Proceeding of the IEEE
International Conference on Information and Automation
Wuyi Mountain, China, August 2018

A Review of Control Algorithms for Quadrotor

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***Abstract*— The unmanned aerial vehicle (UAV) is subject to various disturbances during the flight, such as the noise and drift of the sensor, strong wind and turbulence, and model variation caused by the excessive inclination. These would seriously affect the flight quality of the aircraft, so UAV control technology is particularly important. The quadrotor UAV is an important platform for control technology research, which has become the ideal choice for the synthesis and analysis of the control algorithm due to its nonlinearity and under-actuated properity. This paper briefly reviews the dynamic modeling of the quad-rotor, and compares the linear control algorithm, nonlinear control algorithm and intelligent control algorithm. Then the challenges and development trends of the quadrotor UAV control algorithm are summarized.**

***Index Terms*— Quadrotor, Linear controller, Nonlinear controller, Intelligent controller**

I. Introduction

Aircarft technology has developed for more than a century since the Wrighter brothers completed their experiments of plants with motors in 1903. Many aircraft with traditional and novel structures have been developed to meet different tasks. Among them, the most innovative and widely used UAV is the quadrotor. Compared with the traditional fixed-wing UAV, it can adapt to a more complex flight environments and can travel in narrow space, turn back, vertical take-off and landing(VTOL), roll and ultra low flight and hovering, flexible motion. The latter cannot be engaged in environments where stationary or quasi-stationary flights are required [1]. Simultaneously, quadrotor has the characteristics of simple structure, strong mobility, small size, low cost and good concealment. They have recently been widely used worldwide, which include Emergency rescue, aerial surveying, pipeline inspection, military reconnaissance, 3D mapping, agriculture monitoring [2-6].

The flight control system is the core of the UAV. In order to complete the autonomous flight, the UAV requires the control system to have good control characteristics for the internal loop (attitude loop) and outer loop (horizontal position and height loop). In addition, the issues that must be taken into account in studying the flight control process of UAV are as follows: the motion equation is nonlinear; there is coupling between channels; there is a time delay, inertia; input uncertainty; model uncertainty and so on.

At present, the performance requirements of UAV flight control systems are becoming more complex. Classical control methods are difficult to handle and coordinate the multi-variable input-output characteristics of the system. With the development of modern control theory, many new control methods have appeared. This paper summarizes the application of several typical control methods in the field of flight control, and analyzes their advantages and disadvantages.

II. Quadrotor Modeling and Control Architecture

In this section, a brief description of the main mathematical equation and control architecture for the quadrotor is explained.

A. Dynamics Model of Quadrotor

In the Fig.1, ϕ, θ, ψ represent the euler angles about x_b, y_b, z_b body axis (roll, pitch and yaw angles), respectively. T_n represents the thrust force produced by each propeller, D_n represents for the forward resistance, for $n = (1, 2, 3, 4)$. Earth fixed frame is represented by O and body fixed frame by O_b. Increasing or decreasing speed of the four motors together generates vertical motion. When the motor pair (1,3) are allowed to operate independently then the pitch angle θ (rotation about the $y-$axis) can be controlled along with the indirect control of motion along the $x-$axis. Similarly, when the motor pair (2,4) are allowed to operate independently then the roll angle ϕ (rotation about the $x-$axis) can be controlled along with the indirect control of motion along the $y-$axis. Finally, when the motor pair (1,3) is rotating clockwise and the motor pair (2,4) is rotating conuter-clockwise, the yaw angle ψ (rotation about the $z-$axis) can be controlled.

Some assumptions are made here [7]:

- The quadrotor construction is rigid and symmetrical;
- The propellers are rigid;
- Thrust and drag are proportional to the square of the propellers speed.

According to these assumptions, it is possible to describe the dynamics of the rigid body and aerodynamic forces

*This work is supported under the Shenzhen Science and Technology Innovation Commission Project Grant Ref. JCYJ20160510154736343 and Ref. JCYJ20170818153635759, and Science and Technology Planning Project of Guangdong Province Ref. 2017B010117009, and Guangdong Provincial Engineering Technology Research Center of Intelligent Unmanned System and Autonomous Environmental Perception.

