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The development status and analysis of motion control algorithms applied to UAVs

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Abstract. Due to the high mobility and longer durability, UAVs are widely used in military and various civilian fields. The control system of the UAVs is a key part of ensuring that the UAVs fulfil various instructions and complete the tasks. In response to the above issues, this paper summarizes and analyses the current status of motion control algorithms for unmanned aerial vehicles based on existing data. Firstly, the mainstream control technology of UAVs is divided into linear control technology, nonlinear control technology and machine learning-based control technology, and they are discussed separately. Subsequently, the performance of three technologies is evaluated and compared, and the advantages, disadvantages and the applicable environment of each controller are introduced. Finally, the future development direction of UAVs controller is analysed and prospected.

Keywords: UAVs technology, control algorithms analysis, motion control.

1. Introduction

Unmanned aerial vehicles (UAVs) is a type of aircraft without the requirement of on-board pilot. Due to the high mobility, longer durability, lower cost, ingenious design and smaller mass, it is widely used in military and various civilian fields. UAVs are mainly divided into four categories which are fixed-wing, single-rotor, multi-rotor and mixed-wing UAVs. They are suitable for different scenarios [1].

At present, UAVs has been applied in agriculture, forestry, traffic management and other fields. In agriculture, UAVs can quickly and accurately record the growth of plants in the field or identify potential problems in the field, so that decisions can be made quickly, which saves a lot of money and time. In forestry, UAVs can accurately perform tasks such as fire monitoring, vegetation monitoring, and species identification, greatly improving the efficiency of completing tasks. In terms of traffic monitoring, UAVs can more comprehensively monitor the driving speed, driving time and driving trajectory of the vehicle to achieve the stronger control of traffic [2].

The UAV control system is a key part of the fulfillment of various instructions. For the flight of UAVs, advanced control algorithms can make the UAV flight more stable and respond to commands faster. In addition, advanced control algorithms can also achieve high accuracy in hovering and slow control of UAVs. Beyond that, the use of appropriate control algorithms can strengthen the quality of control of the UAV in abnormal flight situations. For instance, in the event of a drone blade break, sudden impact, sudden loading, or interference by other external forces, control of the UAVs can be quickly restored, which is especially important for flight safety.

In response to the above issues, this paper summarizes and analyzes the current status of motion control algorithms for unmanned aerial vehicles based on existing data. Firstly, the mainstream control technology of UAVs is divided into linear control technology, nonlinear control technology and machine learning-based control technology, and they are discussed separately. Subsequently, the performance of three technologies is evaluated and compared, and the advantages, disadvantages and the applicable environment of each controller are introduced. Finally, the future development direction of UAVs controller is analyzed and prospected.

2. Classification

The main application controllers are mainly divided into three categories, which are linear and nonlinear controllers, and machine learning-based control systems, as shown in figure 1.

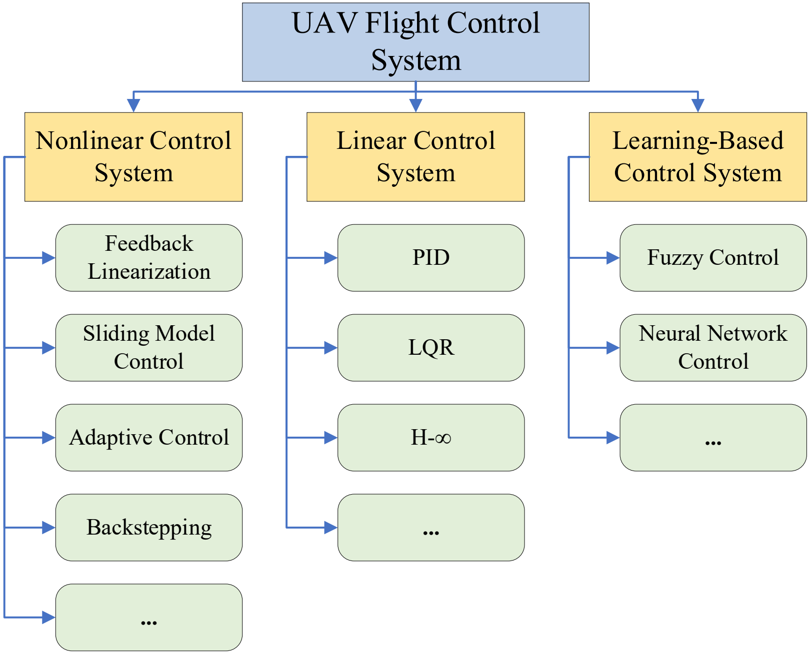

Figure 1. Classification of UAV control algorithms.

