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A REVIEW OF CONTROL METHODS FOR QUADROTOR UAV

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ABSTRACT

This study reviews numerous control approaches utilized to address various issues encountered by unmanned aerial vehicles (UAVs). Specifically, focusing on the quadrotor system. Due to its versatility and compact size, quadrotors have gained popularity as UAVs in recent decades. Quadrotors face challenges such as ambient disturbances, impediments, non-parametric and parametric perturbations while performing tasks. Consequently, a robust and efficient control system is essential for such a system to ensure the stability and enhance their performance. It should be noted that, in this review, we have examined and analyzed the most recent highly cited papers selected from esteemed journals and magazines renowned for their exceptional quality and reputation.

KEYWORDS

Control Methods, Quadrotor, SMC, Adaptive control, Nonlinear control, Intelligent control, PID, Linear control.

1. INTRODUCTION

The quadrotor UAV, also known as a drone, is a type of UAV that generally has a symmetrical airframe, four rotors attached to on-board data processing, and high-performance propellers. This combination of features has generated significant attention among contemporary researchers (Legowo, Sulaeman and Rosli, 2019). UAVs have been contributing to a wide variety of applications, including military applications since UAVs have significant advantages rather over manned aerial vehicles due to their low-cost, maneuverability, (Utsav et al., 2021),(Jeler, 2019), include image and video mapping, construction, medical services, parcel delivery, search and rescue operations, wireless communication, aerial surveillance, hidden area exploration, precision farming, and oil rigs and power line monitoring (Mohsan et al., 2022),(Chaturvedi et al., 2019). Moreover, the quadrotor industry is gaining attention because to its role in service, delivery convergence, and manufacturing, creating synergy between several new fields. UAVs provide unique advantages such operating in disaster regions, longer flying duration, improved payload capacity, access to isolated locations, and quick mobility (Mohsan et al., 2023).

Recently, the issue of controlling UAVs has garnered significant interest to researchers due the intriguing control challenges it presents and the promising opportunities for creating and evaluating innovative control design approaches. However, designing control systems for UAVs comes with several challenges. At top list of these challenges would be the dynamic models of UAVs which exhibits traits of underactuation, nonlinearity, static instability, and substantial coupling between dynamic states. Additionally, the small weight and size of UAVs make them highly susceptible to external disturbances. Furthermore, accurately measuring parameters like aerodynamic coefficients and inertial moments poses difficulties in the control design process (Nguyen et al., 2020). Disturbances and uncertainties are significant factors that can lead to unsatisfactory performance in control systems. Designing flight controllers that consider disturbances, such as wind gusts, sensor measurement noise, and modeling errors, is crucial for achieving reliable performance. Therefore, modern robust design techniques aim to provide performance robustness, ensuring satisfactory operation even in the presence of disturbances would be a possible solution for such issue and making it difficult to design controllers with the desired structure (Zuo et al., 2022). Hence, conducting a comprehensive study concerning the previous UAVs control algorithms and challenges is essential and a fruitful in this field. These control methods are designed and optimized to development the stability, performance, and adaptability of the quadrotor in different operating conditions. The main contribution of this paper is to provide a general overview of the control method which have been employed in the UAVs field. In addition, will present the structure of each control strategies as will as a simple guideline to how it would be designed. Finally, these control strategies have been systematically tabulated based on theire control structure to further simplified the review and enhance readability.

This paper discusses the literature review on control algorithms for quadrotor UAV. This article consists as follows: section 2 describes the mathematical model of the quadrotor. Section 3 presented the methods of control. Finally, the contribution and conclusion of this paper will be discussed in Section 4.

2. MODELLING OF QUADROTOR

To develop a control system for the quadrotor, the first step is to derive the quadrotor mathematical model. Fig. 1 displays the schematic diagram of the quadrotor, the derivation of the UAV dynamics involves two frames the earth frame E and the body frame B. The quadrotor is a complex system with nonlinearity. To simplify, the math modeling at the UAV, a few assumptions are adopted by (Nascimento and Saska, 2019).

Assumption 1: The body frame origin aligns with the center of mass of the quadrotor body. Assumption 2: The UAV's interaction with the ground and any other surface is disregarded.

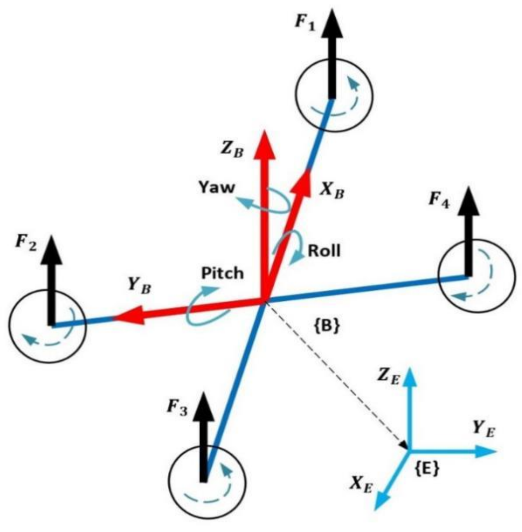

Fig. 1. The schematic diagram of the quadrotor.

