Quadrotor Attitude Control via Feedforward All-Coefficient Adaptive Theory

HONGYU CHU, (Member, IEEE), QI JING, (Graduate Student Member, IEEE), ZHIYUAN CHANG, YANHUA SHAO, XIAOQIANG ZHANG, (Member, IEEE), AND MITHUN MUKHERJEE, (Senior Member, IEEE)

1School of Information Engineering, Southwest University of Science and Technology, Mianyang 621010, China
2Guangdong Provincial Key Laboratory of Petrochemical Equipment Fault Diagnosis, Guangdong University of Petrochemical Technology, Maoming 525000, China

Corresponding author: Hongyu Chu (chuhongyu@swust.edu.cn)

This work was supported in part by the National Natural Science Foundation (NSFC) of China under Grant 61601382, in part by the Sichuan Provincial Science and Technology Support Project under Grant 2019YJ0325, in part by the Doctoral Fund of Southwest University of Science and Technology under Grant 16zx7148 and Grant 19zx7123, in part by the Longshan Academic Talent Research Supporting Program of Southwest University of Science and Technology (SWUST) under Grant 18LZX632, and in part by the Fund for Robot Technology Used for Special Environments, Key Laboratory of Sichuan Province, under Grant 13zxtk08.

ABSTRACT The use of quadrotors is proliferating across many civil applications, including those in the areas of the Internet of Things (IoT) and communications. Attitude control plays an important role in these applications, and designing a quadrotor attitude controller is a challenging task. Recently, several design methods for the attitude controller were presented with an accurate model. However, during the flying state, the quadrotor may be affected by several factors that cause unpredictable disturbances to the model. As a result, an accurate model of disturbances is difficult to establish. To address this problem, in this paper, a novel linear feedforward all-coefficient adaptive control (FACAC) strategy based on characteristic modeling is proposed. The contributions of our work are as follows. First, a second-order characteristic model of the quadrotor attitude control is established based on the dynamic equations. Second, an all-coefficient adaptive control (ACAC) controller that consists of the golden-section adaptive control law, the logic integral, and logic differential control laws is designed. The feedforward maintaining and tracking control law is integrated into the ACAC controller to shorten the settling time. Finally, extensive simulation results demonstrate that the performance of the proposed FACAC controller outperforms the state-of-the-arts.

INDEX TERMS Attitude control, all-coefficient adaptive control, characteristic model, feedforward, quadrotor.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) have attracted much attention from many scholars worldwide [1]. Due to their ubiquitous usability, UAVs will play an important role in the Internet of Things (IoT) and the communication field, and currently, realizing flexible coverage via 5th-generation (5G) mobile networks and millimeter wave networks has been a promising approach [2]–[4]. Among various UAVs, the quadrotor, consisting of four individual rotors in an “×” or a “+” arrangement, has been widely used in the IoT and communications due to its merits of small size, great mobility, and precise hovering in applications [5], such as data collection and transmission, crowd surveillance, and transmission line inspection [6]–[8]. Because communications and control are highly coupled in UAV systems and UAV attitude variation affects the beam direction of data communications, attitude control plays an important role in UAV communications [9]–[11], and a stable quadrotor attitude controller is the basis of these applications. A quadrotor is an underactuated, strongly coupled and nonlinear complex system [12], so there are many challenges in designing the attitude controller. Currently, the design of the attitude controller is an academic research focus [13].
In the last few years, various control methods have been proposed for attitude tracking control and stabilization of quadrotors. Some researchers linearize dynamic models of quadrotors and design proportional-integral-derivative (PID) controllers based on traditional linear control methods. In [14], the PID control method was applied to obtain quadrotor attitude stability. Sun et al. [15] proposed a linear quadratic regulator (LQR) controller to control the attitude of a quadrotor. To improve the robustness, Shulong et al. [16] proposed a combination of feedback linearization and an LQR control strategy to stabilize the attitude of quadrotors under disturbances. In addition, Wang et al. [17] proposed a robust H-infinity attitude tracking controller to track a desired attitude trajectory for quadrotor UAVs on SO(3) via variation-based linearization. This controller could satisfactorily complete the control tasks of large angle flip and complex attitude tracking of quadrotor UAVs and had a strong disturbance rejection ability and robust performance. Although the aforementioned linear control methods are widely used, the loss of dynamic performance with linear control methods cannot be ignored.

In recent years, several nonlinear control methods have garnered significant attention from both academia and industry. For instance, Garcia et al. [18] proposed an adaptive backstepping approach to control the attitude and translational displacement of quadrotors. However, adaptive backstepping control techniques cannot compensate for the influence of internal disturbance on the system well, and residual internal disturbance exits. For this problem, Liu et al. [19] proposed a nonlinear adaptive backstepping with an extended state observer (ESO) trajectory tracking controller for a quadrotor subject to multiple disturbances, including parametric uncertainties, actuator faults and external disturbances. Later, Fethalla et al. [20] proposed a novel robust backstepping-based approach combined with sliding mode control (SMC) for trajectory tracking of a quadrotor subject to external disturbances and parameter uncertainties associated with the presence of aerodynamic forces and possible wind forces. To enhance the robustness, the nonlinear disturbance observer (NDO) was employed alongside the controller. Shi et al. [21] proposed a generalized extend state observer (GESO) based disturbance and uncertainty estimation and attenuation control strategy to meet the requirement of high precision attitude control. And they believed that the 3rd order GESO was preferred considering the performance improvements and the computational complexity into account. For the problem of high-accuracy control for quadrotor unmanned aerial vehicles subject to external disturbance force and unknown disturbance torque, Xiao and Yin [22] proposed an observer-based full control scheme. Two observer-based estimators were designed to estimate external disturbance force and torque, respectively. Then a nonlinear tracking controller was designed with disturbance compensated. Labbadi and Cherkaoui [23] proposed a super-twisting PID sliding mode control (STPIDISMC) strategy for a disturbed quadrotor. To increase the robustness of the quadrotor system and to remove the chattering phenomenon in integral SMC (ISM C), the super twisting algorithm was combined with proportional integral derivative sliding mode control, and a new optimization was used to tune the proposed controller parameters. Labbadi and Cherkaoui [24] proposed robust adaptive nonsingular fast terminal sliding mode control (RANFTSMC) algorithms for orientation and translation tracking of an underactuated quadrotor under disturbances. The fast convergence of all the state variables was achieved, and the influence of the chattering effect in SMC was eliminated, while the online estimation of the parameters was presented, and the singularity problem of terminal SMC was avoided. Xu et al. [25] proposed an anti-Gaussian random disturbance control method for the path following of a quadrotor. To suppress the negative effects of Gaussian random disturbances and to simplify the design process of the linear-quadratic optimal output tracking control problem, a new information fusion estimation-based robust control named the Gaussian information fusion control (GIFC) scheme was proposed. The convergence of the output tracking errors of the GIFC control system was indicated via Lyapunov theory. Labbadi and Cherkaoui [26] proposed an adaptive backstepping fast terminal sliding mode control (ABFTSMC) method to control the attitude of uncertain quadrotors under external disturbances. To estimate the proposed controller parameters of the position and the upper bounds of the uncertainties and disturbances of the attitude, an online adaptation procedure for the controller parameters was presented. The proposed ABFTSMC had a strong robustness against time-varying uncertainties, nonlinearities and external disturbances and had characteristics such as simple design and continuous control signals. These nonlinear controllers achieve relatively more robust performance but entail a plant model and an accurate characterization of the uncertainties. However, in the flying state, the quadrotor may be affected by many factors causing unpredictable disturbances, such as motion coupling, inertial coupling, and aerodynamic coupling. Moreover, an accurate model of disturbances is difficult to establish. To address this problem, a series of control methods based on intelligent control theory, including model predictive control [27], adaptive control [28], neural network control [29] and others [30], have been investigated. Additionally, the theory of characteristic modeling, a data-based model-free approach for control system design proposed by Wu et al. [31], has been applied in several emerging fields.

