Research Article

Fault-Tolerant Control of Quadrotor UAVs Based on Back-Stepping Integral Sliding Mode Approach and Iterative Learning Algorithm

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Received 19 March 2021; Revised 15 July 2021; Accepted 18 August 2021; Published 26 August 2021

Academic Editor: Hao Shen

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In this paper, a fault-tolerant control system based on back-stepping integral sliding mode controller (BISMC) is designed and analyzed for both nonlinear translational and rotational subsystems of the quadrotor unmanned aerial vehicles (UAVs). The novelty of this paper is about combination of a classic controller with a repetitive algorithm to reduce the response time to actuator faults and have better tracking performance. The actuator fault is defined based on the loss of effectiveness and bias fault. Next, the iterative learning control algorithm (ILCA) is used to compensate for the unknown fault input according to previous recorded experiences. In the normal condition (without actuators fault), BISMC can force the actual trajectories toward the desired commands and reduce chattering about control signals, and in the presence of the actuators fault or external disturbances, the mentioned learning algorithm can incline the accuracy of the tracking performance and compensate for the occurred error. The Lyapunov theory illustrates that the proposed control strategy can stabilize the system despite the actuators' fault and external disturbances. The simulation results show the effectiveness of the proposed scheme in comparison with another method.

1. Introduction

Over the last decade, quadrotor UAVs have been noticed for their properties such as speed, small size, and harmless for the environment in weather monitoring, payload transportation, power line inspection, and commercial industries. The dynamic of the quadrotor is highly coupled, nonlinear, and under-actuated, and it is affected by aerodynamic effects and inertial torque during the flight pass. During a flight, one actuator maybe break down or weather conditions may influence the dynamic as an external disturbance so designing a fault-tolerant control system (FTCS) is necessary for quadrotor UAVs.

In recent years, repeatedly, FTCS has been designed based on back-stepping and sliding mode control (SMC). A combination of back-stepping and SMC was used to design a

FTCS where actuator fault was considered as a single-rotor failure [1]. By attending to unmeasured states, actuator fault, control input constraints, and external disturbances, an adaptive back-stepping was designed for quadrotor [2] and a robust FTCS based on constraint back-stepping technique was designed [3]. A robust back-stepping controller with adaptive interval type-2 fuzzy logic was proposed to control the attitude and position of the modified quadrotor UAVs under actuator faults and external disturbances [4, 5]. In [6], to cope with wind effect and actuator faults, the decentralized fractional-order (FO) back-stepping adaptive neural fault-tolerant control (FTC) method was presented for the altitude subsystem of UAVs. To ensure fast and global finite-time stability of the UAVs states in the presence of motor failure, a FTCS based on back-stepping terminal sliding mode controller was designed [7]. In [8, 9], a FTCS based on

a dual adaptive back-stepping method was considered despite the actuator's effectiveness. A new FTCS design according to an adaptive neural network and SMC was presented for quadrotor UAVs where external disturbances and actuator faults were approximated by the neural network [10].

Sliding mode control is a nonlinear control strategy to cope with the uncertainties and external disturbances on the sliding surface [11–14], and this method repeatedly was applied for designing a FTCS for the quadrotor UAVs. In [15], a SMC for quadrotor UAVs was designed to obtain sustained performance in the presence of actuator faults. Based on a nonsingular terminal sliding mode control (NTSMC), finite-time position, and altitude condition, a flight controller was proposed for a quadrotor with a total rotor failure [16]. A fault-tolerant normal adaptive sliding mode control (NASMC) approach was presented to account with uncertainties and actuator faults [17]. A dual adaptive fault-tolerant control strategy for a quadrotor helicopter based on adaptive sliding mode control and adaptive boundary layer was designed despite the unknown actuator's faults and uncertainties [18]. In the presence of the rear servo's stuck fault of tri-rotor [19], a nonlinear FTCS according to an adaptive sliding mode control was presented. A comparative study of SMC, ISMC, and ITSMC based on fault-tolerant controllers for trajectory tracking of the quadrotor UAVs subject to actuator faults was presented [20, 21]. In [22, 23], an observer based on sliding mode observer (SMO) was utilized to estimate the input saturation and actuator faults, and also a finite-time fault-tolerant controller was presented for quadrotor UAVs. In [24], a fault-tolerant attitude stabilization control problem of a quadrotor UAV was addressed by a FTCS based on an integral-type sliding mode control strategy. By utilizing the fuzzy neural networks (FNNs), the unknown nonlinear fault actuator was estimated, and an adaptive fractional-order fault-tolerant cooperative control based on distributed sliding mode (DSM) was proposed [25]. For multi UAVs despite the rotor failure and input saturation, a distributed finite-time sliding mode observer was used to estimate unknown nonlinear fault terms [26]. In [27], an observer based on SMC was designed and analyzed for a discrete T-S fuzzy model in the presence of communication burden and a logarithmic quantizer that reachability of the prescribed sliding surface was improved. In order to improve the reachability of the sliding surface, a SMC in the discrete form was presented with integral sliding surface [28].

In an attempt to design ILCA for quadrotor UAVs, in [29], to solve the effect of external disturbances and system model uncertainties, generated control input by ILCA was added to PID controller. A developed fault-tolerant iterative learning control law for a class of linear time-delay system with actuator faults was presented in [30]. A cooperative adaptive iterative learning fault-tolerant control algorithm with the radial basis function neural network is proposed for multiple subway trains subject to the time-iteration-dependent actuator faults [31]. In [32], to compensate the systematic modeling errors, the iterative learning algorithm by contribution of feed forward controller was used until the

error of states was zero. To reject the external disturbances and improve the accuracy of performance, ILC was used for control of multi-quadrotor where each vehicle learns from the experience of its own and its neighbours' previous task repetitions [33].

