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# Current status and prospects of adaptive PID control in spacecraft attitude control

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**Abstract.** Spacecraft attitude control is a precise aspect that requires accurate operation. Adaptive PID control, in this case, could be a promising approach for improving the performance. In order to provide a better comprehension about the adaptive PID control in spacecraft attitude control, This paper will mainly discuss the aspect in current solutions, challenges, and future directions through providing and interpreting the scientific and reliable essays in this area. Several kinds of classic adaptive PID control will be introduced in the paper for their feasibility and applicability. Then, paper will discuss several kinds of limitations faced by traditional adaptive PID control in reality such as the complexity of spacecraft dynamics. To overcome these limitations, this paper will also discuss a couple of machine learning based adaptive PID control proposed by researchers such as fuzzy logic systems. These adaptive schemes can adjust the controller parameters through advanced algorithms to ameliorate the control performance of the spacecraft.

**Keywords:** adaptive PID control, spacecraft attitude control, machine learning.

## 1. Introduction

Given the great enthusiasm for space exploration, spacecraft engineering, which is fundamental to all space missions, always remain a widely valued aspect. The attitude control of spacecrafts is an essential part to every space program. The precise control of the spacecraft is crucial for the success of any space mission and requires the use of sophisticated control algorithms. For long years the traditional PID control is widely used in spacecraft attitude and propulsion control. According to research of Wen and Kreutz-Delgado [1], Tsiotras [2], classic PID control have good performance under certain models. However, given the complex and uncertain environment of space, it is often impossible to acquire accurate physical parameters. As a result, adaptive control techniques are widely used to improve the performance of PID control for its advantages in dealing with objects with high time-varying and nonlinearity.

The aim of this review paper is to give a comprehensive overview of the research progress of adaptive PID control in spacecraft attitude control. Specifically, this paper will discuss the design, implementation and performance of several adaptive PID control such as adaptive Kalman filter [3] and Indirect Robust Adaptive Fault-Tolerant Control [4] in various spacecraft systems recent years. In addition, this paper will also discuss several latest research trends and future directions about the machine learning based adaptive PID control such as intelligent PD control for spacecraft attitude control [5].

This review paper will be organized in the following structures [6]. Within section 2 a general foreword about adaptive PID control theory and the association with spacecraft attitude control will be provided first. Then section 2 will discuss several different kinds of adaptive PID control in spacecraft attitude control [7]. In section 3 the paper will highlight the challenges and limitations of adaptive PID control mainly experienced in real applications, such as the non-linear and time-varying dynamics, actuator saturation, and disturbances. The section 4 will then outline the future directions of spacecraft attitude control by introducing several kinds of machine learning based adaptive PID control. Finally, in section 5 the major contributions of this essay will be summarized [8].

Given the potential of adaptive PID control in spacecraft attitude control, this review paper aims to give a comprehensive overview about some research progress and development about PID control within spacecraft applications, and to identify the future research directions in this field.

## 2. Adaptive PID control in spacecraft attitude control

As a matured auto control system, the PID control is widely applied on spacecraft engineering. However, given the dynamics of the spacecraft system can be complex and may vary depending on various factors like the orientation of the spacecraft or the existence of external forces, for instance, when a spacecraft is in orbit around a planet, it experiences varying levels of gravity and atmospheric drag, which can affect its orientation and velocity. Traditional PID control in this case might fail to adapt to these changing conditions and may result in oscillations or overshoot. So is not always suitable for spacecraft attitude control for it can result in poor performance and even instability if the controller gains are not properly tuned.

As a result, the adaptive PID control is introduced for it could addressee these issues by adjusting the controller gains in real-time based on the current operating conditions of the spacecraft. This allows for greater precision and accuracy in controlling the spacecraft, even in complex and changing environments.

Spacecraft attitude control is an essential part in space engineering and is the place where adaptive control is widely used. The attitude control mainly contains two parts, the attitude determination and control system (ADCS), which is responsible for determining and maintaining the orientation of the spacecraft and the reaction control system (RCS), which is responsible for adjusting the thrusters to maintain the desired orientation and velocity of the spacecraft are two main aspects of the attitude control.

A common and major challenge here could be the nonlinearities of the attitude control of the spaceship which is affected by various factors such as the uncertainties dynamics of the spacecraft, the nonlinearities in the actuators and the coupling between the spacecraft's attitude and its position. The aim of adaptive PID control in this case is to maintain stable attitude tracking.