Characteristic modeling is established by combining object dynamics and environmental features with the control performance requirements. One of the main differences from the traditional dynamic model is the consideration of the control performance requirements before building the characteristic model. Based on the characteristic modeling theory, the all-coefficient adaptive control (ACAC) theory was proposed in [32]. The ACAC theory is an adaptive control theory for a class of linearly constant (or slowly varying) objects with unknown parameters and partial nonlinear systems.
Its advancements and stability have been verified in rigorous mathematical proofs and various industrial fields [33]. Huang [34] proposed the characteristic model-based all-coefficient adaptive control method into the quadrotors attitude control, and the control performance was compared with the PID controller. Because the response time is long so that the performance is influenced for a quadrotor attitude system, in this paper, a feedforward all-coefficient adaptive control (FACAC) method is proposed via integrating the feedforward maintaining and tracking control law into the ACAC controller to shorten the settling time and to improve the response speed.

We apply the characteristic model to the attitude system of a quadrotor. Our objective is to achieve stable control of the quadrotor attitude in the presence of uncertain disturbances and to reduce the tracking error as much as possible. Simulation results verify the effectiveness of our control method regarding the attitude of the quadrotor. These results not only provide an avenue for controlling the attitude of the quadrotor but also help to further demonstrate the promise of the emerging characteristic model-based FACAC design method.

The main contributions of this paper are summarized as follows:

- Based on the second-order characteristic model of the quadrotor attitude system, the ACAC method is proposed to stabilize the attitude of the quadrotor in the presence of the external uncertain disturbance, which consists of the golden-section adaptive control law, the logic integral, and logic differential control laws.
- The response time is important for a quadrotor attitude system. Considering the problem of the response time of ACAC method, the FACAC method is proposed via integrating the feedforward maintaining and tracking control law into the ACAC controller to shorten the settling time and improve the response speed. The golden-section adaptive control law is utilized to ensure stability of the quadrotor attitude system when the system is in its transient process. Additionally, the process of the parameter tuning is not needed. The logic differential control law solves the problem that the control variable suddenly increases caused by the measurement noises differential of the inertial navigation system.

The remainder of this paper is organized as follows. In Section II, the theory of characteristic modeling is introduced. Section III discusses the dynamic and characteristic model of the quadrotor. The FACAC controller design is detailed in Section IV. The simulation results and analysis are discussed in Section V. Finally, the conclusion and discussion of future work are summarized in Section VI.

II. CHARACTERISTIC MODELING

In general, an accurate mathematical model is needed to describe the control plant and the environment of a system. However, as controlled objects grow increasingly complex, accurate dynamic modeling becomes very difficult to achieve. Even if a precise mathematical model can be established, the order of the model is extremely high, and the structure is very complicated. For the abovementioned reasons, the characteristic modeling theory was proposed by Wu et al. [31].

Basically, characteristic modeling is based on plant dynamic characteristics and control performance requirements rather than only relying on accurate plant dynamic analysis. It combines the dynamic characteristics, environmental characteristics and control performance requirements of the controlled object to overcome the shortcomings of traditional modeling. The main features [35] of characteristic modeling are as follows:

1) A plant characteristic model is equivalent to its actual plant in output for the same input, i.e., the output error can be maintained within a permitted range in a dynamic process, and their outputs are equal during a steady-state process.
2) The order and form of a characteristic model mainly depends on the control performance requirements in addition to the plant characteristics.
3) Compared with that of an original dynamic equation, the structure of a characteristic model should be simpler, easier, and more convenient to realize in engineering.
4) Unlike the reduced-order model of a high-order system, the characteristic model compresses all the information of the high-order system into several characteristic parameters; i.e., no information is lost. In general, a characteristic model is represented by a slowly time-varying difference equation.

For a multi-input multi-output affine nonlinear system, the dimensions of input and output are identical. \( x \in \mathbb{R}^n, u_i \in \mathbb{R}, \) and \( y_i \in \mathbb{R} \) denote the state, input, and output of the system, respectively. Then, we obtain the following:

\[
\begin{align*}
\dot{x} &= \varphi(x, \vartheta) + \sum_{i=1}^{m} g_i(x, \vartheta) u_i \\
y_i &= h_i(x) \quad i = 1, 2, \ldots, m,
\end{align*}
\]

(1)

where \( \vartheta \in \Gamma \subseteq \mathbb{R}^p \) is an unknown parameter related to time, state and system parameters belongs to compact subset \( \Gamma \). \( \varphi(x) \) and \( g_i(x) \) are n-dimensional smooth vectors, and \( h_i(x) \) is the smooth scalar function. In (1), \( \varphi(0, \vartheta) = 0, h_i(0) = 0 \) and \( g_i(0, \vartheta) \neq 0 \).

We assume that the properties of nonlinear system (1) are as follows:

**Assumption 1**: The system state is measurable in (1).
**Assumption 2**: Suppose that the relative degree of \( (\varphi, g_i, h_i) \) can be defined as \( \{r_1, \ldots, r_m\} \). For
where $\beta$ is a known nominal constant vector. From the above, we can easily derive that there exists an $\alpha(x,u)$ such that $\beta_i(x,\dot{\theta},u) \leq \alpha(x,u)$.

**Assumption 3:** Suppose that $\alpha(x,u)$ is bounded.

Based on the above assumptions, we obtain the following.

