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Comparative analysis and the prospect of flight control strategies and performance of quadrotor UAV

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Abstract. Quadcopter UAVs are increasingly used for military and civilian applications such as surveillance, reconnaissance, pesticide spraying, and traffic monitoring due to their simplicity of operation, ease of attitude adjustment, and ability to take off and land vertically. The flight control system is the key to the aircraft's ability to perform flight tasks. However, when faced with external disturbances, obstacles, and uncertain parameters, traditional PID control is unable to meet the demands of complex flight tasks. Research on more advanced control strategies is the trend of future development. This paper surveys the flight control methods of quadrotor UAVs in the past two decades and classifies and introduces these methods one by one. Finally, the experimental feasibility of these methods is discussed, the advantages and disadvantages of these methods are briefly compared, and the future development trend of UAV flight control systems is analyzed. An important reference is provided for the development of quadrotor UAV flight control algorithm research.

Keywords: quadrotor, flight control, linear controllers, nonlinear controllers, intelligent controllers.

1. Introduction

Since the Wright brothers invented the aircraft and the flight control device, they have realized the controlled and continuous flight of the powered aircraft heavier than air and made the fixed-wing aircraft possible [1]. Aircraft technology has developed rapidly over the past few decades. Initially, aircraft mostly used fixed-wing designs. However, a major disadvantage of fixed-wing aircraft is the need for take-off and landing runways. To overcome this limitation, various rotorcraft have been investigated. Quadrotors have received a lot of attention recently because of its flexibility, ability to hover in midair, and vertical takeoff and landing. Its applications are not limited to civilian fields such as material delivery, pesticide spraying, and traffic monitoring, but also include military tasks such as maritime cruise, target detection, and long-range strikes. [2]. The quadrotor aircraft's flight control technique is essential to its ability to complete its job, and studying this strategy is crucial to the development of the quadrotor aircraft. Although the flight control methods of UAVs have made great progress, some control methods are still difficult to complete the flight tasks when they are subject to external disturbances, obstacles, and uncertain parameters [3]. This paper provides a survey of quadrotor flight control techniques over the past two decades. These methods are classified and their characteristics and

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applications are discussed in detail. In addition, the feasibility of these methods and the future development trend of quadrotor UAV flight control methods are analyzed.

The rest of the paper is organized as follows: Section 2 presents the quadrotor flight control architecture, and Section 3 describes the research on control methods of the quadrotor UAV over the past two decades, categorizing and comparing them. The application of the control method of the quadrotor UAV is discussed in detail. Section 4 discusses applications and future developments of quadrotor control methods. The conclusions are contained in section 5.

2. The flight control system of quadrotor UAV

The UAV flight control system generally adopts the form of a double closed loop, which separates the attitude loop and the position loop for control. To complete the flight mission, the UAV must have good control over both internal and external circuits. The core problem of flight control is: Given a desired position, control the motors of the multi-rotor so that it can fly to the target position. In the general block diagram of the controller, our given inputs are P_d and Ψ_d . The position controller obtains the expected pulling force f_c , the expected roll angle ϕ_d , and the expected pitch angle θ_d through the expected position P_d , actual position P and actual speed V in the space coordinate system, and the expected θ_d , ϕ_d , ψ_d , the actual Euler angle Θ and the actual body angular velocity ω are input to the attitude controller to obtain the desired torque τ_d . Secondly, the control distributor obtains the expected rotational speed $\varpi_{d,k}$ according to the expected pulling force f_c and the expected torque τ_d . Finally, the motor controller generates the desired instruction $\sigma_{d,k}$ according to the desired rotational speed $\varpi_{d,k}$. The following two figures show the quadrotor controller architecture and the nonlinear quadrotor SIMULINK model.

