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Study on Flight Attitude Control of Four-rotor UAV

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Abstract: Four-rotor UAV is a type of small aircraft. Because of its flexibility, stability, good maneuverability and other characteristics, it can be widely used in various fields. Attitude control of four-rotor UAV is a core technology in the field of UAVs, which is worth studying. In this paper, previous research progress in the field of attitude control of four-rotor UAV is reviewed. The main control methods can be divided into linear control, nonlinear control and intelligent control. In this paper, PID control, sliding mode control, backward step control, intelligent control, neural network control and fuzzy control are introduced in detail, and the characteristics, advantages, disadvantages and research status of these different attitude control technologies are summarized and analyzed. Relevant references show that the focus of researches in resent five years is to combine a variety of control technologies, improve the traditional control technology to obtain better control effects, and use MATLAB/Simulink simulation to draw conclusions. Then, the research on attitude stability control technology of four-rotor UAV in response to adverse weather environment is analyzed, and some future research directions are proposed, including but not limited to establishing a reasonable environmental disturbance model, improving UAV dynamics model in wind field environment, developing fault-tolerant control technology and reducing the delay of system response.

1. Introduction

An unmanned aerial vehicle (UAV) is operated by a wireless control unit and a self-provided program control unit. Researches related to UAV attitude control in the twenty years have become a hot topic. Compared with manned aircraft, UAVs do not need pilots to perform dangerous tasks. Besides, UAV can do better in the design of the structure and the shape of the aircraft, which allows UAV to work normally under the extreme condition. The UAV is small, light, flexible and relatively low in cost, so it can be widely used in various fields. To be specific, for military use, it can be used in reconnaissance aircraft, target strike etc. For civil use, it can also be used in environment monitor, agricultural plant insurance, disaster relief, power inspection, delivery, photography, etc. Four-rotor UAV is the most widely used in this type of aircraft, with six degrees of freedom, four propellers and the main cross-shaped structure, belonging to multi-rotor aircraft. It can hover, fly forward, fly sideways and fly backward [1]. Therefore, the four-rotor UAV has broad application prospects and is worthy of further study.

Four-rotor UAVs generally operate at lower altitudes and are prone to be influenced by complex weather and environmental impacts such as strong winds, rain, dust, and so on. Furthermore, the rotor UAVs themselves are small in size and light in weight, resulting in poor resistance to external environmental interference. In the process of flight, the UAV may easily lose balance, deviate from the target path and fail to complete the task. UAV may even roll over and crash in some unfavorable cases, leading to negative consequences such as property loss. In order to make the four-rotor UAV more efficient in all fields, it is very important to improve its stability in a complex environment. Quiet a few scholars choose to build simulation models, including wind field model and UAV dynamics model and engaged in the research on control system and technology optimization in the UAV field. The common attitude control methods are mainly linear and nonlinear two kinds. Nowadays, PID control is the most widely used linear control technology. The main nonlinear control method includes sliding mode control and backstepping control. Besides, a type called intelligent control is also being studied, mainly including fuzzy control and neural network. Nevertheless, due to the limited resources of experiments in the actual wind tunnel laboratory or environment, although many articles have proposed various solutions, few have been verified in actual flight tests and natural environment. There are still some problems need to be investigated and solved. In the end, this paper puts forward some research prospects for the quad-rotor UAV in dealing with strong disturbance weather environment.

By referring to the relevant literature in the past five years, this paper firstly summarizes five control technologies commonly used in the attitude control research of four-rotor UAV. They are PID control, sliding mode control, backward step control, neural network and fuzzy logic. Then the article analyses the advantages and disadvantages of each control technology, and expounds the practical and research applications of these control technologies in UAV control. Secondly, the research status is summarized, concluding that the research trend in recent years tends to combine the development of a variety of control technologies. Thirdly, some improvement schemes and research directions are proposed for the control system of four-rotor UAV in strong weather disturbance environment, including establishing a more accurate and practical environmental disturbance model, developing fault-tolerant control, applying machine learning to the attitude control system of UAV, and improving the response accuracy and response speed of the control system. Finally, the limitations and advantages of this paper will be analyzed.

2. Comparison of Attitude Control Techniques

2.1. Linear Control

PID control is a widely used control algorithm with a history of more than 80 years. This method only needs three parameters, which is simple in structure, convenient in design and easy to master.

The three parameters of PID control are as follows:

1) Proportional control (P): The system output is adjusted by calculating the proportion proportional to the input error according to the existing error, and the steady-state error exists in the system output only when the proportional control is performed.

2) Integral control (I): Errors are accumulated to eliminate steady-state errors of the system. Then the integral term of the accumulation of errors can generate control quantities.

