# A Survey of Control Methods for Quadrotor UAV

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## ABSTRACT

Flight control design of unmanned aerial vehicles UAVs is becoming increasingly important due to advances in computational power of computers with lower cost. The control algorithms are mainly employed for the attitude and position control of the UAVs. In the past decades, quadrotors have become the most popular UAVs, their adaptability and small size. They are employed to carry out tasks such as delivery, exploration, fumigation, mapping, surveillance, rescue mission, traffic monitoring, and so on. While carrying out these tasks, quadrotor UAVs face various challenges, such as environmental disturbances, obstacles, and parametric and non-parametric perturbations. Therefore, they require robust and effective control to stabilize them and enhance their performance. This paper provides a survey of recent developments in control algorithms applied to attitude and position loops of quadrotor UAVs. In addition, the limitations of the previous control approaches are presented. In order to overcome the relative drawbacks of the previous control techniques and enhance the performance of the quadrotor, researchers are combining various control approaches to obtain the hybrid control architecture. In this study, a review of the recent hybrid control schemes is presented.

## 1. Introduction

In the past decades, aircraft technology has been evolving since the time Orville and Wilbur Wright concluded their experiments of plants with motors [1]. Several aircraft with conventional and innovative configurations have been built to perform various tasks. The innovation gives rise to unmanned aerial vehicles (UAV). The UAV is an aircraft that can fly without a human pilot aboard. Among them, the most novel and commonly used unmanned aerial vehicle (UAV) is the quadrotor [2]. UAVs have grown tremendously in popularity in recent years. In addition, there has been an increase in new UAV applications for more than a decade now. Initially, the motive behind the UAV was military reconnaissance, surveillance, intelligence gathering, and target acquisition [3]. Nevertheless, advances in Global Positioning System (GPS), electronics, motors, and microcontrollers encouraged manufacturers to build lighter and cheap drones [4]. The quadrotors are widely used for many non-military applications such as crop assessments, climate, and environmental studies, education, first aid, tourism, traffic monitoring, weather, and so on.

Many researchers have built UAVs that work autonomously. Developments in autonomous flight gave rise to breakthroughs in control theory, and have contributed immensely to the literature. Over the years, quadrotors have become important platforms for UAV research and development [5]. More-

over, the flight control system is the fundamental aspect of the quadrotor [6]. To achieve autonomous flight, the quadrotor requires the control system to have excellent control performance for the attitude loop (internal loop) and the horizontal position and altitude loop (outer loop). Furthermore, the problems that must be considered in investigating the control design of a quadrotor are the complex nonlinear dynamic equations of motion, multi-input-multi-output characteristics of the dynamic equations, coupled subsystems, dynamic uncertainties, wind disturbances, and so on. However, the classical control techniques cannot meet the requirements. Thus, numerous control techniques have been proposed to improve the performance of the quadrotors. This survey article summarises the recent control strategies applied to quadrotors.

## 2. Modelling of the quadrotor

The schematic diagram of the quadrotor is shown in Fig. 1. The fixed body frame $\mathrm{B}(0_b, x_b, y_b, z_b)$ and the earth fixed frame $\mathrm{E}(0_e, x_e, y_e, z_e)$ of the quadrotor are described in Fig. 1. The position of the quadrotor in the E-frame is represented by the vector $\beta = [x, \ y, \ z]^T$ and the attitude is denoted by $A = [\phi, \ \theta, \ \psi]^T$, with $\phi$, $\theta$ and $\psi$ stand for the roll, the pitch, and the yaw angles, respectively.
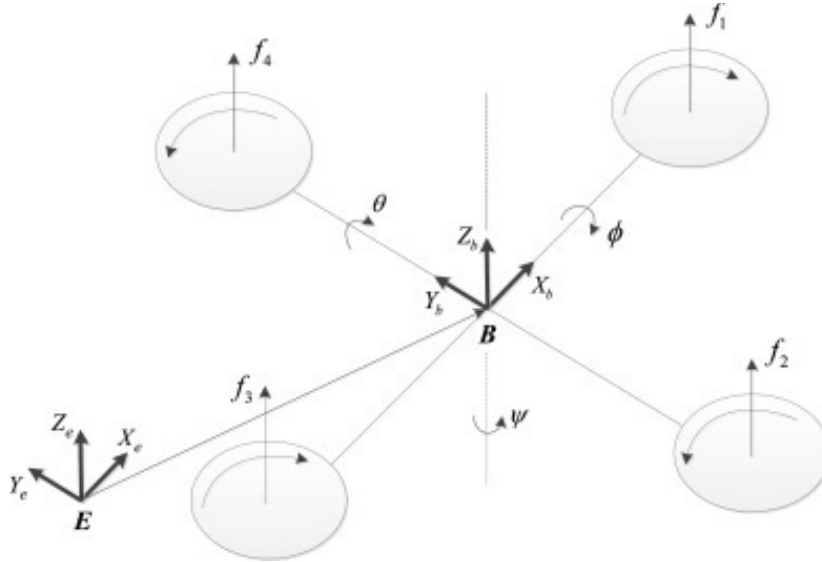


**Fig. 1.** Schematic for the quadrotor system

The quadrotor dynamic model is written as [7]:

$$\begin{cases} \dot{\beta} & = RV \\ \dot{A} & = S^{-1}\Pi \end{cases} \tag{1}$$

where R and T are the rotation matrices defined by

$$R = \begin{bmatrix} C_\phi C_\theta & S_\phi S_\theta C_\psi - C_\phi S_\psi & C_\phi S_\theta C_\psi + S_\phi S_\psi \\ C_\theta S_\theta & S_\phi S_\theta S_\psi + C_\phi S_\psi & C_\phi S_\theta C_\psi - S_\phi C_\psi \\ -S_\phi & S_\phi C_\theta & C_\phi C_\theta \end{bmatrix} \tag{2}$$

$$S = \begin{bmatrix} 1 & 0 & -S_\theta \\ 0 & C_\theta & C_\theta S_\phi \\ 0 & -S_\phi & C_\phi C_\theta \end{bmatrix} \tag{3}$$

