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Attitude Compensation Control for Quadrotor Under Partial Loss of Actuator Effectiveness

JIE DONG[1], YANZHAO ZHANG[2], AND XIAOTIAN LIU[2]

[1]School of Information Engineering, Dalian Polytechnic University, Dalian 116034, China
[2]Suzhou Nuclear Power Research Institute, Suzhou 215004, China

Corresponding author: Jie Dong (dongjie_dalian1980@163.com)

ABSTRACT In this paper, an augmented fault tolerant attitude control system is presented to address the problem of attitude adjustment for a quad-rotor unmanned aerial vehicle with inertia parameter uncertainties, the external disturbance and the partial loss of actuator effectiveness. To tackle system uncertainty and actuator faults, a fixed time compensation controller is developed based on adaptation mechanism combing with a monitor strategy and Nussbaum gain technique. Robust compensation algorithms under the proposed closed loop system structure are derived in the sense of Lyapunov stability analysis such that the attitude tracking-errors converge to a prescribed compact set in a fixed time. Finally, the simulation results demonstrate the effectiveness of the proposed controller.

INDEX TERMS Quadrotor attitude control, monitor strategy, partial loss of actuator effectiveness, compensation control law design.

I. INTRODUCTION

In recent years, quadrotor unmanned aerial vehicles (QR-UAV) have been widely developed because of their unique features such as their hovering, agility and high maneuverability abilities. Nowadays, quadrotors have been applied in several types of tasks including agricultural services, monitoring over nuclear reactors, mapping and law enforcement and surveillance. The above mentioned tasks imposes new demands in the areas of control theory and flight control system design in order to improve unmanned quad-rotors capable of operating in harsh environments and coping with complex missions [1]–[4]. Currently, many nonlinear control methods have been proposed for unmanned quadrotors [5]–[15]. In [5], iterative learning control is used to update the feed-forward input signal to the quad-rotor system with recurring uncertainties for achieving high two-dimensional tracking performance. In [6], [7], the trajectory tracking problem of quadrotor is analyzed and successfully tackled by a robust control scheme without linear-velocity measurements. In addition, the other control strategy such as adaptive compensation control methods [8], [9], backstepping control strategies [10]–[12], and robust control method [13]–[15] have been also proposed for the attitude and trajectory tracking control of quadrotor.

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Although a number of designed control strategies, inspired from modern control theory, have been proposed for quadrotors, most of the research deals only with the uncertain external disturbances, assuming that there is no actuator fault during the entire flight process. This assumption is rarely satisfied in practice application because some faults may occur due to the increased friction induced by a failure of bearings between stator and rotor, thermal aging of components, and current drive. That means if the flight control system is designed without any fault tolerance capability, an abrupt occurrence of an actuator failure could ultimately fail. Therefore designing an efficient controller to maintain flight stability and acceptable performance, despite an abrupt occurrence of an actuator fault, is a critical issue for flight safety. In [16], a robust control law based on back-stepping technique is proposed for QR-UAV with actuator and sensor faults. Zhang *et al.* [17] developed a robust fault tolerant control of QR-UAV with actuator partial loss of effectiveness faults. Davood *et al.* [18] proposed an approach for fault tolerant control of QR-UAV in trajectory tracking control, which the fault tolerance is achieved by iterative learning control algorithm so that the stability of the closed-loop system can be guaranteed. To deal with the coexistence of the external disturbances and actuator failures, the adaptive compensation control method [19]–[23] using the on-line parameters estimation has been prove to be a powerful tool for solving the flight control problem of quadrotor with the partial loss of actuator effectiveness. Especially based on the idea of Nussbaum gain technique, Song textitet al. [24] designed an adaptive compensation strategy and explored the design of fault tolerant controller in the context of UAV attitude tracking control.

The research results mentioned previously have achieved various degrees of success in solving actuator failures. Nevertheless, the three aspects still need to be explicitly considered in the fault tolerant control design of quadrotor. First of all, many existing attitude tracking of quadrotor with actuator failure assume that the system parameters can be accurately obtained. On the basis of this assumption condition, the fault tolerant controls are developed [16]–[18]. Unfortunately, the system parameters (including the thrust factor and drag coefficients or the inertia moment of rotor about its axis of rotation) are hard to measure exactly in real application. It means that the fault tolerant control schemes with the precise system parameters condition are not easy to be applied in practical engineering. Secondly, the above developed fault tolerant control laws [16]–[18], [20]–[25] can only guarantee that the tracking error converges asymptotically to the equilibrium point or to a small neighborhood of equilibrium point, while the asymptotic convergence feature is not ideal for rapid recovery control performance in dealing with faults arisen from actuators. Indeed, a rapid maneuvering capability incorporating with a preassigned error convergence time can improve the response speed of closed loop system even in case of actuator failure. The third aspect, the control accuracy derived from the aforementioned fault tolerant control methods [19], [22]–[25] cannot be calculated accurately due to the unknown upper bound of the nonlinear term in the closed loop system. The tracking accuracy under these results (see [22], [24], [25]) can be concluded from the inequality in the form of $\dot{V}(t) \leq -\mu \cdot V(t) + \delta$, where $V(t)$ is a Lyapunov energy function, μ is the related design parameter, and δ is unknown but bounded function. It is obvious that the exact error convergence domain cannot be obtained if δ is unknown. Consequently, these methods are difficult to apply to some flight missions that require specific control accuracy.

Motivated by the above discussions and analysis, the main contributions of this thesis are as follows

1) In contrast to the literatures [16]–[18], in this paper an monitor compensation algorithm combing with Nussbaum gain technique is introduced into the closed loop system, which not only does not require knowledge of the system parameters but it also releases the conservative nature of the fixed gains selected in the control law, and hence the proposed strategy is more applicable for the real engineering.
2) Robust fault tolerant control methods [16]–[18] and adaptive fault tolerant control schemes [20]–[25] can achieve asymptotic tracking control of quadrotors subject to partial loss of actuator effectiveness, in this work, an adaptive compensation control structure assisted by the fixed-time prescribed performance function is constructed to regulate the predetermined control performance of the tracking error and to eliminate the effects of adverse factors on the system. Unlike the results in [16]–[25], the proposed control method can set the control indexes in advance, one is the preset control accuracy, and the other is the time to reach the preset control accuracy, and moreover the proposed control approach can ensure that the attitude tracking errors reach the preset control accuracy in a preassigned time instead of unknown time, regardless of whether actuator fault occurs or not. This means that the feature of the proposed approach allows faster corrective responses and maintains the essential safety requirements of the quadrotor.

