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Comparative Study on the Spacecraft Attitude Control Methods: Traditional and Intelligent Methods

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Abstract:

In response to the issues of spacecraft attitude control, this paper comprehensively analyzes the principles, advantages, disadvantages, and application cases of spacecraft attitude control from the perspectives of traditional control design methods and intelligent control design methods, and discusses the current development trends of spacecraft attitude controllers. An overview of the current development and prospects of control methods such as PID control, sliding mode control, fuzzy control, neural networks, etc. is provided. It is found that the traditional controller mainly solves relatively simple control problems such as linear and time-invariant, and it is not easy to adjust parameters. The intelligent controller relies on its algorithm and it simplifies the process of parameter adjustment, has strong adaptability, and can face unpredictable environments. Therefore, spacecraft attitude control will play an increasingly important role in the future.

Keywords: Spacecraft attitude control; PID control; sliding mode control; fuzzy control

1. Introduction

Since the successful launch of the first artificial satellite in human history by the Soviet Union in 1957, space technology has developed for nearly 70 years, and spacecraft attitude control has also rapidly advanced during this period. Early attitude control used simple spin stabilization, but the accuracy was not high. Nowadays, attitude control mostly uses three-axis attitude control, which determines the spacecraft's position by three mutually perpendicular axes and controls the spacecraft's attitude. Due to the long-term exposure of spacecraft in harsh environments, they are prone to malfunctions, so research on attitude control is an important aspect of improving the accuracy of spacecraft.

When studying spacecraft's attitude, analysis can be conducted from various perspectives, such as linear or nonlinear, traditional or intelligent, single or coupled, rigid or flexible aspects, etc. Regarding traditional controllers, reference [1] divides the design methods of attitude controllers into linear and nonlinear design methods. The linear design schemes introduce PID control, pole placement control, optimal

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control, etc. The nonlinear design schemes introduce sliding mode control and backstepping control, pointing out the advantages and disadvantages of each control method, proposing key technologies in attitude control, and looking forward to the future, in terms of coupling controllers.

In the field of flexible spacecraft, reference [2] achieved fast and accurate tracking of attitude angles under robust model predictive control, effectively dealing with disturbances caused by vibrations of large flexible appendages on the central rigid body attitude. Control algorithms are gradually evolving from traditional control methods such as PID control and LQR control to incorporating neural networks and machine learning in control design. This trend indicates the increasing intelligence of control algorithms in the present day.

Early traditional controllers mainly addressed relatively simple control problems such as linearity and time-invariance, with limited ability to handle complexity and uncertainty, lacking flexibility and adaptability. With the rapid development of algorithms in recent years, algorithms are gradually being applied in control systems. Intelligent control focuses more on the intelligence of the controller itself, reducing reliance on mathematical models and simplifying the controller design process through learning and optimized algorithms.

Current research on controllers mainly focuses on traditional controllers, with less research on intelligent control as a controller design pattern that has only developed in recent years. This article focuses on traditional and intelligent controllers, introducing typical controllers, pointing out their advantages and disadvantages, summarizing the current research status, and looking forward to the future.

2. Traditional Design Methods for Spacecraft Attitude Controllers

2.1 PID Control

PID control is a typical linear control method widely used in industrial control systems, attitude control systems, and various other applications that require continuous modulation control and control loop feedback mechanisms. Due to its simple algorithm, good robustness, and high reliability, the PID structure is widely used in 90% of control loops today. PID control is divided into three types: proportional control, integral control and derivative control.

Proportional control adjusts the attitude response speed by generating an output value proportional to the current error but is prone to overshoot.

Integral control is the sum of instantaneous errors over a period of time, providing a cumulative offset that should have been corrected in advance to eliminate steady-state errors in control and improve tracking accuracy of attitude. The drawback is that integral saturation may occur during the initial control, leading to significant overshoot.

Derivative control calculates the rate of error change over time and multiplies this rate by the derivative gain to compute the control output.

The differentiation of attitude error can improve the bandwidth of attitude control, accelerate the response speed of control, and suppress the reverse change of attitude, but the disadvantage is that it is easily affected by external disturbances.