According to the previous references, some challenges occurred during actuator faults such as constant tracking errors, long time to force states toward references trajectory, and the effect of external disturbances on the performance of the quadrotor. The contribution of this work is to design a FTCS for the quadrotor UAVs despite the actuator faults by combination of a classic controller and an online repetitive algorithm; therefore, the mentioned control strategy can reduce the response time to actuator faults and have better tracking performance. The loss of effectiveness and bias faults are considered as actuator faults. ILCA is used to compensate the unknown fault input based on online and simple formulas in each iteration where the next unknown fault inputs are generated according to previous results [34] as a control input. A FTCS is designed and analyzed based on BISMIC for quadrotor UAVs. Finally, in a flight motion in the presence of the actuator failures, the generated inputs based on ILCA and BISMIC are added to calculate the total control input. The Lyapunov theory is utilized to justify the stability of the system. The results show that the proposed method (ILCA) has better performance in comparison with another method, and the mentioned control strategy has better tracking, accuracy, and robustness.

The remainder of the paper is organized as follows. Section 2 illustrates the quadrotor UAVs dynamics despite the actuator faults and external disturbances. ILCA to compensate the effect of the unknown fault inputs and external disturbances is designed in Section 3. The FTCS based on BISMIC and stability study are presented in Section 4. Simulation results are presented in Section 5, and finally Section 6 concludes the paper.

1.1. Notation. Any vector or matrix is presented with bold letter. R^n refers to the n -dimensional Euclidean space and $R^{m \times n}$ is real matrix by $m \times n$ size. All the mode equations are time dependent. The state vector is introduced by x . The first and second time derivations of the states vector are cited, respectively, as $\dot{x}$ and $\ddot{x}$.

2. Quadrotor UAVs with Actuator Faults

In this section, at first, the full nonlinear dynamic of the quadrotor UAVs by considering the external disturbances and without actuators fault is given [35] as follows:

$$\ddot{x} = (\sin \theta \cos \varphi \cos \psi + \sin \varphi \sin \psi) \left(\frac{b}{m} \right) u_1 - \frac{d_x}{m}, \quad (1)$$

$$\ddot{y} = (\cos \varphi \sin \theta \cos \psi + \sin \varphi \sin \psi) \left(\frac{b}{m} \right) u_1 - \frac{d_y}{m}, \quad (2)$$

$$\ddot{z} = -g + \cos \theta \cos \varphi \left(\frac{b}{m} \right) u_1 - \frac{d_z}{m}, \quad (3)$$

$$\ddot{\varphi} = \dot{\theta} \dot{\psi} \frac{I_y - I_z}{I_y} + \dot{\theta} \Omega_r \frac{J_r}{I_x} + \frac{Lb}{I_x} u_2 - \frac{d_\varphi}{I_x}, \quad (4)$$

$$\ddot{\theta} = \dot{\varphi} \dot{\psi} \frac{I_z - I_x}{I_y} + \dot{\varphi} \Omega_r \frac{J_r}{I_y} + \frac{Lb}{I_y} u_3 - \frac{d_\theta}{I_y}, \quad (5)$$

$$\ddot{\Psi} = \dot{\varphi} \dot{\theta} \frac{I_x - I_y}{I_z} + \frac{d}{I_z} u_4 - \frac{d_\Psi}{I_z}, \quad (6)$$

where x , y , and z are relating to the translational subsystem and φ , θ , and ψ denote the roll, pitch, and yaw angle of the rotational subsystem of the quadrotor UAVs.

d_x , d_y , d_z , d_φ , d_θ , and d_ψ are external disturbances. I_x , I_y , and I_z are entitled as moments of inertia of the quadrotor to the corresponding axes. g is the gravitational constant, m is the total mass of the quadrotor, L is the distance from the center of the quadrotor to the center of propeller, J_r is the inertia relating to the rotor, and b and d are the thrust and drag coefficients, respectively. u_1 , u_2 , u_3 , and u_4 are the control inputs that produce thrust, rolling torque, pitching torque, and yawing torque, respectively, in the rotor that are described as follows:

$$\begin{aligned} u_1 &= \Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2, \\ u_2 &= -\Omega_2^2 + \Omega_4^2, \\ u_3 &= -\Omega_3^2, \\ u_4 &= \Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2. \end{aligned} \quad (7)$$

The definition of quadrotor dynamic parameters in equations (1)–(6) is cited in Table 1.

The quadrotor UAVs structure is shown in Figure 1.

The structure of the quadrotor consists of four rotors that each of them can generate thrust and torque for each direction movement. So, in a flight motion, actuators fault or rotors failure may occur or bad weather conditions may influence the dynamic as external disturbances. In this study, the loss of effectiveness and bias fault for the control signals of the main dynamic equations (1)–(6) are modeled as follows:

$$u_i = E\delta_i + \zeta_i, \quad \text{for } i = 1, 2, 3, 4, \quad (8)$$

where $\delta_i = [\delta_1, \delta_2, \delta_3, \delta_4]^T$ is relating to command control vector, $\zeta_i = [\zeta_1, \zeta_2, \zeta_3, \zeta_4]^T$ is bias faults, and $E_i = \text{diag}\{E_1, E_2, E_3, E_4\} \in (\bar{E}, 1]$ is the rotor effectiveness failure matrix with $\bar{E}$ as a known lower bound to keep the

TABLE 1: Parameters of the dynamic.