### *2.1. Adaptive kalman filter*

There are several kinds of adaptive PID control available for these situations. One classical kind is to use an adaptive Kalman filter (AKF) in the system to estimate the state of a system based on measurements of its inputs and outputs [3]. The adaptive Kalman filter has the abilities to work under changing system dynamics and measurement model. As a result, the AKF would estimate the spaceship's attitude and angular velocity in real-time to generate control commands to adjust the spacecraft's orientation and stabilize its motion. One practical example in real world is the Huygens probe launched by the Cassini spacecraft in 1997 and landed on the surface of Titan in 2005. The ADCS and RCS system of it use the AKF to ameliorate the stableness and capability of spacecraft. The algorithms of the adaptive control used here were able to handle the complex dynamics of the spacecraft and achieve accurate control during the descent to Titan.

### *2.2. Indirect robust adaptive fault-tolerant control*

Another example is known as the Indirect Robust Adaptive Fault-Tolerant Control [4]. It refers to a sliding mode based control technique which aims to reckon while offset for the uncertainties in the attitude control system. In this method, a sliding surface along which the system's state trajectory will converge is generated under this method. The input of the control here is designed to move the state route of the system along this sliding surface towards the target state. The controller includes a robust term that compensates for indeterminacy and interference inside this system, ensuring robustness against modeling indeterminacy together with unanticipated interference. As a result, the input parameter of the control system can be expressed as (1).

$$u = -k\,\mathrm{sign}(s) - k_r\,\hat{s} \tag{1}$$

The u in equation (1) is the control input, k and $k_r$ are positive constants, sign(s) refers to sign function of s, while $\hat{s}$ refers to an estimation of s. $\hat{s}$ can be obtained using an adaptive rule that estimates an spacecraft's dynamics' unknown parameters. This adaptive law uses a Lyapunov function to confirm steadiness and conjunction about the estimated parameters. Given the sliding surface equation as (2).

$$s = e + \lambda\dot{e} \tag{2}$$

where s in equation (2) is the sliding surface, e is the tracking error, $\dot{e}$ is the derivative of the tracking error, and λ is a positive constant. The adaptive law formula would be as (3).

$$\theta = -\gamma\Pi s^2\mathrm{sign}(s)e \tag{3}$$

The θ in (3) is the estimated parameters, γ refers to a constant with positive value, e refers to tracking error while Π is a diagonal matrix with positive elements that ensures boundedness of θ. Figure 1 shows the indirect robust adaptive fault-tolerant control process.

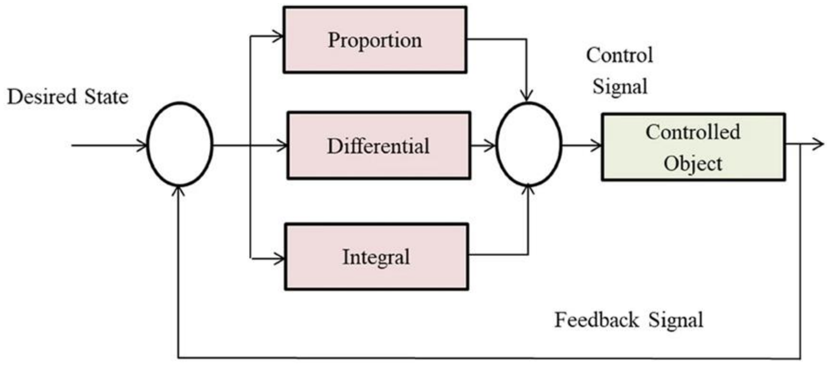

**Figure 1.** Schematic diagram of indirect robust adaptive fault-tolerant control process.

### *2.3. Adaptive fuzzy PID control*

Adaptive Fuzzy PID Control (AFPID) is also a popular solution [5]. The AFPID controller shows a high controllability towards the varying system dynamics and external disturbances by adjusting its control gains in real-time. As a result, the convergence time could be swifter while better performance could be realized in this way compared to a conventional PID controller.

Fuzzy logic is used to incorporate human-like reasoning into the control system. It allows the controller to handle imprecise and uncertain information by using linguistic variables and fuzzy rules. The fuzzy rules are used to ascertain the appropriate control action on the basis of the current state about this system.

The sliding mode-based adaptation mechanism is applied here in order to update FPID controller's control gains in real-time. This allows the controller to adjust towards the variation among the system dynamics together with external disturbances. The adaptation mechanism ensures that the control gains are updated in such a way that the performance of the controller is improved.

Other popular methods include Quaternion-based tracking maneuvers based on quasi-continuous second and third order sliding controllers and differentiators [6], Nonsingular Terminal Sliding Mode (NTSM) control scheme for the small satellite's roll, pitch together with yaw axes attitude trail control [7], a tracking controller based on integrator backstepping and quaternion feedback to steady a small satellite's stance by making the equal points in the closed-loop system evenly while gradually towards steady [8], and etc.

In conclusion, there are numerous kinds of adaptive PID control available for spacecraft attitude control and engineers could choose among a combination of these considering the real situations their spacecraft would face.