Note that $S$ and $C$ stand for $sin(.)$ and $cos(.)$ respectively. Let $N(\Pi)$ be a skew-symmstric matrix given by

$$N(\Pi) = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \tag{4}$$

then, the relation $\dot{R} = RN(\Pi)$ is valid. Differentiating (1) with respect to time and ignoring S at low speed, one has

$$\begin{cases} \ddot{\beta} & = R(\dot{V} + \Pi \times V) \\ \ddot{A} & = \dot{\Pi} \end{cases} \tag{5}$$

Applying Newton's laws in B-frame, we get

$$\begin{cases} \sum F_{ex} = M\dot{V} + (\Pi \times MV) \\ \sum T_{ex} = I\dot{\Pi} + (\Pi \times IV) \end{cases} \tag{6}$$

where $M = diag(m, m, m)$ denotes the mass of the quadrotor, $I = diag(I_x, I_y, I_z)$ represents the inertial matrix, $\sum F_{ex}$ and $\sum T_{ex}$ stand for the external forces and the torques, respectively such that

$$\begin{cases} \sum F_{ex} = F + F_{gf} \\ \sum T_{ex} = T + T_{gy} \end{cases} \tag{7}$$

where F and T are given by

$$F = \begin{bmatrix} 0 \\ 0 \\ \eta \sum_{i=1}^{4} \omega_i^2 \end{bmatrix}, \quad T = \begin{bmatrix} \eta l(\omega_2^2 - \omega_4^2) \\ \eta l(\omega_3^2 - \omega_1^2) \\ \kappa l \sum_{i=1}^{4}(-1)^{i+1}\omega_i^2 \end{bmatrix} \tag{8}$$

$F_g$ and $T_{gyr}$ stand for the gravitational forces and gyroscopic effects due to propeller rotation, respectively written as

$$\begin{cases} F_{gf} = MR^T G \\ T_{gy} = \sum_{i=1}^{4} \Pi \times J_r(-1)^{i+1}\omega_i^2 \end{cases} \tag{9}$$

where $\eta$, $\kappa$, $J_r$ and $\omega_i$ represent the thrust factor, drag factor, rotor inertia and ith propeller angular speed, respectively, $G = [0,\ 0,\ g]^T$ with $g$ being the acceleration due to gravity. From (5) and (6), we have

$$\begin{cases} \ddot{\beta} & = M^{-1}R\sum F_{ex} \\ \ddot{A} & = I^{-1}\left[\sum T_{ex} - (\Pi \times I\Pi)\right] \end{cases} \tag{10}$$

Therefore, the mathematical model of the quadrotor with external disturbances is thus:

$$\ddot{x} = \frac{1}{m}(cos\phi \ sin\theta \ cos\psi + sin\phi \ sin\psi)u_1 \tag{11}$$

$$\ddot{y} = \frac{1}{m}(cos\phi \ sin\theta \ sin\psi + sin\phi \ cos\psi)u_1 \tag{12}$$

$$\ddot{z} = -g + \frac{1}{m}(cos\phi \ cos\theta)u_1 \tag{13}$$

$$\ddot{\phi} = \frac{1}{I_x}[(I_y - I_z)\dot{\psi}\dot{\theta} - J_r\Omega_r\dot{\theta}] + \frac{l}{I_x}u_2 \tag{14}$$

$$\ddot{\theta} = \frac{1}{I_y}[(I_z - I_x)\dot{\psi}\dot{\phi} + J_r\Omega_r\dot{\theta}] + \frac{l}{I_x}u_3 \tag{15}$$

$$\ddot{\psi} = \frac{1}{I_x}[(I_x - I_y)\dot{\phi}\dot{\theta}] + \frac{l}{I_z}u_4 \tag{16}$$

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} K_p & K_p & K_p & K_p \\ -K_p & 0 & -K_p & 0 \\ 0 & -K_p & 0 & -K_p \\ C_d & C_d & C_d & C_d \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \tag{17}$$

where $I_x$, $I_y$, $I_z$ are the inertia values with respect to $x$, $y$, $z$ axis, respectively, $g$ is the acceleration due to gravity, $J_r$ is the rotor inertia, $\omega_i$ ($i = 1, 2, 3, 4$) is the angular speed of the rotor, $K_p$ is associated with the lift force and $u_1$ is the control signal of the position subsystem, $u_2$, $u_3$, and $u_4$ are the control signals for $\phi$, $\theta$, and $\psi$, respectively.

The entire quadrotor model can be written in the form:

$$\dot{\chi} = F(\chi, u) \tag{18}$$

$$F(\chi, u) = \begin{bmatrix} \dot{x} \\ (cos\phi \ sin\theta \ cos\psi + sin\phi \ sin\psi)\frac{u_1}{m} \\ \dot{y} \\ (cos\phi \ sin\theta \ sin\psi + sin\phi \ cos\psi)\frac{u_1}{m} \\ \dot{z} \\ -g + \frac{1}{m}(cos\phi \ cos\theta)\frac{u_1}{m} \\ \dot{\phi} \\ c_1\dot{\psi}\dot{\theta} + c_2\omega\dot{\theta} + b_1u_2 \\ \dot{\theta} \\ c_3\dot{\psi}\dot{\phi} + c_4\omega\dot{\theta} + b_2u_3 \\ \dot{\psi} \\ c_5\dot{\phi}\dot{\theta} + b_3u_4 \end{bmatrix} \tag{19}$$

where $\chi = [x, \ \dot{x}, \ z, \ \dot{z}, \ y, \ \dot{y}, \ z, \ \dot{z}, \ \phi, \dot{\phi}, \ \theta, \ \dot{\theta}, \ \psi, \ \dot{\psi}]^T$ is the state vector,

$$c_1 = \frac{I_y - I_z}{I_x}, \ c_2 = \frac{J_r}{I_x}, \ c_3 = \frac{I_z - I_x}{I_y}, \ c_4 = -\frac{J_r}{I_x}$$

$$c_5 = \frac{I_x - I_y}{I_z}, \ b_1 = \frac{l}{I_x}, \ b_2 = \frac{l}{I_y}, \ b_3 = \frac{l}{I_z}$$