By applying these assumptions and information provided in the forgoing subsection on the quadrotor shown in Fig. 1. The dynamic model of the quadrotor may be obtained using the Euler-Lagrange approach, this model describes a six-degree of freedom (6 -DOF) to the x-type rigid body quadcopter, influenced by forces and moments is given as

$$\ddot{x} = \frac{U_1(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi)}{m} \tag{1}$$

$$\ddot{y} = \frac{U_1(\sin\phi \sin\theta \cos\psi - \cos\phi \sin\psi)}{m} \tag{2}$$

$$\ddot{z} = \frac{U_1(\cos\phi \cos\theta)}{m} - g \tag{3}$$

$$\ddot{\phi} = \dot{\theta}\dot{\psi}\left(\frac{I_y - I_z}{I_x}\right) + \frac{l}{I_x}U_2 \tag{4}$$

$$\ddot{\theta} = \dot{\phi}\dot{\psi}\left(\frac{I_z - I_x}{I_y}\right) + \frac{l}{I_y}U_3 \tag{5}$$

$$\ddot{\psi} = \dot{\phi}\dot{\theta}\left(\frac{I_x - I_y}{I_z}\right) + \frac{l}{I_z}U_4 \tag{6}$$

The variables x, y, z represent the three locations of translational in the earth frame, while the pitching, rolling, and yawing movements are represented by the Euler angles ϕ, θ and ψ in radians. g is the gravitational acceleration. I_x, I_y and I_y are the moments of inertia of each axes measured by (kg.m).

The variable m represents the mass of the quadrotor in kg, whereas I represent the inertia and l is the distance between the center of mass and the rotor of the quadrotor in meters. As an underactuated system, the quadrotor has four inputs that are applied to derive the 6-DOF. The input can be written as

$$U_1 = F_1 + F_2 + F_3 + F_4 \tag{7}$$

$$U_2 = l\,(F_3 - F_1) \tag{8}$$

$$U_3 = l\,(F_4 - F_2) \tag{9}$$

$$U_4 = F_1 + F_3 - F_2 - F_4 \tag{10}$$

the variables F_1,F_2, F_3 and F_4 represent the control forces produced by the propellers.U_1 the total thrust created by the UAV, which is the combined thrust of each rotor. Finally the roll torque is given by U_2 while the pitch torque is denoted by U_3 . The yaw moment about the z-axis is represented by U_4. Variations alter the yaw motion while maintaining constancy.

3. CONTROL METHODS

This section offers a technical overview and essential background on current controller synthesis methods used for navigating and controlling UAV. The unique benefits and limitations of each technique are examined about their suitability for the new generation of UAV. Authors in (Nascimento and Saska, 2019), have studied the control method. On the other hand, researchers in (Al-Younes, Al-Jarrah and Jhemi, 2010), categorized control methods as linear and nonlinear. In (Shauqee, Rajendran and Suhadis, 2021), (Kim, Gadsden and Wilkerson, 2019), categorized control methods as linear, nonlinear, and intelligent. In (Abdelmaksoud, Mailah and Abdallah, 2020), classified control method into linear, nonlinear, intelligent, and hybrid. Considering that each control method has its own set of advantages and disadvantages, making them suitable for different applications and objectives, we have classified the control methods based on our literature review into five categories: linear controllers, nonlinear controllers, intelligent controllers, hybrid controls, and adaptive controllers. The following block diagram in Fig. 2 display's the typical schematic of the closed loop control system of the under-actuated quadrotor that controlling its six degree of freedoms to follow the desired input.

