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RESEARCH ARTICLE

Adaptive Prescribed-Time Fault-Tolerant Control for a Class of Uncertain Nonlinear Systems With Time-Varying Sensor and Actuator Faults

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ABSTRACT This paper addresses the prescribed-time fault-tolerant control (PT-FTC) problem for a class of uncertain nonlinear systems in the strict-feedback form, which are subject to completely unknown time-varying virtual control coefficients, uncertain time-varying parameters, and unknown time-varying multiplicative faults in both sensors and actuators. By combining a descending power time-varying feedback technique, a bound estimation approach, and the backstepping design framework, along with employing a Lyapunov function that incorporates lower bounds of the virtual control coefficients, a novel adaptive PT fault compensation control strategy is proposed. Under the proposed scheme, the system states can converge to zero within an arbitrarily predefined finite time and remain there thereafter, while the control input remains continuous and bounded throughout the entire time interval, despite the presence of the time-varying sensor and actuator faults. Finally, simulation results are provided to validate the effectiveness of the proposed algorithm.

INDEX TERMS Adaptive control, fault-tolerant control, prescribed-time control, time-varying systems, sensor faults.

I. INTRODUCTION

It is well-known that the convergence time is one of the most important performance indicators in control system evaluation. Over the past few decades, substantial research efforts have focused on designing finite-time (FT) and fixed-time (FixT) control schemes to ensure system states converge to a desired value (e.g., the origin) within a finite time, see [1], [2], [3], [4], [5], [6], [7], and [8] for example. Compared to asymptotic control, these FT and FixT control techniques offer several advantages such as faster response, higher precision, and improved robustness [4]. However, the settling time of the resulting systems typically depends on the initial state and/or controller parameters. In many practical applications, such as missile guidance and autonomous aircraft rendezvous, it is more desirable to complete the task within a prescribed finite time. To address such a requirement, the predefined-time (PdT, also refers to prescribed-time) control approach was exploited in [9] and [10], where the convergence time can be prescribed in advance regardless of the initial conditions and controller parameters.

The PT control was systematically proposed by Song et al. [11] for regulating high-order nonlinear systems in normal form. Their approach, which utilizes a time-varying function (that grows infinitely as time approaches a prescribed terminal time) to scale the system state, has a clear advantage that the convergence time can be preset a priori, regardless of the initial conditions and controller

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parameters. A thorough study of the differences between prescribed-time control and traditional finite-time control was conducted in [12]. Following the seminal work of Song et al. [11], [12], many important PT control results have been developed. For instance, [13], [14] and [15] studied the PT control of linear time-invariant systems by extending the state-scaling design [11] and using parametric Lyapunov equations, respectively. References [16] and [17] investigated the PT stabilization of nonlinear strict-feedback-like systems using state- and output-feedback, respectively, by combining a dynamic high-gain technique with a novel temporal transformation. For the same class of systems, [18] developed a new prescribed-time regulation algorithm by scaling both the states and virtual controls, ensuring the system continues to operate smoothly beyond the settling time. A time-space deformation approach was developed in [19] to stabilize feedback-linearized controllable systems with matched disturbances. Reference [20] addressed PT mean-square stabilization and inverse optimality control for stochastic strict-feedback systems through a novel nonscaling backstepping design. For strict-feedback systems with uncertain parameters, [21] introduced a new PT stability criterion and solved the adaptive control problem with a new nonscaling design. In contrast, [22] employed a descending power coordinate transformation to design a dynamic surface control (DSC)-based adaptive PT algorithm. Apart from these, recent studies have also yielded several excellent results in the adaptive PT control of other complex nonlinear systems, such as [23], [24], [25], [26], and [27] and so on. [28] provides a comprehensive review of the latest developments in PT control. Notably, while earlier works, such as [11], [16], and [17], considered PT control within a finite time interval and were inapplicable at or beyond the terminal time, later studies, including [21], [22], and [23], have designed bounded, continuous controllers to ensure PT control over the entire time interval, thus facilitating practical implementation.

Despite the plentiful advancements, it is important to note that the vast majority of existing PT control methods rely on the assumption that the system states can be precisely measured and the control commands can be perfectly executed. However, in modern industrial applications, the system components such as actuators and sensors may experience faults—either individually or simultaneously—during long-term operation, which can degrade system performance or even lead to instability. In the literature, a variety of effective adaptive FT and FixT fault-tolerant control (FTC) designs have been proposed to enhance the reliability, safety, and performance of the systems [29], [30], [31], [32], [33]. Nevertheless, the convergence time in these designs can only be conservatively estimated and cannot be specified a priori. Moreover, it is worth noticing that most of currently available results on adaptive PT control are obtained for systems with constant uncertain parameters. Although [25], [26], and [27] have addressed adaptive prescribed-time (PT) control for strict-feedback systems with time-varying parameters, they have not considered the effects of actuator and sensor faults. Note that when the time-varying multiplicative faults in sensors and actuators are taken into account, the controlled plant can be transformed into a new system with unknown virtual control coefficients. However, in [25], [26], and [27], these coefficients are generally assumed to be known constants or to have known lower bounds. As a result, the existing approaches cannot be directly applied to address the adaptive prescribed-time fault-tolerant control problem.

Motivated by the above discussions, this paper further investigates the PT control problem for a class of time-varying uncertain strict-feedback systems subject to both sensor and actuator faults, and proposes a novel adaptive fault-tolerant stabilizing scheme to address this technically significant issue. The main contributions and advantages are reflected in the following aspects.

1) We consider a fairly general class of strict-feedback systems involving completely unknown time-varying virtual control coefficients and unknown time-varying multiplicative faults occurring in the sensors and actuators, in which their bounds do not need to be known. This distinguishes our work from most of the currently available results on this issue, such as [21], [22], [23], [24], [25], [26], and [27].
2) By combining the descending power time-varying feedback with a bound estimation approach, and utilizing a Lyapunov function that incorporates the lower bounds of the virtual control coefficients, a new adaptive backstepping-based PT FTC scheme is developed. In contrast to the finite/fixed-time FTC schemes [29], [30], [31], [32], [33], our approach allows the convergence time to be arbitrarily preassigned.
3) The proposed design ensures that the system states converge to zero within the prescribed finite time and stay there thereafter, while the control input remains continuous and bounded over the entire time interval, thereby guaranteeing the system operates over an infinite time horizon, which is different from [11], [16] and [17].

The remaining parts are organized as follows. Section II provides the problem formulation and preliminaries. Section III presents an adaptive prescribed-time fault-tolerant control scheme. In Section IV, the analysis of resulting closed-loop system are presented. In Section V, simulations are conducted to verify the validity of the proposed control scheme. Section VI gives the conclusions.

Notation: $\mathbb{R}$ represents the set of real numbers, $\mathbb{R}^n$ denotes the n-dimensional Euclidean space. The initial time t is set as $t = 0$. For a scalar $x \in \mathbb{R}$, $|x|$ is the absolute value of x; For a vector x, x^{T} denotes its transpose, $\|x\|$ stands for the Euclidean vector norm; $\sup_{t\geq 0} f(t)$ stands for the supremum of $f(t)$ on the interval $[0, +\infty)$.

II. PROBLEM FORMULATION AND PRELIMINARIES

A. PROBLEM STATEMENT

Consider the following class of uncertain strict-feedback systems:

$$\begin{cases} \dot{x}_i = b_i(t)x_{i+1} + \theta_i(t)\varphi_i(\bar{x}_i), \quad i = 1, \dots, n-1, \\ \dot{x}_n = b_n(t)\bar{u} + \theta_n(t)\varphi_n(x), \end{cases} \tag{1}$$

where $x = \bar{x}_n = [x_1, \cdots, x_n]^{\mathrm{T}} \in \mathbb{R}^n$ is the state vector and $\bar{x}_i = [x_1, \cdots, x_i]^{\mathrm{T}} \in \mathbb{R}^i$; $\bar{u} \in \mathbb{R}$ is the control input; For $i = 1, \dots, n, \theta_i(t) \in \mathbb{R}$ are unknown time-varying parameters and $b_i(t) \in \mathbb{R}$ denote the unknown time-varying virtual control coefficients; $\varphi_i(\bar{x}_i)$ are known smooth functions with the properties $\varphi_i(0) = 0$.

In this study, the commonly encountered unanticipated sensor and actuator faults are explicitly addressed. These faults cause the measured states to differ from the true system states and the actual control inputs to deviate from the designed commands. More specifically, the following multiplicative sensor and actuator faults are considered:

$$\check{x}_i(t) = \sigma_{s_i}(t)x_i(t), \tag{2}$$

$$\bar{u} = \sigma_a(t)u_a, \tag{3}$$

where $\check{x}_i(t)$ and $\bar{u}$ are the outputs of the sensor and actuator, respectively; x_i is the true system state, u_a represents the controller-designed command; the time-varying weights $\sigma_{s_i}(t) \in (0, 1]$ and $\sigma_a(t) \in (0, 1]$ are unknown, representing health indices that reflect the effectiveness of measurement and actuation, respectively. Apparently, if $\sigma_{s_i}(\cdot) = 1$, then the ith sensor is working normally, and the true state x_i can be accurately measured. However, if $0 < \sigma_{s_i}(\cdot) < 1$, then the ith sensor experiences a partial loss of effectiveness due to faults, and only the faulty state $\check{x}_i$ can be obtained and used for feedback. Similarly, if $\sigma_a(\cdot) = 1$, then the actuator is operating healthily, and the designed control input u_a can be executed perfectly. Conversely, if $0 < \sigma_a(\cdot) < 1$, then the actuator is suffering from partial loss of effectiveness, and its output $\bar{u}$ is no longer the same as the command u_a.

The objective of this article is to design an adaptive controller for the uncertain system (1) subject to sensor and actuator faults in the form of (2) and (3), respectively, such that:

1) the system states $x_i(t), i = 1, 2, \cdots, n$ converge to zero within a prescribed-time T;
2) all closed-loop signals are bounded.

To achieve the control objective, the following assumptions are made.

Assumption 1: The signs of $b_i(t)$, $i = 1, 2, \cdots, n$ are known. Without loss of generality, it is assumed that $b_i(t) > 0$. Moreover, there exist unknown constants $\underline{b}_i > 0$, $\bar{b}_i > 0$ such that $0 < \underline{b}_i \le b_i(t) \le \bar{b}_i$.