The remainder of this paper is organized as follows: Section II introduces the quadrotor model and gives the problem description. The control solution is presented in Sec. III. Section IV demonstrates the application of the derived control algorithm to a quadrotor with the partial loss of actuator effectiveness. Conclusions are given in Sec. V.

II. PROBLEM FORMULATION AND PRELIMINARIES

A. PRELIMINARIES

Definition 1: A function is said to be a fixed-time performance function $\beta(t)$ if it has the following properties:

1) $\beta(t) > 0$ is continuous and non-increasing function for $t \in [0, +\infty)$;
2) $\dot{\beta}(T) = 0$ with the arbitrarily setting time $T \in (0, +\infty)$;
3) $\beta(t) = \bar{\beta}$ if $t \geq T$, where $\bar{\beta}$ is a design parameter.

Combining with the definition above, the following fixed-time performance function β_i $(i = 1, 2, 3)$ are proposed for the design of the closed-loop system:

$$\beta_i(t) = \begin{cases} c_{i1} \cdot \sin^{n+1}\left(\frac{\pi}{2T}(T-t)\right) + c_{i2}, & \text{if } 0 \leq t \leq T \\ c_{i2}, & \text{if } t > T \end{cases} \quad (1)$$

where T, $c_{i1} > 0$, and $c_{i2} > 0$ are design parameters; $n+1$ is the integer power of function $\sin(\pi(T-t)/(2T))$. Obviously, formula (1) satisfies the all properties of definition 1. In the control system design, we select $n+1 = 3$. For brevity, the time variable t will be omitted in the following.

Lemma 1 [26]: The following inequality holds for any $a \in R^+$ and $y \in R$:

$$0 \leq |y| - y \cdot \tanh\left(\frac{y}{a}\right) \leq 0.2758 \cdot a. \quad (2)$$

Lemma 2 [27]: For a continuous and non-increasing function $\beta(t)$, the following inequality holds for $z \in R$ in the interval $|z| < \beta(t)$:

$$\ln \frac{\beta^2(t)}{\beta^2(t) - z^2} \leq \frac{z^2}{\beta^2(t) - z^2}, \quad (3)$$

B. PROBLEM FORMULATION

Consider a quadrotor with possible actuator faults, and its attitude model is described as follows [24], [25]:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \dfrac{1}{I_x}\left[(I_y - I_z)\cdot x_4 x_6 + x_4 J_r \bar{\Omega}_r + b l_b \rho_1 u_1 + T_x\right] \end{cases} \tag{4a}$$

$$\begin{cases} \dot{x}_3 = x_4 \\ \dot{x}_4 = \dfrac{1}{I_y}\left[(I_z - I_x)\cdot x_2 x_6 + x_2 J_r \bar{\Omega}_r + b l_b \rho_2 u_2 + T_y\right] \end{cases} \tag{4b}$$

$$\begin{cases} \dot{x}_5 = x_6 \\ \dot{x}_6 = \dfrac{1}{I_z}\left[(I_x - I_y)\cdot x_4 x_2 + \chi l_b \rho_3 u_3 + T_z\right] \end{cases} \tag{4c}$$

where x_1, x_2, and x_3 are the roll angle, pitch angle, and yaw angle, respectively; I_i $(i = x, y, z)$ are the inertia parameter of quadrotor; b and χ are the aerodynamic drag coefficients; $\rho_i (i = 1, 2, 3)$ are the health indicator satisfying $0 < \rho_i \leq 1$; $\bar{\Omega}_r$ is the overall residual rotor angular being considered as a bounded disturbance; $u_i (i = 1, 2, 3)$ represent control inputs; l_b represent the arm length of quadrotor; J_r denotes the moment of inertia of each rotor; $T_i (i = x, y, z)$ are the external disturbances. The flight attitude of the quadrotor is shown in Figure 1.

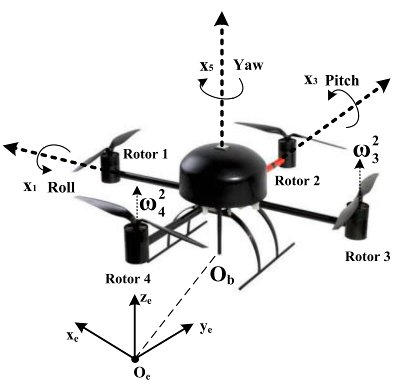

FIGURE 1. Flight attitude of quadrotor.

For simplicity's sake, the attitude subsystem $(4a)$–$(4c)$ can be rewritten as

$$\begin{cases} \dot{x}_{2i-1} = x_{2i}, \\ \dot{x}_{2i} = \varpi_i\, \Xi_i + \lambda_i u_i, \ \ (i = 1, 2, 3) \end{cases} \tag{5}$$

where $\Xi_1 = [-x_4 x_6, x_4, 1]$, $\Xi_2 = [x_2 x_6, x_2, 1]$, $\Xi_3 = [x_4 x_2, 1]$, $\varpi_1 = [(I_z - I_y)/I_x, J_r \bar{\Omega}_r x / I_x, T_x / I_x]^T$, $\varpi_2 = [(I_z - I_x)/I_y, J_r \bar{\Omega}_r / I_y, T_y / I_y]^T$, $\varpi_3 = [(I_x - I_y)/I_z, T_z / I_z]^T$, $\lambda_1 = \rho_1 b\, l_b / I_x$, $\lambda_2 = \rho_2 b\, l_b / I_y$, and $\lambda_3 = \rho_3 \chi\, l_b / I_z$.

To develop our main results, we need the following assumptions and lemmas:

Assumption 1: There exist a unknown constant ϑ such that $\max\{|T_x|,\ |T_y|,\ |T_z|\} \leq \vartheta$.

Assumption 2: The parameters of subsystems $(4a)$–$(4c)$ belong to the compact set $\Omega_1 = \{\ \delta_1 \leq I_x \leq \bar{\delta}_1,\ \ \delta_2 \leq I_y \leq \bar{\delta}_2, \delta_3 \leq I_z \leq \bar{\delta}_3, \delta_4 \leq b \leq \bar{\delta}_4, \delta_5 \leq d \leq \bar{\delta}_5, \delta_6 \leq J_r \bar{\Omega}_r \leq \bar{\delta}_6\}$, where $\bar{\delta}_1, \bar{\delta}_2, \bar{\delta}_3, \bar{\delta}_4, \bar{\delta}_5, \bar{\delta}_6, \delta_1, \delta_2, \delta_3, \delta_4, \delta_5$, and δ_6 are unknown positive constants.

Assumption 3: The command signals $x_{(2i-1)d} (i = 1, 2, 3)$ are bounded, and moreover their first and second derivatives are bounded.