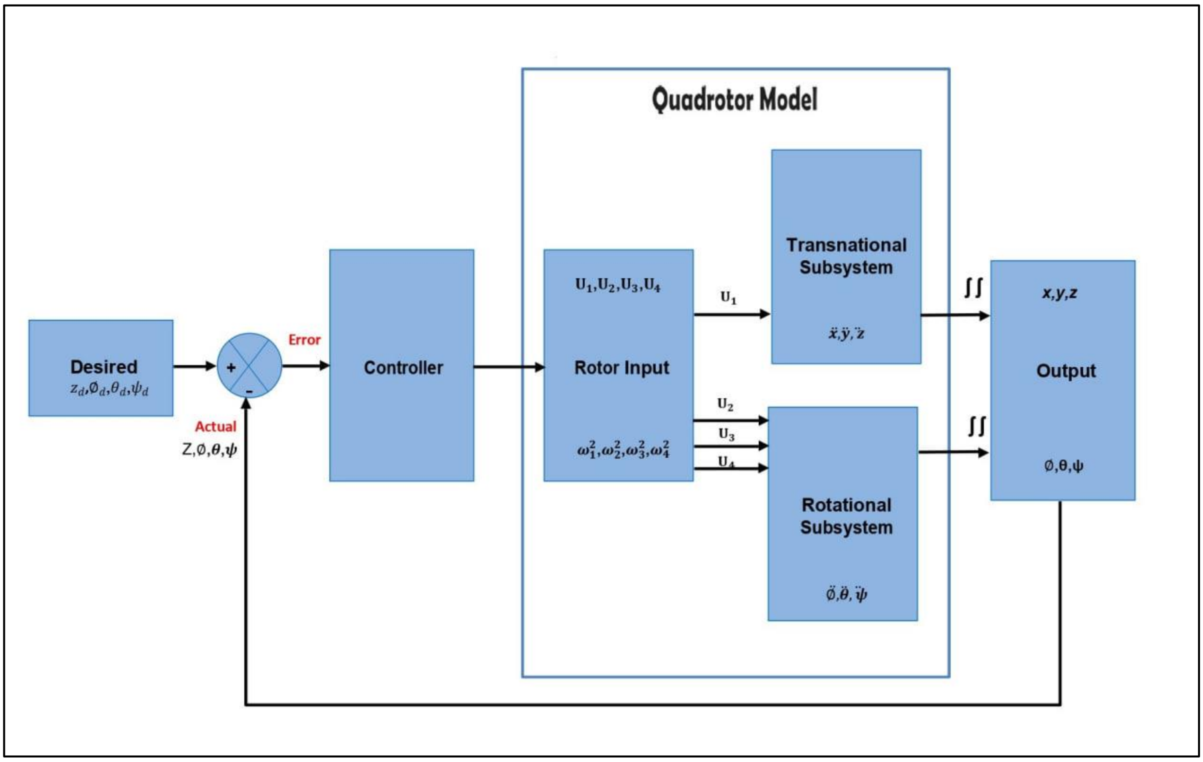

Fig. 2. Schematic block diagram of a quadrotor.

3.1. Linear Control

Linear control for quadrotor UAV involves designing control strategies that approximate the nonlinear dynamics of the quadrotor system with linear models for ease of analysis and controller design. This approach simplifies the control design process while maintaining satisfactory performance (Rinaldi, Primatesta and Guglieri, 2023). The linear methods used in UAV controls are conventional flight control algorithms (Kangunde, Jamisola Jr and Theophilus, 2021). Common linear controls that received from researchers a large interest are linear quadratic regulator, proportional integral derivative, and H_∞ control.

3.1.1. Proportional Integral Derivative (PID)

A proportional integral derivative (PID) controller is a traditional control method utilized in various electrical and mechanical systems. The PID controller is commonly utilized in manufacturing because of its ease of installation, simplicity, and satisfactory performance with minimal control efforts (Maaruf, Mahmoud and Ma'arif, 2022). The proportional (P) term improves the response time of the system. The integral (I) term eliminates steady-state error. The derivative (D) term provides a damping effect for unwanted overshoots (Apriaskar et al., 2019). Nowadays, the PID controller is employed by many researchers for trading quadrotor systems.

In (Bouaiss, Mechgoug and Ajgou, 2020), used PID to handle the height control and rotations (roll, yaw, and pitch) of the quadrotor. The results demonstrate acceptable errors in roll, yaw, and pitch angles during hovering mode. In (Salih and Saleh, 2022), a genetic algorithm to optimize the PID parameters for altitude and attitude control of a drone carrying a suspended payload. In (Noordin, Basri and Mohamed, 2020), applied PID control in the field of quadrotor MAVs, showcasing its potential to improve flight stability and maneuverability in challenging environments. In (Cedro, Wieczorkowski and Szcześniak, 2024), increased the PID performance by incorporating gain scheduling and differential filters. The resistance of the control algorithm to external disturbances is evaluated, and the efficiency of the developed control algorithm is confirmed through experimental and simulations results. In (B.-M. Nguyen et al., 2022), proposed multi-sensor-based for altitude control of quadcopters includes a state observer, a disturbance observer, and a position controller. also used a PID, in one of the operating modes of the proposed control system. In (Hamdy and Hassan, 2019), the PID is developed to control the position, heading, attitude, and altitude of quadcopter. The results display in figures the responses, such as altitude, heading, pitch angle, and roll angle, demonstrating the effectiveness of PID controller in controlling the quadcopter. In (Bayisa and

Li-Hui, 2019), The PID controller is utilized to stabilize the quadcopter and regulate its movements, including roll, pitch, yaw angles, and altitude. However, PID controllers have some disadvantages: may not perform well in non-linear and complex systems, Tuning the PID parameters for optimal performance can be challenging, especially in systems with varying dynamics or external disturbances, and PID controllers may not be suitable for systems with long time delays or those that require precise control over operating conditions a wide range of (Zouaoui, Mohamed and Kouider, 2019), (Gomez et al., 2020), (Božić et al., 2020), (Vamsi et al., 2019), (SUNAY et al., 2020), (Darwish et al., 2022).

3.1.2. H∞ Control

The H∞ controller is a type of robust controller used in control systems engineering. The H∞ designed to minimize the effect of uncertainties and disturbances on the performance of a control system (Saleem et al., 2021), (Hamza, Mohamed and El-Badawy, 2022).

In (Said, Larabi and Kherief, 2023), compared the performance of PID and H∞ controller for controlling the yaw and pitch angels of a quadcopter. The results of the simulation display that the H∞ outperformed PID in robustness terms and stability. In (Hegde et al., 2021), provide a design and mathematical modeling of an H∞ controller for an autonomous vertical take-off and landing (VTOL) Quad Tiltrotor hybrid UAV. On the other hand, the author in (Hegde et al., 2020), designed and employment of a robust H∞ controller for a VTOL. In (Noormohammadi-Asl et al., 2020), H∞ control for quadrotor attitude control addresses uncertainties such as unmodeled dynamics and unknown parameters. The result shows robust stability and improved tracking performance compared to well-tuned μ-synthesis and PID controllers. In summary, H∞ control offers robustness and performance benefits for quadcopters but comes with challenges related to complexity, tuning, and practical implementation in real-time systems. Careful consideration of these factors is essential when deciding to apply H∞ control to quadcopter systems (Zanatta, 2021).