3) Derivative control (D): The rate of error change can be measured to help predict the future change trend of the system. The derivative term can reduce overshoot and adjust the control amount.

However, PID control is a linear controller, but most cases in real life are nonlinear model and can only be approximated by linear model, which cannot achieve high accuracy. In order to alleviate this shortcoming, cascade PID controller is mostly used in UAV control, compared with single-stage PID control, its response speed is faster, anti-interference ability is stronger, and it can better approximate nonlinear systems. The structure diagram example of cascade PID is shown in Figure 1, which is characterized by the fact that the outer loop output can be used as the inner loop input. There are many researches on PID control optimization in recent years. Specifically, some scholars apply fuzzy control to PID control and use MATLAB/Simulink to simulated. The conclusion showed that fuzzy PID control can effectively shorten the adjustment time of yaw Angle and reduce the adjustment amplitude better than traditional PID control, which proves its rationality in improving the flight stability of UAV [2]. Some adopted the double closed-loop adaptive PID algorithm as the flight attitude control scheme and carried out simulation, which obtained a relatively ideal attitude control effect [3].

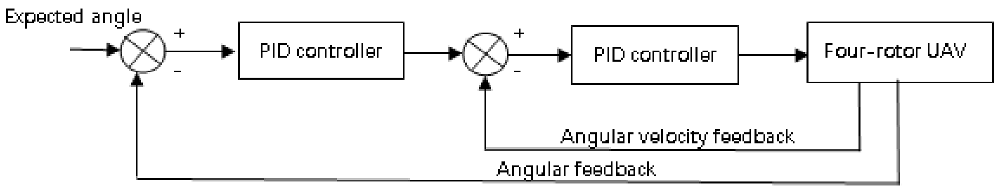

Figure 1: Cascade PID structure diagram of four-rotor UAV (Picture credit: Original)

2.2. Nonlinear Control

Sliding mode control algorithm and backstepping control algorithm are the two most commonly used control algorithms for nonlinear control strategies.

2.2.1. Sliding Mode Control

The sliding mode control has the advantages of fast response, strong robustness, insensitivity to parameter change and disturbance, simple physical implementation, etc. It can be widely used in the control of practical systems [4-5].

The principle of design can be briefly described as follows:

1) The first step is to set a sliding surface or slider variable that describes the difference between the system state and the desired state.

2) An appropriate approach rate is introduced to force the system state to approach the desired state by making the system state slide quickly on the sliding surface.

One of the main problems in sliding mode control is buffeting, which may adversely affect the stability and performance of the system, including the increase of control energy consumption, the damage of the system hardware, etc. The common methods to suppress buffeting include saturation function method, sigmoid function method, progressive sliding mode method, etc. Another problem is that there are certain requirements for the design of the sliding mode surface to ensure that the system can always be on the sliding mode surface. Based on the traditional sliding mode control algorithm, many scholars have improved the algorithm and applied it to the attitude control of four-rotor UAV. For example, when multiple actuators of a quad-rotor UAV fail, its attitude control cannot quickly restore to a stable state. To solve this problem, some scholars proposed a fault-tolerant control of a quad-rotor UAV based on the sliding mode theory, which utilizes the observed values provided by the observer to compensate for the influence caused by external interference. Simulation experiments have proved that this method can effectively reduce steady-state errors and chattering phenomena [6]. In addition, an adaptive sliding mode controller has been designed to extend the integral sliding mode surface to the fractional order sliding mode surface. Simulation results show that the controller can effectively control the UAV to complete the flight task [7].

2.2.2. Backstepping Control

Backstepping method is a self-adaptation controller design method for nonlinear systems based on Lyapunov stability theory. The idea is to divide the system into several subsystems, and then derive the actual control law based on the designed virtual control law. Its advantage is that the controller can be designed simultaneously and the adaptive law can be updated at any time, but the design process is relatively complicated. Relevant studies have pointed out that the RBF neural network can be combined with the adaptive backstepping sliding mode attitude controller of the four-rotor UAV and the parameters of the controller can be optimized by particle swarm optimization algorithm to further improve the accuracy and stability of the controller. Finally, the MATLAB/Simulink simulation analysis shows that the controller has superior performance and meet control requirements [8]. But due to the large amount of computation, this method may increase the processing burden for the control system with real-time data.

2.3. Intelligent Control

2.3.1. Neural Network

Neural network control is actually a nonlinear system with strong information synthesis ability, but the research and development process are complicated. The structure diagram of the neural network control structure is shown in Figure 2.

The process of neural network control can be divided into the following steps:

1) System modeling: This process includes creating the model of control object and determining the input and output variables.

2) Network design: The procedure involves designing a suitable neural network structure according to the results of system model, and determining the number of nodes and activation functions of the input layer, the hidden layer and the output layer of the network.

