IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received August 25, 2020, accepted August 28, 2020, date of current version September 24, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3022724

Robust Adaptive Multilevel Control of a Quadrotor

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This work was supported by the Deanship of Scientific Research (DSR) at KFUPM through the Distinguished Professorship Award under Project DUP 19106.

ABSTRACT This study proposes a new multilevel control of a quadrotor with dynamic uncertainties and time-varying external disturbances. The quadrotor model is partitioned into three subsystems: the vertical position, the horizontal position and the rotational subsystems. First, a double loop integral fast terminal sliding mode control with an adaptive estimator for disturbances' upper-bounds (ADIFTSMC) is proposed for the altitude subsystem to ensure that the quadrotor reaches the desired height. Secondly, a radial basis function neural network backstepping controller (RBFNNBC) is applied to the horizontal subsystem. Finally, by combining a finite time exact disturbance observer with backstepping nonsingular fast terminal sliding mode control (FDOBNFTSMC), the rotational angles converge to the reference angles in the presence of the time-varying disturbances. Furthermore, a Lyapunov stability analysis is used to prove that the tracking errors converge to a small neighborhood of the origin. Numerical simulations illustrate the feasibility of the compound control structure.

INDEX TERMS Fast terminal SMC, RBFNN, backstepping, disturbance observer, quadrotor.

I. INTRODUCTION

The applications of unmanned aerial vehicles (UAV), quadrotors to be specific, have increased in many areas. The main attributes of quadrotors lie in hovering, very fast maneuvers, vertical take-off and landing (VTOL), low cost and small size [1]–[4]. Quadrotors have several applications such as military surveillance, exploration, wild fire surveillance, delivery, aerial photography, rescue missions, agriculture, mapping, e.t.c [5]–[7]. The quadrotor dynamic model is underactuated strongly coupled nonlinear system. Implementing robust control for such systems is challenging and have attracted tremendous interest from the field automatic control. In recent years, researchers have proposed various nonlinear control methods to cope with the varying operating conditions of the quadrotor [8], [9].

The dynamic model of a quadrotor is usually in strict feedback form which is appropriate for designing backstepping control [10]–[13]. In order to eliminate the steady state errors, an integral error term is included in the backstepping design [14], [15]. Nonetheless, these papers did not account for the uncertainties and external disturbances. An adaptive backstepping controller was used to addressed the uncertainties [16]–[18]. However, adaptive control methods are limited to systems with constant or slow time varying disturbances. A sliding mode control (SMC) technique is essential for mitigating all kind of bounded uncertainties and disturbances [19]–[21]. A SMC was combined with adaptive backstepping approach for the altitude and the attitude tracking of an octorotor [22]. Furthermore, fuzzy logic system (FLS) and neural networks (NN) based controllers have recently caught the attention of researchers [23]–[28].

The singularity issue that may arise in the control of a quadrotor is avoided by using the unit quaternion representation of the quadrotor attitude [29]. In [30], a robust chattering-free SMC was studied for the quaternion model of a hovering quadrotor. A quaternion-based attitude tracking controller was proposed for a quadrotor subjected to external disturbances. Nevertheless, the quaternion representation of the quadrotor may bring ambiguities. A nonsigular fast terminal (NFTSMC) was suggested in [31], [32] to avoid singularities and achieve a tracking control of the quadrotor with actuator faults. A robust adaptive NTFSMC was designed in [33] for attitude and displacement tracking control of a quadrotor subjected to unknown modelling errors. An adaptive NFTSMC based on dynamic

The associate editor coordinating the review of this manuscript and approving it for publication was Shihong Ding.

inversion has been designed for trajectory tracking of a quadrotor [34].

A cascade structure consisting of the orientation and the position dynamics of the quadrotor was proposed in [35]. The orientation part consists of the fully actuated subsystem while the position part consists of the underactuated subsystem, which were managed by independent controllers. In [36], the quadrotor model is not only divided into fully actuated and underactuated subsystems, but also included the propeller subsystem to tackle the actuator faults. In [37], a linear parameter varying controller and feedback linearization controller were designed for the attitude and the position of a quadrotor respectively. In [38], an active disturbance rejection control (ADRC) and backstepping SMC have been constructed for the quadrotor attitude and the position respectively. In [39], a backstepping SMC and an internal model controller have been implemented for the quadrotor rotational and translational subsystems. In [40], an adaptive backstepping controller was implemented for the position subsystem, and an adaptive backstepping FTSMC was developed for the attitude subsystem. In [41], a regular SMC and backstepping SMC with adaptive fault observer have been presented for quadrotor attitude and position respectively. In [42], a backstepping controller and a chattering-free backstepping SMC have been presented for the quadrotor rotational and translational subsystems respectively. In [43], a backstepping control method was designed for the displacement subsystem, while a SMC strategy was utilised to control the attitude. In [44], a RBFNN based SMC was developed for the position subsystem and a robust integral of the signum error (RISE) was designed for the orientation subsystem. In [45], an integral SMC has been designed for the position subsystem and a backstepping SMC has been developed for the rotation subsystem.

In order to obtain an improved control performance and disturbance attenuation, a disturbance observer (DO) can be integrated into the quadrotor control design. A nonlinear DO assimilated with SMC was used to control the hovering state of a quadrotor [46]. A DO based attitude tracking controller was developed in [47] to estimate the Coriolis terms and external disturbances. The actuator faults and the uncertainties hampering the performances of the quadrotor have been tackled using the DO based controllers [48]–[50]. Contrary to the traditional DO which guarantees asymptotic stability, the finite time DO (FDO) can attained a finite time stability [50]–[53].

In the light of the foregoing discussion, we present a new robust control scheme for a quadrotor under time-varying disturbances and model uncertainties. The proposed control strategy is divided into into three subcontrollers: ADIFTSMC for altitude control, RBFNNBC for horizontal position control, and FDOBNFTSMC for rotational angle control. The main contributions of the proposed method are presented as follows

1) Contrary to [37]–[43], [45] where the quadrotor control design is divided into two subcontrollers, we divided the proposed control scheme into three subcontrollers: the altitude, the horizontal position and the attitude controllers.
2) Unlike the adaptive NFTSMC [33], ADRC [38], backstepping FTSMC [40], RISE [44], backstepping SMC [45] implemented for the attitude control, in this paper, a backstepping is combined with NFTSMC and FDO (FDONFTSMC) to control the attitude angles. The advantage of this scheme is that the disturbances are exactly estimated and guarantees the robust trajectory following in finite time.
3) In contrast to Adaptive backstepping [40], backstepping [43], RBFNN based SMC [44], integral SMC [45] developed for the position subsystem, a RBFNN based backstepping is devised to stabilised the horizontal position subsystem and produce the desired Euler angles. The RBFNN identify the uncertain functions together with the external disturbances and the time derivative of the virtual control laws.
4) For the first time, an ADIFTSMC is proposed to control the altitude of the quadrotor in the face of environmental disturbances and dynamic uncertainties. This controller is free from singularities and integrates the advantages of integral and fast terminal SMC. Moreover, it requires no knowledge of the disturbances' upper-bounds.
5) The finite time stability of the multilevel control, ADIFTSMC-RBFNNBC-FDOBNFTSMC, has been established using the Lyapunov function.

The remainder of this article is arranged as follows. Section II presents the quadrotor dynamic model. Section III displays the design of the proposed control strategy. Section IV demonstrates the simulation and comparison results. We conclude the paper in Section V.