Parameters	Value	Unit
L (arm length)	0.232	M
b (thrust coefficient)	3.13×10^{-5}	n.s^2
d (drag coefficient)	7.5×10^{-7}	m.s^2
m (mass of quadrotor)	0.52	kg
I_x (moment of inertia)	6.228×10^{-3}	kg.m^2
I_y (moment of inertia)	6.228×10^{-3}	kg.m^2
I_z (moment of inertia)	1.121×10^{-2}	kg.m^2
J_r (rotor inertia)	6×10^{-5}	kg.m^2
Ω_r (speed component)	297	rad/s

FIGURE 1: Quadrotor UAVs structure.

controllability of the quadrotor UAVs. It should be taken into consideration that when $E_i = 1$ and $\zeta_i = 0$, it means that the rotors work without any problem and failure, and $0 < \bar{E} < E_i < 1$, $\zeta_i \neq 0$ illustrates that the i_{th} the rotor is working with low effectiveness and bias fault.

Remark 1. Constants of the rotor effectiveness and bias failures are known, but the lower bound as $\bar{E}$ should be defined to maintain controllability and avoid actuator saturation of the quadrotor after the occurrence of the fault. This limitation can be calculated based on rotor and quadrotor physical parameters so that the following inequality condition is satisfied:

$$\bar{E} > \left(\frac{1}{2\Omega_{\max}} \right) \left(\frac{mg}{b} \right), \quad (9)$$

where $\Omega_{\max}$ is the maximum rotor velocity limit. It should be taken into consideration that $\bar{E}$ can be reduced by changing the total quadrotor mass or employing another rotor with a higher velocity saturation limit.

By considering actuator fault as equation (8), the dynamic of quadrotor UAVs equations (1)–(6) by considering states vector as $X_i = [x, y, z, \varphi, \theta, \psi, \dot{x}, \dot{y}, \dot{z}, \dot{\varphi}, \dot{\theta}, \dot{\psi}]$ can be rewritten in the following form:

$$\dot{X}_i = \begin{bmatrix} x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ (\sin x_5 \cos x_4 \sin x_6 + \sin x_4 \sin x_6) \left(\frac{b}{m} \right) (E_1 \delta_1 + \zeta_1) - \left(\frac{d_x}{m} \right) \\ (\cos x_4 \sin x_5 \cos x_6 - \sin x_4 \sin x_6) \left(\frac{b}{m} \right) (E_1 \delta_1 + \zeta_1) - \left(\frac{d_y}{m} \right) \\ -g + \cos x_5 \cos x_4 \left(\frac{b}{m} \right) (E_1 \delta_1 + \zeta_1) - \left(\frac{d_z}{m} \right) \\ x_{11} x_{12} \frac{I_y - I_z}{I_y} + x_{11} \Omega_r \frac{J_r}{I_x} + \frac{Lb}{I_x} (E_2 \delta_2 + \zeta_2) - \left(\frac{d_\varphi}{I_x} \right) \\ x_{10} x_{12} \frac{I_z - I_x}{I_y} + x_{10} \Omega_r \frac{J_r}{I_y} + \frac{Lb}{I_x} (E_3 \delta_3 + \zeta_3) - \left(\frac{d_\theta}{I_x} \right) \\ x_{11} x_{12} \frac{I_x - I_y}{I_z} + \frac{d}{I_z} (E_4 \delta_4 + \zeta_4) - \left(\frac{d_\psi}{I_x} \right) \end{bmatrix}. \quad (10)$$

3. Actuator Faults Estimation Based on ILCA

To incline the accuracy of tracking performance and reject the external disturbances during a flight motion, machine learning control is designed and analyzed repeatedly for quadrotor UAV [36]. ILCA is a powerful method for approximating the uncertainties of nonlinear dynamics [37]. The mentioned learning algorithm is proposed to solve the repeated tasks in each iteration, and it runs until the errors of states are zero [38]. ILCA is a more accurate method in comparison with other approximation methods because it is an online method that the next unknown control input is calculated based on recorded experiments in the previous iterations. The main contribution of ILCA is to calculate the control signal as unknown fault input U_d . Next, U_{di} is combined with u_i for calculating the total control input. In this paper, ILCA is used to estimate the loss of effectiveness fault and bias fault for the quadrotor dynamic. The control system schematic diagram is shown in Figure 2.

The states for designing ILCA is selected as the following vector:

$$\begin{bmatrix} \dot{Z} \\ \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -g + \cos \theta \cos \varphi \left(\frac{1}{m} \right) u_1 - \frac{d_z}{m} \\ \dot{\theta} \dot{\psi} \frac{I_y - I_z}{I_y} + \dot{\theta} \Omega_r \frac{J_r}{I_x} + \frac{1}{I_x} u_2 - \frac{d_\varphi}{I_x} \\ \dot{\varphi} \dot{\psi} \frac{I_z - I_x}{I_y} + \dot{\varphi} \Omega_r \frac{J_r}{I_y} + \frac{1}{I_x} u_3 - \frac{d_\theta}{I_x} \\ \dot{\theta} \dot{\psi} \frac{I_x - I_y}{I_z} + \frac{1}{I_z} u_4 - \frac{d_\psi}{I_x} \end{bmatrix}. \quad (11)$$

It should be taken into consideration that without actuator fault, BISMCM can track the reference commands as follows:

$$X_{\text{ref}} = f(U_{\text{BISMCM}}). \quad (12)$$

The formulation of ILCA for the next iteration is described as follows:

FIGURE 2: Control system schematic diagram.

$$U_{di,t+1} = U_{di,t} - F^T K_i e_X, \quad \text{for } i = 1, 2, 3, 4, \quad (13)$$

where $U_{di,0}$ is the initial input, K_i is the positive learning gains, and e_X is considered as an error vector as follows:

$$e_{Xi} = X_i - X_{\text{ref},i}, \quad (14)$$

where F is a learning rate matrix along the desired trajectories. According to equation (11) and the linear time-varying method, F is written as follows:

$$F = \begin{bmatrix} \frac{dX_9}{du_1} & \cdots & \frac{dX_9}{du_4} \\ \vdots & \ddots & \vdots \\ \frac{dX_{12}}{du_1} & \cdots & \frac{dX_{12}}{du_4} \end{bmatrix}. \quad (15)$$