The linearized model of (18) near $\chi^*$ can be written as:

$$\dot{\chi} = A\chi + Bu$$
$$y = C\chi$$

(20)

where $A\chi + Bu = \frac{\partial F(\chi,u)}{\partial \chi}|\chi = \chi^*$.

## 3. Control Techniques

While carrying out certain tasks, quadrotor UAVs face various challenges such as environmental disturbances, obstacles, parametric and non-parametric perturbations, etc. As a result, they require robust and effective control to stabilize them and enhance their performances. In an ideal situation, different control methods give acceptable results, but their effectiveness and performances differ. For control of quadrotor UAVs, the control methods that attracted interest from researchers are linear quadratic regulators (LQR), proportional integral derivative (PID), $H_\infty$ control, gain-scheduling, feedback linearization, sliding mode controllers (SMC), backstepping, and adaptive control. Since these control approaches are commonly utilized for attitude stabilization and position control of the quadrotor, this survey paper will provide an overview of the characteristics and the results achieved with the controllers.

### 3.1. Proportional-Integral-Derivative Controller (PID)

PID controller is a classical control scheme used for several electrical and mechanical systems. It is the most widely used control technique in the industry due to its simplicity, ease of implementation, and acceptable performance with relatively small control efforts. Nowadays, many researchers are employing the PID controller for commercial quadrotor systems.

Cárdenas et al. [8] designed a PID controller to stabilise a quadrotor UAV. In [9], a robust PID controller was applied to a quadrotor vehicle for trajectory tracking tasks and minimizing power consumption. In [10], a PID controller is implemented to address the dynamic uncertainties of a quadrotor and stabilize its attitude and position. Their simulation results show that the controller can attain a stable and acceptable performance even when disturbed by the wind. Nevertheless, the responses of the quadrotor states exhibit some overshoots. Üstünkök, et al. [11] compared the P, PID, and PD for the flight control of a quadrotor. The simulation results demonstrated that PID is superior to both P and PD. Castillo-Zamora, et al. [12] compared the PID, PD, and Sliding Mode Controller (SMC) for position control of a V-tail quadrotor. They observed that the SMC gives a quick settling time, but the pitch and roll angles exceed $20^0$, which makes it unfavorable in real-world conditions. Both PID and SMC can get rid of the steady-state errors whereas the PD controller cannot as time increases. In [13], the authors presented a hierarchical P-PID controller to stabilize the orientation angles of a quadrotor. The overshoot of the system is less than $25\%$ in roll, pitch, and yaw motion, respectively. Nonetheless, PID control may not give satisfactory performance when applied to a quadrotor system which is a nonlinear underactuated system.

### 3.2. Linear Quadratic Regulator (LQR)

LQR is a type of optimal feedback control method. In this method, the system output is feedback through a controller gain designed for closed-loop stabilization. A trade-off between the control effort and the transient response needs to be considered [14].

Okyere, et al. [15] designed an LQR for the linearized model of the quadrotor UAV. The control system has a cascade structure, and the LQR is able to stabilize the system with an acceptable overshoot and small steady-state error. In [16], an LQR with integral error action is implemented for the linear longitudinal model of the quadrotor. The simulation results indicate that the controller is able to

eliminate the steady-state error. In [17], the authors presented an optimal control of a quadrotor UAV using the discrete-time, finite-horizon, LQR. The quadrotor is linearized by utilizing a left-invariant error about a reference trajectory, giving rise to an optimal gain sequence that can be computed offline.

### 3.3. Model Predictive Control (MPC)

MPC is among the most widely used controllers for industrial applications due to its advantage of handling constraints and disturbances, state prediction, easier tuning, and execution with multi-variables concurrently. It is regarded as a nonlinear control scheme that predicts the future states of a system [18]. MPC is an optimal control where the objective function is minimized using the present control variable and future time horizon by working with constraints of inputs and states.

The authors in [18] presented an MPC to track the desired state taking into account disturbances to achieve a robust performance of the quadrotor. In [19], a reinforcement learning-based MPC was proposed for hovering control of a quadrotor. This control technique utilizes DC motor input signals, onboard sensors, and no initial conditions. In [20], the authors presented a cascaded linear MPC (LMPC) for the position and attitude control of the quadrotor. The advantage of the cascaded technique is that the desired attitude angle and thrust can directly be limited within an acceptable range. The Cascaded linear MPC gives a satisfactory performance and can follow the desired position and maintain the attitude angle close to the operating point without violating motor speeds.

### 3.4. $H_\infty$ Controller

$H_\infty$ controller is one of the commonly used robust control techniques. Robust control takes into account the nominal model of a system as well as the effects of uncertainties and disturbances on the system. The controller has the capability to mitigate the impacts of uncertainties and achieve the performance requirement. In addition, $H_\infty$ controller can tackle modeling errors, but its computational complexity is expensive. The controller is designed in the frequency domain, and therefore its gains are difficult to adjust. The $H_\infty$ control problem is formulated as mathematical optimization problem that minimizes the $H_\infty$ norm of the closed-loop transfer function [21].