II. QUADROTOR DYNAMIC MODEL

The schematic representation of the quadrotor is depicted in Fig. 1. The quadrotor dynamic model is a six degrees of freedom underactuated system with four inputs. The dynamic model is given by [19]

$$\ddot{x} = b_1\dot{x} + V_x + \Delta_x \tag{1}$$
$$\ddot{y} = b_2\dot{y} + V_y + \Delta_y \tag{2}$$
$$\ddot{z} = b_3\dot{z} + V_z + \Delta_z \tag{3}$$
$$\ddot{\phi} = b_4\dot{\phi}^2 + b_5\dot{\psi}\dot{\theta} + b_6\dot{\theta} + a_1u_2 + \Delta_\phi \tag{4}$$
$$\ddot{\theta} = b_7\dot{\theta}^2 + b_8\dot{\psi}\dot{\phi} + b_9\dot{\theta} + a_2u_3 + \Delta_\theta \tag{5}$$
$$\ddot{\psi} = b_{10}\dot{\psi}^2 + b_{11}\dot{\phi}\dot{\theta} + a_3u_2 + \Delta_\phi \tag{6}$$

where x,y,z stand for the position of quadrotor centre of gravity, ϕ, θ, and ψ denote the pitch, roll and yaw angles respectively, Ω_r is the moment of inertia of the rotor, I_x, I_y, I_z are the moment of inertia of the quadrotor, Δ_i $(i = x, y, z, \phi, \theta, \psi)$ represent the time-varying disturbances, $b_1 = -\frac{K_{a_x}}{m}$, $b_2 = -\frac{K_{a_y}}{m}$, $b_3 = -\frac{K_{a_z}}{m}$, $b_4 = \frac{-K_{a_\phi}}{I_x}$, $b_5 = \frac{(I_y-I_z)}{I_x}$, $b_6 = \frac{-J_r\Omega_r}{Ix}$, $a_1 = \frac{l}{I_x}$, $b_7 = \frac{-K_{a_\theta}}{I_y}$, $b_8 = \frac{(I_z-I_x)}{I_y}$, $b_9 = \frac{J_r\Omega_r}{Ix}$, $a_2 = \frac{l}{I_y}$,

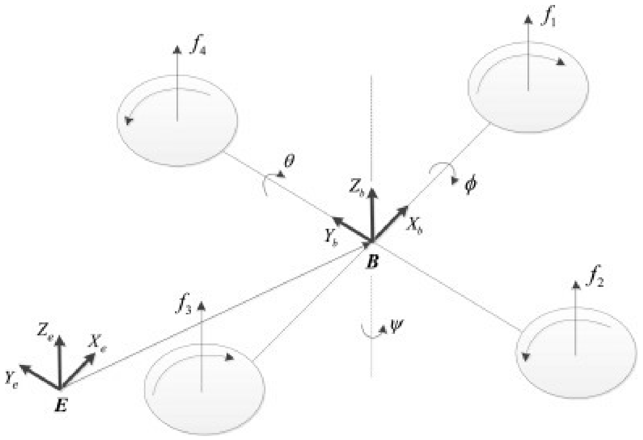

FIGURE 1. Schematic for the quadrotor system [14].

$b_{10} = \frac{-K_{a\psi}}{I_y}$, $b_{11} = \frac{(I_x - I_y)}{I_z}$, $a_3 = \frac{l}{I_z}$. The relation between the thrusts, u_i $(i = 1, 2, 3, 4)$, and the angular velocities of the four propellers, ω_i $(i = 1, 2, 3, 4)$, is given by

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} K_p & K_p & K_p & K_p \\ -K_p & 0 & -K_p & 0 \\ 0 & -K_p & 0 & -K_p \\ C_d & C_d & C_d & C_d \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \tag{7}$$

$$\begin{cases} V_x = \frac{1}{m}(cos\phi\ sin\theta\ cos\psi + sin\phi\ sin\psi)u_1 \\ V_y = \frac{1}{m}(cos\phi\ sin\theta\ sin\psi + sin\phi\ cos\psi)u_1 \\ V_z = -g + \frac{1}{m}(cos\phi\ cos\theta)u_1 \end{cases} \tag{8}$$

where C_d and K_p denote the drag and aerodynamic coefficients respectively, g stands for the acceleration due to gravity, V_x, V_y and V_z are false inputs created to take care of the under-actuated subsystem. From (8), the total thrust u_1 and the desired angles $(\phi_d,\ \theta_d)$ can be derived as

$$u_1 = m\sqrt{V_x^2 + V_y^2 + (V_z + g)^2} \tag{9}$$

$$\phi_d = arctan\left(cos\theta_d\left(\frac{sin\psi_d V_x - cos\psi_d V_y}{V_z + g}\right)\right) \tag{10}$$

$$\theta_d = arctan\left(\frac{cos\psi_d V_x + cos\theta_d V_y}{V_z + g}\right) \tag{11}$$

III. CONTROL DESIGN

In this section, a nonlinear robust adaptive controllers are developed to steer the quadrotor states to track the reference trajectories in the premise of external disturbances and model uncertainties. The control block diagram is illustrated in Fig. 2. We designed ADIFTSMC, RBFNNBC, and FDOBNFTSMC for the quadrotor vertical position, horizontal position and attitude subsystems respectively.

A. ALTITUDE CONTROL

For movement in the vertical direction, the tracking error is defined by $e_z = z - z_d$. The DIFTSM surface is given as [54]

$$\begin{cases} S_z = \dot{e}_z + \lambda_z e_I \\ \dot{e}_I = e_z + \beta_z e_z^{q/r}, \quad with\ e_z(0) = 0 \end{cases} \tag{12}$$

where $0 < q < r$, $\beta_z > 0$, $\lambda_z > 0$ are constants.

Assumption 1: The disturbance Δ_z is bounded by $\Delta_z < (\alpha_0 + \alpha_1|e_z| + \alpha_2|\dot{e}_z|^2)$,
where α_i (i = 0,1,2) are unknown constants.

Theorem 1: Consider the altitude subsystem (3), the DIFTSM surface (12), if the controller is constructed as

$$V_z = V_{z0} + V_{z1} + V_{z2} \tag{13}$$

$$V_{z0} = -\lambda_z(e_z + \beta_z e_z^{q/r}) + \ddot{z}_d \tag{14}$$

$$V_{z1} = -b_3\dot{z} \tag{15}$$

$$V_{z2} = -(\hat{\alpha}_0 + \hat{\alpha}_1|e_z| + \alpha_2|\dot{e}_z|^2)sgn(S_z) \tag{16}$$

$\hat{\alpha}_i$ $(i = 1, 2, 3)$ are the estimate of α_i $(i = 1, 2, 3)$ and they are updated online by the following adaptation laws

$$\begin{cases} \dot{\hat{\alpha}}_0 = \gamma_0\left[|S_z| - \tau\hat{\alpha}_0\right] \\ \dot{\hat{\alpha}}_1 = \gamma_1\left[|S_z||e_z| - \tau\hat{\alpha}_1\right] \\ \dot{\hat{\alpha}}_2 = \gamma_2\left[|S_z||\dot{e}_z|^2 - \tau\hat{\alpha}_2\right] \end{cases} \tag{17}$$

in which $\gamma_i > 0$ $(i = 0, 1, 2)$ are constant adaptation gains, then the altitude closed-loop system is ultimately bounded.