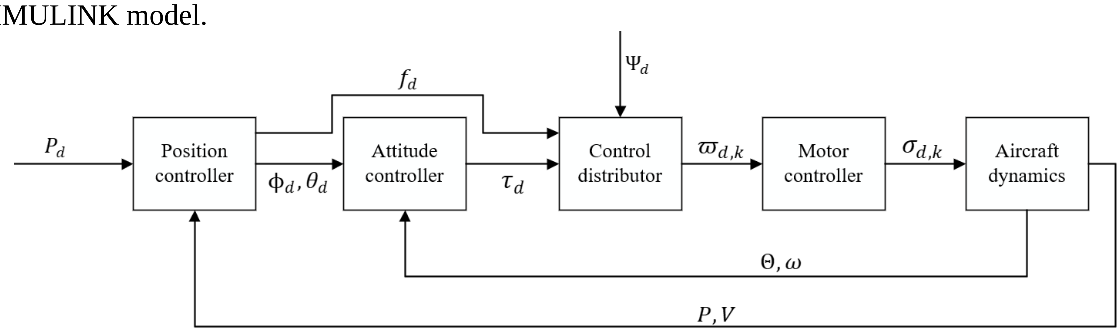

Figure 1. Quadrotor Controller Architecture Block Diagram.

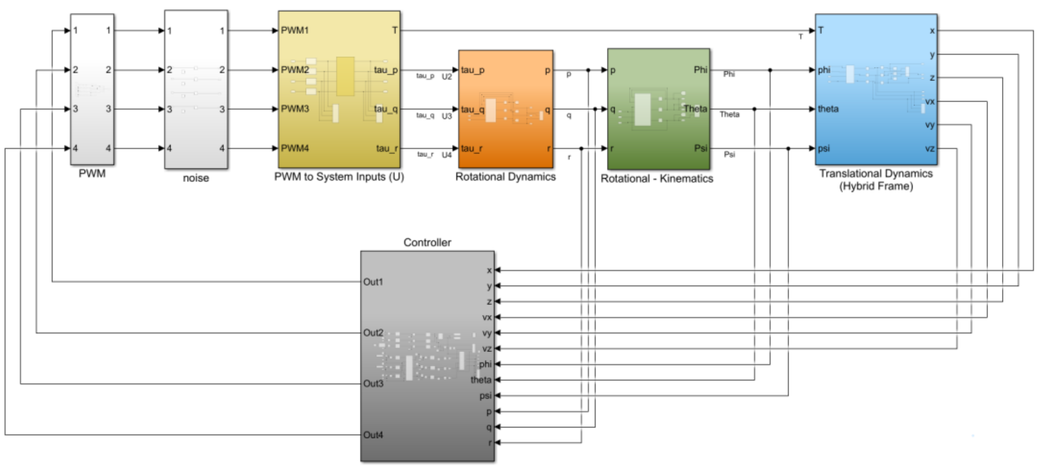

Figure 2. SIMULINK block diagram for simulation studies.

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3. Technical analysis of quadrotor drone flight control system

The flight control systems of quadrotor UAVs have been extensively studied during the past 20 years. For quadrotor UAVs, many different flight control methodologies have been developed. The flight control methods of quadrotor UAVs can be divided into three categories.

The classification of flight control methods is shown in the figure below.