Linear control systems are usually controlled by linear differential equations, and their outputs and inputs are usually proportional. Nonlinear control systems include a wider range of systems that do not conform to the superposition principle, which are usually controlled by nonlinear differential equations. They are more applicable to real-world systems because all actual control systems are nonlinear. The design process of nonlinear controllers is more complex than linear controllers, and the mathematical techniques developed to deal with them are more difficult and less versatile. And the application scope is also narrower than linear controllers. However, its control performance is better.

At present, the machine learning control algorithm has gradually matured. After being applied in UAV, many problems of traditional control system have been solved. The machine learning control algorithm has more stable control of the system, smaller error and stronger adaptability to different conditions.

In recent years, the research on flight control algorithm of quadrotor UAV has gradually increased. The research of sliding mode control (SMC), backstepping control, adaptive control feedback linearization and other algorithms has gradually become a hot issue in the field of UAV.

3. Control algorithms

3.1. Linear controller

3.1.1. PID controller. PID controller is the most widely used algorithms in system control due to its simple characteristics. It is essentially a single-input and single-output system. It designed with the sequential closure technology. The outermost loop is the slowest. The position information required by the UAVs as input and the speed required as outputs. Then converts the speed into the angular velocity change of the UAV rolling, pitching and yaw through the closed-loop system to control the attitude of the UAV [1]. This method determines the deviation between the setpoint and the actual value using the equation below, and the gain values in the equation include the proportional gain coefficient (K_P), integral gain coefficient (K_I), and derivative gain coefficient (K_D). The PID controller controls the altitude, attitude angle, and flight speed by changing these three gain coefficients.

$$u(t) = K_P e(t) + K_{I \int_0^t e(t)dt} + K_D \frac{de(t)}{dt} \tag{1}$$

where $u(t)$ is the control factor, K_P is the proportional gain coefficient, K_I is the integral gain coefficient and K_D is the derivative gain coefficient. $e(t)$ is the offsets between the set value and the actual value [3].

PID controller is a simple and effective way to maintain the stability of quadcopter flight well. It also has the high robustness and adaptability to various movements of UAVs so that it is currently widely used in the UAVs market. However, the anti-interference ability of complex nonlinear systems is poor.

3.1.2. LQR controller. LQR, also known as the linear quadratic regulator, is an optimal control method based on closed-loop control with linear state feedback or output feedback. It is also a widely used controller at present. The basic principle of the LQR controller is to obtain the minimum value of the cost function.

$$J = \int_0^\infty (x^T Q x + u^T R u) dt \tag{2}$$

The two definite symmetric matrices of Q and R can be selected by corresponding requirements, but the magnitude of both will affect the result. After that, the positive definite symmetry constant matrix P is obtained by the Riccati equation. Finally, the state space model of the system can be obtained, as shown below [4].

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \tag{3}$$

Complex dynamics and multiple actuators can be well handled by LQR controllers. Compared to the PID controller, LQR controller are more complex, but its control performance is higher. And because it is necessary to know the status information of the entire system, the control over the entire system is also stronger.

3.2. Nonlinear controller

3.2.1. Feedback linearization. Feedback linearization is to convert the dynamics of a nonlinear system into a partially or completely linear system, thereby applying linear control technology to control the system. Dynamic model inversion, a branch of feedback linearization, has been applied to manned and unmanned aerial vehicles [3].

Since the controller needs to change variables and control inputs to convert the nonlinear model to a linear model, resulting in a loss of accuracy. Thus, feedback linearization requires a more accurate model to achieve [5]. In addition, although the feedback linearization has a good tracking effect, it is more sensitive to sensor noise. It has poor immunity and low robustness. Another disadvantage of the feedback linearization is that it has a narrow scope of application [6]. To improve performance, feedback linearization is often combined with other control algorithms.

3.2.2. Sliding model control. SMC is applied in many nonlinear control systems, which uses the discontinuities of the control signal to control the dynamic characteristics of nonlinear systems. The design of SMC can be divided into two parts. Firstly, a suitable sliding surface is designed based on motion constraints. And then, select the appropriate control rules to make the nonlinear system state move to the sliding surface. Once the sliding surface is reached, the system state moves strictly within the neighbourhood of the sliding surface [6].

SMC has the good tracking performance and fast response for signal. In addition, it also has good robustness when noise and interference are introduced because it has the low sensitivity to external interference. However, because the movement on the sliding surface is like the high-frequency switch control, it will cause chattering. This undesirable phenomenon causes the energy loss, so that the control effect is unstable. At present, SMC is also often used in combination with other control algorithms to eliminate the chattering [6].

There are also many teams that have studied chattering. Ahmad proposes an improved double-integral SMC, which has strong robustness for system uncertainty and eliminate chattering effectively [7]. In addition, for the corresponding speed and control effect, SMC is better than that of linear controllers. Kopecki proposed that the sliding model controller has better control of the UAV roll angle and a shorter response time than the classic PID controller for controller of small UAVs [8].