Due to its ease of implementation, PID control is widely used in attitude control. In reference [3], for quadcopters, SC-PID control rates are designed for pitch and roll channels to effectively reduce the system's overshoot. The stability of the subsequent control is guaranteed by Lyapunov stability theory. Through multiple experiments, it can be found that PID control is easy to understand, fast in attitude control, stable in control, and accurate in precision. However, its shortcomings are also apparent, and the parameters are difficult to determine. Therefore, in recent years, with the introduction of intelligent control technology, the combination of PID control with fuzzy control, neural network control, and other intelligent control methods can achieve self-tuning of PID parameters, simplifying the difficulty of tuning.

2.2 Synovial Control

Synovial control is essentially a special type of nonlinear control, with the nonlinearity manifesting as discontinuity in the control. Sliding mode control is designed based on the system's desired dynamic characteristics to switch the system's hyperplane, and the system state is converged from outside the hyperplane to the switching hyperplane through the sliding mode controller. Once the system reaches the switching hyperplane, the control action will ensure that the system reaches the system origin along the switching hyperplane. Sliding along the switching hyperplane towards the origin is called sliding mode control.

The traditional sliding mode is for nonlinear system $\dot{x} = f(x,u,t)$, where $x \in R^n$, $u \in R^m$, $t \in R$, in its state space, there is a hyperplane s(x)=0 as shown in Fig. 1.

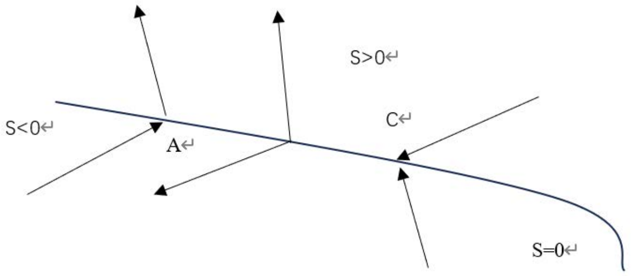

Fig. 1 hyperplane in state space

In the figure, the state space is divided into two parts: s>0 and s<0 at s=0. A is called the common point, B is the starting point, and C is the ending point.

Model predictive control has its advantages, such as fast response, good robustness, no need for online system identification, and simple physical implementation. The paper [3] uses the characteristics of good stability control of the synovium to consider the advantages and disadvantages of adaptive estimation and disturbance observer and designs an adaptive fixed-time disturbance observer. However, there are also drawbacks to the sliding mode control. When the sliding mode control slides the system state onto the sliding surface, it may lead to an overshoot. In addition, in order to achieve fast sliding, high-frequency modulation signals are usually introduced, which may lead to high-frequency oscillation problems in the control system, posing certain requirements for the system's stability and noise suppression capabilities.

3. Intelligent Spacecraft Attitude Control Method

3.1 Fuzzy Control

Fuzzy control is essentially a type of nonlinear control, generally consisting of five main parts: defining variables, fuzzification, knowledge base, logical inference, and defuzzification. Fuzzy control is the process of converting the precise value of an error signal into a fuzzy variable value, then using fuzzy language to describe fuzzy variable rules, and finally de-fuzzifying and reasoning to obtain a clear quantity of control for actual control.

Fuzzy control can also be combined with PID to solve the problem of excessive reliance on an engineer's experience in the PID tuning process. By applying the basic theory of fuzzy mathematics, the conditions and operations of rules are represented by fuzzy sets, and these fuzzy control rules and related information are input into the knowledge base. The computer adjusts the parameters of the PID controller through fuzzy reasoning based on the actual response of the control system. The schematic diagram is shown in Fig. 2.

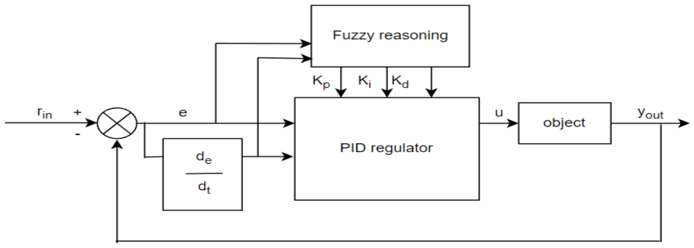

Fig. 2 PID controller through fuzzy reasoning

Currently, fuzzy control is also applied in the attitude control design of spacecraft. Based on an adaptive fuzzy observer and enhanced coupling strategy, a smart control algorithm is designed in reference [4], which solves the problem of weak coupling in roll channels using the enhanced coupling concept. The algorithm combines adaptive fuzzy observers to achieve a precise approximation of strong disturbances and uncertainties, thereby improving the robustness of attitude control under strong attitude disturbances. Reference [5] proposes a finite-time control strategy for the attitude control system of a formation spacecraft under the presence of adversarial torque output for non-cooperative targets, based on a Fuzzy Neural Network Disturbance Observer (FNNDO) in a Nonsingular Terminal Sliding Mode (NTSM). The advantage of fuzzy control is that it greatly reduces the difficulty of parameter tuning and solves the traditional problem of the inability to adjust PID parameters in real time. Similarly, fuzzy algorithms also have their drawbacks: the design of the algorithm lacks systematicity and cannot define control objectives; it is difficult to obtain clustering conclusions when the sample size is large.