Assumption 2: For the sensor faults, there exist unknown positive constants $\underline{\sigma}_{s_i}$, $\bar{\sigma}_{s_i}$ and $\bar{\sigma}_{s_d}$ such that $0 < \underline{\sigma}_{s_i} \le \sigma_{s_i}(t) \le \bar{\sigma}_{s_i} \le 1$ and $|\dot{\sigma}_{s_i}(t)| \le \bar{\sigma}_{s_d}$, $i = 1, 2, \cdots, n$.

Assumption 3: For the actuator fault, there exist unknown positive constants $\underline{\sigma}_a$ and $\bar{\sigma}_a$ such that $0 < \underline{\sigma}_a \le \sigma_a(t) \le \bar{\sigma}_a \le 1$.

Consequently, the system (1) under the sensor and actuator faults (2), (3) can be rewritten as

$$\begin{cases} \dot{\check{x}}_i = \lambda_i(t)\check{x}_i + g_i(t)\check{x}_{i+1} + \rho_i(t)\varphi_i(\bar{x}_i), \\ \qquad i = 1, 2, \cdots, n-1, \\ \dot{\check{x}}_n = \lambda_n(t)\check{x}_n + g_n(t)u_a + \rho_n(t)\varphi_n(x), \end{cases} \tag{4}$$

where $\lambda_i(t) = \frac{\dot{\sigma}_{s_i}(t)}{\sigma_{s_i}(t)}$, $g_i(t) = \frac{\sigma_{s_i}(t)}{\sigma_{s_{i+1}}(t)}b_i(t)$, $\rho_i(t) = \sigma_{s_i}(t)\theta_i(t)$ and $g_n(t) = b_n(t)\sigma_{s_n}(t)\sigma_a(t)$ are unknown time-varying parameters.

From Assumptions 1-3, it can be inferred that there exist positive constants $\underline{g}_i := \frac{\underline{\sigma}_{s_i}}{\bar{\sigma}_{s_{i+1}}}\underline{b}_i$, $\underline{g}_n := \underline{b}_n\underline{\sigma}_{s_n}\underline{\sigma}_a$, $\bar{g}_i := \frac{\bar{\sigma}_{s_i}}{\underline{\sigma}_{s_{i+1}}}\bar{b}_i$, $\bar{g}_n := \bar{b}_n\bar{\sigma}_{s_n}\bar{\sigma}_a$ and $\bar{\lambda}_i := \frac{\bar{\sigma}_{s_d}}{\underline{\sigma}_{s_i}}$ such that $0 < \underline{g}_i \le g_i(t) \le \bar{g}_i$, $0 < \underline{g}_n \le g_n(t) \le \bar{g}_n$ and $|\lambda_i(t)| \le \bar{\lambda}_i$.

Remark 1: Assumptions 1–3 are very common in existing relevant works, see, e.g., [23], [30], and [33]. Assumption 1 is a basic condition to guarantee the controllability of the system (1). For Assumptions 2–3, all sensors and actuator are allowed to suffer from partial loss of effectiveness faults simultaneously, while the knowledge of the bounds are not required to be known.

Remark 2: System (1) represents an important class of systems in the field of nonlinear control and has been extensively studied across various scenarios (see, e.g., [25], [26], [27]). Moreover, many practical systems, such as the spacecraft attitude control system, quad rotor control system, and single-link robotic manipulator system, can be modeled or transformed into the form of (1). Notably, system (1) simultaneously involves mismatched unknown time-varying parameters and virtual control coefficients, along with potential unknown time-varying sensor and actuator faults, which make the PT control design problem particularly challenging.

B. PRELIMINARIES

Definition 1 [25]: If a smooth function $\mu(t)$ satisfies

$$\mu(t) > 0, \quad \forall t \in [0, T),$$
$$\lim_{t \to T^-} (T - t)\mu(t) = o, \tag{5}$$

where o is a positive constant or $+\infty$, then $\mu(t)$ is called a prescribed-time adjustment (T_p-PTA) function.

In this work, $\mu(t)$ is designed as

$$\mu(t) = \frac{c}{T - t}, \tag{6}$$

where c is a positive design constant. A straightforward calculation shows that $\dot{\mu}(t) = \mu^2(t)/c$. Let $v(t) = \mu^{-1}(t)$, then $v(t) : [0, T) \to (0, \frac{T}{c}]$ is bounded and satisfies $\lim_{t \to T} v(t) = 0$.

Lemma 1 [22]: Let $V(t)$ be a smooth function defined on $[0, T)$ with $V(t) \geq 0$. If the following inequality holds:

$$\dot{V}(t) \leq -k\mu(t)V(t) + \mu(t)\Delta, \quad 0 \leq t < T, \tag{7}$$

where $\mu(t)$ is a T_p-PTA function, k and Δ are positive constants, then $V(t)$ must be bounded on $[0, T)$.

Lemma 2 [34]: For any continuous function $f(x, d) : \mathbb{R}^n \times \mathbb{R}^l \mapsto \mathbb{R}$, there exist smooth functions $a(x), b(d) \geq 0$, such that

$$|f(x, d)| \leq a(x)b(d). \tag{8}$$

Lemma 3: For the smooth functions $\varphi_i(\bar{x}_i)$ in (1), there exist unknown positive constants ϖ_i and known positive-valued smooth functions $\phi_i(\bar{\check{x}}_i)$ such that

$$|\varphi_i(\bar{x}_i)| \leq \varpi_i\phi_i(\bar{\check{x}}_i)\sum_{j=1}^{i}|\check{x}_j|. \tag{9}$$

Since $\varphi_i(\bar{x}_i)$ are smooth and vanish at $x = 0$, according to [35], $\varphi_i(\bar{x}_i)$ can be expressed as

$$\varphi_i(\bar{x}_i) = \sum_{j=1}^{i}\bar{\varphi}_{ij}(\bar{x}_i)x_j, \quad i = 1, \cdots, n, \tag{10}$$

where $\bar{\varphi}_{ij}(\bar{x}_i)$ are continuous functions. From (2), it is obtained that $x_i = \sigma_{s_i}^{-1}\check{x}_i$. By Lemma 2, there exist smooth functions $\beta_{ij}(\cdot)$ and $a_{ij}(\cdot)$ such that

$$\begin{aligned}|\bar{\varphi}_{ij}(\bar{x}_i)| &= |\bar{\varphi}_{ij}(\sigma_{s_1}^{-1}(t)\check{x}_1, \cdots, \sigma_{s_i}^{-1}(t)\check{x}_i)| \\ &\leq a_{ij}(\bar{\sigma}_{s_i}^{-1}(t))\beta_{ij}(\bar{\check{x}}_i),\end{aligned} \tag{11}$$

where $\bar{\sigma}_{s_i}^{-1}(t) = \left[\sigma_{s_1}^{-1}(t), \cdots, \sigma_{s_i}^{-1}(t)\right]^{\mathrm{T}}$. Then, noting the continuity and boundedness of $\sigma_{s_i}^{-1}(t)$, it follows that there exist positive constants $\bar{a}_{ij}$ such that $a_{ij}(\bar{\sigma}_{s_i}^{-1}(t)) \leq \bar{a}_{ij}$. Therefore

$$|\bar{\varphi}_{ij}(\bar{x}_i)| \leq \bar{a}_{ij}\beta_{ij}(\bar{\check{x}}_i). \tag{12}$$

This, together with (10) and Assumption 2, gives rise to

$$\begin{aligned}|\varphi_i(\bar{x}_i)| &= \sum_{j=1}^{i}|\bar{\varphi}_{ij}(\bar{x}_i)||\sigma_{s_j}^{-1}(t)\check{x}_j| \\ &\leq \varpi_i\sum_{j=1}^{i}\beta_{ij}(\bar{\check{x}}_i)|\check{x}_j| \\ &\leq \varpi_i\phi_i(\bar{\check{x}}_i)\sum_{j=1}^{i}|\check{x}_j|,\end{aligned} \tag{13}$$

where $\varpi_i = \max\left\{\bar{a}_{i1}/\underline{\sigma}_{s_1}, \cdots, \bar{a}_{ii}/\underline{\sigma}_{s_i}\right\}$ and $\phi_i(\bar{\check{x}}_i) = \sum_{j=1}^{i}\beta_{ij}(\bar{\check{x}}_i)$. The proof is completed. □

III. ADAPTIVE PRESCRIBED-TIME FAULT-TOLERANT CONTROL DESIGN

In this section, a PT stabilization control scheme is designed for the uncertain nonlinear system (1) subject to sensor and actuator faults. The PT-FTC scheme is developed based on an n-step adaptive backstepping design procedure and can ensure the convergence of the states to zero within a given time T.

To begin with, the following change of coordinates are introduced

$$\omega_1 = \check{x}_1, \quad \omega_i = \check{x}_i - \alpha_{i-1}, \; i = 2, \cdots, n, \tag{14}$$

and the state transformation is presented as follows:

$$z_i = \mu^{L_i}\omega_i, \quad i = 1, 2, \cdots, n, \tag{15}$$

where $L_i = n + m + 1 - i$ with $m > 0$ being a positive design constant, α_{i-1} is the virtual control at the ith step, which will be determined later. The actual control u_a will be constructed at the last step. To simplify the notation, some independent variables are omitted when no confusion is likely to arise, for example, $\psi(x)$ and $\chi(x)$ are denoted by $\psi(\cdot)$ and $\chi(\cdot)$, respectively. Moreover, for ease of description, the following definitions are provided:

$$G_i = \frac{\bar{g}_i}{\underline{g}_i}, \quad H_i = \frac{\varpi_i}{\underline{g}_i}\sup_{0\leq t<T}|\rho_i(t)|, \tag{16}$$

$$\tau_i = 2L_i - 1, \quad l_i = \frac{i(i-1)}{2}, \; i = 1, 2, \cdots, n. \tag{17}$$

Furthermore, denote $\hat{\vartheta}_i$ as the estimate of the unknown constant ϑ_i, which will be specified at the ith step. Correspondingly, the estimation error is defined as $\tilde{\vartheta}_i = \vartheta_i - \hat{\vartheta}_i$. Then, bearing in mind that only $\check{x}_i$ can be used for feedback, the detailed design procedure is presented as follows:

Step 1: From (4), (14) and (15), the derivative of z_1 is

$$\begin{aligned}\dot{z}_1 = &\frac{L_1}{c}\mu z_1 + \lambda_1(t)z_1 + \rho_1(t)\mu^{L_1}\varphi_1 + g_1(t)\mu z_2 \\ &+ g_1(t)\mu^{L_1}\alpha_1.\end{aligned} \tag{18}$$

Consider the positive definite and radially unbounded function $V_{z_1} = \frac{1}{2\underline{g}_1}z_1^2$, whose time derivative along (18) is

$$\begin{aligned}\dot{V}_{z_1} = &\frac{1}{\underline{g}_1}\bigg(\frac{L_1}{c}\mu z_1^2 + \lambda_1(t)z_1^2 + \rho_1(t)\mu^{L_1}z_1\varphi_1 \\ &+ g_1(t)\mu z_1 z_2 + g_1(t)\mu^{L_1}z_1\alpha_1\bigg).\end{aligned} \tag{19}$$

By invoking Lemma 3 and Young's inequality, along with the definitions of G_1 and H_1, it is obtained that

$$\frac{g_1(t)}{\underline{g}_1}\mu z_1 z_2 \leq G_1^2\mu z_1^2 + \mu\frac{1}{4}z_2^2, \tag{20}$$

$$\begin{aligned}\frac{\rho_1(t)}{\underline{g}_1}\mu^{L_1}z_1\varphi_1 &\leq H_1\mu^{L_1}|z_1|\phi_1|\check{x}_1| \\ &\leq H_1\mu^{\tau_1}z_1^2\psi_1(\cdot) + \mu\frac{H_1}{4},\end{aligned} \tag{21}$$

where $\psi_1(\cdot) = \phi_1^2\check{x}_1^2$.

To deal with the unknown but bounded parameters, let

$$\Theta_1 = \frac{1}{\underline{g}_1}\left[\bar{\lambda}_1, \frac{L_1}{c} + \underline{g}_1 G_1^2, \underline{g}_1 H_1\right]^{\mathrm{T}}, \tag{22}$$

$$\xi_1(t) = \left[\check{x}_1, \mu\omega_1, \mu^{L_2} z_1 \psi_1(\cdot)\right]^{\mathrm{T}}, \tag{23}$$

and define $\vartheta_1 = \|\Theta_1\|$, then it can be shown that

$$\begin{aligned}&\frac{\lambda_1(t)}{\underline{g}_1} z_1^2 + \left(\frac{L_1}{\underline{g}_1 c} + G_1^2\right)\mu z_1^2 + H_1 \mu^{\tau_1} z_1^2 \psi_1(\cdot)\\ &\le \vartheta_1 \mu^{L_1} |z_1| \, \|\xi_1(t)\|\\ &\le \vartheta_1 \mu^{\tau_1} z_1^2 \xi_1^{\mathrm{T}}(t)\xi_1(t) + \mu\frac{1}{4}\vartheta_1. \end{aligned}\tag{24}$$

Substituting (20), (21) and (24) into (19) yields

$$\begin{aligned}\dot{V}_{z_1} \le{}& \vartheta_1 \mu^{\tau_1} z_1^2 \xi_1^{\mathrm{T}}(t)\xi_1(t) + \frac{g_1(t)}{\underline{g}_1}\mu^{L_1} z_1 \alpha_1\\ &+ \mu\frac{1}{4}z_2^2 + \mu\frac{1}{4}(\vartheta_1 + H_1). \end{aligned}\tag{25}$$

For $0 \le t < T$, the virtual control input α_1 is designed as

$$\alpha_1 = -k_1 \mu \check{x}_1 - \hat{\vartheta}_1 \mu^{L_2} z_1 \xi_1^{\mathrm{T}}(t)\xi_1(t), \tag{26}$$

where k_1 is a positive design constant; $\hat{\vartheta}_1$ is updated according to

$$\dot{\hat{\vartheta}}_1 = \gamma_1 \mu^{\tau_1} z_1^2 \xi_1^{\mathrm{T}}(t)\xi_1(t) - \eta_1 \mu \hat{\vartheta}_1, \tag{27}$$

where γ_1 and η_1 are positive design constants. $\hat{\vartheta}_1(0)$ is chosen to be nonnegative. Note that by doing so, $\hat{\vartheta}_1(t)$ is rendered nonnegative for all $t \ge 0$.

Next, the following augmented Lyapunov function candidate is considered

$$V_1 = \frac{1}{2\underline{g}_1} z_1^2 + \frac{1}{2\gamma_1}\tilde{\vartheta}_1^2. \tag{28}$$

Taking the time derivative of V_1, substituting (25)–(27), and considering the following facts

$$\frac{\eta_1}{\gamma_1}\mu\tilde{\vartheta}_1\hat{\vartheta}_1 \le \frac{\eta_1}{2\gamma_1}\mu\vartheta_1^2 - \frac{\eta_1}{2\gamma_1}\mu\tilde{\vartheta}_1^2, \tag{29}$$

$$\frac{g_1(t)}{\underline{g}_1}\mu^{L_1} z_1 \alpha_1 \le \mu^{L_1} z_1 \alpha_1, \tag{30}$$

where the first inequality follows from completing the square, and the second from the condition $g_1(t)/\underline{g}_1 \ge 1$, the derivative of V_1 satisfies

$$\begin{aligned}\dot{V}_1 &\le -k_1 \mu z_1^2 - \frac{\eta_1}{2\gamma_1}\mu\tilde{\vartheta}_1^2 + \frac{\eta_1}{2\gamma_1}\mu\vartheta_1^2 + \frac{\mu}{4}(\vartheta_1 + H_1) + \frac{\mu}{4}z_2^2\\ &\le -C_1 \mu V_1 + \mu\Delta_1 + \frac{\mu}{4}z_2^2, \end{aligned}\tag{31}$$

where $C_1 = \min\left\{2k_1\underline{g}_1, \eta_1\right\}$ and $\Delta_1 = \frac{1}{4}(\vartheta_1 + H_1) + \frac{\eta_1}{2\gamma_1}\vartheta_1^2$ are positive constants.

Step i ($i = 2, \cdots, n-1$): Note that α_{i-1} is a smooth function of $(\check{x}_1, \cdots, \check{x}_{i-1}, \mu, \hat{\vartheta}_1, \cdots, \hat{\vartheta}_{i-1})$. In view of (4), (14) and (15), the dynamics of z_i can be expressed as

$$\begin{aligned}\dot{z}_i ={}& \frac{L_i}{c}\mu z_i + \lambda_i(t)\mu^{L_i}\check{x}_i + \rho_i(t)\mu^{L_i}\varphi_i\\ &+ g_i(t)\mu z_{i+1} + g_i(t)\mu^{L_i}\alpha_i - \mu^{L_i}\mathcal{F}_{\alpha_{i-1}}(\cdot)\\ &- \mu^{L_i}\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\check{x}_j}\Big(\lambda_j(t)\check{x}_j + g_j(t)\check{x}_{j+1}\Big)\\ &- \mu^{L_i}\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\check{x}_j}\rho_j(t)\varphi_j, \end{aligned}\tag{32}$$

where $\mathcal{F}_{\alpha_{i-1}}(\cdot) = \sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\hat{\vartheta}_{i-1}}\dot{\hat{\vartheta}}_{i-1} + \frac{\partial\alpha_{i-1}}{\partial\mu}\dot{\mu}$ is computable and available for controller construction.

Define the ith positive definite and radially unbounded function $V_{z_i} = \frac{1}{2\underline{g}_i}z_i^2$. Differentiating with respect to time and employing (32), the derivative of V_{z_i} satisfies

$$\begin{aligned}\dot{V}_{z_i} ={}& \frac{1}{\underline{g}_i}\Bigg[\frac{L_i}{c}\mu z_i^2 + \lambda_i(t)\mu^{L_i} z_i\check{x}_i + \rho_i(t)\mu^{L_i} z_i\varphi_i\\ &+ g_i(t)\mu z_i z_{i+1} + g_i(t)\mu^{L_i} z_i\alpha_i - \mu^{L_i} z_i\mathcal{F}_{\alpha_{i-1}}(\cdot)\\ &- \mu^{L_i} z_i\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\check{x}_j}\Big(\lambda_j(t)\check{x}_j + g_j(t)\check{x}_{j+1}\Big)\\ &- \mu^{L_i} z_i\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\check{x}_j}\rho_j(t)\varphi_j\Bigg]. \end{aligned}\tag{33}$$

From Lemma 2, Young's inequality and the definitions of G_i, H_i in (16), one can show that

$$\frac{g_i(t)}{\underline{g}_i}\mu z_i z_{i+1} \le G_i^2 \mu z_i^2 + \mu\frac{1}{4}z_{i+1}^2, \tag{34}$$

$$\frac{\rho_i(t)}{\underline{g}_i}\mu^{L_i} z_i\varphi_i \le H_i \mu^{\tau_i} z_i^2 \psi_i(\cdot) + \mu\frac{i}{4}H_i, \tag{35}$$

$$-\frac{\mu^{L_i} z_i}{\underline{g}_i}\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\check{x}_j}\rho_j(t)\varphi_j \le Q_i \mu^{\tau_i} z_i^2 \chi_i(\cdot) + \mu\frac{l_i}{4}Q_i, \tag{36}$$

where $\psi_i(\cdot) = \phi_i^2\sum_{j=1}^{i}\check{x}_j^2$, $Q_i = \max\left\{q_{i,1}, \cdots, q_{i,i-1}\right\}$ with $q_{i,j} := \frac{\varpi_j}{\underline{g}_i}\sup_{0 \le t < T}|\rho_j(t)|, j = 1, \cdots, i-1$ and $\chi_i(\cdot) = \sum_{k=1}^{i-1}(\frac{\partial\alpha_{i-1}}{\partial\check{x}_k})^2\phi_k^2\sum_{j=1}^{k}\check{x}_j^2$.