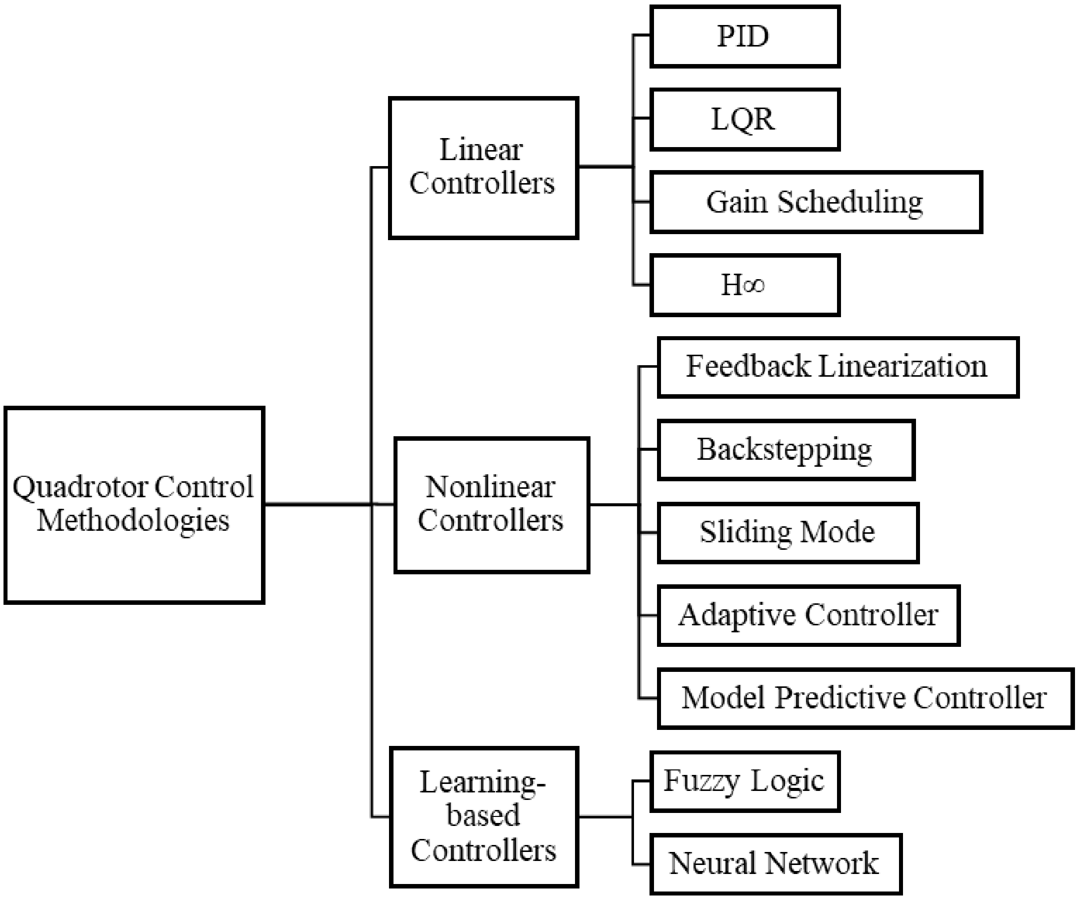

Figure 3. Classification of quadrotor flight control methods [4].

3.1. Linear controllers

Linear control theory is the basis of modern control theory, and its technology in system analysis and controller design is relatively mature. The design idea of the linear controller is to linearize the mathematical model of the quadrotor at the working point. PID, LQR, gain scheduling and H∞ are several linear control methods commonly used for quadrotor UAVs.

As the most common UAV flight control algorithm, the PID controller has the advantages of an extremely simple structure, easy parameter setting, and a certain degree of robustness that can be guaranteed without the precise mathematical model of the controlled object. However, when dealing with systems with more external disturbances such as UAVs, the ability of PID control to compensate for external disturbances is weak, and there is a contradiction between response speed, smoothness, and accuracy. PID controllers for quadrotors have been successfully used by numerous studies [5], [6]. Some researchers have modified the standard PID and achieved good results in improving flight stability and control accuracy [7], [8].

LQR, that is, linear quadratic regulator, uses state space to analyze and design the system. It is the quadratic function integral of the state parameters and control parameters of the objective function, and

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the state parameters and the control law are related linearly. This method is easy to form the optimal law of closed-loop control. However, the traditional LQR controller loses the nonlinear characteristics of the model in the process of obtaining the linearized model, thereby reducing the robustness of the system. To overcome this shortcoming, Alsharif et al. introduced an LQI controller that can efficiently stabilize the system and track reference commands when the system is disturbed by noise and uncertainty [9]. A quadrotor UAV's best possible control was investigated by Cohen et al. using discrete-time, finite-horizon, and LQR [10]. The outcomes demonstrate that their proposed controller performs better when the initial error is significant.

The nonlinear dynamics of UAVs are typically simulated using a combination of linear models, each with a discrete working zone. This model-based approach permits the control of nonlinear systems through the application of linear control methods. Gain scheduling involves employing a set of linear controllers to govern nonlinear systems. In practice, a function that can choose the best scheduling varies depending on the control state is typically used to adjust the gain of the controller. The majority of the time, outside operating conditions, or system status details like azimuth speed are included in these scheduling variables [11].