In the presence of the actuator faults, the total control input is written based on unknown fault input U_{di} and u_i as follows:

$$U_{\text{total},i} = u_i + U_{di}. \quad (16)$$

There are two cases in the FTCS of this paper as follows:

- (a) If the quadrotor flight is in the normal condition, it means that there are no faults and external disturbances, and the total control input is calculated based on the BISMIC as follows:

$$\begin{aligned} U_{\text{total},i} &= u_i, \\ \dot{X}_i &= f(X_i) + P_i g(X_i) U_{\text{total}} = u_i, \\ \dot{X}_i &= f(X_i) + P_i g(X_i) (u_i). \end{aligned} \quad (17)$$

- (b) If the quadrotor is not in the normal condition, it means that there are loss of effectiveness and bias fault and external disturbances, and the total control input is calculated based on the BISMIC and unknown fault input as follows:

$$\begin{aligned} U_{\text{total}} &= u_i + U_{di}, \\ \dot{X}_i &= f(X_i) + P_i g(X_i) U_{\text{total}}, \\ \dot{X}_i &= f(X_i) + P_i g(X_i) (u_i + U_{di}), \end{aligned} \quad (18)$$

where P_i is the coefficient matrix. Then, equation (17) is rewritten in the following form around the ideal operating point of u_i :

$$\dot{X}_i \sim f(X_i) + P_i g(X_i)(u_i) + P_i \left(\frac{d}{dU} g|_{u_i} \right) \cdot U_{di}. \quad (19)$$

The error vector equation (14) can be rewritten as a function of the unknown failure input as follows:

$$e_{Xi} = X_i - X_{\text{ref},i} = P_i \left(\frac{d}{dU} g|_{u_i} \right) \cdot U_{di} = P_i \cdot F U_{di}. \quad (20)$$

To analyze the stability of the mentioned ILCA, that is, the convergence of the learned input as the number of iterations goes to infinity, lifted-system in vector format is deployed [39]. The system dynamic and the updating rule can be presented as follows:

$$\begin{bmatrix} \dot{X}_3 \\ \dot{X}_4 \\ \dot{X}_5 \\ \dot{X}_6 \end{bmatrix} = f(X_i) + g(X_i) P_i \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} + \begin{bmatrix} U_{d1} \\ U_{d2} \\ U_{d3} \\ U_{d4} \end{bmatrix}, \quad (21)$$

$$\begin{bmatrix} U_{d1,t+1} \\ U_{d2,t+1} \\ U_{d3,t+1} \\ U_{d4,t+1} \end{bmatrix} = \begin{bmatrix} U_{d1,t} \\ U_{d2,t} \\ U_{d3,t} \\ U_{d4,t} \end{bmatrix} - F^T K_i \begin{bmatrix} e_{X3} \\ e_{X4} \\ e_{X5} \\ e_{X6} \end{bmatrix}. \quad (22)$$

By considering P_i and K_i as lower-triangular, Toeplitz matrices, we have

$$P_i = \begin{bmatrix} P_1 & 0 & 0 & 0 \\ P_2 & P_1 & 0 & 0 \\ P_3 & P_2 & P_1 & 0 \\ P_4 & P_3 & P_2 & P_1 \end{bmatrix}, \quad (23)$$

$$K_i = \begin{bmatrix} K_1 & 0 & 0 & 0 \\ K_2 & K_1 & 0 & 0 \\ K_3 & K_2 & K_1 & 0 \\ K_4 & K_3 & K_2 & K_1 \end{bmatrix}. \quad (24)$$

By the combination of equations (23) and (24) with equations (21) and (22), we have

$$\begin{bmatrix} \dot{X}_3 \\ \dot{X}_4 \\ \dot{X}_5 \\ \dot{X}_6 \end{bmatrix} = f(X_i) + g(X_i) \underbrace{\begin{bmatrix} P_1 & 0 & 0 & 0 \\ 0 & P_1 & 0 & 0 \\ 0 & 0 & P_1 & 0 \\ 0 & 0 & 0 & P_1 \end{bmatrix}}_{I_N \oplus P} \underbrace{\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}}_{u_i} + \underbrace{\begin{bmatrix} U_{d1} \\ U_{d2} \\ U_{d3} \\ U_{d4} \end{bmatrix}}_{U_{di}}, \quad (25)$$

$$\underbrace{\begin{bmatrix} U_{d1,t+1} \\ U_{d2,t+1} \\ U_{d3,t+1} \\ U_{d4,t+1} \end{bmatrix}}_{U_{di,t+1}} = \underbrace{\begin{bmatrix} U_{d1,t} \\ U_{d2,t} \\ U_{d3,t} \\ U_{d4,t} \end{bmatrix}}_{U_{di,t}} - \underbrace{\begin{bmatrix} \frac{dX_9}{du_1} & \cdots & \frac{dX_9}{du_4} \\ \vdots & \ddots & \vdots \\ \frac{dX_{12}}{du_1} & \cdots & \frac{dX_{12}}{du_4} \end{bmatrix}}_F \underbrace{\begin{bmatrix} K_1 & 0 & 0 & 0 \\ 0 & K_1 & 0 & 0 \\ 0 & 0 & K_1 & 0 \\ 0 & 0 & 0 & K_1 \end{bmatrix}}_{I_N \oplus K_i} \underbrace{\begin{bmatrix} e_{X3} \\ e_{X4} \\ e_{X5} \\ e_{X6} \end{bmatrix}}_{e_{xi}}, \quad (26)$$