$H_\infty$ controllers have been applied to the quadrotor systems for linear control around some operating conditions. In [22], a robust $H_\infty$ control is utilized for hovering control of a quadrotor subjected to external disturbances. The simulation shows that the controller successfully mitigates the effects of the disturbances. The authors in [23] presented a robust $H_\infty$ controller for quasi hover conditions using the Glover-McFarlane loop shaping method. The controller can handle high bandwidth input changes without any problems and produces an aggressive pitch response when subjected to longitudinal movement.

### 3.5. Feedback linearization Control

Feedback linearization is one of the common nonlinear control techniques. In this approach, the nonlinear dynamic system is transformed into a linear dynamic system by model inversion. Then, a stabilizing controller can be designed for the linearized system to keep it stable using the linear systems. Many successful applications of this method are reported in the literature [24].

The authors in [25] developed an optimal tracking control of a quadrotor based on feedback linearization. Then, an LQR was designed to stabilize the linearized quadrotor model and a particle swarm optimization (PSO) algorithm was employed to optimize the gains of the LQR. In [26], the authors presented a study of the FL to achieve attitude control and stabilize the quadrotor system. An Integrator was added to the Feedback linearization control system to reduce the tracking error. In [27], the authors investigated the robust control of a small quadrotor. Feedback linearization is adopted to handle the complex nonlinear dynamics. The simulation results demonstrated promising hovering control performance.

### 3.6. Sliding Mode Control (SMC)

Sliding mode control is a robust nonlinear control strategy that compensates for system uncertainties and perturbations [28]. The control signal is discontinuous and switches from one state to another to ensure convergence of the states to the reference state. During the flight operation, the quadrotors encountered environmental disturbances and parametric perturbations. They require a very agile and robust control system [29].

In [30], a double loop integral SMC was developed for robust trajectory tracking control of a quadrotor. The simulation results indicated that the proposed controller outperformed the conventional PID controller. In [31], a terminal sliding mode control (TSMC) approach was developed for an uncertain quadrotor. The limitation of the TSMC is that it does not take into account the nonsingularities that may arise in the system. In order to avoid this issue, a nonsingular fast terminal sliding mode control (NTSMC) was proposed for fault-tolerant control of a quadrotor [32]. In [33], a global fractional-order SMC was developed for a quadrotor with actuator faults. The main drawback of SMC is chattering effects which cause energy wastage, wear and tear in mechanical systems. To tackle this problem, the authors in [34] developed a robust chattering-free SMC for the hovering operation of the quadrotor.

### 3.7. Backstepping Control

Backstepping is a recursive strategy for controlling nonlinear dynamics systems. This strategy partitioned the control design into several steps that ensure the asymptotic stability of the system at each step. Notably, backstepping requires the exact system dynamics and uncertainties to provide excellent performance.

In [35], the authors have investigated backstepping integrated with PID to stabilize the orientation of the Quadrotor. The performance of the backstepping controller is compared with that of a traditional PID controller. The proposed control scheme greatly enhanced the transient response and robustness of the system. In [36], an integral backstepping-based SMC has been proposed for attitude and position tracking of a quadrotor. A fractional-order backstepping SMC was implemented for a quadrotor in [37]. In [38], the quadrotor system is decoupled into three subsystems, the propeller subsystem, the fully actuated subsystem, and the underactuated subsystem. Then, a backstepping technique is applied to stabilize the quadrotor system.

### 3.8. Fractional-order Control

The fractional calculus theory which extends the derivatives and integrals of integer-order to non-integer orders become one of the most interesting topics in control theory. It can describe some non-classical phenomena in natural sciences and engineering applications with higher accuracy than the conventional integer-order approach [39]. Recently, various fractional-order control techniques have been applied to a quadrotor UAV.

In [40], a fractional-order PID controller has been implemented for attitude and position control of a quadrotor. Simulation results show that the controller greatly enhanced the robustness and performance of the quadrotor. In [41], a fractional-order super twisting sliding mode control has been implemented for path following control of a quadrotor. The efficient performance of the controller is studied under different scenarios. In [42], a fractional-order backstepping control of a quadrotor has been proposed to achieve robust attitude performance in the presence of uncertainties and external disturbances. In [43], an adaptive fractional-order sliding mode control of a quadrotor with slung has been presented to tackle the uncertainties in the quadrotor mass.

### 3.9. Gain Scheduling

Gain scheduling is a technique for controlling nonlinear systems with many operating points. The nonlinear system is linearized at each operating point and a corresponding linear controller is designed for each of the operating points. There are several studies in the literature that investigates gain scheduling control of a quadrotor [44], [45], [46].

### 3.10. Adaptive Control

Adaptive control is a fruitful and robust control technique for dynamic systems with unknown dynamics and parametric uncertainties [47]. This control algorithm automatically compensates for parameter changes in system dynamics by adjusting the controller characteristics so that the overall system performance remains the same, or rather maintained at an optimum [48].

In [49], the authors designed a Lyapunov-based composite adaptive control for a quadrotor UAV. This controller achieved an excellent tracking performance in the presence of uncertainties and time delays. In [50], a continuous time-varying adaptive controller is implemented in the condition of unknown parameters. The simulation results of the proposed approach have good performance for the quadrotor flight controller. In literature [51], the authors developed an adaptive backstepping control for trajectory tracking operation of an underactuated quadrotor UAV. In [52], a robust adaptive multilevel control of a quadrotor has been presented. The dynamic model of the quadrotor was divided into three subsystems and the different control methods were designed for the systems.