3.1.3. Linear Quadratic Regulator (LQR)

The linear quadratic regulator (LQR) is used to stabilize the quadcopter UAV, control its position and orientation, and enable it to follow desired trajectories with minimal control effort (Shehzad, Bilal and Ahmad, 2019). The LQR have optimal control, robustness, state feedback, and versatility (Cohen, Abdulrahim and Forbes, 2020),(Zuo et al., 2022).

In (Elkhatem and Engin, 2022), used the LQR control method for controlling the dynamics of UAVs. The results display that the LQR control method, when combined with a PI controller (referred to as LQR-PI), was able to achieve good tracking performances with respect to various criteria. In (Ahmad et al., 2020), designed a LQR-based controller for a quadcopter to regulate positions in orientation, vertical directions, lateral, and longitudinal in the yaw direction. In (Priyambodo, Dhewa and Susanto, 2020), used (LQR) control method to minimize steady state error and multiple overshoot in the flight mission of a flying wing UAV. In (Minervini et al., 2021), the LQR controller is implemented as the control strategy for the quadcopter. In (Acakpovi et al., 2020), LQR improves the stability and accuracy of the drone, allowing it to follow complex trajectories with high fidelity. The results confirmed superiority in terms of stability and tracking accuracy over counterpart UAVs controlled with PID techniques. In (Ingabire and Sklyarov, 2019), the LQR has been selected due to its strong robustness and good stability margin. In (Setyawan, Kurniawan and Gaol, 2019), proposed the LQR approach to perform landing of the UAV by control attitudes and control altitudes. The results of research show that the average for landing of settling time is 1.74 seconds of altitude for every increment of one meter. However, LQR controllers offer stability, optimality, and robustness, they also come with challenges related to complexity, sensitivity to model mismatch, computational requirements, and limitations in handling nonlinear systems (Priyambodo, Dhewa and Susanto, 2020), (Shukla and Kumar, 2020).

3.2. Nonlinear Control

Nonlinear control for quadrotor UAVs involves the application of control strategies specifically designed to address the complex and nonlinear dynamics of quadrotor UAV. Quadrotors are inherently nonlinear systems due to their multivariable, underactuated, and coupled nature, making traditional linear control approaches insufficient for achieving precise control and stability (Rinaldi, Primatesta and Guglieri, 2023). Nonlinear techniques aim to ensure stable and precise control of UAVs, including trajectory tracking, altitude control, attitude stabilization, and obstacle avoidance, by secretarial for the uncertainties and nonlinearities inherent in quadrotor dynamics (Roy et al., 2021). Recently, multiple articles on nonlinear flight controllers for quadrotor UAVs have been published. Among these, backstepping, feedback linearization, sliding mode control (SMC), active disturbance rejection rontrol (ADRC), and model predictive control have received much attention.

3.2.1 Feedback Linearization

The feedback linearization (FBL) of a UAV quadrotor involves transforming the non-linear model of the quadrotor into an equivalent linear one. This is achieved by introducing a proper state transformation and a non-linear feedback (Lotufo, Colangelo and Novara, 2019),(Cai, Zhang and Jing, 2021).

In (Shen and Tsuchiya, 2022), proposed FBL in the context of quadrotor control, focusing on the yaw-position tracking problem. In (Ma'arif et al., 2023), comparing PID and Integral State Feedback (ISF) controller. The integral state feedback (ISF) control compared to PID control demonstrated better settling time with zero overshoot. On the other hand, PID control showed a better rise time but with a significant overshoot in the system response. The author in (Sadiq et al., 2024), used robust feedback linearization based (RFBL) controller, which is compared with other controllers such as the integral SMC (ISMC) and the terminal SMC (TSMC). The results display that the RFBL outperforms the other controllers in most cases, especially in tracking the circular and infinity-shaped trajectories. In (Alyoussef and Kaya, 2019), display the advantages and disadvantages of SMC, back-stepping control, and FBL. In summary, SMC and backstepping demonstrate superior performance compared to FBL across several applications and in the presence of uncertainty.

3.2.2 Model Predictive Control (MPC)

Model predictive control (MPC) a predictive model of the system to be controlled is used to predict future behavior based on current measurements and control inputs. The control algorithm calculates the best control sequence within a limited time frame by solving an optimization problem at every time interval (Romero et al., 2022).The benefits of MPC include its ability to handle multivariable systems, incorporate constraints on system inputs and outputs, and account for system dynamics and disturbances (Nguyen et al., 2021).