Assumption 4: The initial states $x_{2i-1}(0) (i = 1, 2, 3)$ are bounded, and there exist a positive constant ζ such that $\max\{[x_{2i-1}(0) - x_{(2i-1)d}(0)]^2\} \leq \zeta$.

Remark 1: From a practical point of view, considering that the unknown external disturbance energy is finite and the physical parameters (e.g. aerodynamic drag, the inertia parameter, etc.) are objectively existing and bounded in real system, hence Assumptions 1 and 2 are reasonable. It should be noted that the respective boundary value for external disturbances and the system parameters are not involved in the design of the control law. Additionally, we plan a bounded smooth function as the desired attitude command signal to achieve low-speed missions rather than aggressive attitude task, it means that the upper bound of initial attitude angles can be determined previously. Therefore, Assumptions 3 and 4 are valid.

Remark 2: In $(4a)$–$(4c)$, ρ_i $(i = 1, 2, 3)$ are introduced into the attitude subsystem in order to describe the partial loss of actuator effectiveness. In particular, the actuators work normally if $\rho_i = 1$. Correspondingly, there exist the partial loss of actuator effectiveness if $0 < \rho_i < 1$. Noting that, the case $\rho_i = 0$ is beyond the scope of this paper. Combining the Assumption 2 and $0 < \rho_i \leq 1 (i = 1, 2, 3)$, it is obviously that λ_i $(i = 1, 2, 3)$ are positive and unknown bounded parameter based on the definition of λ_i, and therefore there exist the positive constants ι_i $(i = 1, 2, 3)$ such that $0 < \lambda_i \leq \iota_i$. Notice that ι_i are only used for analysis and are not involved in the design of the control law.

In this paper, the control objective is to design an fault tolerant control law for attitude tracking of QR-UAV with the partial loss of actuator effectiveness such that the attitude tracking errors reach the preset control accuracy in the specified time.

III. THE CONTROL SYSTEM DESIGN

In this section, we use back-stepping design procedure to obtain a fault tolerant attitude controller with fixed-time prescribed performance [26], [27] and the main theorem.

A. THE FAULT TOLERANT ATTITUDE CONTROLLER DESIGN

Step 1: To develop the fixed time fault tolerant control method, the following the attitude tracking error e_{2i-1} and the auxiliary error e_{2i} $(i = 1, 2, 3)$ are introduced first, i.e.,

$$e_{2i-1} = x_{2i-1} - x_{(2i-1)d}, \tag{6}$$

$$e_{2i} = x_{2i} - \alpha_i, \tag{7}$$

where $\alpha_i (i = 1, 2, 3)$ are the virtual control laws, and it will be given later. From (5), (6) and (7), the time derivative of e_{2i-1} yields

$$\dot{e}_{2i-1} = \dot{x}_{2i-1} - \dot{x}_{(2i-1)d} = x_{2i} - \dot{x}_{(2i-1)d}$$

$$= e_{2i} + \alpha_i - \dot{x}_{(2i-1)d}. \tag{8}$$

Consider the following barrier Lyapunov function $V_{1i}\,(i = 1, 2, 3)$ and define a compact set Ω_V:

$$V_{1i} = \frac{1}{2}\log\frac{\beta_i^2}{\beta_i^2 - e_{2i-1}^2}, \tag{9}$$

$$\Omega_V = \{e_{2i-1} \mid |e_{2i-1}| < \beta_i \le \beta_i(0), \quad i = 1, 2, 3\}, \tag{10}$$

where β_i are defined in (1). To ensure that $e_{2i-1}^2(0) < \beta_i^2(0)$, the design parameters c_{i1} and c_{i2} (c_{i1} and c_{i2} are presented in β_i) need to meet the following condition:

$$(c_{i1} + c_{i2})^2 > \zeta. \tag{11}$$

Remark 3: On the basis of $e_{2i-1}^2(0) = [x_{2i-1}(0) - x_{(2i-1)d}(0)]^2 \le \zeta$ in Assumption 4 and $\beta_i(0) = c_{i1} + c_{i2}$. Obviously,$e_{2i-1}^2(0) < \beta_i^2(0)$ if the condition (11) hold, and moreover $e_{2i-1}(t) < \beta_i(t)$ for $\forall t > 0$ can be satisfied as long as $1/(\beta_i^2 - e_{2i-1}^2)$ is made bounded. The boundedness of $1/(\beta_i^2 - e_{2i-1}^2)$ will be prove in stability analysis.

By differentiating V_{1i} and using (8), we have

$$\begin{aligned}\dot{V}_{1i} &= \frac{1}{2}\cdot\frac{\beta_i^2 - e_{2i-1}^2}{\beta_i^2} \\ &\quad\cdot\frac{2\beta_i\dot{\beta}_i(\beta_i^2 - e_{2i-1}^2) - \beta_i^2(2\beta_i\dot{\beta}_i - 2e_{2i-1}\dot{e}_{2i-1})}{(\beta_i^2 - e_{2i-1}^2)^2} \\ &= \frac{e_{2i-1}\dot{e}_{2i-1}}{\beta_i^2 - e_{2i-1}^2} - \frac{\dot{\beta}_i}{\beta_i}\cdot\frac{e_{2i-1}^2}{\beta_i^2 - e_{2i-1}^2} \\ &= \frac{e_{2i-1}}{\beta_i^2 - e_{2i-1}^2}\left(e_{2i} + \alpha_i - \dot{x}_{(2i-1)d}\right) - \frac{\dot{\beta}_i}{\beta_i}\cdot\frac{e_{2i-1}^2}{\beta_i^2 - e_{2i-1}^2}.\end{aligned} \tag{12}$$

Then, the virtual control law $\alpha_i\,(i = 1, 2, 3)$ are deigned as

$$\alpha_i = \dot{x}_{(2i-1)d} - \frac{\eta_{2i-1}\cdot e_{2i-1}}{2} + \frac{\dot{\beta}_i e_{2i-1}}{\beta_i}, \tag{13}$$

where $\eta_{2i-1}(i = 1, 2, 3)$ are positive design parameters. The derivatives of α_i is used in subsequent section. Here, $\dot{\alpha}_i$ can be calculated as $\dot{\alpha}_i = \ddot{x}_{(2i-1)d} - \eta_{2i-1}(x_{2i} - \dot{x}_{(2i-1)d})/2 + \ddot{\beta}_i e_{2i-1}/\beta_i + \dot{\beta}_i(x_{2i} - \dot{x}_{(2i-1)d})/\beta_i - \dot{\beta}_i^2 \cdot e_{2i-1}/\beta_i^2$.