**Lemma 1:** When both tracking function $y_{ir}$ and its derivative are bounded, if the sampling period satisfies $\Delta t \ll \min \left\{ \frac{L_{\max}}{b_i}, \frac{L_{\max}}{M_i} \right\}$, the error characteristic model can be expressed by the following two-order time-varying difference equation:

$$e_i(k + 2) = f_{i1}(k + 1) e_i(k + 1) + f_{i2}(k) e_i(k) + f_{i3}(k + 1) u_i(k + 1) + f_{i4}(k) u_i(k),$$  \(i = 1, 2, \ldots, m, e_i = y_i - y_{ir}\) represents the system error and $u_i$ denotes the bounded sampling control.

### III. QUADROTOR ATTITUDE MODELING

In this section, the characteristic model of the quadrotor is established based on the dynamic equations of the quadrotor. First, the coordinate system is established, and the dynamic equations are given. Second, the characteristic model of the quadrotor is derived with the second-order time varying difference equation.

### A. DYNAMIC MODEL OF THE QUADROTOR

There are two reference frames applied to the quadrotor: body-fixed frame B ($o_0x_0y_0z_0$) and Earth-fixed inertial frame N ($o_nx_ny_nz_n$). The coordinate systems and free body diagram for the quadrotor are shown in Fig. 1. The quadrotor shape is chosen as the “+” shape in this paper. The body-fixed frame B is fixed with the quadrotor body, and the origin $o_0$ is at the center of mass of the quadrotor. The axis $x_0$ is parallel to the longitudinal axis of the body and is directed toward the front of the quadrotor. The axis $y_0$ is parallel to the transverse axis of the body and is directed toward the right of the quadrotor. The axis $z_0$ is perpendicular to the plane of the quadrotor and is directed downward from the quadrotor. The Earth-fixed inertial frame N is fixed with the ground, the quadrotor take-off point is located at the origin $o_n$, the axis $x_n$ points to geographical north, the axis $y_n$ points to geographical east, and the axes $z_n$ and $x_n$, $y_n$ constitute a right-hand coordinate frame.

The model developed in this paper assumes the following:

- The quadrotor body is a symmetrical rigid body. Elastic deformation does not occur during flight.

- The center of mass coincides exactly with the center of the body.

- Thrust is proportional to the square of the propeller’s speed.

Based on the above assumption, the attitude dynamics equation is built in body-fixed frame B as follows according to the Newton-Euler formalism:

$$J \cdot \ddot{b} \omega = -b \omega \times (J \cdot b \omega) + \tau + d$$

where $J = \text{diag} [J_x, J_y, J_z]$ denotes the moment of inertia matrix, $b \omega = [\omega_x, \omega_y, \omega_z]^\top$ is the body angular rate, and $\tau = [r_x, r_y, r_z]^\top$ is the control torque vector. $d = [d_1, d_2, d_3]^\top$ is the uncertain disturbance. $\Theta = [\phi, \theta, \psi]^\top$ are the Euler angles expressed in inertial frame N, which are the roll angle $\phi$, pitch angle $\theta$, and yaw angle $\psi$, respectively.

Then, the matrix $W$ is expressed as

$$W \triangleq \begin{bmatrix} 1 & \tan \theta \sin \phi & \tan \theta \cos \phi \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi \sec \theta & \cos \phi \sec \theta \end{bmatrix}.$$  \(5\)

When the quadrotor flies at small angles, considering (4) and (5), we obtain the following:

$$\begin{cases} \ddot{\phi} = \dot{\theta} \omega J_y - J_z + \frac{r_x}{J_x} + \frac{d_1}{J_x} \\ \ddot{\theta} = \dot{\phi} \omega J_z - J_x + \frac{r_y}{J_y} + \frac{d_2}{J_y} \\ \ddot{\psi} = \dot{\phi} \omega J_x - J_y + \frac{r_z}{J_z} + \frac{d_3}{J_z} \end{cases}$$

Afterward, the propellers’ speed inputs can be derived as

$$\begin{cases} r_x = b_l (\Omega_1^2 - \Omega_2^2) \\ r_y = b_l (\Omega_1^2 - \Omega_3^2) \\ r_z = d_l (\Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2) \end{cases}$$

where parameter $l$ is the distance between each propeller from the center of each propeller. $\Omega_1, \Omega_2, \Omega_3$ and $\Omega_4$ are the rotation speeds of the rotors. Parameter $b_l$ is the thrust factor, and $d_l$ is the drag factor.

### B. CHARACTERISTIC MODEL OF THE QUADROTOR

If the controlled object satisfies certain conditions, the characteristic model could be expressed as a second-order time-varying difference equation (see (3)) when the sampling
Afterward, the input vector is mapped by

\[ X = [\phi_e, \theta_e, \psi_e]^T. \]  

(8)

**Input vector:**

\[ U = [U_2\ U_3\ U_4]^T. \]  

(9)

Afterward, the input vector is mapped by

\[
\begin{bmatrix}
U_2 \\
U_3 \\
U_4 \\
\end{bmatrix} = 
\begin{bmatrix}
0 & -b & 0 & b \\
-\frac{1}{d} & 0 & -\frac{1}{d} & 0 \\
0 & -d & 0 & -d \\
\end{bmatrix} \begin{bmatrix}
\Omega_2^2 \\
\Omega_2^3 \\
\Omega_2^4 \\
\end{bmatrix}.
\]  

(10)

According to the above attitude dynamics of the quadrotor (see (4)–(10)), based on Lemma 1, the characteristic model of the quadrotor can be expressed as follows:

\[ X(k + 1) = \alpha_1(k)X(k) + \alpha_2(k)X(k - 1) + \beta_0(k)U(k), \]  

(11)

where

\[
\begin{align*}
\alpha_1(k) &= [A(k) + \Delta tB(k)]^{-1}[2A(k) + \Delta tB(k)] \\
\alpha_2(k) &= -[A(k) + \Delta tB(k)]^{-1}A(k) \\
\beta_0(k) &= -[A(k) + \Delta tB(k)]^{-1}C(k)\Delta t^2,
\end{align*}
\]  

(12)

and

\[
\begin{align*}
A &= \begin{bmatrix} I_{xx} & 0 & 0 \\
0 & I_{yy} & 0 \\
0 & 0 & I_{zz} \end{bmatrix} \\
B &= \begin{bmatrix} 0 & -\dot{\psi}(I_{yy} - I_{zz}) & 0 \\
\dot{\psi}(I_{zz} - I_{xx}) & 0 & 0 \\
0 & 0 & 0 \end{bmatrix} \\
C &= \begin{bmatrix} -I & 0 & 0 \\
0 & -I & 0 \\
0 & 0 & -1 \end{bmatrix}.
\end{align*}
\]  

(13)