In (Zhang, Shi and Sheng, 2021), developed MPC to control the quadrotor relative position and yaw angle towards a specified visual target using images and velocity measurements. In (Andriën et al., 2024), proposed MPC control method offers a systematic approach for trajectory tracking in quadcopters with formal closed-loop tracking guarantees. In (Wehbeh, Rahman and Sharf, 2020), used MPC for the collaborative transport of a payload using several quadrotor vehicles. In (D. Wang et al., 2021), observed that the efficient MPC outperformed backstepping control in terms of tracking the performance for the quadrotor UAV. In (Sun et al., 2022), compared the MPC and the differential-flatness based Control (DFBC) for quadrotor agile flight trajectory tracking. In (Cavanini, Ippoliti and Camacho, 2021), developed MPC based autopilot for a UAV for sampling tasks meteorological data. The result presented the performance improvement achieved by these method, particularly in controlling the attitude and altitude dynamics of the UAV. However, while MPC offers several advantages, the potential disadvantages should be carefully considered and addressed to ensure successful implementation in practical applications such as computational complexity, real-time implementation, approximation errors, and tuning complexity (Jung and Bang, 2021).

3.2.3 The Backstepping Controller

Backstepping control is a nonlinear control technique used for stabilizing and controlling complex dynamic systems, such as quadrotors. Backstepping control enables the control of the orientation and position of the quadrotor subsystem, addressing the challenges posed by the system non-linearity and providing robustness to parametric variation (Saibi, Boushaki and Belaidi, 2022).

In (Zhang, Yan and Zhang, 2020), utilized the back-stepping method to ensure that quadrotors UAV quickly converges to the desired trajectory, achieves a steady state, and maintains the desired formation with fast convergence speed and minimal steady-state error. Additionally, the proposed method outperforms other control methods such as the Laplace method and MPC in terms of dynamic response and tracking error effect. In (Thanh et al., 2022), authors used robust backstepping based on disturbance observer and extended State for a quadcopter UAV. Comparative between backstepping control and other algorithms as SMC and ADRC on the smeller quadrotor model in an identical employed environment, the proposed method shows superior of performance. In (Kucherov et al., 2021), used backstepping to stabilize the spatial position of a quadcopter. The accurate and superior performance compared to other control methods such as PID and smoothed sliding mode controller. In (Kadhim and Hassan, 2020), used backstepping control method for the autonomous quadrotor. however, backstepping control require for full information about all system states. This can comprise a challenge in practical implementation, as obtaining measurements for all states of a quadrotor UAV may not always be feasible. This limitation necessitates the design of observers or estimation techniques to offer the required state information for the controller to operate effectively (Mo and Farid, 2019).

3.2.4. Sliding Mode Controller (SMC)

Slide mode control (SMC) a robust control method that aims to ensure stability and performance in the presence of uncertainties and disturbances (Rehman et al., 2021). SMC can be used for attitude and position control, helping to achieve stability and robust performance in various flight conditions (Nascimento and Saska, 2019).

In (Eltayeb, Rahmat and Musa, 2019), compares the performance of FBL and SMC controllers, the SMC control showing better performance in the presence of disturbances. In resent years, the researchers employed many different type of SMC to control quadrotor UAV. The author in (N. P. Nguyen et al., 2022), proposed the fast TSMC (FTSMC). In (Eltayeb et al., 2020), the authors improved ISMC for the quadrotor UAV. In (Labbadi and Cherkaoui, 2019), used a robust integral TSMC (RITSMC) with external disturbances for the quadrotor. Comparison with classical SMC and backstepping sliding mode control techniques. RITSMC shows the effectiveness and superiority. The authors in (Hou, Lu and Tu, 2020), designed nonsingular TSMC (NTSMC) to a flight controller for a quadcopter with a four-rotor failure. In (Muñoz et al., 2017), the authors implemented three different second order slide mode control: the super twisting SMC (ST-SMC), the nonsingular terminal super twisting SMC (NSTST-SMC), and the modified super twisting SMC (MST-SMC). The result show that the NSTST-SMC presented the fastest response and the best performance in terms of transient response and steady state during altitude tracking. The MST-SMC also showed effective performance in rejecting disturbances and tracking altitude references. In (Sanwale et al., 2020), the authers used third-order SMC (TOSMC) to provided effective disturbance rejection capability and increased robustness. In (Nguyen, Phung and Ha, 2021), proposed a novel iterative learning SMC (ILSMC) to tracking the trajectory of quadrotor to model external disturbances and uncertainties. In (Al-Dhaifallah et al., 2023), used fractional-order SMC (FOSMC). In summary, SMC offers robustness against uncertainties and disturbances, simplicity in implementation, and insensitivity to modeling errors. However, drawbacks include the chattering effect leading to high-frequency oscillations, high control effort or rapid switching of the control signal, and the tuning complexity of controller parameters. These factors should be considered when applying SMC in control system applications (Rubí, Pérez and Morcego, 2020).

3.2.5. Active Disturbance Rejection Control (ADRC)

The active disturbance rejection control (ADRC) is a nonlinear control method technique that provides robust control in the presence of disturbances without relying heavily on accurate models. ADRC offers advantages such as short adjustment times and strong anti-interference capabilities (Liang, Xu and Yu, 2019).