To address the bounded time-varying uncertainties, define $\vartheta_i = \|\Theta_i\|$ with

$$\Theta_i = \left[\Theta_{i,1}^{\mathrm{T}}, \Theta_{i,2}^{\mathrm{T}}, \Theta_{i,3}^{\mathrm{T}}\right]^{\mathrm{T}}, \tag{37}$$

where

$$\Theta_{i,1} = \frac{1}{\underline{g}_i}\left[1, \bar{\lambda}_i, \frac{L_i}{c} + \underline{g}_i G_i^2, \underline{g}_i H_i, \underline{g}_i Q_i\right]^{\mathrm{T}},$$

$$\Theta_{i,2} = \frac{1}{\underline{g}_i}\left[\bar{\lambda}_1, \cdots, \bar{\lambda}_{i-1}\right]^{\mathrm{T}},$$

$$\Theta_{i,3} = \frac{1}{\underline{g}_i}\left[\bar{g}_1, \cdots, \bar{g}_{i-1}\right]^{\mathrm{T}}.$$

Moreover, let

$$\xi_i(t) = \left[\xi_{i,1}^{\mathrm{T}}(t), \xi_{i,2}^{\mathrm{T}}(t), \xi_{i,3}^{\mathrm{T}}(t)\right]^{\mathrm{T}}, \tag{38}$$

where

$$\xi_{i,1}(t) = \left[\mathcal{F}_{\alpha_{i-1}}(\cdot), \check{x}_i, \mu\omega_i, \mu^{\tau_i}\omega_i\psi_i(\cdot), \mu^{\tau_i}\omega_i\chi_i(\cdot)\right]^{\mathrm{T}},$$
$$\xi_{i,2}(t) = \left[\frac{\partial\alpha_{i-1}}{\partial\check{x}_1}\check{x}_1, \cdots, \frac{\partial\alpha_{i-1}}{\partial\check{x}_{i-1}}\check{x}_{i-1}\right]^{\mathrm{T}},$$
$$\xi_{i,3}(t) = \left[\frac{\partial\alpha_{i-1}}{\partial\check{x}_1}\check{x}_2, \cdots, \frac{\partial\alpha_{i-1}}{\partial\check{x}_{i-1}}\check{x}_i\right]^{\mathrm{T}},$$

then it can be verified that

$$\begin{aligned}
&\frac{\mu^{L_i}z_i}{\underline{g}_i}\Bigg(\lambda_i(t)\check{x}_i + \underline{g}_i G_i^2\mu\omega_i - \mathcal{F}_{\alpha_{i-1}}(\cdot) \\
&\quad + \underline{g}_i H_i\mu^{\tau_i}\omega_i\psi_i(\cdot) + \underline{g}_i Q_i\mu^{\tau_i}\omega_i\chi_i(\cdot) \\
&\quad + \frac{L_i}{c}\mu\omega_i - \sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\check{x}_j}\left(\lambda_j(t)\check{x}_j + g_j(t)\check{x}_{j+1}\right)\Bigg) \\
&\le \vartheta_i\mu^{L_i}|z_i|\,\|\xi_i(t)\| \\
&\le \vartheta_i\mu^{\tau_i}z_i^2\xi_i^{\mathrm{T}}(t)\xi_i(t) + \mu\frac{1}{4}\vartheta_i.
\end{aligned} \tag{39}$$

Substituting (34)-(36) and (39) into (33), $\dot{V}_{z_i}$ satisfies

$$\begin{aligned}
\dot{V}_{z_i} &\le \vartheta_i\mu^{\tau_i}z_i^2\xi_i^{\mathrm{T}}(t)\xi_i(t) + \frac{g_i(t)}{\underline{g}_i}\mu^{L_i}z_i\alpha_i \\
&\quad + \mu\frac{1}{4}z_{i+1}^2 + \mu\frac{1}{4}(iH_i + l_iQ_i + \vartheta_i).
\end{aligned} \tag{40}$$

For $0 \le t < T$, the virtual control input α_i and the update law for $\hat{\vartheta}_i$ are designed as

$$\alpha_i = -(k_i + \frac{1}{4})\mu\omega_i - \hat{\vartheta}_i\mu^{L_{i+1}}z_i\xi_i^{\mathrm{T}}(t)\xi_i(t), \tag{41}$$
$$\dot{\hat{\vartheta}}_i = \gamma_i\mu^{\tau_i}z_i^2\xi_i^{\mathrm{T}}(t)\xi_i(t) - \eta_i\mu\hat{\vartheta}_i, \quad \hat{\vartheta}_i(0) \ge 0, \tag{42}$$

where k_i, γ_i and η_i are positive design constants. $\hat{\vartheta}_i(0)$ is chosen to be nonnegative. Note that by doing so, $\hat{\vartheta}_i(t)$ is rendered nonnegative for all $t \ge 0$.

To continue, the augmented Lyapunov function candidate is constructed as

$$V_i = \frac{1}{2\underline{g}_i}z_i^2 + \frac{1}{2\gamma_i}\tilde{\vartheta}_i^2. \tag{43}$$

Similar to (29) and (30), it can be shown that

$$\frac{\eta_i}{\gamma_i}\mu\tilde{\vartheta}_i\hat{\vartheta}_i \le \frac{\eta_i}{2\gamma_i}\mu\vartheta_i^2 - \frac{\eta_i}{2\gamma_i}\mu\tilde{\vartheta}_i^2, \tag{44}$$
$$\frac{g_i(t)}{\underline{g}_i}\mu^{L_i}z_i\alpha_i \le \mu^{L_i}z_i\alpha_i. \tag{45}$$

Then, upon using (44) and (45), $\dot{V}_i$ finally becomes

$$\begin{aligned}
\dot{V}_i &\le -k_i\mu z_i^2 - \frac{\eta_i}{2\gamma_i}\mu\tilde{\vartheta}_i^2 + \frac{\eta_i}{2\gamma_i}\mu\vartheta_i^2 + \frac{\mu}{4}z_{i+1}^2 - \frac{\mu}{4}z_i^2 \\
&\quad + \frac{\mu}{4}(iH_i + l_iQ_i + \vartheta_i)
\end{aligned}$$

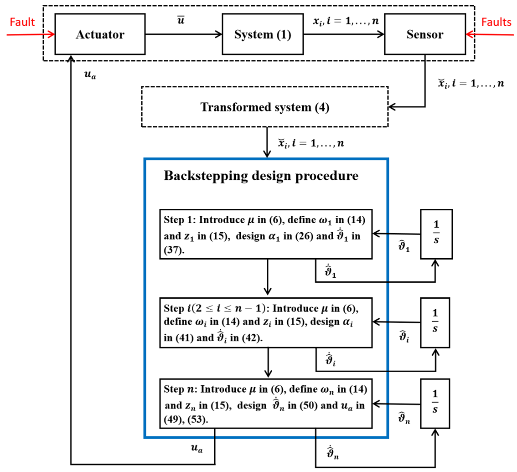

FIGURE 1. **Block diagram of the proposed scheme.**

$$\le -C_i\mu V_i + \mu\Delta_i + \frac{\mu}{4}z_{i+1}^2 - \frac{\mu}{4}z_i^2, \tag{46}$$

where $C_i = \min\left\{2k_i\underline{g}_i, \eta_i\right\}$ and $\Delta_i = \frac{1}{4}(iH_i + l_iQ_i + \vartheta_i) + \frac{\eta_i}{2\gamma_i}\vartheta_i^2$ are positive constants.

Step n: Following the same line as in Step i, the derivative of z_n is

$$\begin{aligned}
\dot{z}_n &= \frac{L_n}{c}\mu z_n + \lambda_n(t)\mu^{L_n}\check{x}_n + \rho_n(t)\mu^{L_n}\varphi_n \\
&\quad + g_n(t)\mu^{L_n}u_a - \mu^{L_n}\mathcal{F}_{\alpha_{n-1}}(\cdot) \\
&\quad - \mu^{L_n}\sum_{j=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial\check{x}_j}\left(\lambda_j(t)\check{x}_j + g_j(t)\check{x}_{j+1}\right) \\
&\quad - \mu^{L_n}\sum_{j=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial\check{x}_j}\rho_j(t)\varphi_j,
\end{aligned} \tag{47}$$

where $\mathcal{F}_{\alpha_{n-1}}(\cdot) = \sum_{j=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial\hat{\vartheta}_{n-1}}\dot{\hat{\vartheta}}_{n-1} + \frac{\partial\alpha_{n-1}}{\partial\mu}\dot{\mu}$ is a computable function.

Using the similar definitions of Θ_i and $\xi_i(t)$ in (37) and (38) for $i = n$, and define $\vartheta_n = \|\Theta_n\|$, then

$$\begin{aligned}
\mu^{L_n}z_n\Theta_n^{\mathrm{T}}\xi_n(t) &\le \vartheta_n\mu^{L_n}|z_n|\,\|\xi_n(t)\| \\
&\le \vartheta_n\mu^{\tau_n}z_n^2\xi_n^{\mathrm{T}}(t)\xi_n(t) + \mu\frac{1}{4}\vartheta_n.
\end{aligned} \tag{48}$$

For $0 \le t < T$, the actual control input u_a and the parameter updating law are designed as

$$u_a = -(k_n + \frac{1}{4})\mu\omega_n - \hat{\vartheta}_n\mu^{L_{n+1}}z_n\xi_n^{\mathrm{T}}(t)\xi_n(t), \tag{49}$$
$$\dot{\hat{\vartheta}}_n = \gamma_n\mu^{\tau_n}z_n^2\xi_n^{\mathrm{T}}(t)\xi_n(t) - \eta_n\mu\hat{\vartheta}_n, \quad \hat{\vartheta}_n(0) \ge 0, \tag{50}$$

where k_n, γ_n and η_n are positive design constants.

Choose the nth Lyapunov function as

$$V_n = \frac{1}{2\underline{g}_n}z_n^2 + \frac{1}{2\gamma_n}\tilde{\vartheta}_n^2. \tag{51}$$

Upon using (47)–(51), it can be derived that

$$\begin{aligned}\dot{V}_n \leq& -k_n\mu z_n^2 - \frac{\eta_n}{2\gamma_n}\mu\tilde{\vartheta}_n^2 + \frac{\eta_n}{2\gamma_n}\mu\vartheta_n^2 - \frac{\mu}{4}z_n^2 \\ &+ \frac{\mu}{4}(nH_n + l_nQ_n + \vartheta_n) \\ \leq& -C_n\mu V_n + \mu\Delta_n - \frac{\mu}{4}z_n^2, \end{aligned} \tag{52}$$

where $C_n = \min\left\{2k_n\underline{g}_n, \eta_n\right\}$ and $\Delta_n = \frac{1}{4}(nH_n + l_nQ_n + \vartheta_n) + \frac{\eta_n}{2\gamma_n}\vartheta_n^2$ are positive constants.