**IV. DESIGN OF THE LINEAR FACAC CONTROLLER**

In this part, the novel linear FACAC controller is designed for the attitude control system of the quadrotor. The FACAC controller consists of feedforward maintaining and tracking control, i.e., \( u_0(k) \), linear golden section adaptive control, i.e., \( u_g(k) \), logic integral control, i.e., \( u_i(k) \), and logic differential control, i.e., \( u_d(k) \). The diagram of the proposed linear FACAC control architecture is shown in Fig. 2, where \( T_r(k) \) is the desired attitude angle and \( T(k) \) is the output attitude angle of the quadrotor. Finally, the total FACAC control variable \( u(k) \) is expressed as:

\[ u(k) = u_0(k) + u_g(k) + u_i(k) + u_d(k). \]  

(14)

In the FACAC controller, the feedforward maintaining and tracking control law, which is simple to design, is derived via the second-order characteristic model. The golden-section adaptive control law can ensure the stability of the closed-loop system when the system is in its transient process. It has strong robustness and adaptability, and the process of the parameter tuning is not needed. The logic integral control law can automatically adjust the magnitude of integral action with the change trend of the tracking errors. It solves the problem of the overshoot caused by integral saturation when the system in the adjustment process. The logic differential control law can dynamically change the differential action to improve the dynamic quality of the system. It is useful for the problem that the control variable suddenly increases caused by the measurement noises differential of the inertial navigation system.

**A. THE FEEDFORWARD MAINTAINING AND TRACKING CONTROL LAW**

The feedforward maintaining and tracking control variable \( u_0(k) \) is designed to track the desired attitudes. It is designed as follows:

\[ u_0(k) = \frac{1}{\beta_0(k) + \lambda} [T_r(k) - \alpha_1(k)T_r(k - 1) - \alpha_2(k)T_r(k - 2)]. \]  

(15)

where \( T_r(k) \) is the expected value and \( \lambda \) is a small normal number to avoid an infinite variable of control if \( \beta_0(k) = 0, \alpha_1(k), \alpha_2(k) \) and \( \beta_0(k) \) are calculated by (12).

To smooth the control variable \( u_0(k) \), the output filter is designed, and the following equation is obtained:

\[ u_0'(k) = fu_0(k) + (1 - f)u_0'(k - 1), \]  

(16)

where \( u_0(k) \) is the current calculated result, \( u_0'(k - 1) \) is the previous control variable and \( 0 < f < 1 \).

**B. THE LINEAR GOLDEN-SECTION ADAPTIVE CONTROL LAW**

When the parameters are not convergent or the system is in a transient process, the golden-section adaptive control law [33] can ensure stability of the closed-loop system for the unknown parameters and time-invariant systems. It is simple to design and has strong robustness and adaptability. This adaptive controller is designed as follows:

\[ u_g(k) = -\frac{1}{\beta_0(k) + \lambda} [l_1 \alpha_1(y)(k) + l_2 \alpha_2(y)(k - 1)]. \]  

(17)
where $l_1 = 0.382$ and $l_2 = 0.618$ are the coefficients of the golden-section adaptive control law [32] and $y(k) = T(k) - T_e(k)$ is the tracking error.

C. THE LOGIC INTEGRAL CONTROL LAW

Compared with the traditional integral control law, the logic integral control law [32] can automatically adjust the magnitude of integral action with the change in the tracking error. Obviously, this can accelerate the adjustment speed of the system. When the tracking error $y(k)$ is increasing and $y(k) > 0$, the integral coefficient should be adjusted to reduce the tracking error. When $y(k)$ is positive and starts to decrease, the integral coefficient should decrease. When $y(k)$ decreases and $y(k) < 0$, the integral coefficient should increase as well. The logic integral control law is designed as follows:

$$u_i(k) = u_i(k-1) + k_i y(k), \quad (18)$$

with

$$k_i = \begin{cases} k_1, & \text{when } y(k)[y(k) - y(k-1)] - \Delta \leq 0, \\ k_2, & \text{when } y(k)[y(k) - y(k-1)] - \Delta > 0, \end{cases} \quad (19)$$

where $k_2 > k_1 > 0$ and $\Delta$ is a small positive number.

D. THE LOGIC DIFFERENTIAL CONTROL LAW

Differential control can increase the damping of the system and change the system characteristics. In contrast, logic differential control can dynamically change the differential action to improve the dynamic quality of the system. In the attitude control system of the quadrotor, when the system output value is far away from the desired value, this parameter is expected to arrive at the desired value quickly, and the damping should be small. When the system is in a steady process, especially with slight oscillations, the damping should be increased to curb the oscillations. Consequently, the logic differential control law is designed as follows:

$$u_d(k) = k_d (y(k) - y(k-1))$$

$$k_d = d' \sqrt{\sum_{i=1}^{N} |y(k-N+i) - y(k-N+i-1)|}. \quad (20)$$

For the stability analysis, we consider the general form of the characteristic model as in (11):

$$y(k + 1) = a_1(k)y(k) + a_2(k)y(k - 1) + b_0(k)u(k). \quad (21)$$

According to [33], the coefficients in the characteristic model for an unstable plant satisfy the following conditions:

$$\begin{cases} a_1 \in [1.9844, 2.2663] \\ a_2 \in [-1.2840, -1] \\ a_1 + a_2 \in [0.9646, 1] \\ b_0 \in [0.003, 0.3]. \end{cases} \quad (22)$$

For the characteristic model of the quadrotor (10), when the Euler angles are limited to $\phi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ rad, $\theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ rad and $\psi \in [-\pi, \pi]$ rad, and the angle velocity is limited to $[-2, 2]$ rad/s, then:

$$\begin{cases} \hat{a}_1 \in [1.9855, 2.0149] \\ \hat{a}_2 \in [-1.0149, -1] \\ \hat{a}_1 + \hat{a}_2 \in [0.98, 1] \\ \hat{b}_0 \in [0.003, 0.004], \end{cases} \quad (23)$$

where $\hat{a}_1$, $\hat{a}_2$ and $\hat{b}_0$ are the estimated values of the quadrotor.

It is clear that (23) satisfies the conditions of (22). Then, according to [36] and [37], the stability of the system can be indicated.

V. SIMULATION RESULTS

In this section, we present the simulation results to evaluate the performance of the proposed control method. To verify the control performance of FACAC, attitude settling simulations, Monte Carlo simulations, noise environment simulations, and external disturbance simulations are carried out. The simulations are performed in MATLAB/SIMULINK. The quadrotor model parameters and control parameters are summarized in Tables 1 and 2, respectively. In addition, the control effort cannot be infinite in the actual system, so the output values of the controller are limited in the simulations.