## 3. Challenging

However, it should also be noticed that because of the complicacy and the uncertainty of the outer space, it is common that the physical parameters related to spacecraft attitude control is changing, nonlinearity or sometimes even inaccuracy. In this case, the traditional adaptive PID control would face several difficult challenges.

One of the main challenges is the complexity of spacecraft dynamics. Spacecraft attitude control is subject to nonlinear couplings and uncertainties, which can make it difficult to accurately model the system and design an effective adaptive PID controller. This can result in suboptimal performance or instability if the controller is not properly designed.

Another challenge is the design of an effective adaptation mechanism. The adaptation mechanism is responsible for adjusting the control gains of the PID controller in real-time to improve performance. This requires a thorough understanding of the system dynamics and the ability to accurately estimate the current state of the system. The adaptation mechanism must also be able to handle variations inside the system dynamics or external interference to ensure robust performance.

Robustness is another important challenge for adaptive PID control in spacecraft attitude control. The controller must be able to maintain stable and accurate performance despite variations inside the system dynamics and external disturbances. This can be challenging owing to the complexity of spacecraft dynamics together with the existence of ambiguity.

Computational complexity is also a challenge for adaptive PID control in spacecraft attitude control. The use of advanced techniques such as fuzzy logic or machine learning during the design the adaptive PID control could increase the computational complexity about controllers, which can be a challenge for real-time implementation. This requires careful consideration of the trade-off between computational complexity and performance when designing an adaptive PID controller.

The combination of these challenges place higher requirement for the more advanced adaptive PID control, because the traditional adaptive PID control which is based on a certain model could face great limitations when comes to precise control. As a result, it is urgent to develop new kinds of adaptive PID control to meet advanced requirements. The machine learning based adaptive PID control becomes a popular direction for its strong estimation ability about NNs together with fuzzy logi. The existence of Artificial intelligence has the ability to achieve attitude control of high class through only fuzzy input data.

## 4. Future directions

There are several different approaches to combine machine learning with the adaptive PID control in spacecraft attitude control.

### *4.1. Intelligent proportional-derivative control*

One possible method of using machine learning in adaptive control is using the intelligent PD control method in the spaceship attitude steadiness with indeterminacy input saturation which was presented through the use of the neural networks with radial basis formula [9]. It is a new control scheme to tackle the complex issues about the spaceships' attitude control. The elastic vibration of the flexible attachment can affect the precision of the attitude pointing and cause system instability. The proposed controller uses modified Rodriguez parameters to show the attitude movements of spaceships. It does not involve estimation of elastic displacement and simplifies the design process and online calculations. The controller also includes a saturation compensator on the basis of a neural network with radial basis functionality to address the impact of input saturation on this system.

The principle about intelligent PID control is on the basis of the concept of semi-global input state stabilization (ISS). Semi-global ISS means that if the control gain here is created properly, the closed-loop system is robust under all kinds of interferences and indeterminate inertial parameters. The control design starts by developing a non-linear PD-type controller through a special Lyapunov function construction. The controller is given by equation (4).

$$J0\dot{\omega} = -S(\omega)J0\omega + \delta T\psi + u(t) + d(t) + \delta T\,[KC]\,\eta\psi - \delta T\,C\delta\omega \tag{4}$$

The J0 in equation (4) is given in (5).

$$J0 = J - \delta T \tag{5}$$

This control law refers to the function about the system's error together with derivatives. And control function (4) provides a minimization of the system's trajectory towards the equilibrium point through the error derivative.

In addition to the non-linear PD-type controller, a compensator (6) which is feed-forward is added in order to diminish the impact of the unconscious saturation of the control input about this system. The radial basis function neural networks is then derived here for the compensator to estimate the unconscious nonlinearity.

$$\hat{V}1 = \lambda\mathrm{min}(W)\,\hat{x}T\,W\,\hat{x} + \lambda\mathrm{max}(W)\,\hat{x}T\,(\varepsilon I - W)\,\hat{x} + \rho T\,\rho + \xi T\,\xi \tag{6}$$

And the result of the compensator (6) is added to the control law (4) as shown in (7)

$$\begin{gathered} u(t) = -kp\,\eta - kd\,\psi - \gamma\,(\tau)\sigma + \Phi T\,\hat{\Phi}\,\sigma + \varepsilon 0\,\mathrm{sign}(\sigma) + R \\ -1\,K\,(\eta\psi - C\delta\omega - \delta T\,[KC] \quad -1\,C\delta\delta\text{^}T) \end{gathered} \tag{7}$$

This could provide the extended case of the input of the control. The compensator is on the basis of the saturation nonlinearity, and it is considered as an NN saturation compensator. This approach explicitly addresses the issue about saturation. Figure 2 shows the process of intelligent proportional differential control.