### 3.11. Active Disturbance Rejection Control (ADRC)

Active disturbance rejection control (ADRC) is a kind of nonlinear robust control technique that is based on extending the state of a system with a fictitious state variable denoting the disturbance in the system. The disturbance is estimated in real-time with a state observer. The estimate is included in the control input in order to compensate the disturbance in the system. The important attribute of this technique is that it does not require full information about the system.

In [53], an approach integrating robust SMC with linear active disturbance rejection control (LADRC) is proposed for the quadrotor with a varying mass. In [54], attitude control is presented for a quadrotor in the presence of external disturbances based on a double closed-loop control technique. This technique integrates the advantages of ADRC and ISMC. A nonlinear extended state observer is adopted in the inner loop to estimate internal uncertain dynamics and external wind disturbances timely for the quadrotor. In [55], an ADRC strategy is developed to tackle the effects of external disturbances in the quadrotor system. Then, an extended state observer is employed to measure and mitigate the lumped disturbances online which can enhance the disturbance suppression and robustness of the system.

### 3.12. Intelligent control

Intelligent control is a control method that uses artificial intelligence computing approaches such as Neural networks, Fuzzy Logic, GA, etc. In dealing with a complex system, some traditional controllers are still unable to give a satisfactory performance to ensure the robustness of the system against parameter uncertainties and external disturbance [56]. The capability of intelligent control methods in controlling such a system is why it is used because basic control methods face difficulty in controlling a complex system. Some of the most widely used intelligent controllers in quadrotor applications, namely Fuzzy Logic, and Neural Network, are discussed.

Due to the global properties of neural networks and fuzzy logic systems, they are widely used to approximate continuous and smooth nonlinear functions [48], [57]. In [58], a distributed adaptive neural network formation control of quadrotors has been investigated. An adaptive fuzzy FTSMC was proposed in [59]. A neuro-adaptive backstepping trajectory tracking control of a quadrotor has

been presented in [60]. A FLS control scheme was designed for a quadrotor in [61].

### 3.13. Hybrid Control Techniques

Recently, researchers are combining different control approaches for the attitude and the position subsystems of the quadrotor in order to obtain enhanced robust performances. In [36], an integral backstepping-based SMC and an adaptive PID have been proposed for attitude and position tracking of a quadrotor, respectively. In [62], a feedback linearization controller and a linear parameter varying controller were implemented for the attitude and position of the quadrotor, respectively. In [63], an adaptive backstepping controller and a backstepping FTSMC have been utilized to control the position and the attitude subsystems of a quadrotor, respectively. In [64], a backstepping SMC and an active disturbance rejection control (ADRC) have been developed for the position and the attitude tracking control of a quadrotor, respectively. In [65], an integral SMC and a backstepping SMC were designed for attitude and position tracking of a quadrotor, respectively.

## 4. Conclusions

Recently, the applications of quadrotor UAVs in military and nonmilitary sectors is increasing tremendously because of their flexibility and versatility. Nevertheless, several challenges are deemed to arise during the flight or while executing certain tasks and must be addressed and resolved. The challenges include dynamic uncertainties, environmental disturbances, underactuation, and a strongly coupled nonlinear dynamic model. As a result, developing effective and reliable control mechanisms for the quadrotor dynamical system is critical. This paper discusses a survey of various control approaches applied on a quadrotor UAV. The control methods possess their own unique advantages, limitations, and algorithms. Therefore, the choice of a suitable controller depends on the performance requirement and the intended application of the quadrotor. As the number of applications expands, the demand for hybrid control techniques that build on old control strategies will definitely increase. Interestingly, some articles utilized multiple control algorithms to guarantee the fruitful performance of the controllers. This article presents the recent studies that employed the hybrid control techniques to ensure the promising operation of the quadrotor. Future studies will cover cloud control, guidance, and navigation of quadrotors.

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## References

[1] Z. Li, X. Ma, and Y. Li, "Robust trajectory tracking control for a quadrotor subject to disturbances and model uncertainties," *International Journal of Systems Science*, vol. 51, no. 5, pp. 839–851, 2020, https://doi.org/10.1080/00207721.2020.1746430.

[2] Y. Zou and B. Zhu, "Adaptive trajectory tracking controller for quadrotor systems subject to parametric uncertainties," *Journal of the Franklin Institute*, vol. 354, no. 15, pp. 6724 – 6746, 2017, https://doi.org/10.1016/j.jfranklin.2017.08.027.

[3] O. Mechali, L. Xu, Y. Huang, M. Shi, and X. Xie, "Observer-based fixed-time continuous nonsingular terminal sliding mode control of quadrotor aircraft under uncertainties and disturbances for robust trajectory tracking: Theory and experiment," *Control Engineering Practice*, vol. 111, p. 104806, 2021, https://doi.org/10.1016/j.conengprac.2021.104806.

[4] M. E. Antonio-Toledo, E. N. Sanchez, and A. Y. Alanis, "Neural inverse optimal control applied to quadrotor uav," in *2018 IEEE Latin American Conference on Computational Intelligence (LA-CCI)*, Nov 2018, pp. 1–8, https://doi.org/10.1109/LA-CCI.2018.8625204.

[5] H. Mo and G. Farid, "Nonlinear and adaptive intelligent control techniques for quadrotor uav – a survey," *Asian Journal of Control*, vol. 21, no. 2, pp. 989–1008, 2019, https://doi.org/10.1002/asjc.1758.

[6] B. Xu, "Composite learning finite-time control with application to quadrotors," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 48, no. 10, pp. 1806–1815, Oct 2018, https://doi.org/10.1109/TSMC.2017.2698473.

[7] Z. Tang, R. Cunha, D. Cabecinhas, T. Hamel, and C. Silvestre, "Quadrotor going through a window and landing: An image-based visual servo control approach," *Control Engineering Practice*, vol. 112, pp. 104–116, 2021, https://doi.org/10.1016/j.conengprac.2021.104827.