### TABLE 1. Quadrotor parameters in simulations.

| Parameter | Definition | Value |
|-----------|------------|-------|
| $I_x$ | Roll inertia | $7.5 \times 10^{-3}$ kg $\cdot$ m$^2$ |
| $I_y$ | Pitch inertia | $7.5 \times 10^{-3}$ kg $\cdot$ m$^2$ |
| $I_z$ | Yaw inertia | $1.3 \times 10^{-2}$ kg $\cdot$ m$^2$ |
| $l$ | Arm length | 0.23 m |
| $b$ | Thrust factor | $3.13 \times 10^{-5}$ N $\cdot$ s$^2$ |
| $d$ | Drag factor | $7.5 \times 10^{-7}$ Nm $\cdot$ s$^2$ |

### TABLE 2. Controller parameters in simulations.

| Parameter | Definition | Value |
|-----------|------------|-------|
| $\Delta t$ | fixed-sampling time | 0.01 s |
| $\lambda$ | small normal number | 0.00001 |
| $f$ | filter coefficient | 0.618 |
| $k_1$ | integral coefficients (Roll, Pitch, Yaw) | (1.1, 0.7, 0.4) |
| $k_2$ | integral coefficients (Roll, Pitch, Yaw) | (2.3, 1.1, 0.4) |
| $\Delta$ | small positive number in integral control | 0.00002 |
| $d'$ | differential coefficients (Roll, Pitch, Yaw) | (200, 200, 80) |
1) CASE 1: COMPARISON BETWEEN FACAC AND ACAC
To verify the effectiveness of the feedforward maintaining and tracking control law, the attitude settling performances of the FACAC controller and the ACAC controller are compared. The desired reference commands are selected by \( \Theta_d = [0.3 \ 0.3 \ 0.3]^\top \) rad. Furthermore, the initial conditions of the attitude angles and angular velocities are set as \( \Theta_i = [0 \ 0 \ 0]^\top \) rad and \( \Omega = [0 \ 0 \ 0]^\top \) rad/s, respectively.

Fig. 3 shows that the two controllers can both achieve a stable state for the attitude angle. However, for the FACAC controller, the system response speed is effectively faster and the settling time is shorter than those of the ACAC controller. The effectiveness of the feedforward maintaining and tracking control law integrated into ACAC is verified. The main performance parameters when the prescribed error band is defined as \( \pm 2\% \) of the final value are listed in Table 3.

Compared with the ACAC controller, the rise time and settling time are both reduced due to the addition of the feedforward maintaining and tracking control law when using the FACAC controller. However, the overshoot is increased slightly. The effect of the feedforward control law is found to be weak because the tracking signal is a constant signal.

2) CASE 2: COMPARISON BETWEEN FACAC AND PID
We further apply the FACAC controller in the attitude control system and compare its performance with that of the traditional PID controller. The desired reference commands are selected by \( \Theta_d = [0.3 \ 0.3 \ 0.3]^\top \) rad. The initial values of the attitude angles and angular velocity are set to \( \Theta_i = [0 \ 0 \ 0]^\top \) rad and \( \Omega = [0 \ 0 \ 0]^\top \) rad/s, respectively.

Fig. 4 shows that the traditional PID controller has poor control performance compared with that of the proposed FACAC controller. In particular, its overshoot is larger, and its convergence time is longer. The error in the attitude control can converge to the prescribed error band in the expected time when the FACAC controller is used. However, the tracking errors violate the prescribed error bounds and good performance cannot be achieved within the expected time when the PID controller is used. Table 4 summarizes the main performance parameters. From the table, we observe that the rise time, settling time, and overshoot with the FACAC controller are significantly lower than those with the PID controller.
3) CASE 3: COMPARISON BETWEEN FACAC AND MSTW

The MSTW is proposed to solve the problem of attitude tracking of quadrotor subject to disturbances and uncertainties. It is designed by extending the super twisting control algorithm (STW) and the theory of finite-time-convergence. Compared with the STW, the MSTW utilizes the continuous control function to replace the discontinuous function to generate a continuous control signal, eliminate chattering effect, perform accurate tracking and achieve the robustness. To verify the superiority of the proposed method, the simulation results, which are compared with those of the MSTW method, are indicated in Fig. 5. The desired reference commands are selected by $\mathbf{2} \mathbf{d} = [0 \ 0.3 \ 0.3 \ 0.3]^{\top}$ rad. Furthermore, the initial conditions of the attitude angles and angular velocities are set as $\Theta_0 = [0 \ 0 \ 0]^{\top}$ rad and $\mathbf{\Omega}_0 = [0 \ 0 \ 0]^{\top}$ rad/s, respectively. The main performance parameters are listed in Table 5.

From Fig. 5 and Table 5, it is clear that the MSTW method tracks the desired attitude more slowly than those of the FACAC method. The rise time and settling time are both reduced significantly when using the FACAC method. But at the same time, it can also be observed that the overshoot of the FACAC is larger than that of the MSTW method.

B. MONTE CARLO SIMULATIONS

To verify the stability of the proposed method, Monte Carlo simulations with 500 runs are carried out for the following two cases. In the Monte Carlo simulations, the system tracks the step signal and sinusoidal signal, respectively, and the attitude is randomly initialized in the specified range.

1) CASE 1: TRACKING THE STEP SIGNAL

The desired reference commands are selected by $\mathbf{2} \mathbf{d} = [0.3 \ 0.3 \ 0.3]^{\top}$ rad. The initial values of the attitude angles...
and angular velocity are set to $\Theta_i = \begin{bmatrix} \phi(0) \\ \theta(0) \\ \psi(0) \end{bmatrix}^{T}$ rad and $\Omega = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}^{T}$ rad/s, where $\phi(0)$, $\theta(0)$ and $\psi(0)$ are randomly selected in the interval $[-\frac{\pi}{4}, \frac{\pi}{4}]$. The attitude tracking, including the roll angle, pitch angle, and yaw angle, is plotted in Fig. 6. From Fig. 6, we can see that the desired attitude commands can be tracked effectively by the proposed control scheme. Furthermore, the tracking errors are provided in Fig. 7.

From Fig. 6 and Fig. 7, it can be observed that the tracking errors in the attitude control converge to the prescribed error bound in a limited time and approach zero when the system is in a steady state.

2) CASE 2: TRACKING THE SINUSOIDAL SIGNAL
The desired reference commands are selected by $\Theta_d = \begin{bmatrix} 0.3\sin(t) \\ 0.3\sin(t) \\ 0.3\sin(t) \end{bmatrix}^{T}$ rad. The initial values of the attitude angles and angular velocity are set to $\Theta_i = \begin{bmatrix} \phi(0) \\ \theta(0) \\ \psi(0) \end{bmatrix}^{T}$ rad and $\Omega = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}^{T}$ rad/s, where $\phi(0)$, $\theta(0)$ and $\psi(0)$ are randomly selected in the interval $[-\frac{\pi}{4}, \frac{\pi}{4}]$. The attitude tracking, including the roll angle, pitch angle,

FIGURE 7. Tracking errors for the step signal in the Monte Carlo simulations. (a) Roll angle. (b) pitch angle. (c) yaw angle.