3.2 Neural Networks

Neural networks are mathematical models or computational models that mimic the structure and function of biological neural networks and perform calculations through connections of artificial neurons. Artificial neural networks can often change their internal structure based on external information, making them an adaptive system. Neural networks have strong fitting capabilities and can fit algorithmic components such as value functions, state functions, and policy outputs. Classical numerical optimization algorithms have drawbacks such as slow-solving processes and high model accuracy requirements, making it difficult to handle complex problems effectively. Therefore, in recent years, artificial intelligence technologies represented by deep reinforcement learning have received widespread attention in the field of control.

Neural networks can handle objects that are difficult to describe with models or rules, and they have strong fault tolerance due to their parallel distributed information processing approach. Reference [13] addresses the uncertainty caused by external disturbances and uses the OpenGym framework for reinforcement learning of spacecraft attitude. The network is trained using policy gradient and temporal difference methods, and the algorithm's effectiveness is tested on spacecraft interaction models. Reference [14] leverages the advantages of deep learning in multi-parameter optimization and proposes a model predictive control algorithm based on convolutional neural networks to meet the low hardware requirements of aerospace engineering. It can be seen that the multiple parameter terms of neural networks can effectively solve fuzzy objects, and high fault tolerance can address the spacecraft attitude offset problem caused by harsh environments.

4. Challenges and Future Trend

Currently, traditional controller designs still face many issues, such as: high algorithm complexity leading to difficult tuning; low algorithm robustness that fails to meet attitude control in harsh environments; and slow response speed, which is a significant problem as traditional controllers cannot generate rapid responses when facing rapid changes in the external environment. Therefore, in the era of rapid AI development, intelligent controllers can improve the shortcomings of traditional controllers. The adaptive characteristics of intelligent controllers can address the robustness issues in harsh environments; intelligent control often deals with dynamic control objects, thus enabling faster response times.

However, intelligent controllers still face some challenges. In the realm of attitude control, future challenges for smart controllers include advancing precision amidst dynamic environments. Maintaining optimal performance in varying conditions demands enhanced sensor fusion and predictive algorithms. Real-time responsiveness remains critical for applications such as aerospace and robotics, necessitating robustness against disturbances and ensuring stable operation. Moreover, integrating AI and machine learning to adaptively optimize control strategies will be pivotal. Overcoming these challenges will drive the evolution of smart attitude control systems, enhancing their reliability and applicability across diverse domains.

Looking ahead, the future of smart control in attitude control is poised for significant advancements. Emerging trends include enhanced precision through advanced sensor technologies and robust predictive algorithms capable of adapting to dynamic environments. Real-time responsiveness will continue to be crucial, particularly in aerospace and robotics, necessitating resilient systems capable of withstanding disturbances. Secure communication protocols and cybersecurity measures will be integral to safeguarding critical operations against evolving threats. Furthermore, the integration of AI and machine learning will enable adaptive control strategies, optimizing performance based on real-time data and predictive analytics. These trends collectively promise to elevate the reliability, versatility, and efficacy of smart attitude control systems, paving the way for their expanded application across various sectors including space exploration, autonomous vehicles, and beyond. Therefore, intelligent control systems will play an increasingly important role in attitude control soon.

5. Conclusion

This article outlines various common attitude control methods, their characteristics, applications, and shortcomings, from the perspectives of traditional spacecraft attitude design methods and intelligent design methods. With the advent of the AI era and the rapid development of algorithms, the advantages of intelligent control gradually appear, and its characteristics of high efficiency and strong self-adaptation will gradually dominate the control design. At the same time, one of them is selected as a typical case for further case analysis to demonstrate the advantages of current intelligent design methods, analyze the key technologies involved, and propose future research directions.

A review of spacecraft attitude design methods can provide researchers with a comprehensive understanding of both traditional and intelligent design methods, which can be informative and reference for their research.

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