3.2.3. Adaptive control. Adaptive controller is currently mainly used in control systems for instability problems caused by parameter uncertainties. When the system parameters are unknown, as well as the actuator uncertainty and time delay, adaptive controller can be used with good application performance [3].

Adaptive control is often combined with other control algorithms to improve control performance. Eltayeb proposes and implements an adaptive feedback linearization (AFBL) algorithm to control the attitude and altitude system of quadcopter UAVs to eliminate the influence of wind interference and parameter uncertainty on UAV performance. Through simulation experiments, they verified the immunity of controller to wind interference and parameter uncertainty. Compared to the traditional feedback linearization controller, the results show that the attitude and height errors are reduced by 82% and 53%, respectively [9].

3.2.4. Backstepping. The principle of Backstepping is to decompose a complex nonlinear system into subsystems that do not exceed the order of the system. Then, reverse the entire system from the determined stable subsystem. Backstepping process continues until the emergence of the actual control term. Finally, the derivation results are integrated to complete the design of the entire control system [6]. Backstepping converge fast and has a good ability to handle the external interference but its robustness is poor. In addition, the design process of entire algorithm is more systematic and structured [3].

3.3. Machine learning-based controller

The machine learning-based control algorithm does not need to establish a detailed dynamic model but needs to train the system through multiple experiments and flight data. So that the control algorithm can control the drone according to the actual situation by themselves.

3.3.1. Fuzzy control algorithm. Fuzzy control algorithm is an intelligent control algorithm that imitates fuzzy reasoning people and decision-making process from the behaviour. The differences between fuzzy control algorithm and the traditional control algorithm is that the fuzzy controller replaces the analog controller. The fuzzy control process is divided into three steps: fuzzing, fuzzy reasoning and non-fuzzing processing [2]. Three steps are completed by the fuzzer of fuzzy controller, the fuzzy inference machine, and the defuzzer [10]. The performance of fuzzy systems mainly depends on factors such as the structure of fuzzy controllers, fuzzy rules, inference algorithms, and fuzzy decision-making methods.

Fuzzy control algorithm can simplify the complexity of system design and do not need to design accurate models and the strong anti-interference ability. But it is difficult to analyse the robustness and stability of the control algorithm [6].

3.3.2. Neural network control algorithm. The neural network control algorithm is similar to the way biological neurons process information. Neural network control algorithm has a strong learning ability. And it corrects its own parameters by constantly correcting the connection weights between neurons and storing them in the connection network [11].

This control algorithm has many advantages. Firstly, the neural network control algorithm can fully approximate arbitrarily complex nonlinear systems so that has good control effects. Secondly, it can learn and adapt to severely uncertain systems and adjust in time according to changes in conditions. Since there are many neuron-like nodes in the algorithm that are widely connected, even if a small number of nodes or connections are damaged, it has little impact on the overall work of the system. Thus, the neural network control algorithm shows the strong robustness and fault tolerance.

In addition, machine learning-based control algorithms can also optimize traditional controllers. Intelligent algorithms such as particle swarm optimization (PSO) neural networks, and fuzzy logic will be added in combination with traditional PID controllers to optimize its performance. The combined dynamic performance of the new PID controller improved apparently. The intelligent control algorithm can automatically control the tuning function of the PID controller, which has the characteristics of fast overshoot response, high robustness, and high tracking, which can reduce the system power consumption. And it also improves the dynamic characteristics and stability accuracy of the UAVs. It also helps to reduce the error between the true value and the expected value to achieve robust convergence.

Saban Ulus proposed a hybrid attitude controller of neural network and fuzzy logic for fixed-wing drones, and the simulation results are shown in the figure 2 below [2].