In (Najm and Ibraheem, 2020) proposed the improved active disturbance rejection control (IADRC) for stabilizing and rejecting disturbances in a UAV quadrotor system. In (Zhang, Chen and Sun, 2020), designed the dynamic surface ADRC to address tracking the trajectory issues for a quadrotor (UAV) by incorporating dynamic surface control and ADRC techniques using nonlinear gains posed challenges in analyzing the frequency response. Due to the complexity of tuning the numerous parameters in the original ADRC, some researchers introduced a linear ADRC (LADRC) as a more easily tunable and analyzable alternative (Song et al., 2016). In (Li et al., 2023), used the ACO algorithm to tune the ADRC parameters and reduce complexity.

However, one of the disadvantages of ADRC is that can be complex to implement and tune compared to traditional control methods like PID controllers. The design and parameter tuning of ADRC require a good understanding of the system dynamics and disturbances, which may pose challenges for some users. Additionally, ADRC may require more computational resources due to its advanced algorithms, which could be a limitation in certain real-time control applications (Zhang et al., 2019).

3.3. Intelligent Control

Intelligent control for quadrotor UAVs involves the use of advanced algorithms and techniques to enhance the autonomy, adaptability, and decision-making capabilities of the UAV's control system (Yüksel, 2019). Intelligent control techniques such as fuzzy control, ANN control, genetic algorithms (GA), and swarm intelligence (such as the ant colony optimization (ACO) and particle swarm optimization (PSO) algorithm) (Pang and Tian, 2021), provided optimized UAV performance, enhanced decision-making processes, and improved overall operational efficiency leading to enhanced stability, robustness, and adaptability (Abbas et al., 2023).

In (He et al., 2019), enhanced the traditional PID control with fuzzy logic control to optimize the control parameters of PID. In (Khosravian and Maghsoudi, 2019), author presented recurrent neural network based non-linear PID control algorithm. In (Rodríguez-Abreo et al., 2020), used GA for tuning the backstepping controller for a quadrotor UAV to optimize the controller performance and response to different trajectories. In (Sahrir and Basri, 2023), employing the PSO algorithm to reduce tuning efforts and achieve optimal results for altitude and attitude stabilization. In (Li et al., 2024), developed two designed specifically observers on the radial basis function neural network (RBFNN) to recreate the compensate, actuator failures and disturbances for the nominal strategies. The results display the effectiveness of RBFNN in reducing control costs and improving overall system performance. In (Hassani, Mansouri and Ahaitouf, 2019), select optimal parameters for the backstepping controller using the ACO algorithm. In summary, intelligent control systems offer advanced capabilities for controlling complex systems such as drones, the intelligent control come with challenges related to complexity, data requirements, interpretability, computational resources, and the risk of overfitting. Understanding these advantages and disadvantages is crucial for selecting the most appropriate control strategy for a given application (Kangunde, Jamisola Jr and Theophilus, 2021).

3.4. Hybrid Control

he hybrid control algorithm refers to a control method that combines multiple control schemes to enhance the overall performance of a system. Hybrid controller leverages the strengths of each individual method while compensating for their weaknesses. This approach often results in improved stability, robustness, and efficiency compared to using a single control scheme (Khalid et al., 2023).

In (Chen and Chen, 2021), combining the FBL method and the LQR method and using PSO algorithm, to analyze and stabilize the highly nonlinear quadrotor system. The results demonstrate the effectiveness of the proposed control design approach in achieving multiple performance objectives for quadrotor systems. In (Singh and Kumar, 2023), tailored MPC method for attitude control, while implemented FBL method for position control. In (Jennan and Mellouli, 2023), designed a new optimal FTSMC combined with neural networks to reduce modeling errors, handle disturbances, and improve overall control performance. In other hand, (Raiesdana, 2020), used neural networks to improve the time indices for TSMC. In (Jiang et al., 2022), used neural network based model predictive control (NNMPC) for modeling the system dynamics and predictive control to optimize the control inputs over a receding horizon. In (Zare, Pazooki and Haghighi, 2022), proposed new fuzzy-SMC and optimised the proposed control by GA. In (Liu et al., 2019), proposed learning rate based ASMC to track the desired altitude and maintain altitude stability. In (Nguyen, Phung and Ha, 2021), combined sliding mode control with iterative learning to improve tracking the trajectory for quadrotor UAVs, especially in the attendance of disturbances and uncertainties. In (Hassani, Mansouri and Ahaitouf, 2021), used an adaptive nonsingular FTSMC (ANFTSMC) for attitude control and backstepping SMC for position control. In (H. Wang et al., 2021), proposed a backstepping sliding mode control. In (Yu et al., 2024), combined ADRC and backstepping control. In summary, while hybrid control systems offer flexibility and performance benefits, their complexity and challenges in design, implementation, and tuning must be carefully addressed (Badr, Mehrez and Kabeel, 2019).

3.5. Adaptive Controller

The adaptive method refers to a control approach used in quadrotor flight controllers that involves adapting and estimating varying system parameters. Adaptive control provides enhanced robustness in the presence of parametric uncertainties (Mo and Farid, 2019).