Substituting (13) into (12) and using the Lemma 2, then we have

$$\begin{aligned}\dot{V}_{1i} &= \frac{e_{2i-1}}{\beta_i^2 - e_{2i-1}^2}\left(\dot{x}_{(2i-1)d} - \frac{\eta_{2i-1}e_{2i-1}}{2} + \frac{\dot{\beta}_i e_{2i-1}}{\beta_i} - \dot{x}_{(2i-1)d}\right) \\ &\quad - \frac{\dot{\beta}_i}{\beta_i}\cdot\frac{e_{2i-1}^2}{\beta_i^2 - e_{2i-1}^2} + \frac{e_{2i-1}e_{2i}}{\beta_i^2 - e_{2i-1}^2} \\ &= -\frac{\eta_{2i-1}}{2}\cdot\frac{e_{2i-1}^2}{\beta_i^2 - e_{2i-1}^2} + \frac{e_{2i-1}e_{2i}}{\beta_i^2 - e_{2i-1}^2} \\ &\le -\frac{\eta_{2i-1}}{2}\cdot\log\frac{\beta_i^2}{\beta_i^2 - e_{2i-1}^2} + \frac{e_{2i-1}e_{2i}}{\beta_i^2 - e_{2i-1}^2}.\end{aligned} \tag{14}$$

Step 2: By taking derivative of (7) with respect to time and using the second equation of (5), one has

$$\dot{e}_{2i} = \dot{x}_{2i} - \dot{\alpha}_i = \varpi_i\,\Xi_i + \lambda_i u_i - \dot{\alpha}_i. \tag{15}$$

Note that the nonlinear lumped term $\varpi_i(i = 1, 2, 3)$ in (15) contain unknown bounded parameters and bounded external disturbances, and therefore there exists the positive constants $\sigma_i\,(i = 1, 2, 3)$ such that $|\varpi_i| \le \sigma_i$. Combining with (15), we can obtain that

$$\begin{aligned}e_{2i}\dot{e}_{2i} = e_{2i}\left(\varpi_i\,\Xi_i + \lambda_i u_i - \dot{\alpha}_i\right) \le\ & |e_{2i}| \\ &\cdot\sigma_i\cdot|\Xi_i| + e_{2i}\left(\lambda_i u_i - \dot{\alpha}_i\right).\end{aligned} \tag{16}$$

In order to deal with the unknown parameters λ_i ($i = 1, 2, 3$), the Nussbaum gain technique is employed in controller design. A function $N(\kappa)$ with smooth function κ is called a Nussbaum-type function if it has the following properties:

$$\lim_{s\to\infty}\sup\frac{1}{s}\int_0^s N(\kappa)\,d\kappa = +\infty,$$

$$\lim_{s\to\infty}\inf\frac{1}{s}\int_0^s N(\kappa)\,d\kappa = -\infty.$$

From the above two properties, we know that Nussbaum functions should have infinite gain and infinite switching frequencies. The commonly used Nussbaum functions include: $\kappa^2\cos\kappa$, $\kappa^2\sin\kappa$, and $e^{\kappa^2}\cos[(\pi/2)\kappa]$. In this paper, the Nussbaum function $N(\kappa) = e^{\kappa^2}\cos[(\pi/2)\kappa]$ is used.

Lemma 3 [28], [29]: For a smooth function $\kappa(t)$ on interval $[0, t_f)$, and a smooth Nussbaum-type function $N(\kappa)$, if a positive definite function $V(t)$ on the same interval satisfies the following inequality:

$$V(t) \le h_0 + \int_0^t \left(\rho^*\cdot N(\kappa)\cdot\dot{\kappa} + \dot{\kappa}\right)e^{-h_1(t-\tau)}d\tau,\ \forall t \in [0, t_f), \tag{17}$$

where h_0 represents a suitable constant, h_1 is a positive constant, ρ^* is a time-varying parameter which takes values in the unknown closed intervals $I = [I^-, I^+]$ with $0 \notin I$, then $V(t)$, κ, and $\int_0^t \rho^*\cdot N(\rho)\cdot\dot{\kappa}d\tau$ must be bounded on $[0, t_f)$.

Next, we construct the attitude control law as

$$u_i = u_{i\_part1} + \mu_i\cdot u_{i\_part2},\ (i = 1, 2, 3), \tag{18}$$

in (18), the detailed contents of u_{i_part1}, u_{i_part2} and μ_i are given as follows

$$u_{i\_part1} = N(\kappa_i)\cdot\left(\eta_{2i-1}\cdot e_{2i} - \dot{\alpha}_i + \frac{e_{2i-1}}{\beta_i^2 - e_{2i-1}^2}\right), \tag{19}$$

$$u_{i\_part2} = N(\kappa_i)\cdot\frac{\hat{\sigma}_i\cdot|\Xi_i|}{\varepsilon}\cdot\tanh\left(\frac{e_{2i}\cdot|\Xi_i|}{a_1}\right), (a_1 > 0), \tag{20}$$

and

$$\mu_i = \begin{cases} \varepsilon \\ \qquad if \ \ |e_{2i-1}|^2 \le b_2^2 + b_3, \\ 1-\cos\left(\frac{\pi}{2}\sin\left(\frac{\pi}{2}\cdot\frac{|e_{2i-1}|^2 - b_2^2}{b_1^2 - b_2^2}\right)\right) \\ \qquad if \ b_2^2 + b_3 < |e_{2i-1}|^2 < b_1^2, \\ 1 \\ \qquad if \ \ |e_{2i-1}|^2 \ge b_1^2. \end{cases} \tag{21}$$

where ε is chosen as

$$\varepsilon = 1-\cos\left(\frac{\pi}{2}\sin\left(\frac{\pi}{2}\cdot\frac{b_3}{b_1^2 - b_2^2}\right)\right), \tag{22}$$

with positive design parameter $b_i (i = 1, 2, 3)$ satisfying $0 < b_3 < b_2^2 < b_1^2 \le 1$ and $b_1^2 - b_2^2 > b_3$.