FIGURE 8. Tracking the sinusoidal signal in the Monte Carlo simulations. (a) Roll angle, (b) pitch angle, and (c) yaw angle.

FIGURE 9. Tracking errors for the sinusoidal signal in Monte Carlo simulation. (a) Roll angle, (b) Pitch angle, and (c) Yaw angle.
and yaw angle, is plotted in Fig. 8. We know that the desired attitude commands can be tracked effectively by the proposed control scheme from Fig. 8. Furthermore, the tracking errors are provided in Fig. 9.

From Fig. 8 and Fig. 9, we observe that the FACAC controller can accurately track the variable signal. It is interesting to note that when tracking the sinusoidal signal, the tracking errors can converge to the prescribed error bound even in the presence of the random diversification of the initial attitude values. Additionally, Fig. 8 illustrates that the tracking accuracy of roll, pitch, and yaw angles is within $\pm 2 \times 10^{-3}$ rad when the system is in a steady state.

C. SIMULATIONS IN NOISE ENVIRONMENTS

Considering the noise that affects actual sensors, we design the noise simulations with different noise densities to verify the stability of the FACAC controller. Table 6 shows the rate noise spectral densities of some common gyroscope sensors for quadrotors.

From Table 6, it is observed that the rate noise spectral densities of these common gyroscope sensors are between $0.00007$ rad $\frac{1}{s \sqrt{Hz}}$ (ICM20602) and $0.00017$ rad $\frac{1}{s \sqrt{Hz}}$ (MPU9250). The values of MPU9250 and ICM20602 in Table 6 are selected as the variances of the noise, $0.00017$ and $0.00007$, respectively, and the mean of the noise is 0 for both sensors. The desired reference commands are selected by $\Theta_d = [0.3 0.3 0.3]^T$ rad. The initial values of the attitude angles and angular velocity are set to $\Theta_i = [0 0 0]^T$ rad and $\Omega = [0 0 0]^T$ rad/s, respectively.

As illustrated in Fig. 10, the attitude tracking errors can converge to small regions around zero even in the presence of noise and attitude tracking errors. Moreover, the attitude tracking errors decrease sharply when the noise density decreases. This validates the practicability of the proposed FACAC controller. A comparison of the main performance parameters from when the system is in a steady state with different noise environments is listed in Table 7. Note that the main performance parameters include the minimum and maximum tracking error and the root mean square (RMS) of the response curve. From Table 7, we can see that the attitude tracking performance is better and more stable when the noise density is 0.00007. Obviously, we can obtain a more satisfactory control performance based on the selection of a suitable sensor.

D. SIMULATIONS WITH EXTERNAL DISTURBANCES

To verify the performance of the proposed method with respect to uncertain external disturbances, constant disturbances and time-varying disturbances are added to the system. Additionally, the disturbance rejection performance of FACAC is compared with that of the MSTW when external disturbances are present.

1) CASE 1: CONSTANT DISTURBANCE

In this case, we verify whether the FACAC strategy performance is stable even in the presence of constant external disturbance. The desired reference commands are selected by $\Theta_d = [0.4 0.4 0.4]^T$ rad. The expressions of the disturbances are given as follows: $d_1 = 1$ Nm at $t = 0.4$ s, $d_2 = 1$ Nm at $t = 0.6$ s, and $d_3 = 1$ Nm at $t = 0.8$ s. Furthermore, the initial conditions of the attitude angles and angular velocities are set as $\Theta_i = [0 0 0]^T$ rad and $\Omega = [0 0 0]^T$ rad/s, respectively. The simulation results are shown in Fig. 11.

From Fig. 11, it is clear that the attitudes of the quadrotor remain in the desired states despite the constant disturbance. Table 8 shows the maximum errors of FACAC and MSTW when the constant external disturbance is present.

From Table 8, the maximum errors of FACAC are smaller than those of MSTW. The antidisturbance per-
TABLE 7. Performance analysis with different noise environments.

| Sensor type | Noise density (rad/s $\sqrt{\text{Hz}}$) | Euler angle | Minimum tracking error | Maximum tracking error | RMS     |
|-------------|--------------------------------------|-------------|------------------------|------------------------|---------|
| ICM20602    | 0.00007                              | $\phi$      | -0.00083               | 0.00691                | 0.00061 |
|             |                                      | $\theta$    | -0.00130               | 0.00110                | 0.00075 |
|             |                                      | $\psi$      | -0.00160               | 0.00649                | 0.00042 |
| MPU9250     | 0.00017                              | $\phi$      | -0.00086               | 0.00140                | 0.00080 |
|             |                                      | $\theta$    | -0.00140               | 0.00130                | 0.00096 |
|             |                                      | $\psi$      | -0.00180               | 0.00073                | 0.00051 |

FIGURE 11. Response curves of the antidisturbance experiment when the constant disturbance is present. (a) Roll angle, (b) pitch angle, and (c) yaw angle.

FIGURE 12. Disturbance torque caused by a wind field.

TABLE 8. Tracking errors of the FACAC and MSTW controllers with the constant disturbance.

| Controller | Euler angle | Maximum error (rad) |
|------------|-------------|---------------------|
| FACAC      | $\phi$      | 0.0166              |
|            | $\theta$    | 0.0163              |
|            | $\psi$      | 0.0412              |
| MSTW       | $\phi$      | 0.0185              |
|            | $\theta$    | 0.0198              |
|            | $\psi$      | 0.0724              |

formance of FACAC is significantly better than that of MSTW. FACAC has less fluctuations and better inhibitory effects when the system is subject to a constant disturbance.

2) CASE 2: TIME-VARYING DISTURBANCE

In case 1, the external disturbance is considered constant. To further verify the antidisturbance performance of FACAC, in this part, the external disturbances are time-varying disturbances caused by a wind field. The Dryden wind gust model is introduced in the attitude system [39]. According to [21], the expressions of these disturbances are given as follows: $d_1 = d_2 = d_3 = d_w$, and $d_w$ is defined in (24). The time-varying disturbances caused by a wind field are visualized in Fig. 12.

$$d_w = \sin(2.5\pi t - 3) + 1.5\sin(2\pi t + 7) + 2\sin(0.4\pi t - 9.5) + \sin(0.2\pi t) + 0.5\sin(0.08\pi t + 1) + \sin(0.07\pi t + 1.5) + 0.5\sin(0.05\pi t + 2)$$  (24)

The desired reference commands are selected by $\Theta_d = [0 \ 0 \ 0]^T \text{ rad}$. The initial conditions of the attitude angles and angular velocities are set as $\Theta_I = [0 \ 0 \ 0]^T \text{ rad}$ and $\Omega = [0 \ 0 \ 0]^T \text{ rad/s}$, respectively. The simulation results are shown in Fig. 13. Table 9 shows the control performances.
of the FACAC and the MSTW when external time-varying disturbances are present. From Fig. 13 and Table 9, it can be observed that FACAC and MSTW are able to ensure the stabilization of the attitude angles under the influence of time-varying disturbances. Additionally, it is clear that the control accuracy and the control stability of FACAC are better than those of MSTW.