where $\oplus$ denotes the Kronecker product and I_N with $(N \times N)$ is the identity matrix. Using the error definition equation (14) with equation (26),

$$\underbrace{\begin{bmatrix} U_{d1,t+1} \\ U_{d2,t+1} \\ U_{d3,t+1} \\ U_{d4,t+1} \end{bmatrix}}_{U_{di,t+1}} = \underbrace{\begin{bmatrix} U_{d1,t} \\ U_{d2,t} \\ U_{d3,t} \\ U_{d4,t} \end{bmatrix}}_{U_{di,t}} - \underbrace{\begin{bmatrix} \frac{dX_9}{du_1} & \cdots & \frac{dX_9}{du_4} \\ \vdots & \ddots & \vdots \\ \frac{dX_{12}}{du_1} & \cdots & \frac{dX_{12}}{du_4} \end{bmatrix}}_F \underbrace{\begin{bmatrix} K_1 & 0 & 0 & 0 \\ 0 & K_1 & 0 & 0 \\ 0 & 0 & K_1 & 0 \\ 0 & 0 & 0 & K_1 \end{bmatrix}}_{I_N \oplus K_i} \underbrace{\begin{bmatrix} X_3 \\ X_4 \\ X_5 \\ X_6 \end{bmatrix}}_{X_i} - \underbrace{\begin{bmatrix} X_{ref,3} \\ X_{ref,4} \\ X_{ref,5} \\ X_{ref,6} \end{bmatrix}}_{X_{ref,i}}. \quad (27)$$

Equation (28) can be rewritten as following form:

$$U_{di,t+1} = U_{di,t} - F^T (I_N \oplus K_i) (X_i - X_{ref,i}). \quad (28)$$

Replacing equation (20) into equation (28),

$$U_{di,t+1} = U_{di,t} - F^T F P_i (I_N \oplus K_i) (U_{di}). \quad (29)$$

Definition 1. The ILC is asymptotically stable if there exist $\overline{U}_i \cdot |U_{total,i}| < \overline{U}_i$ and $\lim_{t \rightarrow \infty} U_{total,i}$.

4. Faults Tolerant Control System Design

In this section, a FTCS based on BISMCM is designed for quadrotor UAVs despite the actuator faults. The dynamic of the system with rotor failures is considered as equation (11). The combination of back-stepping and integral sliding mode control can force the state's error to zero and incline the accuracy of the tracking [40]. Next, the Lyapunov theory is employed to justify the stability of the subsystems.

$z_3 = x_3 - x_{3d}$ is defined as altitude error, and the time derivation can be written as $\dot{z}_3 = \dot{x}_3 - \dot{x}_{3d}$. By considering

positive Lyapunov function and the time derivation as $v_1 = (1/2)z_3^2$ and $\dot{v}_1 = z_3 \dot{z}_3$ respectively, we have

$$\dot{v}_1 = z_3 (\dot{x}_3 - \dot{x}_{3d}). \quad (30)$$

Define $z_9 = \dot{x}_3 - a_1$, where a_1 is a virtual control input. Then, $\dot{v}_1$ can be rewritten as follows:

$$\dot{v}_1 = z_3 z_9 + z_3 (a_1 - \dot{x}_{3d}). \quad (31)$$

To make the stability of equation (31), a_1 is defined as follows:

$$a_1 = \dot{x}_{3d} - c_1 z_3, \quad (32)$$

where $c_1 > 0$. Next, by replacing equation (32) into equation (31), $\dot{v}_1$ can be computed as follows:

$$\dot{v}_1 = z_3 z_9 + z_3 (\dot{x}_{3d} - c_1 z_3 - \dot{x}_{3d}) = -c_1 z_3^2 + z_3 z_9. \quad (33)$$

The integral sliding mode surface for the translation subsystem is selected as follows:

$$s_1 = z_9 + k_1 \int z_3. \quad (34)$$

By the combination of the switching law as $\dot{s}_1 = -\varepsilon s_1 - \text{sgn}(s_1)$ with the time derivation of equation (34),

$$\delta_1 = \frac{m}{e_1 \cos x_5 \cos x_4 b} \left[-(k_1 + c_1)z_3 + g - \varepsilon s_1 - \text{sgn}(s_1) + \dot{x}_{9d} + \frac{d_z}{m} \right] - \frac{U_{1d}}{e_1} - \frac{\zeta_1}{e_1}. \quad (36)$$

Theorem 1. By considering the calculated control command in equation (35), the z position response will be driven to a certain bounded region around sliding surface equation (33).

Proof. A positive Lyapunov function is defined for stability analysis as follows:

$$v_2 = \frac{1}{2}v_1^2 + \frac{1}{2}s_1^2. \quad (37)$$

The time derivation of equation (37) is calculated as follows:

$$\dot{v}_2 = v_1 \dot{v}_1 + s_1 \dot{s}_1, \quad (38)$$

and

$$\dot{z}_9 + k_1 z_3 = -\varepsilon s_1 - \text{sgn}(s_1). \quad (35)$$

Replacing equation (33) with equation (35), the control torque δ_1 is calculated as follows:

$$\dot{v}_2 = v_1 \dot{v}_1 + s_1 \left(-g + \cos x_5 \cos x_4 \left(\frac{b}{m} \right) (e_1 \delta_1 + \zeta_1 + U_d) - \frac{d_z}{m} \right). \quad (39)$$

By replacing equation (36) into equation (39), it can be concluded that the necessary condition of the Lyapunov theorem is verified ($\dot{v}_2 < 0$) and the state trajectory can be driven to a certain bounded region around the sliding surface.