Additionally, the parameter updating laws are designed as

$$\dot{\kappa}_i = e_{2i}\left\{\eta_{2i-1}e_{2i} + \frac{\mu_i\cdot\hat{\sigma}_i\cdot|\Xi_i|}{\varepsilon}\cdot\tanh\left(\frac{e_{2i}\cdot|\Xi_i|}{a_1}\right)\right\} + \frac{e_{2i}e_{2i-1}}{\beta_i^2 - e_{2i-1}^2} - e_{2i}\dot{\alpha}_i, \quad \kappa_i(0) = 1, \tag{23}$$

$$\dot{\hat{\sigma}}_i = \frac{\mu_i\cdot e_{2i}\cdot|\Xi_i|}{\varepsilon}\cdot\tanh\left(\frac{e_{2i}\cdot|\Xi_i|}{a_1}\right) - a_2\hat{\sigma}_i, \quad \left(\hat{\sigma}_i(0) > 0,\ a_2 > 0\right). \tag{24}$$

Remark 4: From (21), we obtain that $\varepsilon \le \mu_i \le 1 (i = 1, 2, 3)$. In this paper, μ_i is regarded as a supervisory regulator. The trajectory of attitude tracking-error is far from the equilibrium point when quadrotor suffer from the partial loss of actuator effectiveness, and then a big weight $\mu_i = 1$ are given to the adaptation term τ_{i_part2} in order to overcome the adverse influence caused by actuator failure. Once the trajectory of tracking error reaches the neighborhood of the equilibrium point, the supervisory regulator μ_i will make the self-adjustment strategy, it means a small weight value is given to the adaptation term in order to reduce the control energy consumption.

Now, we consider the second Lyapunov function as

$$V_{2i} = \frac{e_{2i}^2}{2} + \frac{\tilde{\sigma}_i^2}{2}, \quad (i = 1, 2, 3) \tag{25}$$

where $\tilde{\sigma}_i = \sigma_i - \hat{\sigma}_i$, and $\hat{\sigma}_i$ is used to estimate σ_i.

Differentiating V_{2i} with respect to time and using (16) yields

$$\begin{aligned} \dot{V}_{2i} &= e_{2i}\dot{e}_{2i} + \tilde{\sigma}_i\dot{\tilde{\sigma}}_i \\ &\le |e_{2i}|\cdot\sigma_i\cdot|\Xi_i| + e_{2i}\left(\lambda_i u_i - \dot{\alpha}_i\right) - \tilde{\sigma}_i\dot{\hat{\sigma}}_i \\ &= |e_{2i}|\cdot\sigma_i\cdot|\Xi_i| + \eta_{2i-1}e_{2i}^2 - \eta_{2i-1}e_{2i}^2 \\ &\quad +\dot{\kappa}_i - \dot{\kappa}_i + e_{2i}\dot{\alpha}_i - \tilde{\sigma}_i\dot{\hat{\sigma}}_i. \end{aligned} \tag{26}$$

Combining (18), (19), (20), and (23), we have

$$\begin{aligned} e_{2i}\lambda_i u_i &= e_{2i}\lambda_i\left(u_{i\_part1} + \mu_i\cdot u_{i\_part2}\right) \\ &= N(\kappa_i)\cdot\lambda_i\cdot\left(\eta_{2i-1}\cdot e_{2i}^2 - e_{2i}\dot{\alpha}_i + \frac{e_{2i}e_{2i-1}}{\beta_i^2 - e_{2i-1}^2}\right. \\ &\quad \left. + N(\kappa_i)\cdot\lambda_i\cdot e_{2i}\cdot\frac{\mu_i\cdot\hat{\sigma}_i\cdot|\Xi_i|}{\varepsilon}\cdot\tanh\left(\frac{e_{2i}\cdot|\Xi_i|}{a_1}\right)\right. \\ &= N(\kappa_i)\cdot\lambda_i\cdot\dot{\kappa}_i. \end{aligned} \tag{27}$$

With the help of (23), (24), and (27), then (24) becomes

$$\begin{aligned} \dot{V}_{2i} &\le |e_{2i}|\cdot\sigma_i\cdot|\Xi_i| + \eta_{2i-1}e_{2i}^2 - \eta_{2i-1}e_{2i}^2 + \dot{\kappa}_i \\ &\quad - e_{2i}\left\{\eta_{2i-1}e_{2i} + \frac{\mu_i\cdot\hat{\sigma}_i\cdot|\Xi_i|}{\varepsilon}\cdot\tanh\left(\frac{e_{2i}\cdot|\Xi_i|}{a_1}\right)\right\} \\ &\quad - \frac{e_{2i}e_{2i-1}}{\beta_i^2 - e_{2i-1}^2} + e_{2i}\dot{\alpha}_i + N(\kappa_i)\lambda_i\dot{\kappa}_i - e_{2i}\dot{\alpha}_i \\ &\quad - e_{2i}\cdot\frac{\mu_i\cdot\tilde{\sigma}_i\cdot|\Xi_i|}{\varepsilon}\cdot\tanh\left(\frac{e_{2i}\cdot|\Xi_i|}{a_1}\right) + a_2\tilde{\sigma}_i\hat{\sigma}_i \\ &= |e_{2i}|\cdot\sigma_i\cdot|\Xi_i| - \eta_{2i-1}e_{2i}^2 + N(\kappa_i)\lambda_i\dot{\kappa}_i \\ &\quad +\dot{\kappa}_i - \frac{e_{2i}e_{2i-1}}{\beta_i^2 - e_{2i-1}^2} \\ &\quad -e_{2i}\cdot\frac{\mu_i\cdot\sigma_i\cdot|\Xi_i|}{\varepsilon}\cdot\tanh\left(\frac{e_{2i}\cdot|\Xi_i|}{a_1}\right) + a_2\tilde{\sigma}_i\hat{\sigma}_i. \end{aligned} \tag{28}$$

Based on Lemma 1 and young's inequality, the following two relationships can be established, i.e.,

$$\begin{aligned} &|e_{2i}|\cdot\sigma_i\cdot|\Xi_i| - e_{2i}\cdot\frac{\mu_i\cdot\sigma_i\cdot|\Xi_i|}{\varepsilon}\cdot\tanh\left(\frac{e_{2i}\,|\Xi_i|}{a_1}\right) \\ &\quad \le |e_{2i}|\cdot\sigma_i\cdot|\Xi_i| - e_{2i}\cdot\sigma_i\cdot|\Xi_i|\cdot\tanh\left(\frac{e_{2i}\,|\Xi_i|}{a_1}\right) \\ &\quad \le 0.2758a_1\sigma_i, \end{aligned} \tag{29}$$

$$\begin{aligned} a_2\tilde{\sigma}_i\hat{\sigma}_i &= -a_2\left(\sigma_i - \hat{\sigma}_i\right)\left(\sigma_i - \hat{\sigma}_i - \sigma_i\right) \\ &\le a_2\left[-\left(\sigma_i - \hat{\sigma}_i\right)^2 + \frac{\left(\sigma_i - \hat{\sigma}_i\right)^2}{2} + \frac{\sigma_i^2}{2}\right] \\ &= -\frac{a_2\tilde{\sigma}_i^2}{2} + \frac{a_2\sigma_i^2}{2}. \end{aligned} \tag{30}$$

According to (29) and (30), (28) can be rewritten as

$$\begin{aligned} \dot{V}_{2i} &\le -\eta_{2i-1}e_{2i}^2 + N(\kappa_i)\lambda_i\dot{\kappa}_i + \dot{\kappa}_i - \frac{e_{2i}e_{2i-1}}{\beta_i^2 - e_{2i-1}^2} \\ &\quad -\frac{a_2\tilde{\sigma}_i^2}{2} + \frac{a_2\sigma_i^2}{2} + 0.2758a_1\sigma_i. \end{aligned} \tag{31}$$

B. THE STABILITY ANALYSIS OF THE CLOSED LOOP SYSTEM

The main result of the attitude control performance is summarized in the following theorem.