Proof 1: Take the positive definite Lyapunov function as

$$L_z = \frac{S_z^2}{2} + \frac{1}{2\gamma_0}\tilde{\alpha}_0^2 + \frac{1}{2\gamma_1}\tilde{\alpha}_1^2 + \frac{1}{2\gamma_2}\tilde{\alpha}_2^2 \tag{18}$$

where $\tilde{\alpha}_i = \alpha_i - \hat{\alpha}_i$ $(i = 0, 1, 2)$. Differentiating L_z with respect to time yields

$$\begin{aligned} \dot{L}_z &= S_z\dot{S}_z + \frac{1}{\gamma_0}\tilde{\alpha}_0\dot{\hat{\alpha}}_0 + \frac{1}{\gamma_1}\tilde{\alpha}_1\dot{\hat{\alpha}}_1 + \frac{1}{\gamma_2}\tilde{\alpha}_2\dot{\hat{\alpha}}_2 \\ &= S_z(b_3\dot{z} + V_z + \Delta_z - \ddot{z}_d + \lambda_z(e_z + B_z e_z^{q/r})) \\ &\quad + \frac{1}{\gamma_0}\tilde{\alpha}_0\dot{\hat{\alpha}}_0 + \frac{1}{\gamma_1}\tilde{\alpha}_1\dot{\hat{\alpha}}_1 + \frac{1}{\gamma_2}\tilde{\alpha}_2\dot{\hat{\alpha}}_2 \end{aligned} \tag{19}$$

Substituting (13)-(16) into (19) gives

$$\begin{aligned} \dot{L}_z &\le [\Delta_z - (\alpha_0 + \alpha_1|e_z| + \alpha_2|\dot{e}_z|^2)]|S_z| \\ &\quad + (\tilde{\alpha}_0 + \tilde{\alpha}_1|e_z| + \tilde{\alpha}_2|\dot{e}_z|^2)|S_z| \\ &\quad + \frac{\tilde{\alpha}_0}{\gamma_0}(\dot{\alpha}_0 - \dot{\hat{\alpha}}_0) + \frac{\tilde{\alpha}_1}{\gamma_1}(\dot{\alpha}_1 - \dot{\hat{\alpha}}_1) + \frac{\tilde{\alpha}_2}{\gamma_2}(\dot{\alpha} - \dot{\hat{\alpha}}_2) \\ &\le [\Delta_z - (\alpha_0 + \alpha_1|e_z| + \alpha_2|\dot{e}_z|^2)]|S_z| \\ &\quad + \tilde{\alpha}_0\left(|S_z| - \frac{\dot{\hat{\alpha}}_0}{\gamma_0}\right) + \tilde{\alpha}_1\left(|e_z||S_z| - \frac{\dot{\hat{\alpha}}_1}{\gamma_1}\right) \\ &\quad + \tilde{\alpha}_2\left(|e_z|^2|S_z| - \frac{\dot{\hat{\alpha}}_2}{\gamma_2}\right) \end{aligned} \tag{20}$$

Using the adaptive laws (17) and considering Assumption 1, one has

$$\dot{L}_z \le -\epsilon|S_z| + \tau\tilde{\alpha}_0\hat{\alpha}_0 + \tau\tilde{\alpha}_1\hat{\alpha}_1 + \tau\tilde{\alpha}_2\hat{\alpha}_2 \tag{21}$$

where $\epsilon = (\alpha_0 + \alpha_1|e_z| + \alpha_2|\dot{e}_z|^2) - \Delta_z > 0$.

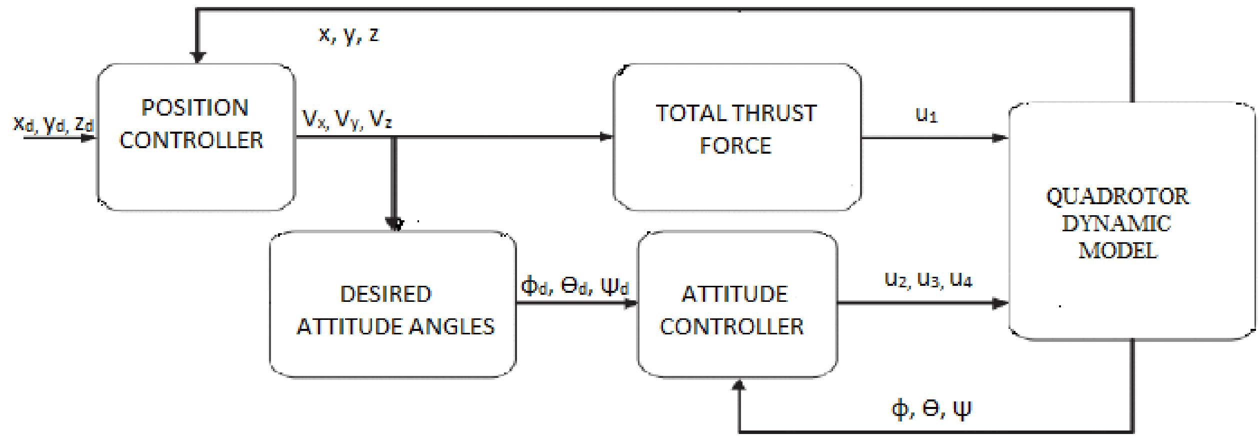

FIGURE 2. Block diagram of the overall control system.

Since

$$\begin{cases} \epsilon|S_z| \le \dfrac{\epsilon^2}{2} + \dfrac{|S_z|^2}{2} \\ \tilde{\alpha}_i\hat{\alpha}_i = \tilde{\alpha}_i(\alpha_i - \tilde{\alpha}_i) \le \dfrac{\alpha_i^2}{2} - \dfrac{\tilde{\alpha}_i^2}{2}, \quad i = (0,1,2) \end{cases} \tag{22}$$

We achieve

$$\begin{aligned} \dot{L}_z &\le -\frac{S_z^2}{2} - \tau\sum_{i=0}^{2}\frac{\tilde{\alpha}_i^2}{2} + \tau\sum_{i=0}^{2}\frac{\alpha_i^2}{2} - \frac{\epsilon^2}{2} \\ &\le -a_zL_z + b_z \end{aligned} \tag{23}$$

where $a_z = min\{1, \tau, \tau, \tau\}$, $b = \tau\sum_{i=0}^{2}\frac{\alpha_i^2}{2} - \frac{\epsilon^2}{2}$. Equation (23) satisfies

$$L_z \le \Big(L_z(0) - \frac{b_z}{a_z}\Big)e^{-a_zt} + \frac{b_z}{a_z} \tag{24}$$

Considering the Lyapunov function (18), we get

$$\frac{\|\zeta_z\|^2}{2} \le \Big(L_z(0) - \frac{b_z}{a_z}\Big) \Longrightarrow \|\zeta_z\| \le \sqrt{2\Big(L_z(0) - \frac{b_z}{a_z}\Big)} \tag{25}$$

According to the above proof, all the error signals, S_z, $\tilde{\alpha}_i$, $(i = 0, 1, 2)$ in the closed loop system are guaranteed to be ultimately bounded in the compact set defined by $\vartheta_z \equiv \{\zeta_z : \|\zeta_z\| \le c_z\}$, with $c_z \equiv \sqrt{2(L_z(0) - b_z/a_z)}$.