VI. CONCLUSION

In this paper, a novel attitude controller for a quadrotor based on the FACAC strategy is proposed. Characteristic modeling theory is utilized to establish the second-order characteristic model, and the feedforward maintaining and tracking control law is integrated into the ACAC controller. Compared with that of the ACAC controller, the traditional PID controller and the MSTW controller, the control performance of FACAC is better. The response time of FACAC is faster, and the overshoot is smaller. Moreover, the Monte Carlo numerical simulations and the simulations in different noise environments are carried out to verify the stability of FACAC. The performance of FACAC with respect to uncertain external disturbances is verified by adding constant and time-varying disturbances. In conclusion, the FACAC controller has the advantages of superior response speed, small overshoot and strong robustness. In the future, we will integrate the FACAC controller into an actual quadrotor to test the performance of the controller.

REFERENCES

[1] E. Kougioumtzis, S. P. Mohanty, G. Coelho, U. Albalawi, and P. Sundararavidel, “Design of a high-performance system for secure image communication in the Internet of Things,” IEEE Access, vol. 4, pp. 1222–1242, 2016.
[2] J. Zhao, F. Gao, L. Kuang, Q. Wu, and W. Jia, “Channel tracking with flight control system for UAV mmWave MIMO communications,” IEEE Commun. Lett., vol. 22, no. 6, pp. 1224–1227, Jun. 2018.
[3] N. H. Mottagh, T. Taleb, and O. Arouk, “Low-altitude unmanned aerial vehicles-based Internet of Things services: Comprehensive survey and future perspectives,” IEEE Internet Things J., vol. 3, no. 6, pp. 899–922, Dec. 2016.
[4] J. Zhang, T. Chen, S. Zhong, J. Wang, W. Zhang, X. Zuo, R. G. Mautner, and L. Hanzo, “Aeronautical Ad Hoc networking for the Internet-above-the-clouds,” Proc. IEEE, vol. 107, no. 5, pp. 868–911, May 2019.
[5] J. Kim, S. A. Gadsden, and S. A. Wilkerson, “A comprehensive survey of control strategies for autonomous quadrotors,” Can. J. Electr. Comput. Eng., vol. 43, no. 1, pp. 3–16, Winter 2020.
[6] A. Islam and S. Y. Shih, “BUS: A blockchain-enabled data acquisition scheme with the assistance of UAV swarm in Internet of Things,” IEEE Access, vol. 7, pp. 103231–103249, 2019.
[7] H. Liang, W. Gao, J. H. Nguyen, M. F. Orpilla, and W. Yu, “Internet of Things data collection using unmanned aerial vehicles in infrastructure-free environments,” IEEE Access, vol. 8, pp. 3932–3944, 2020.
[8] T. He, Y. Zeng, and Z. Hu, “Research of multi-rotor UAVs detailed autonomous navigation technology of transmission lines based on route planning,” IEEE Access, vol. 7, pp. 114955–114965, 2019.
[9] J. Zhao, F. Gao, G. Ding, T. Zhang, W. Jia, and A. Nallanathan, “Integrating communications and control for UAV systems: Opportunities and challenges,” IEEE Access, vol. 6, pp. 67519–67527, 2018.
[10] W. Guo, W. Zhang, Y. Wang, N. Zhao, and F. R. Yu, “Joint attitude and power optimization for UAV-Aided downlink communications,” IEEE Trans. Veh. Technol., vol. 68, no. 12, pp. 12437–12442, Dec. 2019.
[11] A. I. Alishubat and L. Dong, “Performance analysis of mobile ad hoc unmanned aerial vehicle communication networks with directional antennas,” Int. J. Aerosp. Eng., vol. 2010, pp. 1–14, Mar. 2010.
[12] X.-M. Chen, C.-X. Wu, Y. Wu, N.-X. Xiong, R. Han, B.-J. Ju, and S. Zhang, “Design and analysis for early warning of rotor UAV based on data-driven DBN,” Electronics, vol. 8, no. 11, p. 1350, 2019.
[13] O. Mofid and S. Mobayen, “Adaptive sliding mode control for finite-time stability of quad-rotor UAVs with parametric uncertainties,” ISA Trans., vol. 72, pp. 1–14, Jun. 2018.
[14] M. N. Duc, T. N. Trong, and Y. S. Xuan, “The quadrotor MAV system using PID control,” in Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA), Aug. 2015, pp. 506–510.
[15] Y. Sun, N. Xian, and H. Duan, “Linear-quadratic regulator controller design for quadrotor based on pigeon-inspired optimization,” Aircr. Eng. Aerosp. Technol., vol. 88, no. 6, pp. 761–770, Oct. 2016.
[16] Z. Shulong, A. Honglei, Z. Daibing, and S. Lincheng, “A new feedback linearization LQR control for attitude of quadrotor,” in Proc. 13th Int. Conf. Control Autom. Robot. Vis. (ICARCV), Dec. 2014, pp. 1593–1597.
[17] H. Wang, Z. Li, H. Xiong, and X. Nian, “Robust $H_\infty$ attitude tracking control of a quadrotor UAV on SO(3) via variation-based linearization and interval matrix approach,” ISA Trans., vol. 87, pp. 10–16, Apr. 2019.
[18] O. Garcia, P. Ordoz, O.-J. Santos-Sánchez, S. Salazar, and R. Lozano, “Backstepping and robust control for a quadrotor in outdoors environments: An experimental approach,” IEEE Access, vol. 7, pp. 40636–40648, 2019.
[19] J. Liu, W. Gai, J. Zhang, and Y. Li, “Nonlinear adaptive backstepping with ESO for the quadrotor trajectory tracking control in the multiple disturbances,” Int. J. Control, Autom. Syst., vol. 17, no. 11, pp. 2754–2768, Nov. 2019.
[20] N. Fethalla, M. Saad, H. Michalska, and J. Ghommam, “Robust observer-based dynamic sliding mode controller for a quadrotor UAV,” IEEE Access, vol. 6, pp. 45846–45859, 2018.
[21] D. Shi, Z. Wu, and W. Chou, “Generalized extended state observer based high precision attitude control of quadrotor vehicles subject to wind disturbance,” IEEE Access, vol. 6, pp. 32349–32359, 2018.
[22] B. Xiao and S. Yin, “A new disturbance attenuation control scheme for quadrotor unmanned aerial vehicles,” IEEE Trans. Ind. Informat., vol. 13, no. 6, pp. 2922–2932, Dec. 2017.
M. Labbadi and M. Cherkaoui, “Novel robust super twisting integral sliding mode controller for a quadrotor under external disturbances,” Int. J. Dyn. Control, pp. 1–11, Dec. 2019, doi: 10.1007/s40435-019-00599-6.