For $t \geq T$, the actual control input u_a is designed as

$$u_a = 0. \tag{53}$$

For clarity, the block diagram of the proposed scheme is shown in Fig. 1.

IV. STABILITY ANALYSIS

Theorem 1: Consider the closed-loop system consisting of the plant (1) with possible sensor faults (2) and actuator fault (3), and the adaptive controller (49)–(50) and (53), together with the virtual adaptive control laws (26)–(27) and (41)–(42). If Assumptions 1-3 are satisfied, then the following statements hold:
(i) the system states $x_i(t), i = 1, 2, \cdots, n$ can converge to zero within the prescribed time T;
(ii) the control command $u_a(t)$ is continuous and bounded on $[0, +\infty)$;
(iii) all signals of the closed-loop system are bounded.

(i) Define the total Lyapunov candidate function as

$$V = \sum_{i=1}^{n} V_i, \tag{54}$$

where V_1, V_i $(i = 2, \cdots, n-1)$ and V_n are given by (28), (43) and (51), respectively. It is straightforward from (31), (46) and (52) that

$$\dot{V} \leq -C\mu V + \mu\Delta, \tag{55}$$

where $C = \min\{C_1, \cdots, C_n\}$ and $\Delta = \sum_{i=1}^{n}\Delta_i$ are positive constants.

According to Lemma 1, it is known that $V(t)$ is bounded for $0 \leq t < T$. Thus, z_i, $\tilde{\vartheta}_i$ and hence $\hat{\vartheta}_i$ are all bounded on $[0, T)$. Define

$$c_{z_i} = \sup_{0\leq t<T} |z_i(t)|, \quad c_{\vartheta_i} = \sup_{0\leq t<T} |\hat{\vartheta}_i(t)|. \tag{56}$$

From (15) and (56), one obtains that $|\omega_i| \leq c_{z_i}\nu^{L_i}$. Since $\check{x}_1 = \omega_1$, it holds that

$$|\check{x}_1| = |\omega_1| \leq c_{\check{x}_1}\nu^{L_1}, \tag{57}$$

where $c_{\check{x}_1} = c_{z_1}$. Owing to the smoothness of $\phi_1(\check{x}_1)$, there exists a constant c_1 such that $|\phi_1(\check{x}_1)| \leq c_1$. Moreover, $\phi_1(\check{x}_1)$ satisfies the local Lipschitz condition that $\left\|\frac{\partial\phi_1(\check{x}_1)}{\partial\check{x}_1}\right\| \leq c_{\phi_1}$ with a positive constant c_{ϕ_1}.

Then, from the definition of ξ_1, it is obtained that

$$\begin{aligned}|\xi_1^{\mathrm{T}}(t)\xi_1(t)| &= \check{x}_1^2 + \mu^2\omega_1^2 + \mu^{2L_2}z_1^2\phi_1^4\check{x}_1^4 \\ &\leq c_{\check{x}_1}^2\nu^{2L_1} + c_{z_1}^2\nu^{2L_2} + c_{\check{x}_1}^6c_1^4\nu^{2L_1+2} \\ &\leq d_1\nu^{2L_2}, \quad \forall t \in [0, T), \end{aligned} \tag{58}$$

where $d_1 = c_{\check{x}_1}^2(\frac{T}{c})^2 + c_{z_1}^2 + c_{\check{x}_1}^6c_1^4(\frac{T}{c})^4$ is a positive constant.

Based on (56), (57) and (58), it can be easily verified that, for all $t \in [0, T)$,

$$\begin{aligned}|\alpha_1| &= |-k_1\mu\check{x}_1 - \hat{\vartheta}_1\mu^{L_2}z_1\xi_1^{\mathrm{T}}(t)\xi_1(t)| \\ &\leq k_1a_1\nu^{L_2} + c_{\vartheta_1}c_{z_1}d_1\nu^{L_2} \\ &= c_{\alpha_1}\nu^{L_2}, \end{aligned} \tag{59}$$

$$\begin{aligned}|\dot{\hat{\vartheta}}_1| &= |\gamma_1\mu^{\tau_1}z_1^2\xi_1^{\mathrm{T}}(t)\xi_1(t) - \eta_1\mu\hat{\vartheta}_1| \\ &\leq \gamma_1c_{z_1}^2b_1\mu + \eta_1c_{\vartheta_1}\mu \\ &= \kappa_1\mu, \end{aligned} \tag{60}$$

where $c_{\alpha_1} = k_1c_{\check{x}_1} + c_{\vartheta_1}c_{z_1}d_1$ and $\kappa_1 = \gamma_1c_{z_1}^2d_1 + \eta_1c_{\vartheta_1}$.

Since $\omega_2 = \check{x}_2 - \alpha_1$, one has

$$|\check{x}_2| = |\omega_2 + \alpha_1| \leq c_{z_2}\nu^{L_2} + c_{\alpha_1}\nu^{L_2} = c_{\check{x}_2}\nu^{L_2}, \tag{61}$$

where $c_{\check{x}_2} = c_{z_2} + c_{\alpha_1}$.

According to (26), one has

$$\begin{aligned}\left|\frac{\partial\alpha_1}{\partial\check{x}_1}\right| =& \Big|-3\hat{\vartheta}_1\mu^{L_1+L_2}\check{x}_1^2 - 3\hat{\vartheta}_1\mu^{1+2L_1}\check{x}_1^2 - k_1\mu \\ &-4\hat{\vartheta}_1\mu^{3L_1+3L_2}\phi_1^3\frac{\partial\phi_1}{\partial\check{x}_1}\check{x}_1^7 - 7\hat{\vartheta}_1\mu^{3L_1+3L_2}\check{x}_1^6\Big| \\ \leq& 3c_{\vartheta_1}c_{\check{x}_1}^2\nu + 3c_{\vartheta_1}c_{\check{x}_1}^2\mu + 4c_{\vartheta_1}c_{\check{x}_1}^7c_1^3c_{\phi_1}\nu^3 \\ &+ k_1\mu + 7c_{\vartheta_1}c_{\check{x}_1}^6\nu^3 \\ \leq& p_1\mu, \end{aligned} \tag{62}$$

$$\begin{aligned}\left|\frac{\partial\alpha_1}{\partial\hat{\vartheta}_1}\right| =& \Big|-\mu^{L_1+L_2}\check{x}_1(\check{x}_1^2 + \mu^2\check{x}_1^2 + \mu^{2L_1+2L_2}\phi_1^4\check{x}_1^6)\Big| \\ \leq& c_{\check{x}_1}^3\nu^{1+L_1} + c_{\check{x}_1}^3\nu^{L_2} + c_{\check{x}_1}^7c_1^4\nu^{3+L_1} \\ \leq& p_2\nu^{L_2}, \end{aligned} \tag{63}$$

$$\begin{aligned}\left|\frac{\partial\alpha_1}{\partial\mu}\right| =& \Big|-(L_1+L_2)\hat{\vartheta}_1\mu^{2L_2}\check{x}_1^3 - (1+2L_1)\hat{\vartheta}_1\mu^{2L_1}\check{x}_1^3 \\ &-(3L_1+3L_2)\hat{\vartheta}_1\mu^{2L_1+4L_2}\phi_1^4\check{x}_1^7 - k_1\check{x}_1\Big| \\ \leq& (L_1+L_2)c_{\vartheta_1}c_{\check{x}_1}^3\nu^{1+L_1} + (1+2L_1)c_{\vartheta_1}c_{\check{x}_1}^3\nu^{L_1} \\ &+ (3L_1+3L_2)c_{\vartheta_1}c_{\check{x}_1}^7c_1^4\nu^{4+L_1} + k_1c_{\check{x}_1}\nu^{L_1} \\ \leq& p_3\nu^{L_1}, \end{aligned} \tag{64}$$

where p_1, p_2 and p_3 are positive constants. Upon using these bounds, the quantities $\mathcal{F}_{\alpha_1}(\cdot)$, $\psi_2(\cdot)$ and $\chi_2(\cdot)$ in (32), (35) and (36) can be bounded as

$$\begin{aligned}|\mathcal{F}_{\alpha_1}(\cdot)| =& \left|\frac{\partial\alpha_1}{\partial\hat{\vartheta}_1}\dot{\hat{\vartheta}}_1 + \frac{\partial\alpha_1}{\partial\mu}\dot{\mu}\right| \\ \leq& p_2\kappa_1\nu^{L_3} + \frac{p_3}{c}\nu^{L_3} \leq p_4\nu^{L_3}, \end{aligned} \tag{65}$$

$$|\psi_2(\cdot)| = |\phi_2^2(\check{x}_1^2 + \check{x}_2^2)|$$

$$\leq c_2^2 c_{\check{x}_1}^2 v^{2L_1} + c_2^2 c_{\check{x}_2}^2 v^{2L_2} \leq p_5 v^{2L_2}, \tag{66}$$

$$|\chi_2(\cdot)| = \left| \left(\frac{\partial \alpha_1}{\partial \check{x}_1} \right)^2 \phi_2^2 \check{x}_1^2 \right| \leq p_6 v^{2L_2}, \tag{67}$$

where p_4, p_5 and p_6 are positive constants.