B. HORIZONTAL POSITION CONTROL

The horizontal subsystem can be rewritten as

$$\ddot{\chi} = f(\chi) + V + \Delta \tag{26}$$

where $\chi = [x\ y]^T$, $f(\chi) = [b_1\dot{x}\ b_2\dot{y}]^T$, $V = [V_x\ V_y]^T$, $\Delta = [\Delta_x\ \Delta_y]^T$. Define the tracking error variable $e_\chi = \chi - \chi_d$. The Lyapunov function is selected as $L_1 = \frac{1}{2}e_\chi^2$. The derivative of L_1 with respect to time is thus

$$\dot{L}_1 = e_\chi(\dot{\chi} - \dot{\chi}_d) \tag{27}$$

The virtual controller is designed as $\alpha_\chi = \dot{\chi}_d - \Lambda_\chi e_\chi$, with $\Lambda_\chi = \Lambda_\chi^T > 0$ is a constant diagonal matrix. The error between $\dot{\chi}$ and α_χ is computed as $\varepsilon_\chi = \dot{\chi} - \alpha_\chi$. Substituting $\dot{\chi}_d = \alpha_\chi + \Lambda_\chi e_\chi$ into (27) yields

$$\dot{L}_1 = e_\chi^T(\dot{\chi} - \alpha_\chi - \Lambda_\chi e_\chi) = e_\chi^T\varepsilon_\chi - e_\chi^T\Lambda_\chi e_\chi \tag{28}$$

The time derivative of ϵ_χ yields

$$\dot{\epsilon}_\chi = \ddot{\chi} - \dot{\alpha}_\chi = f(\chi) + V + \Delta - \dot{\alpha}_\chi \tag{29}$$

By utilising the approximation property of RBFNN, we have

$$f(\chi) + \Delta - \dot{\alpha}_\chi = W^T\xi(\chi, h_i, c_i) + \varphi \tag{30}$$

where $W = [W_x^T\ W_y^T]^T$ is the optimal weight vector, $\xi = diag\{\xi_x\ \xi_y\}$ is the basis function matrix with h_i as the width, c_i is the center, $\varphi = [\varphi_x\ \varphi_y]^T$ is the RBFNN approximation error vector satisfying $\|\varphi\| \le \varphi^*$, with φ^* being a positive constant. The second Lyapunov function is define as follows

$$L_\chi = \frac{1}{2}e_\chi^Te_\chi + \frac{1}{2}\varepsilon_\chi^T\varepsilon + \frac{1}{2}\tilde{W}^T\gamma^{-1}\tilde{W} \tag{31}$$

where $\gamma = \gamma^T > 0$ is a constant diagonal matrix, $\tilde{W} = W - \hat{W}$ is estimation error. The time-derivative of L_χ is

$$\begin{aligned} \dot{L}_\chi &= e_\chi^T\dot{e}_\chi + \varepsilon_\chi^T\dot{\varepsilon}_\chi + \tilde{W}^T\gamma^{-1}\dot{\tilde{W}} \\ &= -e_\chi^T\Lambda e_\chi + \varepsilon_\chi^T(e_\chi + W^T\xi + \varphi + V) - \tilde{W}\gamma^{-1}\dot{\hat{W}} \end{aligned} \tag{32}$$

Theorem 2: Considering the horizontal subsystem (26), if the controller (33) and RBFNN weight update rule (34) are designed, the signals in (31) are ultimately bounded.

$$V = -e_\chi - K^T\varepsilon_\chi - \hat{W}^T\xi \tag{33}$$

$$\dot{\hat{W}} = \gamma\xi\varepsilon_\chi - \tau\gamma\hat{W} \tag{34}$$

where $\hat{W}$ is the estimate of W, $\tau > 0$ is a constant.

Proof 2: Substituting (33) and (34) into (32), one gets

$$\dot{L}_\chi = -e_\chi^T\Lambda e_\chi - \varepsilon_\chi^TK\varepsilon_\chi + \varepsilon_\chi^T\varphi + \tau\tilde{W}^T\hat{W} \tag{35}$$

The following inequalities exist

$$\varepsilon_\chi^T\varphi \le \frac{\|\varepsilon_\chi\|^2}{2} + \frac{\|\varphi\|^2}{2}$$

$$\tilde{W}^T\hat{W}7 = \tilde{W}^T(W-\tilde{W}) \le \frac{\|W\|^2}{2} - \frac{\|\tilde{W}\|^2}{2}$$

$$\begin{aligned}\dot{L}_\chi &\le -\|\Lambda\|\|e_\chi\|^2 - \Big(\|K\| - \frac{1}{2}\Big)\|\varepsilon_\chi\|^2 - \tau\frac{\|\tilde{W}\|^2}{2} \\ &\quad + \frac{\|W\|^2}{2} + \frac{\|\varphi\|^2}{2} \\ &\le -a_2 L_\chi + b_2 \end{aligned} \tag{36}$$

where $a_\chi = min\{2\|\Lambda\|,\ 2\Big(\|K\| - \frac{1}{2}\Big),\ \tau\}$, $b_\chi = \frac{\|W\|^2}{2} + \frac{\|\varphi\|^2}{2}$. By integrating (36) and considering the definition of the Lyapunov function (31), one can have

$$\frac{\|\zeta_\chi\|^2}{2} \le \Big(L_\chi(0) - \frac{b_\chi}{a_\chi}\Big) \implies \|\zeta_\chi\| \le \sqrt{2\Big(L_\chi(0) - \frac{b_\chi}{a_\chi}\Big)} \tag{37}$$

Therefore, the error signals e_χ, ε_χ and $\tilde{W}$ are bounded in the compact set $\vartheta_\chi \equiv \{\zeta_\chi : \|\zeta_\chi\| \le c_\chi\}$, with $c_\chi \equiv \sqrt{2(L_\chi(0) - b_\chi/a_\chi)}$

C. ATTITUDE CONTROL

The attitude subsystem is as follows

$$\begin{cases} \dot{\eta} = \Omega \\ \dot{\Omega} = f(\Omega) + gu + \Delta_\eta \end{cases} \tag{38}$$

where $\eta = [\phi,\ \theta,\ \psi]^T$ is the orientation of the quadrotor, $\Omega = [\dot{\phi},\ \dot{\theta},\ \dot{\psi}]^T$, $\Delta_\eta = [\Delta_\phi,\ \Delta_\theta,\ \Delta_\psi]^T$, $u = [u_1\ u_2\ u_3]^T$

$$f = \begin{bmatrix} b_4\dot{\phi}^2 + b_5\dot{\psi}\dot{\theta} + b_6\dot{\theta} \\ b_7\dot{\theta}^2 + b_8\dot{\psi}\dot{\phi} + b_9\dot{\theta} \\ b_{10}\dot{\psi}^2 + b_{11}\dot{\phi}\dot{\theta} \end{bmatrix} \quad g = \begin{bmatrix} l/I_x & 0 & 0 \\ 0 & l/I_y & 0 \\ 0 & 0 & l/I_z \end{bmatrix}$$

A finite time disturbance observer [55] can be designed for (38) as follows

$$\begin{cases} \dot{\mu}_0 = \varsigma_0 + f(\Omega) + gu \\ \varsigma_0 = h_1\,R^{1/3}sig^{2/3}(\mu_0 - \Omega) + \mu_1 \\ \dot{\mu}_1 = \varsigma_1 \\ \varsigma_1 = h_2\,R^{1/2}sig^{1/2}(\mu_1 - \varsigma_0) + \mu_2 \\ \dot{\mu}_2 = h_3\,Rsgn(\mu_2 - \varsigma_1) \end{cases} \tag{39}$$

where μ_0, μ_1 and μ_2 are the estimate of Ω, Δ_η and $\dot{\Delta}_\eta$, respectively, $sig^\rho(\chi) = |\chi|^\rho sgn(\chi)$. Subsequently, Δ_η can be exactly estimated in finite time.