Designing a fault-tolerant control system (FTCS) for the rotational subsystem is similar to the translational subsystem. More definition about calculating δ_2 , δ_3 , and δ_4 is presented in Appendix. The control torques δ_2 , δ_3 , and δ_4 are designed as follows:

$$\begin{aligned} \delta_2 &= \frac{I_x}{Lb} \left[-(k_2 + c_2)z_4 - \varepsilon s_2 - \text{sgn}(s_2) + \dot{x}_{10d} + \frac{d_\varphi}{I_x} - x_{11} \Omega_r \frac{J_r}{I_x} - x_{11} x_{12} \frac{I_y - I_z}{I_y} \right] - \frac{U_{2d}}{e_2} - \frac{\zeta_2}{e_2}, \\ \delta_3 &= \frac{I_y}{Lb} \left[-(k_3 + c_3)z_5 - \varepsilon s_3 - \text{sgn}(s_3) + \dot{x}_{11d} + \frac{d_\theta}{I_y} - x_{10} \Omega_r \frac{J_r}{I_y} - x_{10} x_{12} \frac{I_z - I_x}{I_y} \right] - \frac{U_{3d}}{e_3} - \frac{\zeta_3}{e_3}, \\ \delta_4 &= \frac{I_z}{d} \left[-(k_4 + c_4)z_6 - \varepsilon s_4 - \text{sgn}(s_4) + \dot{x}_{12d} + \frac{d_\psi}{I_z} - x_{11} x_{12} \frac{I_x - I_y}{I_z} \right] - \frac{U_{4d}}{e_4} - \frac{\zeta_4}{e_4}. \end{aligned} \quad (40)$$

5. Simulation

In this section, the performance of the proposed control strategy is evaluated in comparison with [10] that used a FTCS based on SMC and neural network. The initial states for the rotational and the translational subsystem are considered as follows: $[x, y, z] = [0.4, 0.7, 0]$ and $[\varphi, \theta, \psi] = [0, 0, -0.12]$. The controller parameters are selected as follows: $k_i = 100$ for $i = 1, 2, 3, 4$ and $K, \varepsilon, c_1, c_2, c_3, c_4 > 0$. The parameters of the quadrotor UAVs dynamic are listed in Table 1. The external disturbances are defined as follows:

$$\begin{aligned} d_x &= 2 \sin t, d_y = 2 \sin t, d_z = 2 \sin t, \\ d_\varphi &= 0.1 \sin\left(\frac{2\pi}{50}t\right), d_\theta = 0.1 \sin\left(\frac{2\pi}{50}t\right), \\ d_\psi &= 0.1 \sin\left(\frac{2\pi}{50}t\right). \end{aligned} \quad (41)$$

The desired trajectories for the rotational subsystem are defined as follows: $x_{1d} = 0.2 * \sin(\pi t)$, $x_{2d} = 0.2 *$

$\cos(\pi t)$, and $x_{3d} = 0.1 * t$, and reference commands for the translational subsystem are selected as follows [31]:

$$\begin{aligned} x_{4d} &= \cos^{-1} \left(\frac{mk_x e_x}{bu_1 \sin x_{5d} \cos x_{6d}} - \frac{\sin x_{4d} \sin x_{6d}}{\sin x_{5d} \cos x_{6d}} \right), \\ x_{5d} &= \sin^{-1} \left(\frac{mk_y e_y}{bu_1 \cos x_{4d} \cos x_{6d}} + \frac{\sin x_{4d} \sin x_{6d}}{\cos x_{4d} \cos x_{6d}} \right). \end{aligned} \quad (42)$$

The unknown actuator loss of effectiveness fault and bias fault occurred at 30 seconds which is described as follows:

$$\begin{aligned} E &= \begin{cases} \text{diag}\{1, 1, 1, 1\}, & 0 < t < 30, \\ \text{diag}\{0.4, 1, 1, 1\}, & \text{else}, \end{cases} \\ \zeta &= \begin{cases} [0, 0, 0, 0]^T, & 0 < t < 30, \\ [0.6, 0, 0, 0]^T, & \text{else}. \end{cases} \end{aligned} \quad (43)$$

The actuator fault influences the controller u_1 at $t = 30$ s by a bias fault $e_1 = 0.4$ and a loss of effectiveness with

FIGURE 3: Position X (M). FIGURE 4: Position Y (M). FIGURE 5: Position Z (M).

FIGURE 6: Roll angle (deg).

FIGURE 7: Pitch angle (deg).

FIGURE 8: Yaw angle (deg).

FIGURE 9: Control input u_1 (N). FIGURE 10: Control input u_2 (nm). FIGURE 11: Control input u_3 (nm).

FIGURE 12: Control input u_4 (nm).

TABLE 2: Numerical index.

Name of index	BISMIC with ILC	SMC with NN
$\int x_3^2 + Z_3$	1.570	2.107
$\int x_4^2 + Z_4$	1.2662	1.470
$\int x_5^2 + Z_5$	0.7384	1.194
$\int x_6^2 + Z_6$	8.4865	10.485

$\zeta_1 = 0.6$. It is crystal clear that the controllers u_2 , u_3 , and u_4 are affected by u_1 .

Figures (3)–(5) illustrate the translational states tracking such as x -, y -, and z -direction. From the results, it can be concluded that by using the proposed scheme based on BISMIC and ILCA approach, system states have a better tracking performance compared with [10]. It is obvious that the unknown actuator loss of effectiveness fault and bias fault at $s = 30$ has a more destructive effect on [10] because the neural network cannot accurately estimate the unknown rotor failure in comparison with ILCA.