Recalling the definition of ξ_2 and combining (65)-(67), the following inequality holds:

$$\begin{aligned} |\xi_2^{\mathrm{T}}(t)\xi_2(t)| &= \check{x}_2^2 + \left(\frac{\partial \alpha_1}{\partial \check{x}_1}\right)^2 \check{x}_1^2 + \left(\frac{\partial \alpha_1}{\partial \check{x}_1}\right)^2 \check{x}_2^2 + \mu^2 \omega_2^2 \\ &\quad + \mathcal{F}_{\alpha_1}^2(\cdot) + \mu^{2\tau_2}\omega_2^2\psi_2^2(\cdot) + \mu^{2\tau_2}\omega_2^2\chi_2^2(\cdot) \\ &\leq c_{\check{x}_2}^2 v^{2L_2} + p_1^2 c_{\check{x}_1}^2 v^{2L_2} + p_1^2 c_{\check{x}_2}^2 v^{2L_3} + c_{z_2}^2 v^{2L_3} \\ &\quad + p_4^2 v^{2L_3} + c_{z_2}^2 p_5^2 v^{2L_1} + c_{z_2}^2 p_6^2 v^{2L_1} \\ &\leq d_2 v^{2L_3}, \end{aligned} \tag{68}$$

where d_2 is a positive constant. Therefore,

$$\begin{aligned} |\alpha_2| &= | -(k_2 + \frac{1}{4})\mu\omega_2 - \hat{\vartheta}_2 \mu^{L_3} z_2 \xi_2^{\mathrm{T}}(t)\xi_2(t)| \\ &\leq (k_2 + \frac{1}{4}) c_{z_2} v^{L_3} + c_{\vartheta_2} c_{z_2} d_2 v^{L_3} \\ &= c_{\alpha_2} v^{L_3}, \end{aligned} \tag{69}$$

where $c_{\alpha_2} = (k_2 + \frac{1}{4})c_{z_2} + c_{\vartheta_2} c_{z_2} d_2$. From $\omega_3 = \check{x}_3 - \alpha_2$, one has

$$|\check{x}_3| = |\omega_3 + \alpha_2| \leq c_{z_3} v^{L_3} + c_{\alpha_2} v^{L_3} = a_3 v^{L_3}, \tag{70}$$

where $a_3 = c_{z_3} + c_{\alpha_2}$.

Following a similar approach as the above, it can be shown that for $t \in [0, T)$, $|\alpha_i(t)| \leq c_{\alpha_i} v^{L_{i+1}} (i = 3, \cdots, n-1)$, $|\check{x}_i(t)| \leq c_{\check{x}_i} v^{L_i} (i = 4, \cdots, n)$ and $|u_a(t)| \leq c_{u_a} v^{L_{n+1}}$ with c_{α_j}, $c_{\check{x}_i}$ and c_{u_a} being positive constants. According to Assumption 2, $|x_i(t)| = |\sigma_{s_i}^{-1}(t)\check{x}_i(t)| \leq c_{x_i} v^{L_i}$ with $c_{x_i} = \underline{\sigma}_{s_i}^{-1} c_{\check{x}_i}$. This, together with the property that $\lim_{t\to T} v(t) = 0$, implies that $x_i(T) = \lim_{t\to T^-} x_i(t) = 0$.

When $t \in [T, +\infty)$, $u_a = 0$. The dynamics of system (1) can be represented as

$$\dot{x} = A(x)x, \tag{71}$$

where

$$A(x) = \begin{bmatrix} A_{11} & b_1(t) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A_{(n-1)1} & A_{(n-1)2} & \cdots & b_{n-1}(t) \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{bmatrix},$$

in which $A_{ij} = \theta_i(t)\varphi_{ij}(\bar{x}_i)$, $i = 1, \cdots, n$, $j = 1, \cdots, i$.

Solving (71) gives

$$x(t) = e^{\int_T^t A(x(s))ds} x(T) = 0, \quad t \geq T, \tag{72}$$

which implies that $x_i(t) \equiv 0$ for $t \in [T, +\infty)$. Therefore, it can be concluded that the system states $x_i(t)$, $i = 1, 2, \cdots, n$ can converge to zero within the prescribed-time T.

(ii) From (i), it is known that $|u_a(t)| \leq c_{u_a} v^{L_{n+1}}$ for $t \in [0, T)$. Since $\lim_{t\to T} v(t) = 0$, one can get that $\lim_{t\to T^-} u_a(t) = 0$. When $t \geq T$, $u_a = 0$. Therefore,

$$\lim_{t\to T^-} u_a(t) = 0 = u_a(T) = \lim_{t\to T^+} u_a(t). \tag{73}$$

This shows that $u_a(t)$ is continuous and bounded on $[0, +\infty)$.

(iii) From (i), it is known that $\check{x}_i$, α_i and x_i satisfy $|\check{x}_i| \leq c_{\check{x}_i} v^{L_i}$, $|\alpha_i| \leq c_{\alpha_i} v^{L_{i+1}}$, $|x_i(t)| \leq c_{x_i} v^{L_i}$, $\forall t \in [0, T)$. Then, with the boundedness of v, it can be deduced that $\check{x}_i$, α_i and x_i are bounded on $[0, T)$. Moreover, $x_i(t)$, $i = 1, 2, \cdots, n$ can converge to zero within the prescribed-time T and remain at zero for $[T, +\infty)$. Thus, $x_i(t)$, $i = 1, 2, \cdots, n$ are bounded on $[0, +\infty)$. Furthermore, since $|u_a| \leq c_{u_a} v^{L_{n+1}}$ on $[0, T)$ and $u_a(t) = 0$ on $[T, +\infty)$, the control command $u_a(t)$ remains bounded on $[0, +\infty)$. Hence, all closed-loop signals are bounded. This completes the proof. □

Remark 3: As observed from (28), (43), and (51), the lower bounds of the virtual control coefficients are incorporated into the Lyapunov synthesis to facilitate the design of an effective adaptive controller.

Remark 4: This work differs from existing related studies in: 1) Unlike previous papers on prescribed-time control of uncertain strict-feedback systems, such as [21], [22], [23], [24], [25], [26], and [27], the system under consideration involves completely unknown time-varying virtual control coefficients and time-varying multiplicative faults in both the sensors and actuators. Moreover, the bounds of these time-varying coefficients and faults are not required to be known; 2) In contrast to existing finite-time or fixed-time fault-tolerant control schemes presented in [29], [30], [31], [32], and [33], the proposed approach ensures that the system states reach zero within a user-defined finite time, which can be specified in advance regardless of the initial conditions or control parameters. An intuitive comparison between related works and the present work is provided in Table 1.

TABLE 1. Comparison between related works and the present work.

Refs.	Control Design Technique	Sensor Faults Addressed	Actuator Faults Addressed	Convergence Time Can Be Preset
[1]-[3], [29]-[31], [33]	FT	×	✓	×
[4], [6], [7]	FixT	×	×	×
[8]	FixT	×	✓	×
[32]	FixT	✓	✓	×
[11]-[27]	PT	×	×	✓
Our work	PT	✓	✓	✓

Remark 5: Like other nonlinear adaptive control methods, the proposed approach involves multiple design parameters that should be properly chosen to ensure satisfactory control performance. Based on the preceding control design, the following guidelines are given.

- The convergence time T should be predetermined based on practical needs and system capabilities;

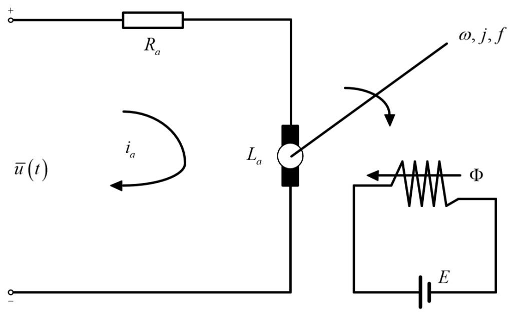

FIGURE 2. Structure of armature-controlled dc motor.

- The parameters γ_i, η_i and k_i ($i = 1, \ldots, n$) should be selected to be positive constants, ensuring the theoretical guarantees of the control scheme;
- The adaptive gains γ_i should be sufficiently large to enable adequate parameter adaptation speed, but not excessively large to avoid undue sensitivity to noise, while η_i should be selected as a small constant to prevent parameter drift;
- The control gains k_i need to balance the convergence rate and the control effort, avoiding overly aggressive control actions that may cause actuator saturation or excite unmodeled dynamics.

Therefore, a trade-off exists between the control system performance and practical realizability. In practice, these parameters should be carefully tuned through simulation or trial-and-error based on the specific system.

V. SIMULATION RESULTS

A. AN ILLUSTRATIVE EXAMPLE

To illustrate the effectiveness of our proposed method, the armature-controlled dc motor system shown in Fig. 2 is considered, whose dynamics are given by

$$\begin{cases} R_a i_a + L_a \dot{i}_a + C_e \omega & = \bar{u}, \\ J\dot{\omega} + f\omega - C_m i_a & = 0, \end{cases} \tag{74}$$

where ω and i_a are the angular speed and the armature current, respectively; $\bar{u}$ is the input voltage; R_a, L_a, C_e, C_m, f and J denote the resistance, the inductance, the back electromotive force coefficient, the electromagnetic torque coefficient, the friction coefficient, and the rotational inertia, respectively. In the simulation, these parameters are set as $R_a(t) = (6 + \sin 2t)\ \Omega$, $L_a(t) = (0.1 + 0.02\cos 5t)\ H$, $C_e = 0.132\ \mathrm{V \cdot s/rad}$, $C_m(t) = 0.2 + 0.1\sin t, f = .15\ N \cdot \mathrm{m \cdot s/rad}$, $J = 0.06125\ \mathrm{kg \cdot m^2}$. Moreover, it is assumed that the system suffers from simultaneous multiplicative sensor and atuator faults, where the weights are respectively given by

$$\sigma_{s_1}(t) = \begin{cases} 1, & t \in [0, 0.3), \\ 0.6 + 0.4\sin(t), & t \in [0.3, +\infty), \end{cases} \tag{75}$$

$$\sigma_{s_2}(t) = \begin{cases} 1, & t \in [0, 0.3), \\ 0.8 - 0.2\cos(5t), & t \in [0.3, +\infty), \end{cases} \tag{76}$$

$$\sigma_a(t) = \begin{cases} 1, & t \in [0, 0.5), \\ 0.7 + 0.2\sin(t), & t \in [0.5, +\infty). \end{cases} \tag{77}$$

The objective is to make ω and i_a converge to zero within the prescribed time $T = 1$ s.