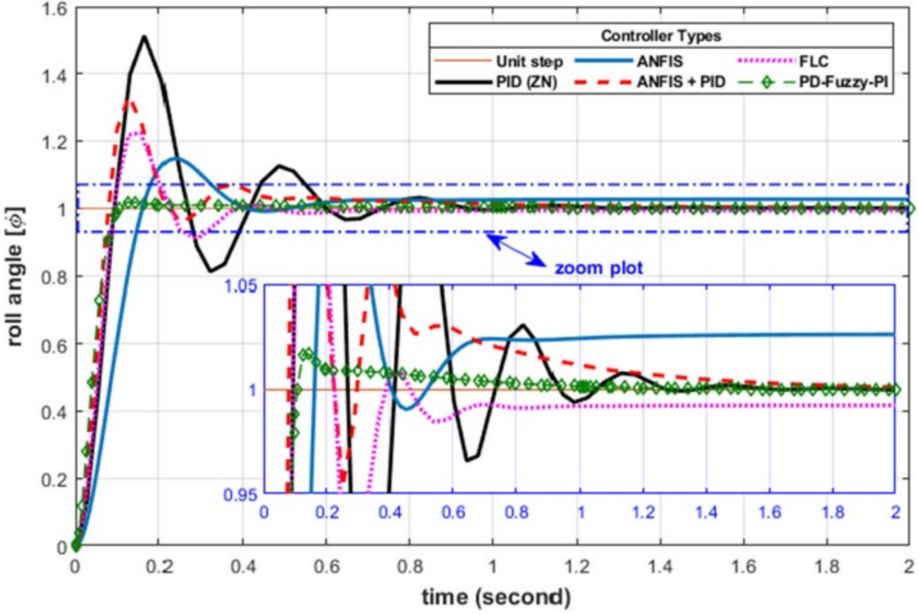

Figure 2. Simulation effect of control algorithm.

The result of the simulation experiment that compared with the traditional PID controller, the new PID controller improved by intelligent algorithm has faster response speed, smaller control error and stronger stability [2].

4. Discussion

This paper compares and analyses three types of control algorithms horizontally, and the results are shown in the Table 1.

Table 1. Comparison of different control algorithms.

Type	Controller	Advantages	Disadvantages
Linear	PID	Simplicity Effective	Low Intelligent Low Optimal
	LQR	Higher Stability	Not Intelligent
	H∞	High Tracking Performance High Robustness	Not Simple Not Intelligent
Nonlinear	Feedback Linearization	Flexible Design Good Tracking Performance	Requires precise model Vulnerable to external interference
	Backstepping	Fast Convergence Ability to handle uncertainties	Lack Robustness
	SMC	Insensitive to external disturbances High Robustness	Chattering Effect Energy Loss
	Adaptive Control	Good Robustness Strong Flexibility	Requires complex model
Machine learning-based	Fuzzy Control	No need of precise model Intelligent Easy to combine with other algorithms Adaptive	Requires experience of system Unable to define stability
	Neural Network Control	Learning ability Adapt to uncertain systems No need of exact model Good Robustness	Requires large computation

From this table, it can be concluded that although the linear controller method is simple, low cost, and not intelligent enough. It cannot be changed in real time according to the environment. Robustness is also somewhat lacking compared to nonlinear control algorithms. On the contrary, nonlinear controllers have better tracking performance, robustness, faster response times. Beyond that, better performance in some specific conditions.

The machine learning-based control algorithms on further improves the shortcomings of the linear and nonlinear control algorithm, thus improving the stability and robustness of the control system. Machine learning-based controllers do not require accurate models. The control results are more intelligently, adaptive, and are easier to combine with other intelligent control algorithms. However, the machine learning-based control algorithms need more and intensive computation. In addition, there are still certain limitations in scenarios with high real-time requirements.

In the study by Muluken, they compared the adjustment of the pitch attitude of the UAV by a linear PID controller and a model reference neural network controller over the same operating frequency range and observe the stability and responsiveness of the control systems of both. Partial results are shown in the figure 3 [12].

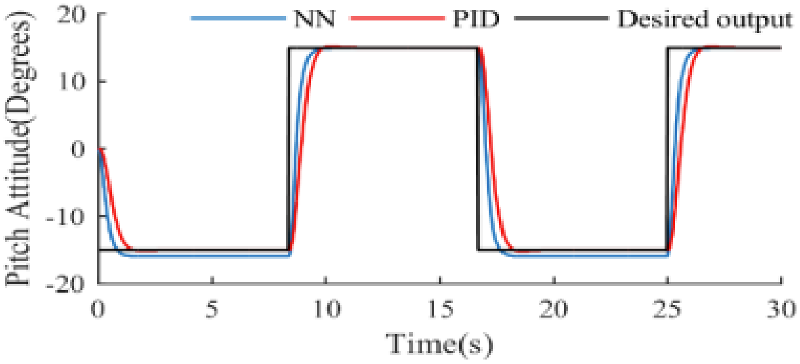

Figure 3. Comparison of simulation results.

The final results of experiment show that the neural network controller has better stability and faster response speed [12].

5. Conclusions

This paper introduces the classification and research of UAV control algorithms. At present, the mainstream control systems are mainly divided into linear control algorithm, nonlinear control algorithm and machine learning-based on control algorithm. This paper evaluates the performance of the above three control algorithms. Although linear control algorithms are currently widely used, nonlinear control algorithms have better performance than linear control algorithms. In the future, the combined control algorithms will become the mainstream of control systems. Different intelligent algorithms are selected to control in different practical application scenarios, which will enhance the autonomous positioning ability of UAVs. The UAV flight path planning is also more scientific, and the air collision rate will also be reduced, which ultimately makes the UAVs more intelligent and the operation more flexible and convenient.

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