[8] C. A. Cárdenas R., V. H. Grisales, C. A. Collazos Morales, H. D. Cerón-Muñoz, P. Ariza-Colpas, and R. Caputo-Llanos, "Quadrotor modeling and a pid control approach," in *Intelligent Human Computer Interaction*, U. S. Tiwary and S. Chaudhury, Eds., Cham, 2020, pp. 281–291, https://doi.org/10.1007/978-3-030-44689-5_25.

[9] R. Miranda-Colorado and L. T. Aguilar, "Robust pid control of quadrotors with power reduction analysis," *ISA transactions*, vol. 98, pp. 47–62, 2020, https://doi.org/10.1016/j.isatra.2019.08.045.

[10] J. Moreno-Valenzuela, R. Pérez-Alcocer, M. Guerrero-Medina, and A. Dzul, "Nonlinear pid-type controller for quadrotor trajectory tracking," *IEEE/ASME Transactions on Mechatronics*, vol. 23, no. 5, pp. 2436–2447, 2018, https://doi.org/10.1109/TMECH.2018.2855161.

[11] T. Üstünkök and M. Karakaya, "Effect of pso tuned p, pd, and pid controllers on the stability of a quadrotor," in *2019 1st International Informatics and Software Engineering Conference (UBMYK)*, 2019, pp. 1–6, https://doi.org/10.1109/UBMYK48245.2019.8965487.

[12] J. J. Castillo-Zamora, K. A. Camarillo-Gomez, G. I. Perez-Soto, and J. Rodriguez-Resendiz, "Comparison of pd, pid and sliding-mode position controllers for v–tail quadcopter stability," *Ieee Access*, vol. 6, pp. 38 086–38 096, 2018, https://doi.org/10.1109/ACCESS.2018.2851223.

[13] P. Burggräf, A. R. Pérez Martínez, H. Roth, and J. Wagner, "Quadrotors in factory applications: design and implementation of the quadrotor's p-pid cascade control system," *SN Applied Sciences*, vol. 1, no. 7, pp. 1–17, 2019, https://doi.org/10.1007/s42452-019-0698-7.

[14] M. S. Mahmoud and M. Maaruf, "Discrete-time attitude stabilization of reusable reentry vehicle by convex optimization," *International Journal of Dynamics and Control*, vol. 9, no. 3, pp. 1092–1099, 2021, https://doi.org/10.1007/s40435-020-00738-4.

[15] E. Okyere, A. Bousbaine, G. T. Poyi, A. K. Joseph, and J. M. Andrade, "Lqr controller design for quadrotor helicopters," *The Journal of Engineering*, vol. 2019, no. 17, pp. 4003–4007, 2019, https://doi.org/10.1049/joe.2018.8126.

[16] A. S. Elkhatem and S. N. Engin, "Robust lqr and lqr-pi control strategies based on adaptive weighting matrix selection for a uav position and attitude tracking control," *Alexandria Engineering Journal*, vol. 61, no. 8, pp. 6275–6292, 2022, https://doi.org/10.1016/j.aej.2021.11.057.

[17] M. R. Cohen, K. Abdulrahim, and J. R. Forbes, "Finite-horizon lqr control of quadrotors on $se_2(3)$," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 5748–5755, 2020, https://doi.org/10.1109/LRA.2020.3010214.

[18] M. Islam, M. Okasha, and E. Sulaeman, "A model predictive control (mpc) approach on unit quaternion orientation based quadrotor for trajectory tracking," *International Journal of Control, Automation and Systems*, vol. 17, no. 11, pp. 2819–2832, 2019, https://doi.org/10.1007/s12555-018-0860-9.

[19] C. E. Luis, M. Vukosavljev, and A. P. Schoellig, "Online trajectory generation with distributed model predictive control for multi-robot motion planning," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 604–611, 2020, https://doi.org/10.1109/LRA.2020.2964159.

[20] J. Schlagenhauf, P. Hofmeier, T. Bronnenmeyer, R. Paelinck, and M. Diehl, "Cascaded nonlinear mpc for realtime quadrotor position tracking," *IFAC-PapersOnLine*, vol. 53, no. 2, pp. 7026–7032, 2020, https://doi.org/10.1016/j.ifacol.2020.12.444.

[21] A. H. Mhmood and H. I. Ali, "Optimal h-infinity integral dynamic state feedback model reference controller design for nonlinear systems," *Arabian Journal for Science and Engineering*, vol. 46, no. 10, pp. 10 171–10 184, 2021, https://doi.org/10.1007/s13369-021-05447-4.

[22] 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 $h_\infty$ synthesis," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 2910–2917, 2018, https://doi.org/10.1109/LRA.2018.2847405.

[23] F. Rekabi, F. A. Shirazi, M. J. Sadigh, and M. Saadat, "Nonlinear $h_\infty$ measurement feedback control algorithm for quadrotor position tracking," *Journal of the Franklin Institute*, vol. 357, no. 11, pp. 6777–6804, 2020, https://doi.org/10.1016/j.jfranklin.2020.04.056.

[24] M. Maaruf, K. A. Khan, and M. Khalid, "Integrated power management and nonlinear-control for hybrid renewable microgrid," in *2021 IEEE Green Technologies Conference (GreenTech)*, 2021, pp. 176–180, https://doi.org/10.1109/GreenTech48523.2021.00037.

[25] C.-C. Chen and Y.-T. Chen, "Feedback linearized optimal control design for quadrotor with multi-performances," *IEEE Access*, vol. 9, pp. 26 674–26 695, 2021, https://doi.org/10.1109/ACCESS.2021.3057378.

[26] H. Ye, "Control of quadcopter uav by nonlinear feedback," Ph.D. dissertation, Case Western Reserve University, 2018, http://rave.ohiolink.edu/etdc/view?acc_num=case1523544168630815.