The H∞ control algorithm can effectively deal with the flight control system's uncertainty to external and model-based perturbations, while still ensuring the closed-loop system's performance. As a result, some researchers use the H∞ controller to strengthen the quadrotor system's resistance to outside disturbances. The H∞ control technique, however, is dependent on an accurate model of the UAV, and it is quite challenging to change the parameters, and the controller's real-time calculation is quite considerable. Hegde et al. applied the H∞ controller to a quadrotor UAV [12]. The simulation results show that the powerful H∞ controller can realize attitude, height, and trajectory adjustment under the condition of uncertain parameters. Ortiz et al. combined H∞ with a PID controller, which proved to be effective in overcoming unmodeled dynamics and parameter uncertainty [13].

3.2. Nonlinear controllers

As one of the more popular techniques in nonlinear control, feedback linearization can linearize the state equation and the output equation. Create a linear differential relationship between the output y(t) and input u(t), convert the original nonlinear system to a linear system with linear state equations, and then apply the linear control approach to build the controller. Freddi et al. used a feedback linearization method to design a dual-control loop controller that allows control of roll and pitch when the aircraft rotor fails [14]. Spitzer et al. applied the acceleration error model to the position controller, reducing the robustness problem and improving the performance of the feedback linearization controller [15].

Backstepping control is an important method in nonlinear controller design. The design idea of it is to decompose the nonlinear system into several subsystems, then design each subsystem from the input end to the output end, construct the Lyapunov function, and select the virtual intermediate quantity, and finally integrate the subsystems back into the complete system. Omar et al. designed a quadrotor autonomous trajectory tracking backstepping controller using a genetic algorithm, which exhibited good performance in the face of parameter uncertainties [16].

A nonlinear control technique with changing structure is sliding mode control. The system's internal feedback control structure will be modified in accordance with the present system state so that the system state slides along the sliding surface. When entering the sliding mode state, the performance of the system is completely determined by the sliding mode surface and has nothing to do with the parameter disturbance and external disturbance of the controlled object. The control method is insensitive to system uncertainty and has strong robustness, which is especially suitable for UAV systems. However, when using this method, the system has the disadvantage of accompanying chattering. In order to overcome this defect, Eltayeb et al estimated the SMC switching gain with an improved adaptive formula and replaced the switching function with a smoothing function, which reduced the chattering phenomenon of the sliding mode controller and improved the stability of the system [17].

When the controlled object is an uncertain system, conventional controllers cannot achieve good control effects. Adaptive control can change the structure and parameters of the controller or switch the

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system model according to the expected value of the system and the real-time system state, parameters and performance during the operation of the system. Adaptive control can be regarded as a correction device of the control system to maintain the state of the system at the optimum state. Kazim et al. introduced an optimized robust adaptive controller, which applied adaptive integral backstepping control to the attitude controller [18]. According to the simulation results, the controller has good robustness and adaptiveness in the gust environment. Ability to perform proper position and attitude control.

MPC, or model predictive control, is a high-performance control method, which predicts the future state of the control system by establishing a precise mathematical model, and determines the output according to the optimal way under the condition of considering relevant constraints. Model prediction, rolling optimization, and feedback correction are the three components of MPC. Among them, the model prediction is responsible for making the system output value infinitely close to the expected value; the rolling optimization is to use the rolling method to reduce the error, solve the optimal solution and output it; the feedback correction is responsible for feeding the error back to the system, so as to ensure the stability of the closed-loop system. Liu et al. applied the traditional MPC model to quadrotor trajectory tracking and used Bezier curve parameterization to track the optimization problem in MPC [19]. The results of the simulation demonstrate that the controller has strong tracking performance and can control the complexity of the solution. On the basis of feedback linearization, Bhattacharjee et al. combined sliding mode control and the MPC method to propose a robust flight control strategy for quadrotor UAVs, which effectively handles the input constraints [20].