Define the observation errors as

$$\pi_1 = \mu_0 - \Omega,\ \pi_2 = \mu_1 - \Delta_\eta,\ \pi_3 = \mu_2 - \dot{\Delta}_\eta \tag{40}$$

The observation error dynamics is thus

$$\begin{cases} \dot{\pi}_1 = \varsigma_0 + f(\Omega) + gu - f(\Omega) - gu - \Delta_\eta \\ \quad = -h_1\,R^{1/3}sig^{2/3}(\pi_1) + \pi_2 \\ \dot{\pi}_2 = -h_2\,R^{1/2}sig^{1/2}(\mu_1 - \varsigma_0) + \mu_2 - \dot{\Delta}_\eta \\ \quad = -h_2\,R^{1/2}sig^{1/2}(\pi_2 - \dot{\pi}_1) + \pi_3 \\ \dot{\pi}_3 = -h_3\,Lsgn(\pi_3 - \varsigma_1) - \ddot{\Delta}_\eta \\ \quad = -h_3\,Lsgn^{1/2}(\pi_3 - \dot{\pi}_2) - \ddot{\Delta}_\eta \end{cases} \tag{41}$$

From [55], the observation errors will converge to zero in finite time. Then, $\mu_0 \equiv \Omega$, $\mu_1 \equiv \Delta_\eta$, $\mu_2 \equiv \dot{\Delta}_\eta$. The attitude tracking errors are as follows

$$\begin{cases} e_\eta = \eta - \eta_d \\ \dot{e}_\eta = \Omega - \dot{\eta}_d \end{cases} \tag{42}$$

where $e_\eta = [e_\phi,\ e_\theta,\ e_\psi]^T$, $\eta_d = [\phi_d,\ \theta\eta_d,\ \psi_d]^T$ is the vector of desired attitude angles. The NFTSMC surface is expressed as [56]

$$S = e_\eta + \varrho sgn^q(e_\eta) + \Lambda sgn^r(\dot{e}_\Omega) \tag{43}$$

where $S = \big[S_\phi,\ S_\theta,\ S_\psi\big]^T$,

$$sgn^r(e_\eta) = \big[|e_\phi|^r sgn(e_\phi),\ |e_\theta|^r sgn(e_\theta), |e_\psi|^r sgn(e_\psi)\big]^T,$$

$$sgn^q(\dot{e}_\eta) = \big[|e_p|^q sgn(e_p),\ |e_p|^q sgn(e_q),\ |e_p|^q sgn(e_r)\big]^T,$$

$\varrho > 0$, $\Lambda > 0$ are design parameters, $q > 0$, $r > 0$ such that $1 < r < 2$ and $q > r$.

Theorem 3: Consider the attitude subsystem (38) with control law (44)-(47) for reaching and staying on the surface (43), and supposed that the parameters of the FDO (39) are properly selected so that the disturbances can be exactly estimated, then the attitude signals track the desired angles in finite time.

$$u = u_e + u_d + u_r \tag{44}$$

$$\begin{aligned} u_e &= g^{-1}[-(f - \ddot{\eta}_d) - \frac{|\dot{e}_\eta|^{2-r}}{\Lambda r}(I + \alpha q|e_\eta|^{q-1})sgn(\dot{e}_\eta) \\ &\quad - \frac{|\dot{e}_\eta|^{1-r}e_\eta}{\Lambda r} - \mu_1] \end{aligned} \tag{45}$$

$$u_d = g^{-1}\mu_1 \tag{46}$$

$$u_r = g^{-1}[-KS - \Upsilon|S|^{r/q}sgn(S)] \tag{47}$$

where $K = K^T > 0$ and $\Upsilon = \Upsilon^T > 0$ are constant matrices, $0 < r/q < 1$, I is identity matrix, $|S|^{r/q} = [|S_\phi|^{r/q},\ |S_\theta|^{r/q},\ |S_\psi|^{r/q}]^T$, μ_1 is the estimate of Δ_η computed by the FDO, $|e_\eta| = diag\big\{\big[|e_\phi|,\ |e_\theta|,\ |e_\psi|\big]\big\}$, $|\dot{e}_\eta| = diag\big\{\big[|\dot{e}_\phi|,\ |\dot{e}_\theta|,\ |\dot{e}_\psi|\big]\big\}$. The virtual control input is designed as

$$\Omega = -Ce_\eta + S + \dot{\eta}_d \tag{48}$$

where $C = C^T > 0$ is a constant diagonal matrix.

Proof 3: Consider a positive Lyapunov function as follows:

$$L_\eta = \frac{e_\eta^T e_\eta}{2} + \frac{S^T S}{2} \tag{49}$$

By differentiating L_η with respect to time, we have

$$\begin{aligned} \dot{L}_\eta &= e_\eta^T\dot{e}_\eta + S^T\dot{S} \\ &= e_\eta^T(\Omega - \dot{\eta}_d) + S^T\big[\dot{e}_\eta + \varrho q|e_\eta|^{q-1}\dot{e}_\eta + \Lambda r|\dot{e}_\eta|^{r-1}\ddot{e}_\eta\big] \end{aligned} \tag{50}$$

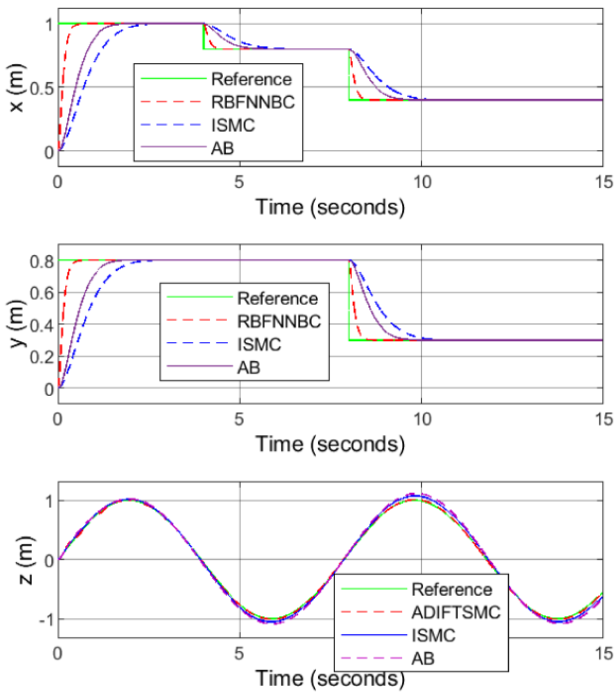

FIGURE 3. Position tracking result.

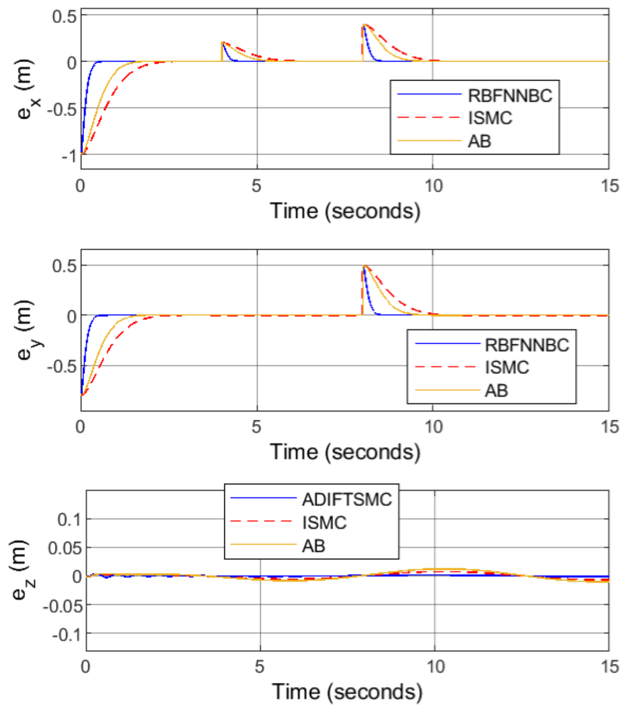

FIGURE 4. Position tracking error result.