Figures (6)–(8) show the roll, pitch, and yaw angle for both methods. It is crystal clear that the mentioned FTCS has better stability for the states at $s = 30$ despite the stuck at 60% of its desired value of rotor 1. The integral terms in the sliding surface and accurate estimation in terms of unknown fault input ensured that the states by considering the mentioned control strategy have good performance to get back to the reference values after the occurrence of the fault.

The total control inputs for the system under the fault actuator are shown in Figures (9)–(12). From these figures, it can be concluded that after the rotor fault, the control signals change at $t = 30$ s for both control strategies but the mentioned FTCS based on BISMIC and ILC has lower fluctuation in comparison with [10]. To validate the effectiveness of the proposed controller, numerical indexes are shown in Table 2 for both methods. The values of indexes in our control strategy are less than the comparative method. It means that our control strategy is faster than the another method to force the error of states toward zero.

6. Conclusion

In this paper, a FTCS based on BISMIC was designed and analyzed for both rotational and translational subsystems of quadrotor UAVs in the presence of actuator faults and external disturbances. The loss of effectiveness fault and bias fault were considered as actuator faults in the dynamic. Next, ILCA was presented to calculate the unknown faults input. The Lyapunov theory was proved that the mentioned FTCA method can guarantee the stability of the closed-loop subsystems of quadrotor UAVs. The simulation results show that the FTCS by considering BISMIC and ILCA has better performance in terms of high accuracy, better tracking, and estimation in comparison with another method [10].

Appendix

$z_4 = x_4 - x_{4d}$ is defined as altitude error, and the time derivation can be written as $\dot{z}_4 = \dot{x}_4 - \dot{x}_{4d}$.

By considering positive Lyapunov function and the time derivation as $v_3 = 1/2z_4^2$ and $\dot{v}_3 = z_4\dot{z}_4$, respectively, we have

$$\dot{v}_3 = z_4(\dot{x}_4 - \dot{x}_{4d}). \quad (\text{A.1})$$

Define $z_{10} = \dot{x}_4 - a_2$, where a_2 is a virtual control input. Then, $\dot{v}_3$ can be rewritten as follows:

$$\dot{v}_3 = z_4 z_{10} + z_4(a_2 - \dot{x}_{4d}). \quad (\text{A.2})$$

To make the stability of equation (A.2), a_2 is defined as follows:

$$a_2 = \dot{x}_{4d} - c_2 z_4, \quad (\text{A.3})$$

where $c_2 > 0$. Next, by replacing equation (A.3) into equation (A.2), $\dot{v}_3$ can be computed as follows:

$$\dot{v}_3 = z_4 z_{10} + z_4(\dot{x}_{4d} - c_2 z_4 - \dot{x}_{4d}) = -c_2 z_4^2 + z_4 z_{10}. \quad (\text{A.4})$$

The integral sliding mode surface for the translation subsystem is selected as follows:

$$s_2 = z_{10} + k_2 \int z_4. \quad (\text{A.5})$$

By the combination of the switching law as $\dot{s}_2 = -\varepsilon s_2 - \text{sgn}(s_2)$ with the time derivation of equation (A.5),

$$\delta_2 = \frac{I_x}{Lb} \left[-(k_2 + c_2)z_4 - \varepsilon s_2 - \text{sgn}(s_2) + \dot{x}_{10d} + \frac{d_\varphi}{I_x} - x_{11}\Omega_r \frac{J_r}{I_x} - x_{11}x_{12} \frac{I_y - I_z}{I_y} \right] - \frac{U_{2d}}{e_2} - \frac{\zeta_2}{e_2}. \quad (\text{A.7})$$

A positive Lyapunov function is defined for stability analysis as follows:

$$v_4 = \frac{1}{2}v_3^2 + \frac{1}{2}s_2^2. \quad (\text{A.8})$$

$$\dot{z}_{10} + k_2 z_4 = -\varepsilon s_2 - \text{sgn}(s_2). \quad (\text{A.6})$$

Replacing equation (A.4) with equation (A.6), the control torque δ_2 is calculated as follows:

The time derivation of equation (A.8) is calculated as follows:

$$\dot{v}_4 = v_3 \dot{v}_3 + s_2 \dot{s}_2, \quad (\text{A.9})$$

and

$$\dot{v}_4 = v_3 \dot{v}_3 + s_2 \left(x_{11}x_{12} \frac{I_y - I_z}{I_y} + x_{11}\Omega_r \frac{J_r}{I_x} - \frac{d_\varphi}{I_x} + \frac{Lb}{I_x} (e_2 \delta_2 + \zeta_2 + U_{2d}) - \frac{d_\varphi}{m} \right). \quad (\text{A.10})$$

By replacing equation (A.7) into equation (A.10), the necessary condition of the Lyapunov theorem is verified ($\dot{v}_4 < 0$).

$z_5 = x_5 - x_{5d}$ is defined as altitude error, and the time derivation can be written as $\dot{z}_5 = \dot{x}_5 - \dot{x}_{5d}$.