3.3. Learning-based intelligent controllers

The amount of information collected from the system object diminishes as the complexity of the controlled object of the control system increases, and it is frequently challenging to develop an appropriate mathematical model of the controlled object. Fuzzy logic control uses fuzzy mathematics to describe the controller, simplifies the design of the control system, and can effectively deal with problems such as model inaccuracy and control system uncertainty. Coza and Macnab applied an adaptive fuzzy control to a quadrotor while being disturbed by sinusoidal wind. According to the simulation results, the controller performs well and maintains excellent stability in a continuous oscillation environment. Mehranpour et al. defined the range of fuzzy rules and membership functions, optimized the tuning of controller parameters, and improved the adaptability of the controller to changes in the aircraft model.

A neural network is an adaptable, nonlinear system made up of numerous small processing units. It can devise a way of processing information that closely resembles the style of the human brain. The information analysis, processing, and self-adaptive capabilities of the control system are significantly improved by the widespread application of neural networks in the field of control. Since the neural network algorithm can approximate any continuous bounded nonlinear function, it is very suitable for the nonlinear system of UAV. On the basis of the PID controller, M. Ö. Efe introduced neural network control to estimate the interference factors such as model mismatch, airflow disturbance, and measurement noise neglected in the quadrotor dynamics model online, and the feedback information output by the neural network Real-time compensation to the PID controller.

4. Discussion

Because the linear controller is easy to design, analyze and implement, it has been the first choice for quadrotor flight experiments and has shown good experimental results. The simulation effect of the nonlinear controller is better; however, it is challenging to achieve the optimal real-world control effect since it depends on an exact mathematical model. The learning-based intelligent controller is very suitable for quadrotor UAV control, but it needs to overcome the difficulties of high calculation and large amounts of experimental data. This section compares the control methods mentioned above and shown in Table 1.

Table 1. Evaluation of control methods.

Control Techniques	Advantages	Disadvantages
PID	Simple structure, easy parameter setting, no need for a precise mathematical model of the controlled object	Weak anti-disturbance ability, unable to deal with coupling, may lead to an integral saturation phenomenon
LQR	Easy to tune, less steady-state error	Requires an accurate system model
Gain scheduling	Fast response, small amount of calculation	Difficult to maintain stability for complex models
H∞	Strong ability to prevent interference, strong ability to deal with uncertainty	Depends on the precise model of the UAV, parameter adjustment is difficult
Feedback linearization	Easy to implement, suitable for both linear and nonlinear systems	Effectiveness depends on the accuracy of the model
Backstepping	Fast response speed, good error convergence effect and robustness	Insufficient anti-interference ability, difficult to select parameters
Sliding mode	Simple structure, fast response, strong robustness, insensitive to uncertainty	Difficult to eliminate jitter issues
Adaptive	Strong robustness, strong fault tolerance, does not rely on precise mathematical models	Lower control accuracy
MPC	Can simultaneously handle various inputs and outputs, good stability	High requirements for model accuracy and a large amount of calculation
Fuzzy Logic	Does not rely on accurate models, strong robustness, strong fault tolerance	Low control precision, time-consuming parameter tuning
Neural Network	Strong information processing and adaptability, very small feedback error	A large number of test results is required, and the system stability is poor

In the future, the key to choosing a quadrotor flight control technique lies in the robustness, response speed, and implementation cost of the flight control system. The selection of flight control methods will be more diversified, and some control algorithms that stay in theory and simulation will be applied. In addition, according to the change in the flight environment, the quadrotor UAV based on multi-model online switching will also occupy an important position. The quadrotor UAV automatically selects the controller that meets the current task in the established model and reduces the cost of the control strategy. While increasing the complexity, the stability of the control system is improved.

5. Conclusion

The objective of this paper is to provide a survey of quadrotor UAV control techniques. This paper first introduces the development of UAV and expounds the important application value of quadrotor UAV. Then, the structure of the UAV flight control system is analyzed. Then the relevant research on quadrotor control methods in the past two decades is introduced, the classification and comparison are carried out, and the application of quadrotor control methods is discussed in detail. Finally, future trends in quadrotor UAV control methods are presented.

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