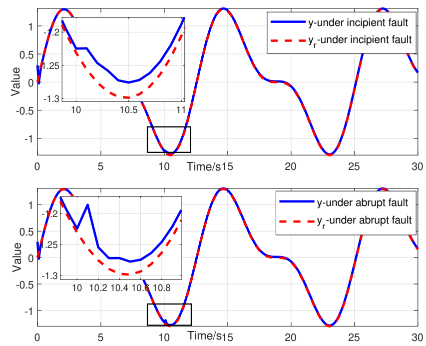

Fig. 6. Actual motion trajectories and reference trajectories of the robotic manipulator.

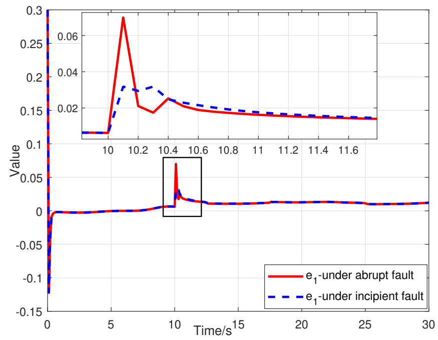

Fig. 7. Tracking errors of the robotic manipulator.

6. CONCLUSIONS

This paper is concerned with FTC of constrained systems in the fixed-time sense, constructing a fixed-time FTC scheme to study the tracking ability and stability of the controlled plant under the dual effects of the unknown dead-zone and the actuator fault. Firstly, two types of constrained factors are converted into nonlinear functions with unknown parameters, so that the difficult-to-handle disturbance model can be converted into a nonlinear function dynamic that can be fitted and estimated by a FLS. Then, applying for the backstepping method and Lyapunov fixed-time stability analysis, a new adaptive fuzzy fixed-time fault-tolerant tracking controller is proposed, which not only ensures the semiglobal fixed-time stability of the system but also guarantees that the tracking error tends to a compact set centered at the number zero. Finally, the effectiveness of the proposed controller is verified by numerical simulation of a second-order system and model simulation of a robotic manipulator system. However, with the increase in automation level, the requirements of the system are getting higher and higher. Therefore, our next research topic is the fixed-time FTC of large and complex systems not considered in this paper.

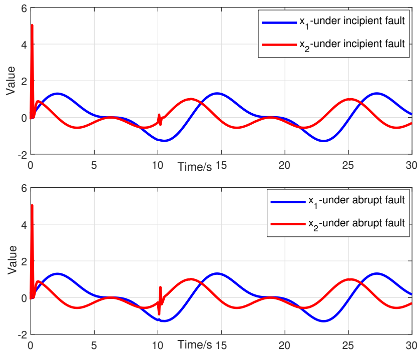

Fig. 8. Angle and angular velocity trajectories of the robotic manipulator.

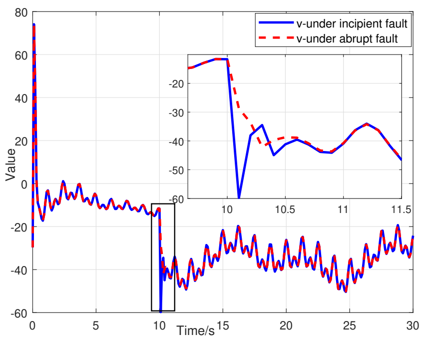

Fig. 9. Actual control signal trajectories of the robotic manipulator.

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