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caused via rotation of the rotors. Using the Newton-Euler formalism, the equations of motion of the quadrotor are given in [8]:

$$\ddot{\phi} = \dot{\theta}\dot{\psi}\left(\frac{I_y - I_z}{I_x}\right) - \frac{J_r}{I_x}\dot{\theta}\Omega + \frac{l}{I_x}U_2 \tag{1}$$

$$\ddot{\theta} = \dot{\phi}\dot{\psi}\left(\frac{I_z - I_x}{I_y}\right) - \frac{J_r}{I_y}\dot{\phi}\Omega + \frac{l}{I_y}U_3 \tag{2}$$

$$\ddot{\psi} = \dot{\phi}\dot{\theta}\left(\frac{I_x - I_y}{I_z}\right) + \frac{l}{I_z}U_4 \tag{3}$$

$$\ddot{x} = (\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)U_1/m \tag{4}$$

$$\ddot{y} = (\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)U_1/m \tag{5}$$

$$\ddot{z} = -g + (\cos\phi\cos\theta)U_1/m \tag{6}$$

where I_x, I_y, I_z are the mass moments of inertia in the x, y, z axes respectively; J_r is the rotor inertia; Ω is the angular velocity of the rotor; l is the length of the rotor arm from the origin of the coordinate system; and the inputs to the four rotors are given by the expressions:

$$U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \tag{7}$$

$$U_2 = b(-\Omega_2^2 + \Omega_4^2) \tag{8}$$

$$U_3 = b(\Omega_1^2 - \Omega_3^2) \tag{9}$$

$$U_4 = d(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \tag{10}$$

where b and d are thrust and drag coefficients respectively.

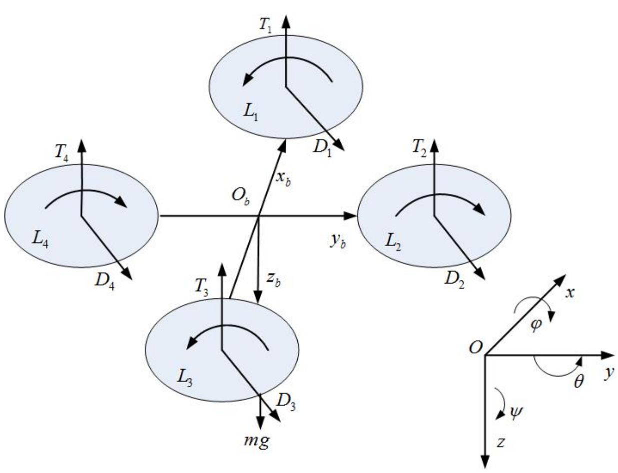

Fig. 1. The structure of quadrotor

B. Control Architecture

Fig. 2 illustrates the structure of a flight controller designed to design quadrotor aircraft in most studies. The control structure has two loops: the outer loop and the inner loop. This control structure can also be considered as a cascade or hierarchical control structure. The outer loop is used to provide the desired attitude angle, and the inner loop is used to track these angles to obtain the desired space Descartes position. The altitude is controlled using command U_1, while U_4 controls the yaw motion. The desired roll and pitch angles are generated to the attitude controller from the position subsystem, which are controlled by U_2 and U_3 respectively. Once the desired (x_b, y_b, z_b, ψ_b) are set, the position controller generates the required (θ_b, ϕ_b) to the attitude controller. The measured quantities are provided as a feedback to both controllers.

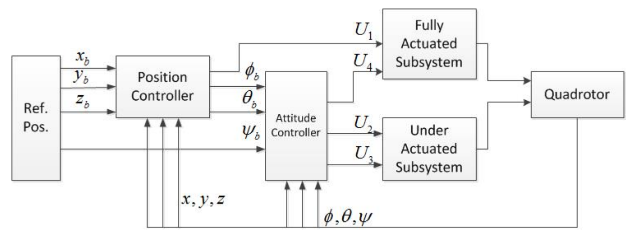

Fig. 2. General control architecture of quadrotor (cascaded control approach)

III. Control Algorithms

This subsection discusses linear control algorithm, non-linear control algorithm and intelligent control algorithm emphatically.

A. Linear Control

Conventional flight control methods and early attempts to control aircraft are based on linear flight control theory, such as Proportional Integral Derivative(PID), Linear Quadratic Regulator(LQR) and H∞ controller.

1) PID: The PID controller has been widely used in industrial control practice, and it is indeed the most widely used controller in the industry [9]. The main advantage of the classic PID is to determine the control strategy of eliminating the error by the error between the target and the actual behavior, rather than on the input-output relation of the object, that is to eliminate the control error by using the current, past and future states of the feedback error.