3) Data collection: Training data is collected, including input and output sample data.

4) Network training: The neural network is trained so that it approximates the dynamic characteristics of the control object and achieves the expected control effect.

5) Control implementation: This process applies the trained neural network to the actual control system, receives the input signal of the system in real time, calculates and generates the control instructions.

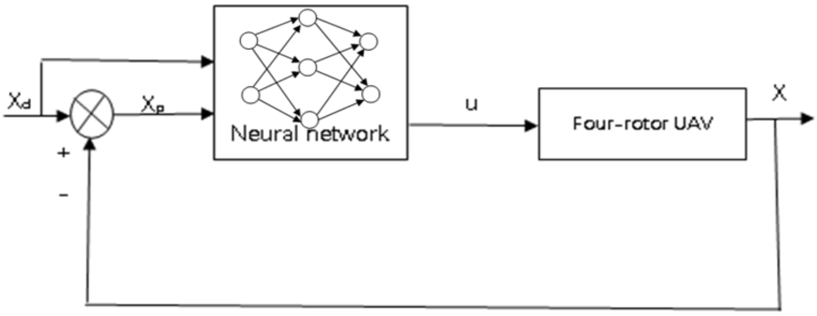

Figure 2: Neural network control structure diagram of four-rotor UAV [9]

Neural network has the characteristics of nonlinear modeling and approximation ability, and can effectively deal with complex attitude control problems. Therefore, neural network control has great application potential in UAV attitude control. However, due to the complexity of the neural network model and training process, there are still some challenges, such as large data demand and long training time, high requirements for the hardware equipment carried by the UAV, which may increase the load and high cost [8]. Future research will continue to explore and improve the application of neural networks in the field of UAV attitude control, and combine with other traditional control methods to further improve performance and stability.

2.3.2. Fuzzy Logic

Fuzzy logic control has good robustness, stability and adaptability. Its principle is that the control scheme can be expressed in language understood by humans, and fuzzy rules can be formulated according to expert rules.

The process of fuzzy logic control can be divided into the following steps:

1) Fuzzification: The input variable is transformed into a fuzzy set and the specific input value is mapped to the fuzzy set through the fuzzification function.

2) Rule base: A series of fuzzy rules are established to describe the relationship between different input fuzzy sets. The rule base contains control strategies and empirical knowledge.

3) Inference engine: The current fuzzy set is deduced according to fuzzy rules, which can determine the output fuzzy set.

4) Defuzzification: Through the defuzzification function, the output fuzzy set is transformed into a specific output value.

Fuzzy control has a certain theoretical basis and can be widely used, but the formulation of fuzzy rules is complicated and difficult to adjust. Too simple information fuzzy processing may lead to the reduction of control accuracy. The main trend in recent years is to combine fuzzy control with other control technologies. So far, a kind of attitude control research is the combination of fuzzy control and PID control. The structure diagram is shown in Figure 3. E indicates the difference between the target angle and the current angle, and E_C indicates the change rate of the difference. The controller first fuzzy the input E and E_C, through the set fuzzy rules for reasoning, and finally clear the result into K_p, K_I, K_D three parameters.

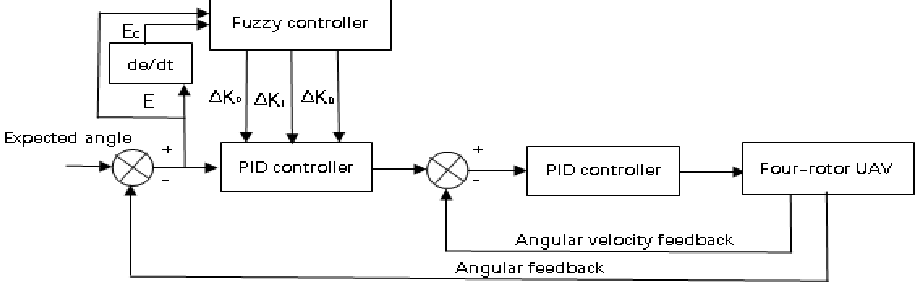

Figure 3: Fuzzy cascade PID control structure diagram of four-rotor UAV [10]

3. Discussion

3.1. Analysis of Current Situation

Attitude control of UAV is one of the core problems in UAV flight, and there have been some mature research results and application practices. The principle of PID control is simple and easy to implement. Therefore, the control algorithm based on PID control has been widely used in the current practical problems. The current research is mainly inclined to nonlinear control and intelligent control, the pursuit of higher anti-interference, nonlinear approximation ability and the ability to deal with attitude control system problems in complex environment. For example, studies on intelligent fuzzy PID control, adaptive PID control, fuzzy PID control and fuzzy sliding mode variable structure controller combine different control techniques to deal with complex nonlinear control problems. Most of the relevant researches use MATLAB/Simulink to conduct simulation experiments, and get some reasonable and good results. According to existing research, the combination of multiple control techniques can bring some benefits. Because the input and output of the four-rotor UAV is strongly coupled and underdriven, it is very sensitive to changes in external parameters and has complex characteristics such as nonlinear, so a single control system cannot meet its high-precision control requirements [11]. Different control technologies usually have different advantages and scope of application. Through the reasonable combination, it can make up for the shortcomings of each control technology and improve the robustness and accuracy of the entire control system.