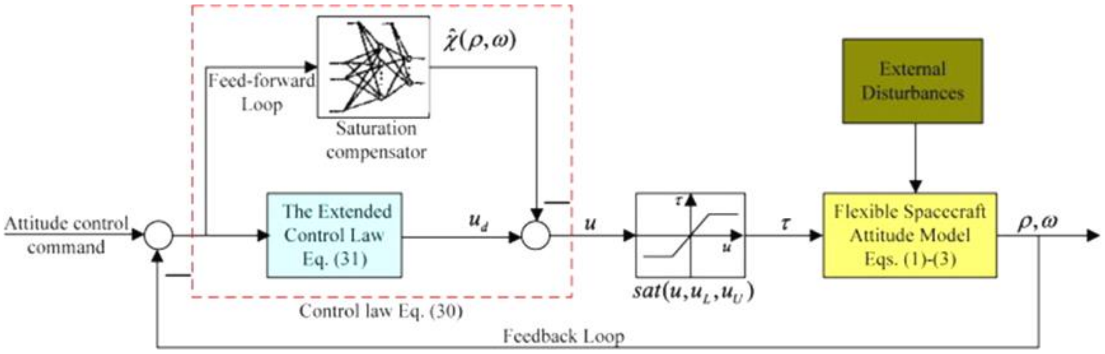

**Figure 2.** Intelligent proportional differential control process.

Some major contributions about this study are to provide the growth of an uncomplicated and robust method for flexible spacecraft attitude control and the explicit addressing of actuator input saturation in the control design process. The controller ensures that the closed-loop attitude system is ISS despite actuator input saturation, interference together with the uncertain parameter uncertainties. The design of this control is very flexible in the choice of control parameters, interference of the input together with the indeterminacy in the parameters. Theoretical and simulation results confirm the effectiveness of the proposed method in comparison with the conventional control schemes. These control strategies give advanced control theory the theoretical grounding it needs to be applied practically to flexible spaceship attitude control systems.

### *4.2. Adaptive neural network-based satellite attitude control*

Another excellent example of using AI in this area is known as the Adaptive Neural Network-based Satellite Attitude Control [10]. It is a control system for a satellite featuring a Control Moment Gyroscopes (CMG) system. The control system can adjust attitude, detect and compensate for external disturbances and internal actuator dynamics, and adapt to non-linear, non-constant errors.

The system utilizes adaptive control and neural networks to address uncertain and non-modeled disturbances. The controller generates an angular rate command to adjust satellite yaw, pitch, and roll, ensuring it stays oriented to its mission objective. The adaptive law equations provide command updates by minimizing the Lyapunov function. This function here acts as a mathematical evaluation about the error between the approximate and the actual system models. The control system adjusts the neural network weights to correct the errors in the approximate model.

To address the uncertainty in the actuator dynamics, equations to describe the adaptive command law are derived. The design also separates the uncertainty in the system's modeled linear parameters by representing them as a square matrix. This matrix is then enhanced by the neural network's estimate, and the resulting control input saturates the system's actuator. The result is a control system that can accommodate time-varying uncertainty in the system's dynamic model and adapt to non-modelled disturbances.

Other possible research directions include the use of the neural network adaptive control for stabilizing the inaccurate inflexible spaceship with unknown system dynamics on the basis of the deterministic studying theory [11], the attitude controller with adaptive fault tolerant which use variant structure control to adjust closed-loop system's transient response through a dedicated parameter and works with uncertain knowledge of actuator faults [12], etc.

In conclusion, provide a self-adaptive model-free approach on the basis of emphasis studying about automated control when the operating condition is changing in real-time is the core of using machine learning based adaptive PID control in spacecraft attitude control. All the papers above emphasize the importance of advanced fuzzy and neural network system in machine learning based adaptive PID control. Given the prosperity of AI technology in recent years, it could be seen that the machine learning based adaptive PID control would experience a swift growth and contributes to the precision and steadiness of the attitude control of the spacecraft.

## 5. Conclusion

This paper mainly discusses several practical adaptive PID control in spacecraft attitude control, including adaptive Kalman filter, Indirect Robust Adaptive Fault-Tolerant Control and Adaptive Fuzzy PID Control. It shows that the adaptive PID control is a promising approach for spacecraft attitude control for it combines the simplicity and ease of implementation of traditional PID control with the adaptability and robustness of progressive control strategies like fuzzy logic together with neural networks. By using adaptive mechanisms to tune the control gains, the capability of adaptive PID control in the attitude control of a spaceship under the existence of indeterminacy together with interference could be significantly enhanced. This research has also shown that the machine learning based adaptive PID control has a good prospect for its self-adjust ability when facing the nonlinearity problems and uncertainty parameters of the outer space environment.

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