PID control law is

$$u = k_0 e + k_1 \int_0^t e(\tau)d\tau + k_2\dot{e} \tag{11}$$

where $k_1 \int_0^t e(\tau)d\tau$ is the integral of error, e is the error and $\dot{e}$ is the error rate of change, and k_0, k_1, k_2 are respectively proportional gain, integral gain and derivative gain coefficient.

The PID control method is simple and has good robustness. It does not depend on mathematical model. However, the PID controller has long adjustment time and large overshoot, the dynamic performance is not ideal and has a large steady-state error, which is suitable for applications where flight accuracy is not high. Gonzalez-Vazquez et al.,[10] based on the classical PID control method, adopt nonlinear PID controller to realize attitude control and position control of quadrotor. Tayebi et al.,[11] proposed a PD^2 controller to control the direction of the quadrotor and compensate the error of the gyroscope and the influence of the Coriolis moment. At the same time, the global asymptotic stability of the method is proved.

2) LQR: The object of the LQR is a linear system that can be represented by a state space expression, and the objective function is the integral of the quadratic function of the state variable or the control variable.

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{12}$$

$$y(t) = Cx(t) \tag{13}$$

$$J = \frac{1}{2}\int_0^{\infty} (x^T Qx + u^T Ru)dt \tag{14}$$

where, A is the state matrix, B is the input matrix, and C is the output matrix. Q and R are weight function matrices, their choice determines this control performance.

LQR provides powerful performance and has been successfully applied to quadrotor control. In [12], the controller is designed by using the longitudinal linearization model of UAV, and an optimal control mode which combines the integrator with the LQR is proposed. In [13], the controller is designed for the longitudinal linearization model of the F-16 UAV. The hierarchical structure method of the controller design is proposed, and the LQR control is adopted for the inner loop control, which can obtain better results.

3) H∞: In view of the uncertainty system, robust control not only considers the standard control model, but also takes into account the worst effects of uncertainty on the system, which makes the controller have the ability to suppress the uncertainty and meet the basic control performance requirements. Robust control deals with control problems with uncertainties and has developed effective control methods. H∞ controller is widely used robust controller in practice. It can solve the modeling error caused by interference and other factors, but its computation is very large and depends on high-performance processors. At the same time, it is difficult to adjust the parameter because of the frequency domain design method.

H∞ controller is actually an optimal control method to study the H∞ norm optimization problem of transfer function from external disturbances to system performance indicators. The control system based on H∞ control theory can be summed up as a feedback controller, which makes the closed loop system stable and the H∞ norm of the closed loop transfer function array is minimum or less than a given value [14]. In [15], a robust H∞ control and control assignment is used to design a flight control system for an aircraft with interference. The simulation verifies that the controller effectively suppresses the influence of interference. In [16], the fault reconstruction attitude control system of satellite is designed by H∞ robust control technology. The simulation results shows the effectiveness of the proposed method.

B. Nonlinear Control

In order to overcome the limitations of linear control methods, nonlinear control methods have been proposed and applied to the control of aircraft. These nonlinear control methods are usually classified as model-based nonlinear control methods, including Integral Sliding Mode Control (ISMC), Backstepping Control, Adaptive control and Active Disturbance Rejection Control (ADRC).

1) ISMC: The variable structure controller is designed to force the system state from any point in the state space to the sliding surface. Once the system state begins to perform sliding mode motion, the system is completely robust to unmodeled dynamics and external disturbances. Therefore, the design of ISMC is divided into two parts. One is to design a suitable sliding surface, so that the system state of the controlled object has the desired dynamic performance when moving on the sliding surface, and the second is to design the variable structure control law, forcing the state of the system to move closer to the sliding surface. This method is robust to the uncertainties of the model and external disturbances, simple algorithm and the response speed is fast. However, sliding mode variable structure control is essentially discontinuous, and the problem of high frequency chattering is associated with the sliding mode, which can easily inspire the system's modeling characteristics and thus affect the control performance of the system.

The application of ISMC has been extensively studied in [17-20]. Sira-Ramirez et al.,[17] first applied this method to the attitude controller design of a small helicopter. On this basis, Zhang et al.,[18] designed a quadrotor UAV attitude controller which can effectively overcome the time-varying disturbance. It is composed of two parts: the compensation part and the sliding mode control, the compensation part is used to compensate the disturbance estimated by the extended state observer, and the residual disturbance is weakened by the sliding mode controller.

2) Backstepping Control: The main idea of the backstepping method is to decompose the design of the whole control system into several parts, then design the Lyapunov function and the intermediate virtual control quantity for each part, push them back to the entire system and integrate them to complete the design of the whole control law [21]. This method has good tracking performance and fast adjustment time, and has a great flexibility in dealing with the underactuation problem with strict negative feedback form.