3.2. Future Outlook

Most conventional flight simulation processes are based on the assumption of a calm atmosphere, meaning there is no wind to interfere. However, in actual flight, wind disturbance poses a great threat to flight safety, so it is necessary to add wind disturbance model in the simulation process. In reality, there are four main types of wind disturbances: average wind, wind shear, turbulence, and gusts [12]. In simulation experiments, the influence of wind disturbance is sometimes ignored, and some studies have mentioned simple wind disturbance models. The representative models of turbulent wind field are Dryden model and Von Karman model [13]. However, the actual weather environment may be more complex, and there is inevitably a gap between a single turbulent wind field model and the actual situation, which may lead to errors between the simulation results and the actual results. Professional scholars can conduct research in this direction, establish a more complete wind field disturbance model that is closer to the actual situation and a more realistic UAV dynamics model under the wind field environment, then conduct controller simulation experiments. In addition, the outdoor operation process will encounter not only complex wind field interference, but also rain, snow, dust and other complex weather, such disturbance model will be more complex than the simple wind disturbance, can be used as a research direction.

In the future, scholars continue to study the fault-tolerant control of UAV, not only for the fault tolerant control of the actuator damage of the quadrotor UAV, but also consider how to deal with the case of controller failure. Deep learning and machine learning technology have achieved remarkable results in many fields. If these technologies can be applied to the UAV attitude control field, the performance and adaptability of the control system can be further improved. Researchers can explore attitude control algorithms based on deep learning and machine learning, so that UAVs can learn from large amounts of data and adapt to different flight environments and mission requirements, with the ability to handle emergency situations.

In order to better cope with the real-time weather changes, sensors, controllers and actuators should be streamlined as far as possible. Too cumbersome control procedures may cause negative impacts on control response. Not only the response accuracy should be ensured, but the response speed of the entire control system also should be improved, reducing delays and costs of UAV. If possible, wind tunnel experiments or real environment experiments can be carried out to get more reliable conclusions. If the attitude control of the four-rotor UAV can make a breakthrough in resisting these complex weather environments, it can not only improve the work efficiency of the UAV and reduce the cost, but also apply the UAV to a wider range of fields, such as replacing people to perform some dangerous tasks in bad weather conditions, rescue missions in disasters, terrain exploration and so on.

3.3. Analysis of Limitation and Strength

There are some limitations to the attitude control of quad-rotor UAV summarized in this paper. First of all, there is a bias in the selection of literature. Due to time and resource constraints, all the research literature samples in this paper are from China, so it is impossible to cover all relevant literature. Moreover, in the analysis of control methods, this paper only selected some representative control methods of quadrotor UAV, which may cause that some key and unpopular studies cannot be fully presented. Secondly, in the selection of literature, most of them are journal papers and dissertations, and the quality and reliability of each literature cannot be evaluated adequately.

This review paper has advantages in several aspects. First, this paper presents the advantages, disadvantages and application status of the five control technologies, which will help relevant scholars to understand and choose different control methods for further researches. Second, the literature selected in this paper is from about last five years, which helps scholars to understand the latest research development direction. Thirdly, this paper summarizes the current research situation in recent years, and puts forward some reasonable solutions and research directions for the attitude control of quad-rotor UAV against weather interference.

4. Conclusion

The four-rotor UAV can be widely used in various fields of military and civil, among which attitude control is one of the key technologies to realize its stable and accurate flight, which has great research value. Through appropriate attitude measurement, attitude controller design, combined with different types of control systems, the UAV attitude can be accurately controlled, meeting the needs of different application fields. So far, the most mature and widely used attitude control technology is PID control, while many nonlinear control and intelligent control technologies are still in the simulation research stage. So far, many scholars have combined a variety of control technologies to make up for the shortcomings of a single control technology, and many of them have obtained good results in simulation experiments. However, due to the dynamic characteristics of the four-rotor UAV itself and the uncertainty of the environment, the attitude control still faces some challenges, such as how to improve the stability of the attitude control system in harsh environments, which needs further research and improvement. The future four-rotor UAV control technology will develop towards automation, intelligence and resistance to strong interference.

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