Theorem 1: Consider the attitude system (5) with the external disturbance, uncertain system parameters and the partial loss of actuator effectiveness under Assumptions 1–4. With the application of the proposed attitude control law (18), and parameters update laws (23)–(24), if the initial condition satisfies $e_{2i-1}(0) \in \Omega_V$, then the following control objectives can be achieved.

1) all signals in the closed-loop system remain bounded for all $t \ge 0$;

2) the attitude tracking errors $e_{2i-1}(t)$ $(i = 1, 2, 3)$ converge to a preset region in a fixed time, that is, $|e_{2i-1}(t)| < c_{i2}$ for $t > T$.

Proof: Select the Lyapunov function candidate as

$$\bar{V} = V_{1i} + V_{2i} = \frac{1}{2}\log\frac{\beta_i^2}{\beta_i^2 - e_{2i-1}^2} + \frac{e_{2i}^2}{2} + \frac{\tilde{\sigma}_i^2}{2}. \quad (32)$$

Differentiating $\bar{V}_i$ with respect to time and using (14) and (31) yields

$$\begin{aligned}\dot{\bar{V}}_i \leq& -\frac{\eta_{2i-1}}{2}\cdot\log\frac{\beta_i^2}{\beta_i^2 - e_{2i-1}^2} + \frac{e_{2i-1}e_{2i}}{\beta_i^2 - e_{2i-1}^2}\\ &+N(\kappa_i)\lambda_i\dot{\kappa}_i + \dot{\kappa}_i - \eta_{2i-1}e_{2i}^2 - \frac{e_{2i}e_{2i-1}}{\beta_i^2 - e_{2i-1}^2}\\ &-\frac{a_2\tilde{\sigma}_i^2}{2} + \frac{a_2\sigma_i^2}{2} + 0.2758a_1\sigma_i\\ \leq& -\frac{\eta_{2i-1}}{2}\log\frac{\beta_i^2}{\beta_i^2 - e_{2i-1}^2} - \frac{2\eta_{2i-1}e_{2i}^2}{2} - \frac{a_2\tilde{\sigma}_i^2}{2}\\ &+N(\kappa_i)\lambda_i\dot{\kappa}_i + \dot{\kappa}_i + \Delta_i \leq -\xi_i\bar{V}_i + N(\kappa_i)\lambda_i\dot{\kappa}_i + \dot{\kappa}_i + \Delta_i.\end{aligned} \quad (33)$$

where $\xi_i = \min\{\eta_{2i-1}, a_2\}$ and $\Delta_i = 0.5a_2\sigma_i^2 + 0.2758a_1\sigma_i$.

Multiply (33) by $e^{\xi_i t}$, and then integrate it over $[0,\ t]$, it becomes

$$\bar{V}_i(t) \leq \bar{V}_i(0) + \Delta_i/\xi_i + \int_0^t (\lambda_i\cdot N(\kappa_i)\dot{\kappa}_i + \dot{\kappa}_i)\cdot e^{-\xi_i(t-\tau)}d\tau. \quad (34)$$

According to Lemma 3, we conclude from (34) that $\bar{V}_i(t)$, κ_i and $\int_0^t \lambda_i N(\kappa_i)\dot{\kappa}_i d\tau$ must be bounded $[0, t_f)$, which implies that V_{1i} and V_{2i} are bounded. From the definition of V_{1i} and V_{2i}, we known that $e_{2i}^2(t)$ and $\tilde{\sigma}_i^2$ are bounded and $e_{2i-1}^2(t) < \beta_i^2(t)$ for $t \in [0,\ +\infty)$ due to the boundedness of V_{1i}. According to (1), one obtain

$$|e_{2i-1}(t)| < c_{i1}\cdot\sin^{n+1}\left(\frac{\pi}{2T}(T-t)\right) + c_{i2},\quad \textit{for } 0 \leq t \leq T, \quad (35)$$

$$|e_{2i-1}(t)| < c_{i2},\quad \textit{for } t > T. \quad (36)$$

Note that c_{i1}, c_{i2}, and T are the preset parameters which can be chosen by the requirement of different tasks. It can be seen from (36) that when the preset parameters (c_{i2} and T) are chosen, the control accuracy of the tracking error after the specified time T is determined accordingly, it means the tracking errors converge to the following prescribed compact set

$$\Omega_e = \{e_{2i-1}(t) \mid |e_{2i-1}(t)| < c_{i2}\} \quad \text{for } t > T. \quad (37)$$

The proof is completed.

The structure of the control system is shown in Figure 2.

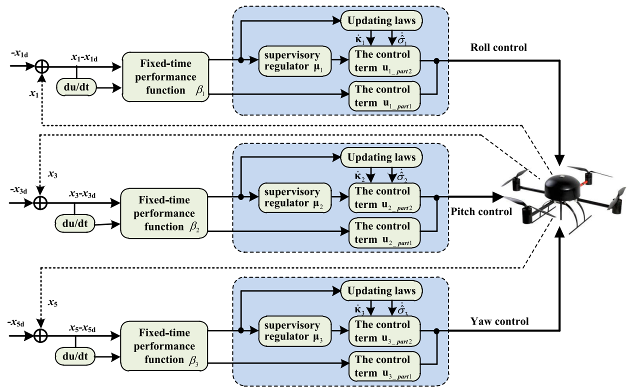

FIGURE 2. Attitude control system structure.

TABLE 1. The nominal parameters of quadrotor model.