Define $x_1 = \omega$, $x_2 = i_a$, $b_1(t) = \frac{C_m(t)}{J}$, $\theta_1 = -\frac{f}{J}$, $b_2(t) = \frac{1}{L_a(t)}$, $\theta_2(t) = \left[-\frac{C_e}{L_a(t)}, -\frac{R_a(t)}{L_a(t)}\right]$, $\varphi(x) = [x_1, x_2]^{\mathrm{T}}$, then the system (74) can be converted into

$$\begin{cases} \dot{x}_1 = b_1(t)x_2 + \theta_1 x_1, \\ \dot{x}_2 = b_2(t)\bar{u} + \theta_2(t)\varphi(x). \end{cases} \tag{78}$$

Following the aforementioned design procedure, the PT adjustment function $\mu(t)$ is chosen as the form of (6) with $T = 1$, $c = 0.4$. The controller parameters are taken as $m = 1$, $\gamma_1 = \gamma_2 = 10$, $k_1 = k_2 = 8$ and $\eta_1 = \eta_2 = 0.5$. The system initial conditions are given by three different values $(x_1(0), x_2(0)) = (2, -1)$, $(x_1(0), x_2(0)) = (-2, 1)$, $(x_1(0), x_2(0)) = (1, -0.5)$, and the initial value of adaptive parameters are chosen as $\hat{\vartheta}_1(0) = \hat{\vartheta}_2(0) = 0$. The simulation results under three different system initial conditions are shown in Fig. 3. It can be seen that the states x_1, $\check{x}_1$, x_2 and $\check{x}_2$ converge to zero as t tends to $T = 1$s. Additionally, the control command u_a and $\bar{u}$ are continuous and bounded.

To further illustrate the convergence time can be arbitrarily prescribed, the values $T = 1$, $T = 1.5$ and $T = 2$ are set for the same initial condition $(x_1(0), x_2(0)) = (1, -0.2)$. The trajectories of x_1, x_2, and u_a are plotted in Fig. 4. From Fig. 4, it is clear that the PT stabilization is also achieved despite the presence of the sensor and actuator faults. These results are consistent with the theoretical results.

B. COMPARATIVE STUDY

In order to further demonstrate the effectiveness of the proposed strategy, a comparative simulation study with the control methods reported in [31] (based on based on the backstepping-based finite-time control technique) and [22] (based on the dynamic surface control (DSC)-based prescribed-time control approach) was conducted. More specifically, following [31], the control algorithm is designed as: $u_a = -z_2\hat{\vartheta}_2\xi^T\xi - k_2 z_2^{2p-1}$, $\alpha_1 = -z_1\hat{\vartheta}_1 - k_1 z_1^{2p-1}$, $\dot{\hat{\vartheta}}_1 = \gamma_1 z_1^2 - \eta_1\hat{\vartheta}_1$ and $\dot{\hat{\vartheta}}_2 = \gamma_2 z_2^2\xi^T\xi - \eta_2\hat{\vartheta}_2$, where $z_1 = \check{x}_1$, $z_2 = \check{x}_2 - \alpha_1$ and $\xi = \left[z_2, \check{x}_1, \check{x}_2, F\check{x}_1, F\check{x}_2, \dot{\hat{\vartheta}}_1\check{x}_1\right]^{\mathrm{T}}$ with $F = -\hat{\vartheta}_1 - k_1(2p-1)\check{x}_1^{2p-2}$. For the method in [22], when $t \in [0, 1)$, the control algorithm is designed as: $u_a = -z_2\mu^{L_3}\hat{\vartheta}_2\xi_2^{\mathrm{T}}\xi_2 - k_2\mu\omega_2, \alpha_1 = -z_1\mu^{L_2}\hat{\vartheta}_1\xi_1^{\mathrm{T}}\xi_1 - k_1\mu\omega_1$, $\dot{\hat{\vartheta}}_1 = \gamma_1 z_1^2\mu^{2L_1-1}\xi_1^{\mathrm{T}}\xi_1 - \eta_1\mu\hat{\vartheta}_1$ and $\dot{\hat{\vartheta}}_2 = \gamma_2 z_2^2\mu^{2L_2-1}\xi_2^{\mathrm{T}}\xi_2 - \eta_2\mu\hat{\vartheta}_2$, where $\omega_1 = x_1$, $\omega_2 = x_2 - \alpha_{2f}$, $\dot{\alpha}_{2f} = \varepsilon_2\mu(-\alpha_{2f} + \alpha_1)$, $z_1 = \mu^{L_1}\omega_1$, $z_2 = \mu^{L_2}\omega_2$, $\xi_1 = \left[\mu z_1^2, z_1^2\right]^{\mathrm{T}}$ and $\xi_2 = \left[\mu z_2^2, \mu^{L_2}x_1 z_2, \mu^{L_2}x_2 z_2, \mu^{L_1}y_2 z_2\right]^{\mathrm{T}}$, and when $t \in [1, 5]$, the control input is set to zero.

In the comparison simulations, the initial conditions are fixed at $(x_1(0), x_2(0)) = (2, -1)$. The control gains in the three controllers take the same values as $\gamma_1 = \gamma_2 = 10$, $k_1 =$

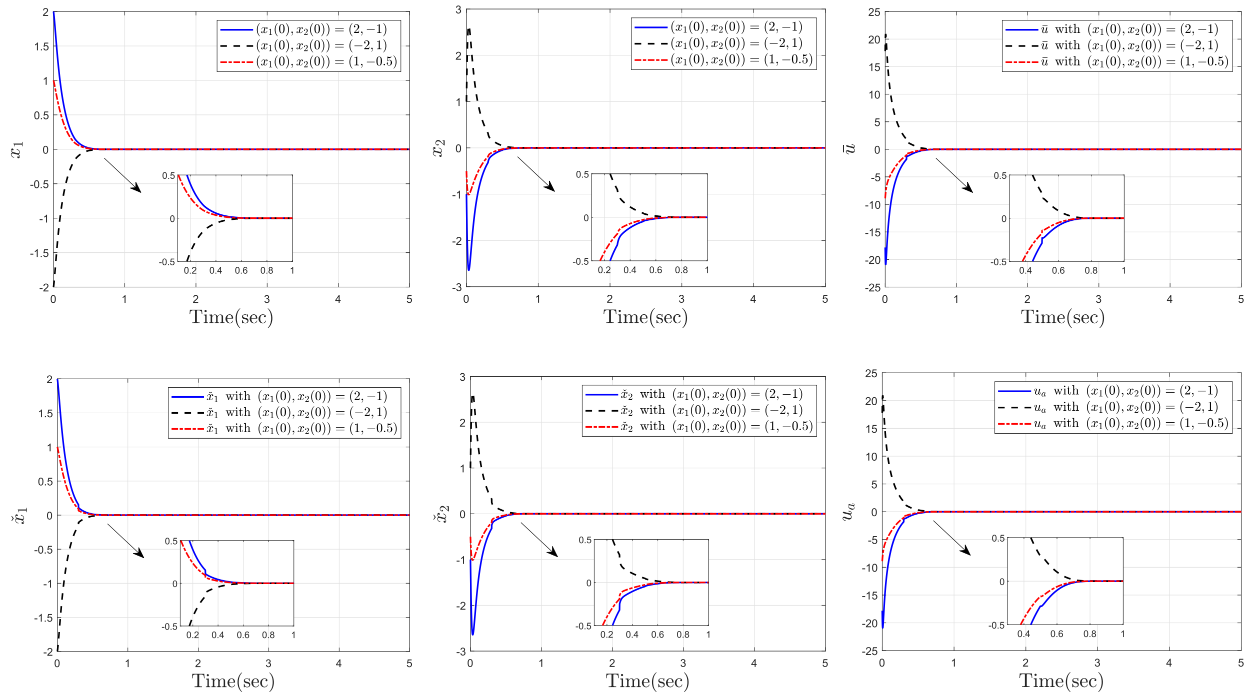

FIGURE 3. Simulation results with different initial conditions.

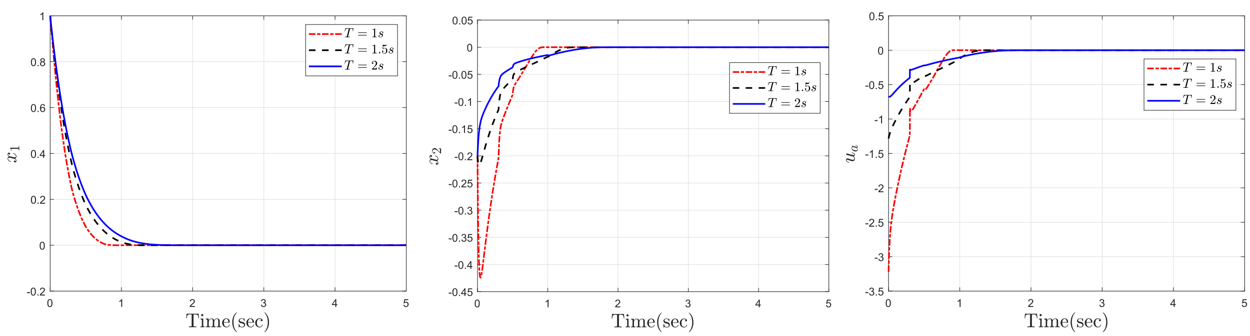

FIGURE 4. Simulation results with different prescribed settling times.

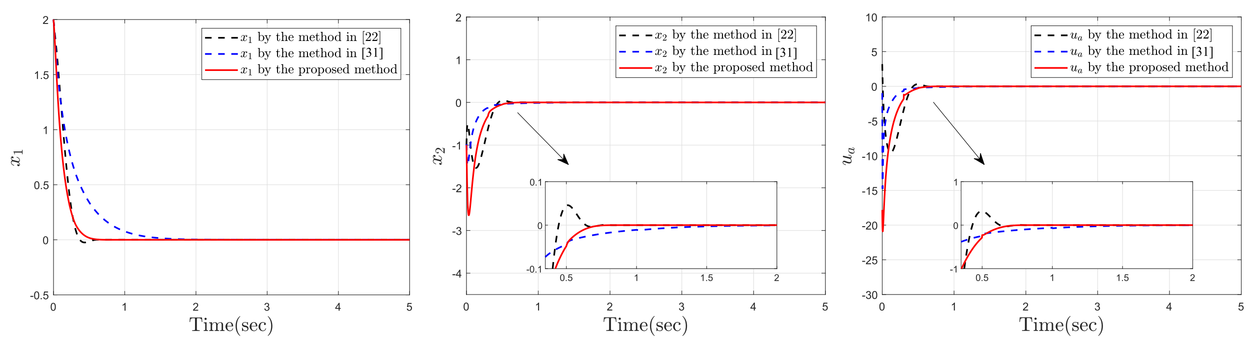

FIGURE 5. Comparison results.