By considering positive Lyapunov function and the time derivation as $v_5 = (1/2)z_5^2$ and $\dot{v}_5 = z_5 \dot{z}_5$, respectively, we have

$$\dot{v}_5 = z_5 + (\dot{x}_5 - \dot{x}_{5d}). \quad (\text{A.11})$$

Define $z_{11} = \dot{x}_5 - a_3$, where a_3 is a virtual control input. Then, $\dot{v}_5$ can be rewritten as follows:

$$\dot{v}_5 = z_5 z_{11} + z_5 (a_3 - \dot{x}_{5d}). \quad (\text{A.12})$$

To make the stability of equation (A.12), a_3 is defined as follows:

$$a_3 = \dot{x}_{5d} - c_3 z_5, \quad (\text{A.13})$$

where $c_3 > 0$. Next, by replacing equation (A.13) into equation (A.12), $\dot{v}_5$ can be computed as follows:

$$\dot{v}_5 = z_5 z_{11} + z_5 (\dot{x}_{5d} - c_3 z_5 - \dot{x}_{5d}) = -c_3 z_5^2 + z_5 z_{11}. \quad (\text{A.14})$$

The integral sliding mode surface for the translation subsystem is selected as follows:

$$s_3 = z_{11} + k_3 \int z_5. \quad (\text{A.15})$$

By the combination of the switching law as $\dot{s}_3 = -\varepsilon s_3 - \text{sgn}(s_3)$ with the time derivation of equation (A.15),

$$\dot{z}_{11} + k_3 z_5 = -\varepsilon s_3 - \text{sgn}(s_3). \quad (\text{A.16})$$

Replacing equation (A.14) with equation (A.16), the control torque δ_3 is calculated as follows:

$$\delta_3 = \frac{I_y}{Lb} \left[-(k_3 + c_3)z_5 - \varepsilon s_3 - \text{sgn}(s_3) + \dot{x}_{12d} + \frac{d_\theta}{I_y} - x_{10}\Omega_r \frac{J_r}{I_y} - x_{10}x_{12} \frac{I_z - I_x}{I_y} \right] - \frac{U_{3d}}{e_3} - \frac{\zeta_3}{e_3}. \quad (\text{A.17})$$

The positive Lyapunov function is defined for stability analysis as follows:

$$v_6 = \frac{1}{2}v_5^2 + \frac{1}{2}s_3^2. \quad (\text{A.18})$$

The time derivation of equation (A.18) is calculated as follows:

$$\dot{v}_6 = v_5 \dot{v}_5 + s_3 \dot{s}_3, \quad (\text{A.19})$$

and

$$\dot{v}_6 = v_5 \dot{v}_5 + s_3 \left(-\frac{d_\theta}{I_y} + x_{10} \Omega_r \frac{I_r}{I_y} + x_{10} x_{12} \frac{I_z - I_x}{I_y} + \frac{Lb}{I_y} (e_3 \delta_3 + \zeta_3 + U_{3d}) - \frac{d_\theta}{m} \right). \quad (\text{A.20})$$

By replacing equation (A.17) into equation (A.20), the necessary condition of the Lyapunov theorem is verified ($\dot{v}_6 < 0$).

$z_6 = x_6 - x_{6d}$ is defined as altitude error, and the time derivation can be written as $\dot{z}_6 = \dot{x}_6 - \dot{x}_{6d}$.

By considering positive Lyapunov function and the time derivation as $v_7 = (1/2)z_6^2$ and $\dot{v}_7 = z_6 \dot{z}_6$, respectively, we have

$$\dot{v}_7 = z_6 (\dot{x}_6 - \dot{x}_{6d}). \quad (\text{A.21})$$

Define $z_{12} = \dot{x}_6 - a_4$, where a_4 is a virtual control input. Then, $\dot{v}_7$ can be rewritten as follows:

$$\dot{v}_7 = z_6 z_{12} + z_6 (a_4 - \dot{x}_{6d}). \quad (\text{A.22})$$

To make the stability of equation (A.22), a_4 is defined as follows:

$$a_4 = \dot{x}_{6d} - c_4 z_6, \quad (\text{A.23})$$

where $c_4 > 0$. Next, by replacing equation (A.23) into equation (A.22), $\dot{v}_7$ can be computed as follows:

$$\dot{v}_7 = z_6 z_{12} + z_6 (\dot{x}_{6d} - c_4 z_6 - \dot{x}_{6d}) - c_4 z_6^2 + z_6 z_{12}. \quad (\text{A.24})$$

The integral sliding mode surface for the translation subsystem is selected as follows:

$$s_4 = z_{12} + k_4 \int z_6. \quad (\text{A.25})$$

By the combination of the switching law as $\dot{s}_4 = -\varepsilon s_4 - \text{sgn}(s_4)$ with the time derivation of equation (A.25),

$$\dot{z}_{12} + k_4 z_6 = -\varepsilon s_4 - \text{sgn}(s_4). \quad (\text{A.26})$$

Replacing equation (A.24) with equation (A.26), the control torque δ_4 is calculated as follows:

$$\delta_4 = \frac{I_z}{d} \left[-(k_4 + c_4) z_6 - \varepsilon s_4 - \text{sgn}(s_4) + \dot{x}_{12d} + \frac{d_\psi}{I_z} - x_{11} x_{12} \frac{I_x - I_y}{I_z} \right] - \frac{U_{4d}}{e_4} - \frac{\zeta_4}{e_4}. \quad (\text{A.27})$$

Positive Lyapunov function is defined for stability analysis as follows:

$$v_8 = \frac{1}{2} v_7^2 + \frac{1}{2} s_4^2. \quad (\text{A.28})$$

The time derivation of equation (A.28) is calculated as follows:

$$\dot{v}_8 = v_7 \dot{v}_7 + s_4 \dot{s}_4, \quad (\text{A.29})$$

and

$$\dot{v}_8 = v_7 \dot{v}_7 + s_4 \left(-\frac{d_\psi}{I_z} + x_{11} x_{12} \frac{I_x - I_y}{I_z} + \frac{d}{I_z} (e_4 \delta_4 + \zeta_4 + U_{4d}) - \frac{d_\psi}{m} \right). \quad (\text{A.30})$$

By replacing equation (A.27) into equation (A.30), the necessary condition of the Lyapunov theorem is verified ($\dot{v}_8 < 0$).

Data Availability

The source code data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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