M. Labbadi and M. Cherkaoui, “Robust adaptive nonsingular fast terminal sliding-mode tracking control for an uncertain quadrotor UAV subjected to disturbances,” ISA Trans., vol. 99, pp. 290–304, Apr. 2020.

Q. Xu, Z. Wang, and Z. Zhen, “Information fusion estimation-based path following control of quadrotor UAVs subjected to Gaussian random disturbance,” ISA Trans., vol. 99, pp. 84–94, Apr. 2020.

M. Labbadi and M. Cherkaoui, “Robust adaptive backstepping fast terminal sliding mode controller for uncertain quadrotor UAV,” Aerosp. Sci. Technol., vol. 93, Oct. 2019, Art. no. 105306.

M. Abdolhosseini, Y. M. Zhang, and C. A. Rabbath, “An efficient model predictive control scheme for an unmanned quadrotor helicopter,” J. Intell. Robotic Syst., vol. 70, nos. 1–4, pp. 27–38, Apr. 2013.

B. Tian, J. Cui, H. Lu, Z. Zuo, and Q. Zong, “Adaptive finite-time attitude tracking of quadrotors with experiments and comparisons,” IEEE Trans. Ind. Electron., vol. 66, no. 12, pp. 9428–9438, Dec. 2019.

C. Luo, Z. Du, and L. Yu, “Neural network control design for an unmanned aerial vehicle with a suspended payload,” Electronics, vol. 8, no. 9, p. 931, Aug. 2019.

J. Hwangbo, I. Sa, R. Siegwart, and M. Hutter, “Control of a quadrotor with reinforcement learning,” IEEE Robot. Autom. Lett., vol. 2, no. 4, pp. 2096–2103, Oct. 2017.

H. Wu, Y. Xie, B. Li, and Y. He, “Intelligent control based on description of plant characteristic model,” Acta Automatica Sinica, vol. 25, no. 1, pp. 9–17, 1999.

H. Wu, J. Hu, and Y. Xie, “Characteristic model-based all-coefficient adaptive control method and its applications,” IEEE Trans. Syst., Man, Cybern. C, Appl. Rev., vol. 37, no. 2, pp. 213–221, Mar. 2007.

B. Meng and H. Wu, “Convergence and stability of the golden-section control,” J. Astronaut., vol. 30, no. 5, pp. 2128–2132, 2009.

H. Huang, “Characterizing modeling and all-coefficient adaptive control of a quadrotor,” in Proc. 12th World Congr. Intell. Control Autom. (WCICA), Jun. 2016, pp. 2493–2497.

L. Chen, Y. Yan, C. Mu, and C. Sun, “Characteristic model-based discrete-time sliding mode control for spacecraft with variable tilt of flexible structures,” IEEE/CAS J. Automatica Sinica, vol. 3, no. 1, pp. 42–50, Jan. 2016.

H. Wu and Y. Xie, “The application of the golden section in adaptive robust controller design,” Acta Automatica Sinica, vol. 18, no. 2, pp. 177–185, 1992.

Y. Yang and H. Wu, “Study on the stability of characteristic model based all-coefficient adaptive control system,” Aerosp. Control, vol. 25, no. 5, pp. 3–6, 2007.

M. Kahouadji, M. R. Mokhtari, A. Choukchou-Braham, and B. Cherki, “Real-time attitude control of 3 DOF quadrotor UAV using modified super twisting algorithm,” J. Franklin Inst., vol. 357, no. 5, pp. 2681–2695, Mar. 2020.

S. Waslander and C. Wang, “Wind disturbance estimation and rejection for quadrotor position control,” in Proc. IEEE Infotech Aerosp. Conf., Apr. 2009, pp. 1–14.

HONGYU CHU (Member, IEEE) received the B.S. degree in electronic information engineering from Jilin University, Changchun, China, in 2002, and the Ph.D. degree in mechanical and electronic engineering from Chongqing University, Chongqing, China, in 2011. He is currently a Faculty Member with the School of Information Engineering, Southwest University of Science and Technology. His current interests include multirotor UAV, special robot, and machine vision.

QI JING (Graduate Student Member, IEEE) received the B.S. degree from the School of Information Engineering, Southwest University of Science and Technology, Mianyang, China, in 2017, where he is currently pursuing the M.S. degree. His research interests include the multirotor UAV control technology and robot control.

ZHIYUAN CHANG received the B.E. and Ph.D. degrees from the Nanjing University of Science and Technology, Nanjing, China, in 2009 and 2016, respectively. He is currently a Faculty Member with the School of Information Engineering, Southwest University of Science and Technology. His current research interests include robot control, geometric control of nonlinear systems, and visual servo.

YANHUA SHAO received the M.S. degree in pattern recognition and intelligent system from the Southwest University of Science and Technology, China, in 2010, and the Ph.D. degree in instrument science and technology from Chongqing University, China, in 2015. His research interests include pattern recognition, computer vision, and machine learning.

XIAOQIANG ZHANG (Member, IEEE) received the B.E., M.S., and Ph.D. degrees from Northwestern Polytechnical University, Xi’an, China, in 2010, 2013, and 2018, respectively. He is currently a Lecturer with the School of Information Engineering, Southwest University of Science and Technology. His current research interests include synthetic aperture imaging, computational photography, computer vision, and pattern recognition.

MITHUN MUKHERJEE (Senior Member, IEEE) received the B.E. degree in electronics and communication engineering from the University Institute of Technology, The University of Burdwan, Bardhaman, India, in 2007, the M.E. degree in information and communication engineering from the Indian Institute of Science and Technology, Shibpur, India, in 2009, and the Ph.D. degree in electrical engineering from IIT Patna, Patna, India, in 2015. He is currently an Assistant Professor with the Guangdong Provincial Key Laboratory of Petrochemical Equipment Fault Diagnosis, Guangdong University of Petrochemical Technology, Maoming, China. He has (co)authored more than 80 publications in peer-reviewed international transactions/journals and conferences. His current research interests include wireless communications, fog computing, and ultra-reliable low-latency communications. He was a recipient of the 2016 EAI International Wireless Internet Conference, the 2017 International Conference on Recent Advances on Signal Processing, Telecommunications and Computing, the 2018 IEEE SYSTEMS JOURNAL, and the 2018 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS) Best Paper Award. He has been an Associate Editor of IEEE ACCESS and a Guest Editor of the IEEE INTERNET OF THINGS JOURNAL, the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, MOBILE NETWORKS AND APPLICATIONS (ACM/Springer), and SENSORS.