$k_2 = 8$ and $\eta_1 = \eta_2 = 0.5$. Besides, we set $p = 0.99$ and $T = 1$s. The simulation results are presented in Fig. 5, which demonstrate that all these algorithms can achieve satisfactory performance. However, under the algorithm in [22] and the proposed scheme, the convergence time can be arbitrarily preassigned. Moreover, as compared with [22], the proposed algorithm is capable of handling both time-varying sensor and actuator faults.

VI. CONCLUSION

In this paper, an adaptive backstepping-based prescribed-time fault-tolerant control (PT-FTC) scheme has been proposed for a class of uncertain strict-feedback systems with unknown time-varying virtual control coefficients, uncertain time-varying parameters, and unknown time-varying multiplicative sensor and actuator faults. The key attributes of the resulting closed-loop system are as follows: i) both time-varying multiplicative sensor and actuator faults are tolerated; ii) the states can converge to zero within an arbitrarily predefined finite time, regardless of initial conditions and controller parameters, and remain at zero thereafter; and iii) the control input remains continuous and bounded throughout the entire time interval. As a result, PT fault-tolerant stabilization can be achieved over the entire time span. The effectiveness of the proposed control scheme has been verified through simulation studies.

Note that the proposed scheme only focuses on the prescribed-time stabilization problem for a single system with multiplicative sensor and actuator faults, which enables us to achieve our objective successfully. Several important prior studies, such as [2] and [3], have investigated fault-tolerant control for more complex uncrewed aerial vehicles with a wider range of fault types. Extending our method to these areas would significantly enhance its applicability, and we plan to address these challenges in future work. It is also noted that the proposed control scheme does not explicitly account for other practical uncertainties such as time delays, external disturbances, and measurement noise. These factors are frequently encountered in real-world applications, and their inclusion would substantially increase the complexity of prescribed-time control design and analysis. Extending the proposed framework to explicitly handle such general uncertainties remains another important and challenging direction for future research.

REFERENCES

[1] J. Wu, Z. Shen, G. You, J. Su, X. Li, and H. Zhang, "Adaptive fuzzy fast finite-time control of nonlinear pure-feedback systems with actuator faults," *IEEE Access*, vol. 12, pp. 158422–158435, 2024.

[2] Z. Yu, Y. Zhang, B. Jiang, and C.-Y. Su, "Distributed FTCC of multi-UAVs under actuator fault and input saturation," in *Fault-Tolerant Cooperative Control of Unmanned Aerial Vehicles*. Cham, Switzerland: Springer, 2024, pp. 51–76.

[3] Z. Yu, Z. Liu, Y. Zhang, Y. Qu, and C.-Y. Su, "Distributed finite-time fault-tolerant containment control for multiple unmanned aerial vehicles," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 31, no. 6, pp. 2077–2091, Jun. 2020.

[4] J. Ma, S. Fei, S. Xu, and G. Cui, "Adaptive fixed-time control for high-order nonlinear systems with unknown control coefficients and quantized input," *IEEE Trans. Autom. Control*, vol. 69, no. 3, pp. 1928–1935, Mar. 2024.

[5] Y. Liu, H. Li, R. Lu, Z. Zuo, and X. Li, "An overview of finite/fixed-time control and its application in engineering systems," *IEEE/CAA J. Autom. Sinica*, vol. 9, no. 12, pp. 2106–2120, Dec. 2022.

[6] X. Zhang, Y. Zhou, C. Feng, and X. Deng, "Adaptive fixed-time command filtered tracking control for parametric nonlinear systems with unknown nonlinear control coefficient and unknown disturbances," *IEEE Access*, vol. 13, pp. 37839–37849, 2025.

[7] Z. Han, J.-J. Li, X.-L. Yin, Y. Ma, and S. Ren, "Fixed-time event-triggered stabilization of high-order nonlinear systems with asymmetric output constraints," *IEEE Access*, vol. 12, pp. 191252–191263, 2024.

[8] J. Wu, Z. Shen, G. You, J. Su, X. Li, H. Zhang, and C. Zhang, "Adaptive fixed-time performance tracking control for unknown nonlinear pure-feedback systems subject to full-state constraints and actuator faults," *IEEE Access*, vol. 12, pp. 137121–137131, 2024.

[9] Y. Zhang, M. Chadli, and Z. Xiang, "Predefined-time adaptive fuzzy control for a class of nonlinear systems with output hysteresis," *IEEE Trans. Fuzzy Syst.*, vol. 31, no. 8, pp. 2522–2531, Aug. 2023.

[10] Y. Zhang, M. Chadli, and Z. Xiang, "Prescribed-time formation control for a class of multiagent systems via fuzzy reinforcement learning," *IEEE Trans. Fuzzy Syst.*, vol. 31, no. 12, pp. 4195–4204, Dec. 2023.

[11] Y. Song, Y. Wang, J. Holloway, and M. Krstic, "Time-varying feedback for regulation of normal-form nonlinear systems in prescribed finite time," *Automatica*, vol. 83, pp. 243–251, Sep. 2017.

[12] Y. Song, Y. Wang, and M. Krstic, "Time-varying feedback for stabilization in prescribed finite time," *Int. J. Robust Nonlinear Control*, vol. 29, no. 3, pp. 618–633, 2018.

[13] J. Holloway and M. Krstic, "Prescribed-time output feedback for linear systems in controllable canonical form," *Automatica*, vol. 107, pp. 77–85, Sep. 2019.

[14] B. Zhou, "Finite-time stabilization of linear systems by bounded linear time-varying feedback," *Automatica*, vol. 113, Mar. 2020, Art. no. 108760.

[15] B. Zhou, "Finite-time stability analysis and stabilization by bounded linear time-varying feedback," *Automatica*, vol. 121, Nov. 2020, Art. no. 109191.

[16] P. Krishnamurthy, F. Khorrami, and M. Krstic, "A dynamic high-gain design for prescribed-time regulation of nonlinear systems," *Automatica*, vol. 115, May 2020, Art. no. 108860.

[17] P. Krishnamurthy, F. Khorrami, and M. Krstic, "Robust adaptive prescribed-time stabilization via output feedback for uncertain nonlinear strict-feedback-like systems," *Eur. J. Control*, vol. 55, pp. 14–23, Sep. 2020.

[18] H. Ye and Y. Song, "Prescribed-time control of uncertain strict-feedback-like systems," *Int. J. Robust Nonlinear Control*, vol. 31, no. 11, pp. 5281–5297, Nov. 2021.

[19] Y. Orlov, "Time space deformation approach to prescribed-time stabilization: Synergy of time-varying and non-lipschitz feedback designs," *Automatica*, vol. 144, Oct. 2022, Art. no. 110485.

[20] W. Li and M. Krstic, "Stochastic nonlinear prescribed-time stabilization and inverse optimality," *IEEE Trans. Autom. Control*, vol. 67, no. 3, pp. 1179–1193, Mar. 2022.

[21] C. Hua, P. Ning, and K. Li, "Adaptive prescribed-time control for a class of uncertain nonlinear systems," *IEEE Trans. Autom. Control*, vol. 67, no. 11, pp. 6159–6166, Nov. 2022.

[22] G. Zuo and Y. Wang, "Adaptive prescribed finite time control for strict-feedback systems," *IEEE Trans. Autom. Control*, vol. 68, no. 9, pp. 5729–5736, Sep. 2023.

[23] C.-C. Hua, H. Li, K. Li, and P. Ning, "Adaptive prescribed-time stabilization of uncertain nonlinear systems with unknown control directions," *IEEE Trans. Autom. Control*, vol. 69, no. 6, pp. 3968–3974, Jun. 2024.

[24] Z.-Y. Sun, J.-J. Li, C. Wen, and C.-C. Chen, "Adaptive event-triggered prescribed-time stabilization of uncertain nonlinear systems with asymmetric time-varying output constraint," *IEEE Trans. Autom. Control*, vol. 69, no. 8, pp. 5454–5461, Aug. 2024.

[25] P.-J. Ning, C.-C. Hua, K. Li, and R. Meng, "Event-triggered adaptive prescribed-time control for nonlinear systems with uncertain time-varying parameters," *Automatica*, vol. 157, Nov. 2023, Art. no. 111229.

[26] H. Ye and Y. Song, "Prescribed-time control for time-varying nonlinear systems: A temporal scaling based robust adaptive approach," *Syst. Control Lett.*, vol. 181, Nov. 2023, Art. no. 105602.

[27] Y. Ji, B. Niu, Y. Gao, B. Zhang, and X. Zhao, ''Adaptive prescribed-time control for nonlinear systems with uncertain time-varying parameters and control gains,'' *Asian J. Control*, vol. 27, no. 4, pp. 1774–1783, Jul. 2025.
[28] Y. Song, H. Ye, and F. L. Lewis, ''Prescribed-time control and its latest developments,'' *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 53, no. 7, pp. 4102–4116, Jul. 2023.
[29] Y.-X. Li, ''Finite time command filtered adaptive fault tolerant control for a class of uncertain nonlinear systems,'' *Automatica*, vol. 106, pp. 117–123, Aug. 2019.
[30] F. Wang and X. Zhang, ''Adaptive finite time control of nonlinear systems under time-varying actuator failures,'' *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 9, pp. 1845–1852, Sep. 2019.
[31] X. Fang, H. Fan, W. Wang, L. Liu, B. Wang, and Z. Cheng, ''Adaptive finite-time fault-tolerant control of uncertain systems with input saturation,'' *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 53, no. 1, pp. 165–177, Jan. 2023.
[32] H. Wang, J. Ma, X. Zhao, B. Niu, M. Chen, and W. Wang, ''Adaptive fuzzy fixed-time control for high-order nonlinear systems with sensor and actuator faults,'' *IEEE Trans. Fuzzy Syst.*, vol. 31, no. 8, pp. 2658–2668, Aug. 2023.
[33] M.-X. Wang, S.-L. Zhu, S.-M. Liu, Y. Du, and Y.-Q. Han, ''Design of adaptive finite-time fault-tolerant controller for stochastic nonlinear systems with multiple faults,'' *IEEE Trans. Autom. Sci. Eng.*, vol. 20, no. 4, pp. 2492–2502, Oct. 2023.
[34] Z. Chen and J. Huang, *Stabilization and Regulation of Nonlinear Systems*. Cham, Switzerland: Springer, 2015.
[35] H. Nijmeijer and A. van der Schaft, *Nonlinear Dynamical Control Systems*. New York, NY, USA: Springer, 1990.

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