Using the virtual controller (48), one has

$$\begin{aligned}\dot{L}_\eta &= -e_\eta^T C e_\eta + S^T\big[e_\eta + \dot{e}_\eta + \varrho q|e_\eta|^{q-1}\dot{e}_\eta \\ &\quad + \Lambda r|\dot{e}_\eta|^{r-1}[f(\Omega) + gu + \Delta_\eta - \ddot{\eta}_d]\big] \qquad (51)\end{aligned}$$

Substituting the overall control law (44)-(47) into (51), we have

$$\begin{aligned}\dot{L}_\eta &= -e_\eta^T C e_\eta + \Lambda q|\dot{e}_\eta|^{q-1} S^T\big[(\Delta_\eta - \mu_1) \\ &\quad - KS - \Upsilon|S|^{r/q} sgn(S)\big] \qquad (52)\end{aligned}$$

Note that the FDO accurately estimate Δ_η in finite time, e.g., $\mu_1 \equiv \Delta_\eta$, then

$$\begin{aligned}\dot{L}_\eta &\leq -\|C\|\|e_\eta\|^2 \\ &\quad - \|\Lambda q|\dot{e}_\eta|^{q-1}\|\big[\|K\|\|S\|^2 + \|S\|^{r/q+1}\|\Upsilon\|\big] \qquad (53)\end{aligned}$$

Considering the inequality $\|S\|^{r/q+1} \geq \|S\|^2$, $\|S\| \longrightarrow 0$ and letting $a_\eta = \{2\|C\|,\ 2\|\Lambda q|\dot{e}_\eta|^{q-1}\|\ (\|K\| - \|\Upsilon\|)\}$, we get

$$\dot{L}_\eta \leq -a_\eta L_\eta \qquad (54)$$

By integrating (54), we can have

$$L_\eta \leq L_\eta(0)e^{-a_\eta t} \qquad (55)$$

If the reaching time is expressed as $T_r = \frac{1}{a_\eta} ln\left(\frac{L_\eta(0)}{L_\eta}\right)$, the closed loop signals are bounded in finite time $\forall t > T_r$.

TABLE 1. Control design parameters.

Parameters	Values
$\lambda_z, \beta_z, \gamma_0, \gamma_1, \gamma_2$	50, 0.1, 0.05, 0.02, 0.02
Λ_x, K, γ h_i, c_i	diag(8,8), diag(16,16), diag(0.02,0.02) 2, [0, 0.1, 0.2, 0.3, 0.4, 0.5]
ϱ, Λ, C q, r h_1, h_2, h_3, L	diag(5,5,8), diag(1,1,1), diag(6,6,15) 2, 5/3 1.5 , 1.4, 2.6, 24

IV. SIMULATION

In this section, a comparison of the simulations is carried out to demonstrate the effectiveness of the proposed control scheme. The efficacy of the proposed ADIFTSMC-RBFNNBC-FDOBNFTSMC has been compared with the controllers in [40] where an adaptive backstepping (AB) and adaptive backstepping FTSMC (ABFTSMC) were designed for the position and the attitude subsystems respectively, and in [45] where integral SMC (ISMC) and Backstepping SMC (BSMC) were utilised for the attitude and the position subsystems respectively.

The quadrotor parameters are obtained from [19]. The initial condition of each of the quadrotor states is 0.001. The time varying external disturbances are modelled as sinusoidal functions $\Delta_i = 2sin(0.8t)$ $(i = x, y, z, \phi, \theta, \psi)$. The control design parameters are given in Table 1. The desired signals are given by

$$x_d = \begin{cases} 1 & 0 \leq t \leq 4 \\ 0.8 & 4 < t \leq 8 \\ 0.4 & 8 < t \leq 15 \end{cases} \quad ; y_d = \begin{cases} 0.8 & 0 \leq t \leq 8 \\ 0.3 & 8 < t \leq 15 \end{cases}$$

$$z_d = sin(t) \quad \psi_d = sin(0.8t)$$

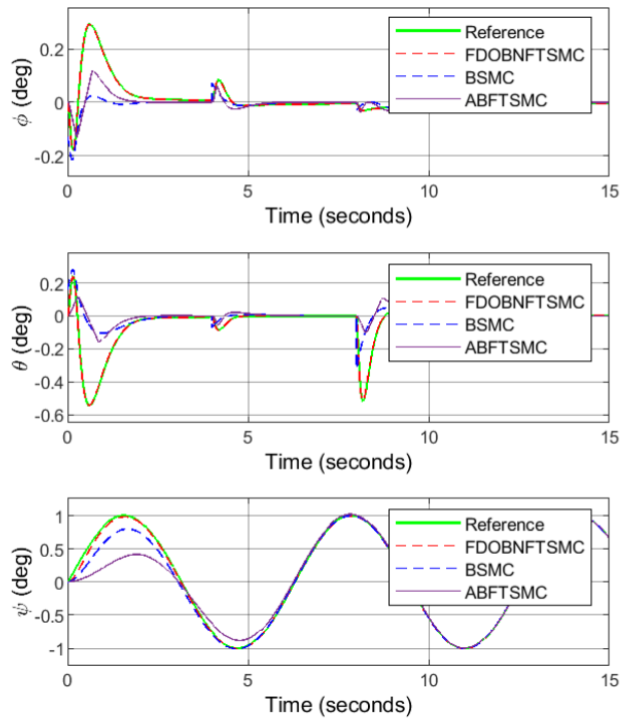

FIGURE 5. Attitude tracking result.

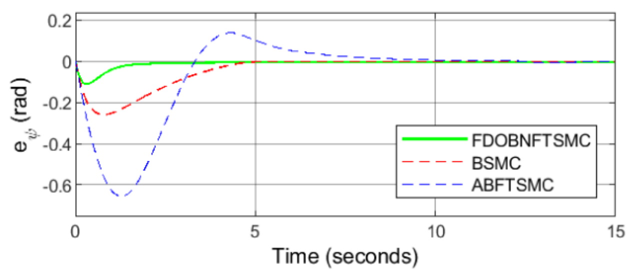

FIGURE 6. Yaw angle tracking error.

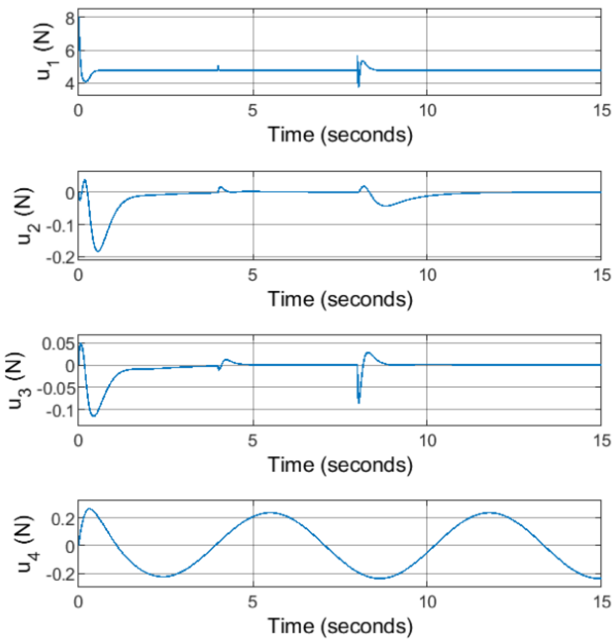

FIGURE 7. Quadrotor control inputs.

The simulation results are presented in Figs. 3-7. From the position responses shown in Fig. 3, it can be inferred that the ADIFTSMC/RBFNNBC provide the highest trajectory tracking precision and the quickest dynamical responses compared to both AB and ISMC. Moreover, the tracking error responses in Fig. 4 show that the ADIFTSMC/RBFNNBC converges to zero in the shortest time.