[27] H. Mo and G. Farid, "Nonlinear and adaptive intelligent control techniques for quadrotor uav–a survey," *Asian Journal of Control*, vol. 21, no. 2, pp. 989–1008, 2019, https://doi.org/10.1002/asjc.1758.

[28] M. Maaruf and M. Khalid, "Power quality control of hybrid wind/electrolyzer/fuel-cell/bess microgrid," in *2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia)*, 2021, pp. 1–5, https://doi.org/10.1109/ISGTAsia49270.2021.9715639.

[29] M. S. Mahmoud and M. Maaruf, "Prescribed performance output feedback synchronisation control of bilateral teleoperation system with actuator nonlinearities," *International Journal of Systems Science*, vol. 52, no. 15, pp. 3115–3127, 2021, https://doi.org/10.1080/00207721.2021.1921308.

[30] K. Wang, C. Hua, J. Chen, and M. Cai, "Dual-loop integral sliding mode control for robust trajectory tracking of a quadrotor," *International Journal of Systems Science*, vol. 51, no. 2, pp. 203–216, 2020, https://doi.org/10.1080/00207721.2019.1622815.

[31] J.-J. Xiong and G.-B. Zhang, "Global fast dynamic terminal sliding mode control for a quadrotor uav," *ISA Transactions*, vol. 66, pp. 233 – 240, 2017, https://doi.org/10.1016/j.isatra.2016.09.019.

[32] Z. Hou, P. Lu, and Z. Tu, "Nonsingular terminal sliding mode control for a quadrotor uav with a total rotor failure," *Aerospace Science and Technology*, vol. 98, p. 105716, 2020, https://doi.org/10.1016/j.ast.2020.105716.

[33] M. Labbadi, Y. Boukal, M. Cherkaoui, and M. Djemai, "Fractional-order global sliding mode controller for an uncertain quadrotor uavs subjected to external disturbances," *Journal of the Franklin Institute*, pp. 212–214, 2021, https://doi.org/10.1016/j.jfranklin.2021.04.032.

[34] H. Abaunza and P. Castillo, "Quadrotor aggressive deployment, using a quaternion-based spherical chattering-free sliding-mode controller," *IEEE Transactions on Aerospace and Electronic Systems*, pp. 1–1, 2019, https://doi.org/10.1109/TAES.2019.2937663.

[35] K. Liu and R. Wang, "Antisaturation command filtered backstepping control-based disturbance rejection for a quadarotor uav," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 68, no. 12, pp. 3577–3581, 2021, https://doi.org/10.1109/TCSII.2021.3069967.

[36] K. Eliker and W. Zhang, "Finite-time adaptive integral backstepping fast terminal sliding mode control application on quadrotor uav," *International Journal of Control, Automation and Systems*, vol. 18, no. 2, pp. 415–430, 2020, https://doi.org/10.1007/s12555-019-0116-3.

[37] X. Shi, Y. Cheng, C. Yin, S. Dadras, and X. Huang, "Design of fractional-order backstepping sliding mode control for quadrotor uav," *Asian Journal of Control*, vol. 21, no. 1, pp. 156–171, 2019, https://doi.org/10.1002/asjc.1946.

[38] K. Liu and R. Wang, "Antisaturation command filtered backstepping control-based disturbance rejection for a quadarotor uav," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 68, no. 12, pp. 3577–3581, 2021, https://doi.org/10.1109/TCSII.2021.3069967.

[39] M. Maaruf and M. Khalid, "Global sliding-mode control with fractional-order terms for the robust optimal operation of a hybrid renewable microgrid with battery energy storage," *Electronics*, vol. 11, no. 1, p. 88, 2021, https://doi.org/10.3390/electronics11010088.

[40] A. Redouane, N. Wahid, Z. Mehdi, and B. S. Yasmina, "Full control of quadrotor aerial robot using fractional-order fopid," *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, vol. 43, no. 1, pp. 349–360, 2019, https://doi.org/10.1007/s40998-018-0155-4.

[41] M. Labbadi, Y. Boukal, and M. Cherkaoui, "Path following control of quadrotor uav with continuous fractional-order super twisting sliding mode," *Journal of Intelligent & Robotic Systems*, vol. 100, no. 3, pp. 1429–1451, 2020, https://doi.org/10.1007/s10846-020-01256-3.

[42] X. Shi, Y. Cheng, C. Yin, S. Dadras, and X. Huang, "Design of fractional-order backstepping sliding mode control for quadrotor uav," *Asian Journal of Control*, vol. 21, no. 1, pp. 156–171, 2019, https://doi.org/10.1002/asjc.1946.

[43] M. Vahdanipour and M. Khodabandeh, "Adaptive fractional order sliding mode control for a quadrotor with a varying load," *Aerospace Science and Technology*, vol. 86, pp. 737–747, 2019, https://doi.org/10.1016/j.ast.2019.01.053.

[44] J. Qiao, Z. Liu, and Y. Zhang, "Gain scheduling based pid control approaches for path tracking and fault tolerant control of a quad-rotor uav," *International Journal of Mechanical Engineering and Robotics Research*, vol. 7, no. 4, pp. 401–408, 2018, http://www.ijmerr.com/uploadfile/2018/0709/20180709111619835.pdf.

[45] L. Abdou *et al.*, "Integral backstepping/lft-lpv $h_\infty$ control for the trajectory tracking of a quadcopter," in *2018 7th International Conference on Systems and Control (ICSC)*, 2018, pp. 348–353, https://doi.org/10.1109/ICoSC.2018.8587839.