System Variable	Value	Units
$\bar{I}_x$	0.0196	$kg\ m^2$
$\bar{I}_y$	0.0196	$kg\ m^2$
$\bar{I}_z$	0.0364	$kg\ m^2$
$\bar{J}_r$	8.5×10^{-4}	$kg\ m$
$\bar{b}$	9.3×10^{-5}	$N\ s^2$
l_b	0.4	m
m	1.1	kg

IV. NUMERICAL SIMULATIONS

In this section, we give a numerical simulation to illustrate the proposed control scheme and demonstrate the effectiveness with Matlab-Simulink. The sampling time for ordinary differential equation solvers tool is 10^{-4}. The desired altitude and attitude signals are chosen as follows

$$\begin{cases}\theta_d = 0.6\sin(0.5t)\cdot(1-\cos(0.5t))\\ \phi_d = 0.6\cos(0.5t)\cdot(1-\cos(0.5t))\\ \psi_d = 0.8\sin(0.5t)\cdot(\sin(0.5\pi t))\end{cases}$$

In simulation, quadrotor parameters satisfy $I_x = \bar{I}_x + \Delta I_x, I_y = \bar{I}_y + \Delta I_y, I_z = \bar{I}_z + \Delta I_z, b = \bar{b} + \Delta b, J_r = \bar{J}_r + \Delta J_r$ where $\bar{I}_x, \bar{I}_y, \bar{I}_z, \bar{b}$, and $\bar{J}_r$ are the nominal part of system parameters which are shown in Table 1, and the uncertain parts $\Delta I_x, \Delta I_y, \Delta I_z, \Delta b, \Delta J_r$ are selected within 45% of the nominal part. The control system parameters are given as $\eta_{2i-1} = 12$, $a_1 = \varepsilon = 0.01, a_2 = c_{i1} = 1, c_{i2} = 0.02, b_1^2 = 1, b_2^2 = 0.5, b_3 = 0.01, T = 1$. The initial values of system states and updating laws are chosen as $\theta(0) = -0.2\,rad$, $\phi(0) = -0.15\,rad$, $\psi(0) = -0.22\,rad$, and $\hat{\sigma}_i(0) = \hat{\kappa}_i(0) = 1$. The disturbances are chosen as $T_x = 1.5\cos(t)$, $T_y = 2\cos(t)$, $T_z = 1.5\cos(t)\sin(t)$. In addition, the health indicator are chosen as

$$\rho_1 = \begin{cases}0.7 + 0.2\cos(t), & \text{for } t \geq 8s\\ 1, & \text{for } t < 8s\end{cases}$$

$$\rho_2 = \begin{cases}0.7 + 0.2\sin(t), & \text{for } t \geq 8s\\ 1, & \text{for } t < 8s\end{cases}$$

TABLE 2. The design parameter configuration with different methods.

Method	Design parameters
[19]	$k=18,\ c_1=c_2=5,\ q=5,\ p=3,\ \varepsilon=0.01,\ \gamma=8$
[23]	$p=32,\ l=23,\ \mu_{k1}=0.01,\ \mu_{k2}=4,\ \vartheta_k=0.001,\ c_i=0.5,\ \sigma_j=7$

$$\rho_3=\begin{cases}0.8+0.2\cos(t), & \text{for } t\geq 8s\\ 1, & \text{for } t<8s\end{cases}$$

To evaluate performance of the proposed control method, adaptive fault tolerant compensation control [19] and robust fault tolerant control based on terminal sliding mode control technique [23] are chosen for comparison. The three control approaches are applied to quadrotor with same model information and the same simulation step, and the control parameters of the methods [19] and [23] are given in Table 2.

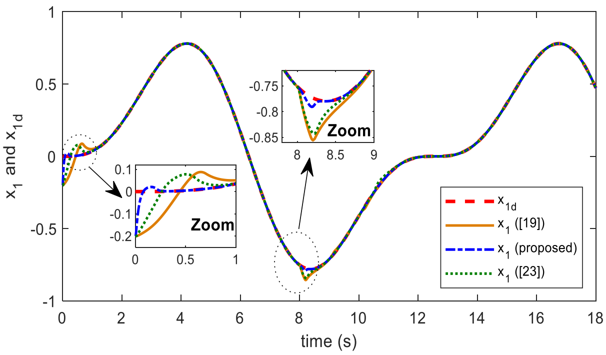

FIGURE 3. The tracking trajectory of x_1 and x_{1d}.

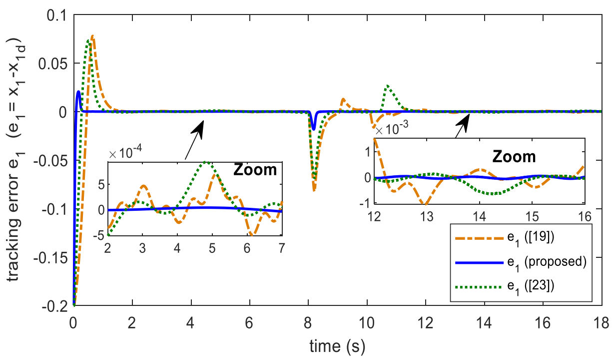

FIGURE 4. The tracking error $e_1(e_1=x_1-x_{1d})$.

The simulation results are shown in Figs. 3–10. The response curves of the attitude tracking trajectories are illustrated in Figs. 3, 5 and 7. These results show that the attitude tracking objectives can be achieved by the three control methods, nonetheless, the fine control performances are different. From Figs. 4, 6, and 8, compared with the other two methods, the proposed method has a fast convergence rate at the initial stage of attitude control (for $0\leq t\leq 1s$), and moreover the proposed method guarantee the attitude error converge into a bounded region when $t>1s$, even when the partial loss of actuator effectiveness occurs, i.e.,

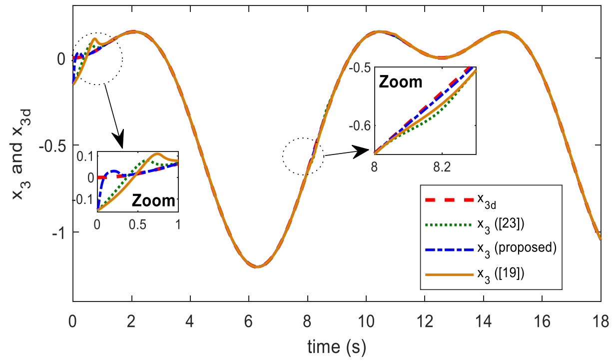

FIGURE 5. The tracking trajectory of x_3 and x_{3d}.

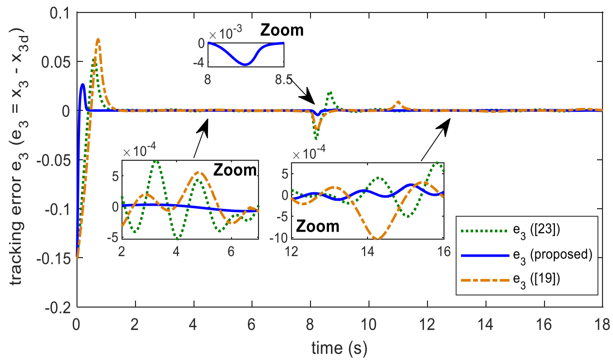

FIGURE 6. The tracking error $e_3(e_3=x_3-x_{3d})$.