In ,(Rahmat, Eltayeb and Basri, 2020) proposed and implemented adaptive feedback linearization (AFBL) to provide robust performance against wind disturbances and parameter uncertainties. In (Mehmood et al., 2021), compare the performance of the adaptive STSMC with fixed gain STSMC. The ASTSMC controllers demonstrate robust behavior in the presence of disturbances, minimizing trajectory deviations for all UAVs. In (Dalwadi, Deb and Muyeen, 2022), (Koksal, An and Fidan, 2020), (Nguyen, Xuan-Mung and Hong, 2019), (Xie et al., 2021),(Zhou et al., 2021), author designed an adaptive backstepping for control a quadrotor UAV to address uncertainties and disturbances, particularly in the presence of wind gusts. In (Thu and Gavrilov, 2017), Compared L1 adaptive control to other adaptive control algorithms as model reference adaptive control (MRAC), L1 adaptive control is considered more realistic and suitable for UAV applications. In (Didier et al., 2021), designed robust adaptive of MPC (RAMPC) to optimize uncertain parameters and ensure state and input constraint satisfaction in real-time, making it suitable for applications where model uncertainties and disturbances are present for the quadrotor. In (Yang and Xian, 2019), designed an energy-based nonlinear adaptive control design to control the position of the quadrotor UAV and the swing angle of the suspended payload. In (Pliego-Jiménez, 2021), an adaptive control system utilizing the unit quaternion is suggested to track the trajectory of a quadrotor UAV. In (Mofid and Mobayen, 2021), proposed an adaptive finite-time backstepping global sliding mode tracker to accurate and fast performance in tracking the required position and altitude of the quadcopter. In (Tilki and Erüst, 2021), designed robust adaptive backstepping global fast dynamic TSMC (RABGFDTSMC) for quadrotors. The coefficients of the controller are determined using a predefined characteristic equation, and the overall system stability is proven using the Lyapunov function. In (Eltayeb et al., 2020), designed an improved adaptive SMC (IASMC) to address the challenges of trajectory tracking and chattering attenuation for the Quadcopter UAV. In (Santos et al., 2019), used the adaptive dynamic controller for quadrotor based on feedback linearization to improve robustness in the existence of uncertain parameters and external perturbations. In (Huang et al., 2021), used adaptive backstepping SMC (ABSMC) to suppress the chattering effect of SMC effectively by constructing an adaptive switching gain and using the backstepping design process. Although, adaptive control offering advantages such as robustness and improved performance, adaptive control have several disadvantages as complexity in designing and implementing, challeng tuning adaptive control parameters, achieving convergence of adaptive control algorithms can be difficult, and potential trade-off between performance and stability (Muthusamy et al., 2021).

4. DISCUSSION

The analysis of various control methods for quadrotor UAVs reveals several key insights. The choice of control strategy significantly impacts the performance, stability, and robustness of quadrotor UAVs under different operational conditions. Based on previous studies, the distribution related to the extent of the use of various control strategies involving quadrotor models using pie charts based on the Web of Science and Scopus databases over the last five years are graphically shown in Fig. 3.