In [22], the backstepping attitude control system of spacecraft is designed by backstepping control. The feasibility of the method is verified by simulation. In [23], the automatic flight control system of Boeing 747 aircraft is designed by the inverse dynamic inverse method. The simulation results verify that the aircraft can fly safely within the flight envelope. Madani et al., [24] decomposed the whole system of a quadrotor into three interrelated subsystems, the underactuated subsystem, the fully driven subsystem, and the propeller subsystem. The backstepping method is used to realize the stability control of the whole system and is verified by simulation.

3) Adaptive Control: According to the change of state, performance and parameter index, the adaptive control law can be used to restrain the influence of uncertainty on the control system and enable the system to track the expected control instruction. It is mainly composed of two closed loops: one is the feedback control closed loop containing the controlled object, and the other is the parameter adjustment closed loop containing the controller. Self-tuning controller and model reference adaptive controller are two kinds of adaptive control methods. Adaptive control combined with other control methods, such as adaptive sliding mode variable structure control, can synthesize the excellent performance of various control methods and make its application more extensive.

Fig. 3 shows an adaptive controller for the quadrotor, including the parameter estimator and quadrotor model.

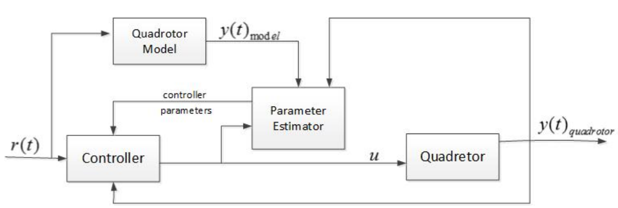

Fig. 3. The structure of adaptive controller

Dydek et al.,[25] designed an adaptive controller based on the baseline trajectory tracking controller. The algorithm has strong robustness to the uncertainty of model parameters, and can effectively alleviate the effect of the lift abnormal loss caused by the failure of the component, and verify it by simulation and in room flight test. In [26], an adaptive flight control system is designed for multi-input and multi-output of large range environment and wind field interference. The simulation results show that adaptive control suppresses the influence of composite interference. Accurate tracking of the target instructions.

4) ADRC: ADRC is a control method that does not depend on the accurate mathematical model of the unknown object. The core idea of ADRC is to select the input and output of the control system as a simple integral series standard, the unmodeled dynamics and external disturbances, which are different from the standard type, are regarded as the total perturbation of the system. The extended state observer is used to estimate the total disturbance, and the estimated value is compensated for the control system. In this way, the influence of uncertain factors on the control system can be eliminated in real time, and the nonlinear control object is transformed into an integral series system [27]. The ADRC is mainly composed of three parts: tracking differentiator (TD), extended state observer (ESO) and nonlinear state error feedback (NLSEF).

The structure of ADRC controller is shown in Fig.4.

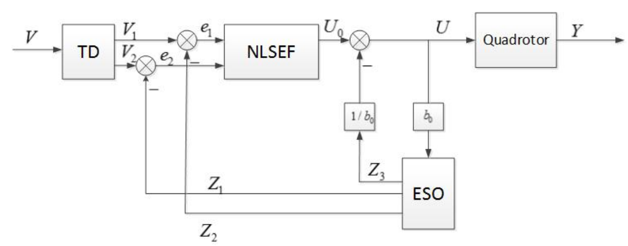

Fig. 4. The structure of ADRC

In [28], the control of pitch angle of UAV is studied by using NLADRC, and the overshoot control under random disturbance is realized. In [29], the LADRC is applied to the attitude control of UAV, which reduces the difficulty of parameter adjustment.

C. Intelligent Control

The traditional controllers can not receive satisfactory results in dealing with nonlinear multivariable control systems, ensuring the system's ability to resist external disturbances, especially the robustness of system parameter perturbation, which restricts the improvement of the dynamic performance and the steady state performance of the flight control. In recent years, intelligent control has been greatly developed both in theory and in application technology. Neural networks (NN), genetic algorithms, fuzzy logic, and particle swarm optimization (PSO) methods can be used to solve several complex engineering problems. However, they usually involve considerable uncertainty and mathematical complexity, and the structure of the controller becomes more complex.