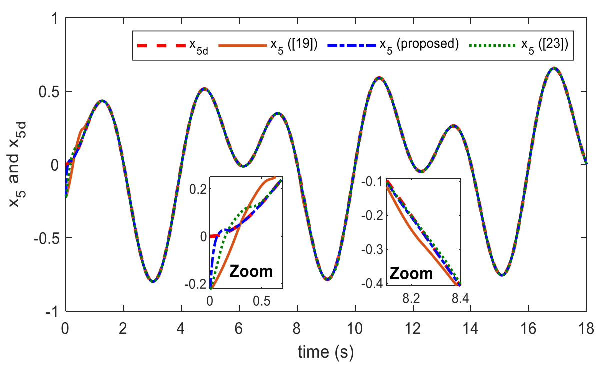

FIGURE 7. The tracking trajectory of x_5 and x_{5d}.

$$\textit{The proposed method}:\begin{cases}\max\{|e_1(t)|,\ \ t>1s\}=0.016,\\ \max\{|e_3(t)|,\ \ t>1s\}=0.005,\\ \max\{|e_5(t)|,\ \ t>1s\}=0.007.\end{cases}$$

Obviously, the simulation results are perfectly matched with Theorem 1. The proposed method realizes the preset control precision after a specified-time (As stated by Theorem 1, the preset tracking precision should be $|e_{2i-1}(t)|<0.02$, for $t>1s$ based on $c_{i2}=0.02$ and $T=1s$). As for the

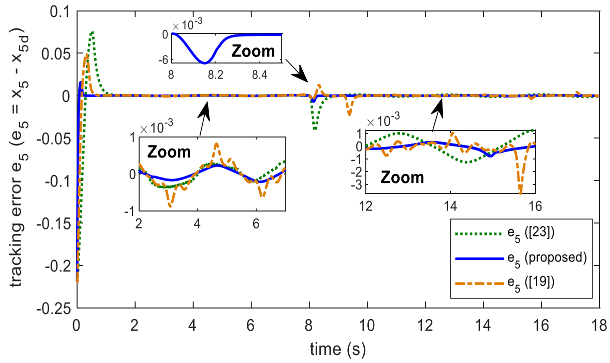

FIGURE 8. The tracking error $e_5 (e_5 = x_5 - x_{5d})$.

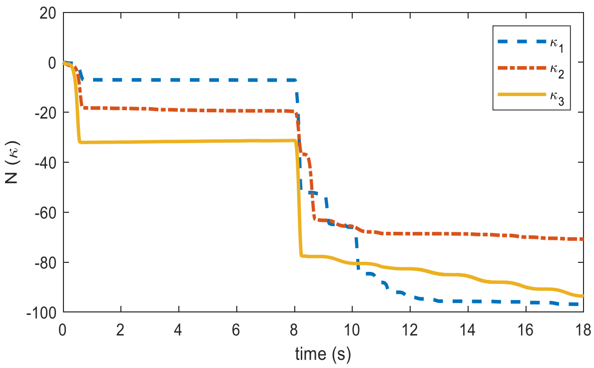

FIGURE 9. The Nussbaum gain.

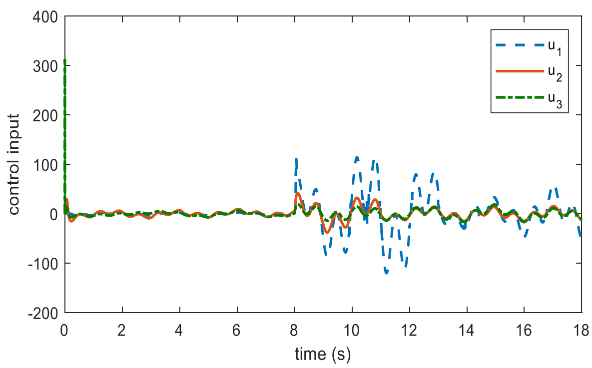

FIGURE 10. The proposed control signals.

other two methods, the maximum errors are as follows:

$$\textit{The method } [19]: \begin{cases} \max\{|e_1(t)|, \quad t > 1s\} = 0.08, \\ \max\{|e_3(t)|, \quad t > 1s\} = 0.038, \\ \max\{|e_5(t)|, \quad t > 1s\} = 0.035. \end{cases}$$

$$\textit{The method } [23]: \begin{cases} \max\{|e_1(t)|, \quad t > 1s\} = 0.072, \\ \max\{|e_3(t)|, \quad t > 1s\} = 0.04, \\ \max\{|e_5(t)|, \quad t > 1s\} = 0.047. \end{cases}$$

It can be observed that the proposed method obtains a good performance than the methods [19] and [23], especially after the occurrence of the partial loss of actuator effectiveness. The curves of Nussbaum gain and control signals are shown in Fig. 9 and Fig. 10, respectively. We can see that the amplitude of Nussbaum gain and control signals suddenly become larger when the actuator fault occurs. This is due to the fact that the control system needs to produce a sufficiently large control output to overcome the adverse influence caused by actuator failure. Through the attitude tracking error curves, we can also find that our method has a rapid response when the partial loss of actuator effectiveness occurs and the tracking error accuracy is always kept within the specified range $|e_{2i-1}(t)| < 0.02$ for $t > 1s$, compared with the other two methods. That means the lumped disturbance (including inertia uncertainties, external disturbance and the partial loss of actuator effectiveness) are well suppressed.

V. CONCLUSION

A new fault tolerant control scheme based on compensation control technique for attitude tracking of a quad-rotor is derived in the presence of the external disturbances, inertia parameter uncertainties and rotor with partial loss of effectiveness. Under the back-stepping design structure, an fixed-time prescribed performance attitude controller using the self-adjusting mechanism are designed to compensate the error caused by the adverse factor including the disturbance, parameter uncertainties and rotor with partial loss of effectiveness in attitude system of quad-rotor. Using the Lyapunov method, it proved is that the designed controller could guarantee the convergence and stability of the closed loopsystem. Numerical simulations are included to support the theory analyses. The results demonstrate that the proposed controller effectively.

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JIE DONG received the Ph.D. degree from the School of Control Science and Engineering, Dalian University of Technology, China, in 2010. He has been an Associate Professor with the School of Information Science and Engineering, Dalian Polytechnic University, China. His research interests include nonlinear control and intelligent control.

YANZHAO ZHANG is a Researcher with the Suzhou Nuclear Power Research Institute, China. His research interests include modeling and identification of biological process.

XIAOTIAN LIU is a Researcher with the Suzhou Nuclear Power Research Institute, China. His research interests include model prediction and process control.