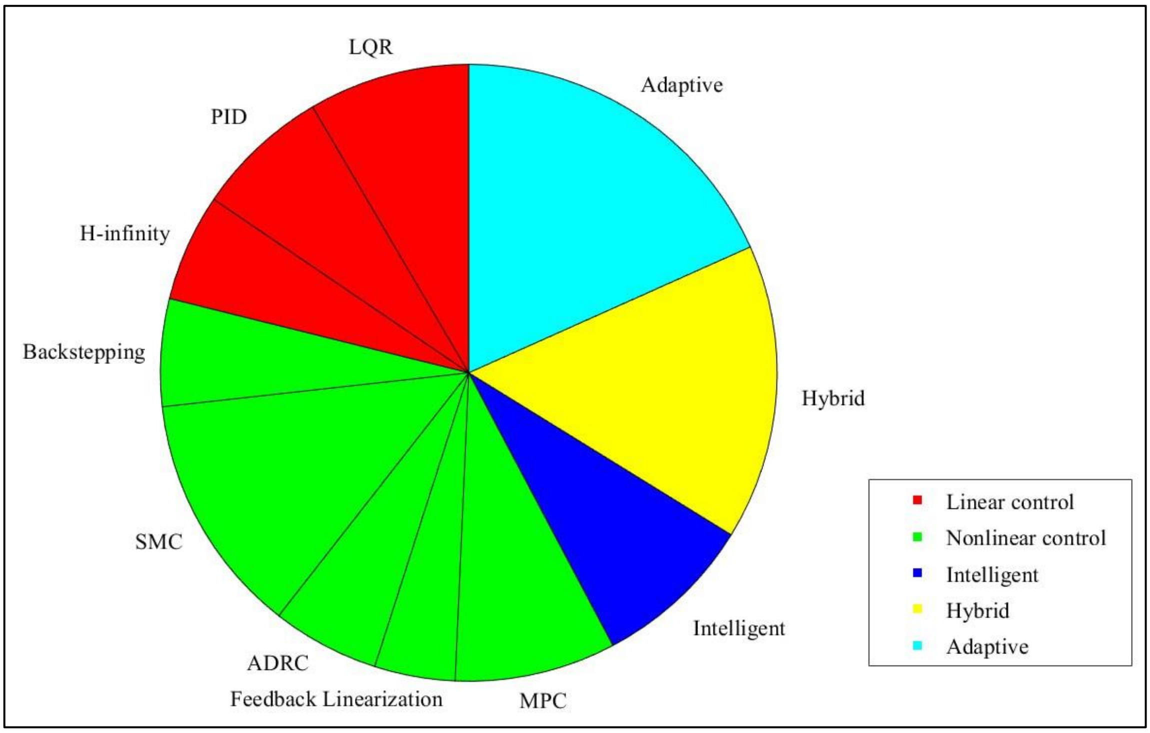

Fig. 3. Control method Distribution

Linear control methods, such as PID and LQR, provide simplicity and ease of implementation. However, they may struggle with the nonlinearity and coupling effects inherent in quadrotor dynamics. Among these, the PID controller remains popular due to its straightforward design and satisfactory performance in many practical applications. LQR, on the other hand, offers optimal control with state feedback, which enhances stability and tracking accuracy but requires precise system modeling. Nonlinear control techniques, including feedback linearization, backstepping, and sliding mode control (SMC), address the limitations of linear methods by directly handling the nonlinearity of quadrotor dynamics. These methods improve performance in terms of response time, disturbance rejection, and robustness. For instance, SMC is particularly noted for its robustness against external disturbances and model uncertainties, making it suitable for environments with varying conditions. However, the chattering phenomenon in SMC requires mitigation to prevent high-frequency oscillations. Intelligent control approaches, such as fuzzy logic, neural networks, and genetic algorithms, enhance the adaptability and decision-making capabilities of quadrotor control systems. These methods offer advanced performance in complex and uncertain environments by learning from data and optimizing control parameters dynamically. Hybrid control strategies combine the strengths of multiple control methods to achieve superior performance. For example, combining MPC with neural networks or SMC with backstepping can provide robust, adaptive, and optimal control solutions.

The analysis also highlights that adaptive control methods offer significant benefits in dealing with parameter variations and uncertainties. By continuously adjusting control parameters in real-time, adaptive controllers maintain performance and stability despite changing dynamics. However, the complexity in design and implementation poses challenges that need to be addressed for practical applications. A complete summary of the advantages and disadvantages of the various control strategies discussed for the rotorcraft UAVs is shown in Table 1.

Table 1 Comparison of Control Methods for Quadrotors: Advantages and Disadvantages

Control Method	Advantages	Disadvantages
Linear Quadratic Regulator (LQR)	Optimal for a specific cost, straightforward, effective for linear systems	Assumes perfect knowledge, poor with uncertainties, not for non-linear systems
Proportional Integral Derivative (PID)	Simple, effective for many problems, easy to implement	Manual tuning needed, poor with non-linearities and disturbances
H∞ Control	Robust against uncertainties, handles multivariables, specific performance	Complex design, requires detailed model, high control effort
Backstepping	Effective for non-linear systems, stabilizes at levels	Precise model needed, complex, computationally intensive
Feedback Linearization	Simplifies control by linearizing, precise control possible	Sensitive to model inaccuracies, complex, exact model needed
Sliding Mode Control (SMC)	Robust, works well with non-linear systems, finite time convergence	Induces chattering, high control activity
Active Disturbance Rejection Control (ADRC)	Estimates and compensates disturbances, robust	Challenging disturbance estimation, performance depends on estimator
Model Predictive Control (MPC)	Handles constraints, optimizes future behavior, multivariable control	Computationally intensive, requires accurate model
Intelligent Control	Adapts to uncertainties, handles non-linearities and uncertainties	Requires extensive training data, decisions can be opaque
Hybrid Control	Combines multiple strategies, tailored to specific conditions	Increased complexity, integration challenges

In summary, the selection of an appropriate control method depends on the specific requirements and operational environment of the quadrotor UAV. A trade-off between simplicity, performance, robustness, and adaptability must be carefully considered to achieve optimal control.

5. CONCLUSIONS

This review provides a comprehensive analysis of various control methods employed in quadrotor UAVs, emphasizing their unique advantages and limitations. The study categorizes the control methods into linear, nonlinear, intelligent, hybrid, and adaptive approaches, each offering distinct benefits tailored to different operational needs and challenges. Linear control methods, such as PID and LQR, are effective for basic control tasks but may not suffice for highly dynamic and nonlinear systems. Nonlinear control techniques address these limitations by accommodating the inherent nonlinearity of quadrotor dynamics, thereby enhancing performance and robustness. Intelligent control approaches introduce adaptability and advanced decision-making capabilities, making them suitable for complex and uncertain environments. Hybrid control strategies leverage the strengths of multiple methods to create robust and adaptive control solutions. These strategies are particularly useful in scenarios where the operational conditions are highly variable. Adaptive control methods stand out for their ability to maintain performance amidst parameter variations and uncertainties, though their complexity requires careful design and implementation. Future research should focus on developing more efficient and less computationally intensive algorithms that can be implemented in real-time systems. Additionally, integrating advanced sensing and communication technologies with control algorithms can further enhance the autonomy and performance of quadrotor UAVs. In conclusion, the control of quadrotor UAVs continues to be an active and evolving field. The insights gained from this review can guide researchers and practitioners in selecting and developing appropriate control strategies to meet the specific requirements of their applications, ultimately advancing the capabilities and applications of quadrotor UAVs.

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