In Fig. 5, the comparison between the FDOBNFTSMC, BSMC and ABFTSMC has been presented. It can be observed that in the presence of the disturbances, the attitude angles followed the reference angles with greater accuracy under the FDOBNFTSMC. Contrary to BSMC and ABFTSMC, the FDOBNFTSMC can exactly estimate and compensate the time varying disturbances in finite time. The tracking responses of the yaw angle are demonstrated in Fig. 6. This figure illustrates that the tracking errors converge to zero in the shortest time under FDOBNFTSMC. The control inputs are presented in Fig. 7.

V. CONCLUSION

In this article, a novel multilevel control of a quadrotor has been developed to guarantees the robust trajectory following in the presence of model uncertainties, system coupling and environmental disturbances. The nonlinear control method is divided into three subcontrollers. Firstly, an ADIFTSMC is developed for the altitude subsystem to keep the quadrotor flying at the desired height irrespective of the external disturbances. Then, the horizontal position subsystem is controlled with a RBFNNBC to stabilised it and generate the reference Euler angles for the attitude subsystem. The RBFNN approximates the uncertain dynamics, external disturbances and the derivatives of the virtual control inputs. Subsequently, a FDOBNFTSMC has been developed for the attitude subsystem. Numerical simulations have shown the superiority of the proposed multilevel control structure, ADIFTSMC-RBFNNBC-FDOBNFTSMC, over some existing methods. The finite time stability of the overall system is presented based on the Lyapunov theory. In future work, the effectiveness of the proposed scheme will be investigated in real time control of a quadrotor.

REFERENCES

[1] S. H. Dolatabadi and M. J. Yazdanpanah, "MIMO sliding mode and backstepping control for a quadrotor UAV," in *Proc. 23rd Iranian Conf. Electr. Eng.*, May 2015, pp. 994–999.
[2] J.-J. Xiong and G.-B. Zhang, "Global fast dynamic terminal sliding mode control for a quadrotor UAV," *ISA Trans.*, vol. 66, pp. 233–240, Jan. 2017.
[3] Y. Zou and B. Zhu, "Adaptive trajectory tracking controller for quadrotor systems subject to parametric uncertainties," *J. Franklin Inst.*, vol. 354, no. 15, pp. 6724–6746, Oct. 2017.

[4] W. Dong, G.-Y. Gu, X. Zhu, and H. Ding, "High-performance trajectory tracking control of a quadrotor with disturbance observer," *Sens. Actuators A, Phys.*, vol. 211, pp. 67–77, May 2014.

[5] S. Mallavalli and A. Fekih, "A fault tolerant control approach for a quadrotor UAV subject to time varying disturbances and actuator faults," in *Proc. IEEE Conf. Control Technol. Appl. (CCTA)*, Aug. 2017, pp. 596–601.

[6] M. E. Antonio-Toledo, E. N. Sanchez, and A. Y. Alanis, "Neural inverse optimal control applied to quadrotor UAV," in *Proc. IEEE Latin Amer. Conf. Comput. Intell. (LA-CCI)*, Nov. 2018, pp. 1–8.

[7] H. Mo and G. Farid, "Nonlinear and adaptive intelligent control techniques for quadrotor UAV—A survey," *Asian J. Control*, vol. 21, no. 2, pp. 989–1008, Mar. 2019.

[8] Y. Qi, J. Wang, and J. Shan, "Aerial cooperative transporting and assembling control using multiple quadrotor–manipulator systems," *Int. J. Syst. Sci.*, vol. 49, no. 3, pp. 662–676, Feb. 2018.

[9] B. Xian, B. Zhao, Y. Zhang, and X. Zhang, "Nonlinear control of a quadrotor with deviated center of gravity," *J. Dyn. Syst., Meas., Control*, vol. 139, no. 1, Jan. 2017, Art. no. 011003.

[10] Y. Yali, J. Changhong, and W. Haiwei, "Backstepping control of each channel for a quadrotor aerial robot," in *Proc. Int. Conf. Comput., Mechatronics, Control Electron. Eng.*, Aug. 2010, pp. 403–407.

[11] A.-W.-A. Saif, M. Dhaifullah, M. Al-Malki, and M. E. Shafie, "Modified backstepping control of quadrotor," in *Proc. Int. Multi-Conf. Syst., Sygnals Devices*, Mar. 2012, pp. 1–6.

[12] D. Lee, C. Ha, and Z. Zuo, "Backstepping control of quadrotor-type UAVs and its application to teleoperation over the Internet," in *Intelligent Autonomous Systems 12*, S. Lee, H. Cho, K.-J. Yoon, and J. Lee, Eds. Berlin, Germany: Springer, 2013, pp. 217–225.

[13] A. Das, F. Lewis, and K. Subbaro, "Modified backstepping control of quadrotor," *J. Intell. Robot. Syst.*, vol. 56, pp. 127–151, 2009, doi: 10.1007/s10846-009-9331-0.

[14] W.-N. Gao and Z. Fang, "Adaptive integral backstepping control for a 3-DOF helicopter," in *Proc. IEEE Int. Conf. Inf. Autom.*, Jun. 2012, pp. 190–195.

[15] M. E. Antonio-Toledo, E. N. Sanchez, A. Y. Alanis, J. Flórez, and M. A. Perez-Cisneros, "Real-time integral backstepping with sliding mode control for a quadrotor UAV," in *Proc. 2nd IFAC Conf. Modeling, Identificat. Control Nonlinear Syst. (MICNON)*, vol. 51, no. 13, 2018, pp. 549–554.

[16] Z. Dong, H. Fan, Y. Wang, L. Xu, and W. Wang, "Adaptive backstepping controller design for quadrotor aircraft with unknown disturbance," in *Proc. 14th Int. Conf. Control, Autom., Robot. Vis. (ICARCV)*, Nov. 2016, pp. 1–5.

[17] F. Javidi-Niroumand and A. Fakharian, "Trajectory tracking via adaptive nonlinear control approach for a quadrotor MAV," in *Proc. AI Robot. (IRANOPEN)*, Apr. 2015, pp. 1–7.

[18] Y. Wei, D. Sheng, Y. Chen, and Y. Wang, "Fractional order chattering-free robust adaptive backstepping control technique," *Nonlinear Dyn.*, vol. 95, no. 3, pp. 2383–2394, Feb. 2019.

[19] 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, Jan. 2018.

[20] S. Ding and S. Li, "Second-order sliding mode controller design subject to mismatched term," *Automatica*, vol. 77, pp. 388–392, Mar. 2017.

[21] X.-H. Chang, Y. Liu, and M. Shen, "Resilient control design for lateral motion regulation of intelligent vehicle," *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 6, pp. 2488–2497, Dec. 2019.

[22] 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.

[23] H. Housny, E. A. Chater, and H. El Fadil, "New deterministic optimization algorithm for fuzzy control tuning design of a quadrotor," in *Proc. 5th Int. Conf. Optim. Appl. (ICOA)*, Apr. 2019, pp. 1–6.

[24] X.-H. Chang and G.-H. Yang, "Nonfragile H_∞ filtering of continuous-time fuzzy systems," *IEEE Trans. Signal Process.*, vol. 59, no. 4, pp. 1528–1538, Apr. 2011.

[25] X. Yu, Z. Lv, Y. Wu, and X.-M. Sun, "Neural network modeling and backstepping control for quadrotor," in *Proc. Chin. Autom. Congr. (CAC)*, Nov. 2018, pp. 3649–3654.