Fuzzy logic and neural network are the two most widely used intelligent controls. Fuzzy control does not need to know the exact mathematical model of the system. It is based on the experience of the operator and determines the parameters and control rules according to the language expression of the operator's experience, and then in the actual system debug and setting. In [30], combining the traditional control method with the fuzzy control method, designed the autopilot under highly maintained mode. In [31], a self-guided controller for drone based on fuzzy logic is designed. In [32], the closed-loop strapdown attitude system of unmanned aerial vehicles based on fuzzy logic is studied. The neural network controller adjusts itself online by learning from the output of the traditional controller. The goal is to make the feedback error close to zero, so that it gradually dominates the control role, so as to cancel the function of the feedback controller. In [33], the neural network is applied to the aerodynamic parameter identification, nonlinear flight control and flight fault diagnosis of the aircraft. In [34], the CMAC neural network is applied to a small unmanned aerial parallel hybrid propulsion control system. In [35], a deep RNN(Recurrent Neural Networks) is used to model the dynamic of the altitude of a real quadrotor. It is also shown that the model significantly outperforms the first principle model in MS(Multi-Step) prediction scenarios. In [36], a hybrid of neuro-fuzzy and a parameteric structured model is used to model a quadrotor for SS(Single-Step) prediction.

Fig.5 shows the structure of a fuzzy logic controller.

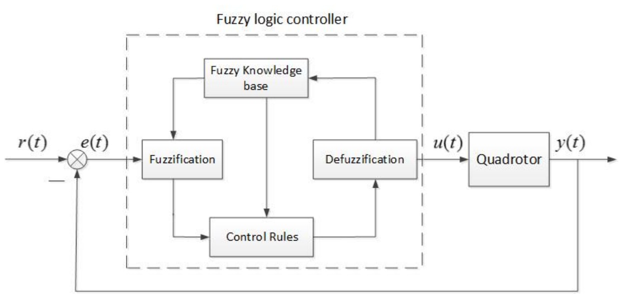

Fig. 5. The structure of fuzzy logic controller

D. The Problems for Designing A Quadrotor Controllor

The quadrotor is a typical underactuated system, which has the advantage of eliminating some drives, effectively saving the cost and reducing the weight of the system itself. Due to the complexity of the internal dynamics of these systems, and nonholonomic constraints, this kind of system brings convenience to the design and manufacture of the quadrotor, and it also brings great difficulties to its control. At present, There are four issues, as follows:

- There is no direct way to provide robust stability and performance, and respond quickly to external disturbances, noise, wind and changes in actual parameters.
- The underactuated system is an intrinsically nonlinear system with nonholonomic constraints and can not be completely feedback linearlly.
- The control algorithm involves more parameters, and it is difficult to select and to optimize the parameters.
- Accurate UAV dynamic model requires complicated aerodynamics and flight experiments. Meanwhile, ignoring the interference may create large model errors between the dynamic model and the actual aircraft, which will adversely affect the flight test.

IV. Comparison of Control Algorithms

The quadrotor control algorithms are summarized in Table I, which listes the advantages and disadvantages of different control methods.

TABLE I
Summary of Quadrotor control Algorithms

Control Algorithm	Advantages	Disadvantages
PID	Simple method, independent of the mathematical model.	Long adjustment time, poor dynamic performance.
LQR	Simple method, more efficient.	Requires precise model, weighted matrix selection.
H∞	Strong robustness, eliminating modeling error.	Calculation explosion, parameter adjustment is difficult.
ISMC	Controller structure is simple and easily to tune, strong robustness, insensitive to external disturbances.	Chattering effect, requires precise model, no finite time convergence.
Backstepping Control	Ability to handle uncertainties to a certain level, Lyapunov-based stability and design procedure.	Produces larger magnitude of control signal, requires precise model.
Adaptive Control	Adaption and estimation of varying system parameters, strong adaptive ability and robustness.	Requires complex adaption laws.
ADRC	Independent of the mathematical model, simple method, strong robustness.	Parameter adjustment is difficult.
Intelligent Control	Resist unknown disturbances and provide adaptive parameters for uncertain models, controller can be trained.	Requires larger computational effort due to stochastic learning policies, offline learning may fail under unknown gusty environment.

V. Conclusion and Future Trends

Based on the control technology, this paper outlines several common control algorithms that have been developed for quadrotor, and analyzes the advantages and disadvantages of various algorithms. No single algorithm presents better performance, so the method of composite control is the future development trend. However, for flight control systems, the complexity of the combined control algorithm makes the control system robust and fault-tolerant not well guaranteed. Therefore, the difficulty of future flight control applications is how to make a reasonable compromise between aircraft dynamic performance, steady state performance and controller complexity.

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