[46] A. González, A. Cuenca, V. Balaguer, and P. García, "Event-triggered predictor-based control with gain-scheduling and extended state observer for networked control systems," *Information Sciences*, vol. 491, pp. 90–108, 2019, https://doi.org/10.1016/j.ins.2019.03.081.

[47] M. Maaruf, M. Shafiullah, A. T. Al-Awami, and F. S. Al-Ismail, "Adaptive nonsingular fast terminal sliding mode control for maximum power point tracking of a wecs-pmsg," *Sustainability*, vol. 13, no. 23, 2021, https://doi.org/10.3390/su132313427.

[48] M. S. Mahmoud, M. Maaruf, and S. El-Ferik, "Neuro-adaptive output feedback control of the continuous polymerization reactor subjected to parametric uncertainties and external disturbances," *ISA transactions*, vol. 112, pp. 1–11, 2021, https://doi.org/10.1016/j.isatra.2020.11.026.

[49] S. Yang and B. Xian, "Energy-based nonlinear adaptive control design for the quadrotor uav system with a suspended payload," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 3, pp. 2054–2064, 2019, https://doi.org/10.1109/TIE.2019.2902834.

[50] B. J. Emran and H. Najjaran, "A review of quadrotor: An underactuated mechanical system," *Annual Reviews in Control*, vol. 46, pp. 165–180, 2018, https://doi.org/10.1016/j.arcontrol.2018.10.009.

[51] W. Chi, Y. Ji, and Q. Gao, "Attitude tracking control for a quadrotor via backstepping and adaptive dynamic programming," in *2019 Chinese Control And Decision Conference (CCDC)*, 2019, pp. 3108–3113, https://doi.org/10.1109/CCDC.2019.8832799.

[52] M. S. Mahmoud and M. Maaruf, "Robust adaptive multilevel control of a quadrotor," *IEEE Access*, vol. 8, pp. 167 684–167 692, 2020, https://doi.org/10.1109/ACCESS.2020.3022724.

[53] Z. Wang and T. Zhao, "Based on robust sliding mode and linear active disturbance rejection control for attitude of quadrotor load uav," *Nonlinear Dynamics*, pp. 3485–3503, 2022, https://doi.org/10.1007/s11071-022-07349-y.

[54] L. Zhao, L. Dai, Y. Xia, and P. Li, "Attitude control for quadrotors subjected to wind disturbances via active disturbance rejection control and integral sliding mode control," *Mechanical Systems and Signal Processing*, vol. 129, pp. 531–545, 2019, https://doi.org/10.1016/j.ymssp.2019.04.040.

[55] Y. Zhang, Z. Chen, X. Zhang, Q. Sun, and M. Sun, "A novel control scheme for quadrotor uav based upon active disturbance rejection control," *Aerospace Science and Technology*, vol. 79, pp. 601–609, 2018, https://doi.org/10.1016/j.ast.2018.06.017.

[56] M. Maaruf and S. E. Ferik, "Distributed control method for heterogeneous multiagent systems subjected to faults," in *2021 18th International Multi-Conference on Systems, Signals Devices (SSD)*, 2021, pp. 1328–1333, https://doi.org/10.1109/SSD52085.2021.9429392.

[57] S. El Ferik, M. S. Mahmoud, and M. Maaruf, "Robust adaptive sliding mode control of nonlinear systems using neural network," in *2020 17th International Multi-Conference on Systems, Signals & Devices (SSD)*, 2020, pp. 591–596, https://doi.org/10.1109/SSD49366.2020.9364137.

[58] Z. Jia, L. Wang, J. Yu, and X. Ai, "Distributed adaptive neural networks leader-following formation control for quadrotors with directed switching topologies," *ISA Transactions*, vol. 93, pp. 93 – 107, 2019, https://doi.org/10.1016/j.isatra.2019.02.030.

[59] V. Nekoukar and N. M. Dehkordi, "Robust path tracking of a quadrotor using adaptive fuzzy terminal sliding mode control," *Control Engineering Practice*, vol. 110, pp. 104–115, 2021, https://doi.org/10.1016/j.conengprac.2021.104763.

[60] M. A. M. Basri, "Trajectory tracking control of autonomous quadrotor helicopter using robust neural adaptive backstepping approach," *Journal of Aerospace Engineering*, vol. 31, no. 2, p. 04017091, 2018, https://doi.org/10.1061/(ASCE)AS.1943-5525.0000804.

[61] H. Housny, E. A. Chater, and H. El Fadil, "New deterministic optimization algorithm for fuzzy control tuning design of a quadrotor," in *2019 5th International Conference on Optimization and Applications (ICOA)*, April 2019, pp. 1–6, https://doi.org/10.1109/ICOA.2019.8727622.

[62] C. Trapiello, V. Puig, and B. Morcego, "Position-heading quadrotor control using lpv techniques," *IET Control Theory & Applications*, vol. 13, no. 6, pp. 783–794, April 2019, https://doi.org/10.1049/iet-cta.2018.6147.

[63] M. Labbadi and M. Cherkaoui, "Robust adaptive backstepping fast terminal sliding mode controller for uncertain quadrotor uav," *Aerospace Science and Technology*, vol. 93, p. 105306, 2019, https://doi.org/10.1016/j.ast.2019.105306.

[64] L.-X. Xu, H.-J. Ma, D. Guo, A.-H. Xie, and D.-L. Song, "Backstepping sliding-mode and cascade active disturbance rejection control for a quadrotor uav," *IEEE/ASME Transactions on Mechatronics*, vol. 25, no. 6, pp. 2743–2753, 2020, https://doi.org/10.1109/TMECH.2020.2990582.

[65] D. J. Almakhles, "Robust backstepping sliding mode control for a quadrotor trajectory tracking application," *IEEE Access*, vol. 8, pp. 5515–5525, 2020, https://doi.org/10.1109/ACCESS.2019.2962722.