[26] Z. Jia, L. Wang, J. Yu, and X. Ai, "Distributed adaptive neural networks leader-following formation control for quadrotors with directed switching topologies," *ISA Trans.*, vol. 93, pp. 93–107, Oct. 2019.

[27] M. A. M. Basri, "Trajectory tracking control of autonomous quadrotor helicopter using robust neural adaptive backstepping approach," *J. Aerosp. Eng.*, vol. 31, no. 2, 2018, Art. no. 04017091.

[28] Q. Jing, Z. Chang, H. Chu, Y. Shao, and X. Zhang, "Quadrotor attitude control based on fuzzy sliding mode control theory," in *Proc. Chin. Control Conf. (CCC)*, Jul. 2019, pp. 8360–8364.

[29] H. Liu, X. Wang, and Y. Zhong, "Quaternion-based robust attitude control for uncertain robotic quadrotors," *IEEE Trans. Ind. Informat.*, vol. 11, no. 2, pp. 406–415, Apr. 2015.

[30] H. Abaunza and P. Castillo, "Quadrotor aggressive deployment, using a quaternion-based spherical chattering-free sliding-mode controller," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 56, no. 3, pp. 1979–1991, Jun. 2020.

[31] Z. Hou, P. Lu, and Z. Tu, "Nonsingular terminal sliding mode control for a quadrotor UAV with a total rotor failure," *Aerosp. Sci. Technol.*, vol. 98, Mar. 2020, Art. no. 105716.

[32] Y. Wang, S. Jiang, B. Chen, and H. Wu, "A new continuous fractional-order nonsingular terminal sliding mode control for cable-driven manipulators," *Adv. Eng. Softw.*, vol. 119, pp. 21–29, May 2018.

[33] 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.

[34] U. Ansari, A. H. Bajodah, and M. T. Hamayun, "Quadrotor control via robust generalized dynamic inversion and adaptive non-singular terminal sliding mode," *Asian J. Control*, vol. 21, no. 3, pp. 1237–1249, May 2019.

[35] J.-J. Xiong and E.-H. Zheng, "Position and attitude tracking control for a quadrotor UAV," *ISA Trans.*, vol. 53, no. 3, pp. 725–731, May 2014.

[36] T. Madani and A. Benallegue, "Backstepping control for a quadrotor helicopter," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2006, pp. 3255–3260.

[37] C. Trapiello, V. Puig, and B. Morcego, "Position-heading quadrotor control using LPV techniques," *IET Control Theory Appl.*, vol. 13, no. 6, pp. 783–794, Apr. 2019.

[38] L. Xu, H. Ma, D. Guo, A. Xie, and D. Song, "Backstepping sliding-mode and cascade active disturbance rejection control for a quadrotor UAV," *IEEE/ASME Trans. Mechatronics*, early access, Apr. 27, 2020, doi: 10.1109/TMECH.2020.2990582.

[39] Z. He and L. Zhao, "Internal model control /backstepping sliding model control for quadrotor trajectory tracking," in *Proc. IEEE 2nd Inf. Technol., Netw., Electron. Autom. Control Conf. (ITNEC)*, Dec. 2017, pp. 1254–1258.

[40] 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.

[41] F. Chen, R. Jiang, K. Zhang, B. Jiang, and G. Tao, "Robust backstepping sliding-mode control and observer-based fault estimation for a quadrotor UAV," *IEEE Trans. Ind. Electron.*, vol. 63, no. 8, pp. 5044–5056, Aug. 2016.

[42] Z. He, L. Zhao, and L. Zhao, "Robust chattering free backstepping/backstepping sliding mode control for quadrotor hovering," in *Proc. IEEE Inf. Technol., Netw., Electron. Autom. Control Conf.*, May 2016, pp. 616–620.

[43] O. Garcia, P. Ordaz, O.-J. Santos-Sanchez, 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.

[44] Z. Li, X. Ma, and Y. Li, "Robust tracking control strategy for a quadrotor using RPD-SMC and RISE," *Neurocomputing*, vol. 331, pp. 312–322, Feb. 2019.

[45] D. J. Almakhles, "Robust backstepping sliding mode control for a quadrotor trajectory tracking application," *IEEE Access*, vol. 8, pp. 5515–5525, 2020.

[46] N. Wang, Q. Deng, H. Zhao, J. Yin, and Z. Zheng, "Nonlinear disturbance observer-based sliding backstepping hovering control of a quadrotor," in *Proc. Chin. Control Decis. Conf. (CCDC)*, Jun. 2018, pp. 3274–3279.

[47] A. Castillo, R. Sanz, P. Garcia, W. Qiu, H. Wang, and C. Xu, "Disturbance observer-based quadrotor attitude tracking control for aggressive maneuvers," *Control Eng. Pract.*, vol. 82, pp. 14–23, Jan. 2019.

[48] A. Baldini, R. Felicetti, A. Freddi, S. Longhi, and A. Monteriu, "Fault-tolerant disturbance observer based control for altitude and attitude tracking of a quadrotor," in *Proc. 26th Medit. Conf. Control Autom. (MED)*, Jun. 2018, pp. 1–6.

[49] X. Lyu, J. Zhou, H. Gu, Z. Li, S. Shen, and F. Zhang, "Disturbance observer based hovering control of quadrotor tail-sitter VTOL UAVs using synthesis," *IEEE Robot. Autom. Lett.*, vol. 3, no. 4, pp. 2910–2917, Oct. 2018.

[50] H. Du, K. Liu, D. Wu, W. Zhu, and S. Ding, ''Disturbance observer-based finite-time control for a quadrotor aircraft,'' in *Proc. IEEE 8th Annu. Int. Conf. Cyber Technol. Autom., Control, Intell. Syst. (CYBER)*, Jul. 2018, pp. 1248–1253.

[51] J. Zhou, Y. Cheng, H. Du, D. Wu, M. Zhu, and X. Lin, ''Active finite-time disturbance rejection control for attitude tracking of quad-rotor under input saturation,'' *J. Franklin Inst.*, May 2019.

[52] X. Cheng and Z.-W. Liu, ''Robust tracking control of a quadcopter via terminal sliding mode control based on finite-time disturbance observer,'' in *Proc. 14th IEEE Conf. Ind. Electron. Appl. (ICIEA)*, Jun. 2019, pp. 1217–1222.

[53] N. Wang, S. Lv, W. Zhang, Z. Liu, and M. J. Er, ''Finite-time observer based accurate tracking control of a marine vehicle with complex unknowns,'' *Ocean Eng.*, vol. 145, pp. 406–415, Nov. 2017.

[54] L. Qiao and W. Zhang, ''Double-loop integral terminal sliding mode tracking control for UUVs with adaptive dynamic compensation of uncertainties and disturbances,'' *IEEE J. Ocean. Eng.*, vol. 44, no. 1, pp. 29–53, Jan. 2019.

[55] H. Wang, L. Shi, Z. Man, J. Zheng, S. Li, M. Yu, C. Jiang, H. Kong, and Z. Cao, ''Continuous fast nonsingular terminal sliding mode control of automotive electronic throttle systems using finite-time exact observer,'' *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7160–7172, Sep. 2018.

[56] M. Boukattaya, N. Mezghani, and T. Damak, ''Adaptive nonsingular fast terminal sliding-mode control for the tracking problem of uncertain dynamical systems,'' *ISA Trans.*, vol. 77, pp. 1–19, Jun. 2018.

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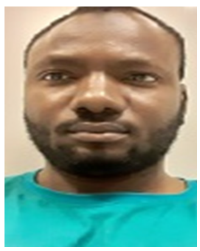

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