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Application of PID Control Technology in Unmanned Aerial Vehicles

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Abstract. The rapid advancement of unmanned aerial vehicle (UAV) technology underscores the essential role of PID (proportional-integral-derivative) control in ensuring flight stability, particularly through precise motor speed adjustments. Thus, this paper systematically analyzes the fundamental principles and limitations of traditional PID control, further highlighting its insufficient adaptability to dynamic external conditions, which includes load fluctuations and wind disturbances. In response to these challenges, it explores adaptive control strategies such as self-tuning PID and fuzzy logic PID, points out how these advanced methods can effectively improve flight stability by dynamically adjusting control parameters, and demonstrates their superiority over traditional PID through comparative analysis. In addition, the paper anticipates future developments in UAV control systems, thereby emphasizing the integration of artificial intelligence and machine learning technologies into PID control. And this integration seeks to optimize control strategies and markedly enhance the autonomous decision-making capabilities and adaptability of UAVs. Meanwhile, the paper also predicts the development trend of hybrid control systems, that is, combining PID with other advanced control methods (such as linear quadratic control) to enhance the overall control capabilities of UAVs. In short, it underscores the necessity for continuous innovation and in-depth research in response to the dynamic flight environment and the diverse mission requirements.

Keywords: Unmanned Aerial Vehicle (UAV), Proportional-Integral-Derivative (PID) Control, Aeronautic Engineering, Adaptive Control.

1. Introduction

The field of unmanned aerial vehicle (UAV) technology has witnessed considerable advancements, particularly in the realms of flight control systems, multi-drone collaboration, battery efficiency, and sensor integration. However, there are still research gaps, with key areas including the development of regulations to address legal and ethical issues, enhancing autonomous decision-making capabilities, and improving reliability and safety in harsh environments. At the same time, improving long-duration flight capability and energy efficiency continues to pose significant challenges, while the application of intelligent systems and deep learning for real-time data processing is becoming more common. This paper summarizes the existing literature on the development, applications, innovations and prospects of PID (Proportional-Integral-Differential) control in the field of UAVs. For those problems that have not yet been solved, this paper provides some development ideas and thoughts. In detail, it discusses

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the vertical motion principle of drones, briefly introduces how PID control can achieve stable hovering and vertical ascent and descent by adjusting the motor speed, explains the principles of yaw, pitch and roll motion, and describes the application of PID control in adjusting the rotor speed to control attitude. In addition, aerodynamic disturbances faced by UAVs in complex environments, such as the effects of wind and air resistance on flight stability, are emphasized, and how PID control can cope with these disturbances is outlined. Literature research and content analysis methods are used to summarize the research progress of scholars in this field based on the existing literature, which may help to provide a holistic understanding for future research.

2. Overview of PID Control Techniques

2.1. The Principle of PID Control

During flight, UAVs are required to maintain stable attitudes, including pitch, roll, and yaw. PID control employs continuous monitoring to assess the UAV's attitude using sensors like gyroscopes and accelerometers. This data is compared with predefined target attitudes to calculate deviations and generate control commands based on the PID algorithm. Additionally, UAVs must maintain or adjust their flight altitude, relying on barometers and GPS to obtain current altitude information, which is then compared to desired altitudes to produce control signals [1]. PID controllers use proportional, integral, and derivative methods for efficient control. Proportional control outputs are directly tied to current error, adjusting the control signal by amplifying the difference between target and actual values. This method responds quickly but may produce a steady-state error. Integral control eliminates steady-state errors, ensuring stability in attitude and altitude control, while derivative control predicts changes in attitude and altitude, suppressing overshoot and oscillation to enhance system stability. By adjusting the PID controller parameters (P, I, and D values), UAV attitude control performance can be optimized for precise and stable flight.

$$\mathrm{GP(s)} = \frac{\mathrm{U(s)}}{\mathrm{E(s)}} = \mathrm{KP} \tag{1}$$

Integral control, on the other hand, is concerned with the accumulation of historical errors and aims to eliminate steady-state errors. By integrating the error, the system can compensate for the past error with the expression shown below:

$$\mathrm{GI(s)} = \frac{\mathrm{U(s)}}{\mathrm{E(s)}} = \frac{1}{\mathrm{T_i S}} \tag{2}$$

Differential control is related to the rate of change of the error and is capable of predicting future behavior, thus improving the response and stability of the system, which is expressed as shown below:

$$\mathrm{GD(s)} = \frac{\mathrm{U(s)}}{\mathrm{E(s)}} = \mathrm{T_D S} \tag{3}$$

By integrating the above three control methods, the output of the PID controller can be expressed as the following equation [2]:

$$\mathrm{GPID(s)} = \frac{\mathrm{U(s)}}{\mathrm{E(s)}} = \mathrm{KP}(1 + \frac{1}{\mathrm{T_i S}} + \mathrm{T_D S}) \tag{4}$$

PID controllers are widely applied for their simplicity and effectiveness in industrial automation systems such as temperature, speed and position control. The popularity of this control method can be attributed to its intuitive and readily comprehensible nature, which renders the fundamental operations accessible to non-specialists. Besides, mastery of PID control principles does not require a complex mathematical background, and is covered in almost all undergraduate control courses. the long history of PID has made it familiar to many engineers, and its use has become an industry standard [3].

2.2. The Development and Evolution of PID Control Technology

PID controllers have been in widespread use for decades due to their straightforward design, superior performance, and ability to effectively lower the overshoot and stabilization time of sluggish processes in industrial process control [4]. Fractional PID controllers, an evolution of traditional PID, show improved robustness to variations in system and controller parameters, facilitating the achievement of iso-damping characteristics, which is anticipated to further enhance overall system performance [5]. In addition, robustness can be significantly improved by using a two-loop model tracking control system (MFC), and the MFC structure is favored for its simplicity, immunity to interference, and ability to stabilize disturbances. Nevertheless, despite these advantages, MFC remains underrepresented in the literature [6]. In recent years, fuzzy logic controllers (FLCs), especially fuzzy PID controllers, have been widely used in industrial processes due to their heuristic properties, demonstrating simplicity and effectiveness in dealing with linear and nonlinear systems [7]. In comparison to conventional PID control, fuzzy PID controllers are distinguished by their capacity to modify parameters in real time. Related research has investigated the design concepts of novel fuzzy PID controllers, thus leading to a computational optimization analysis framework specifically for real-time closed-loop digital control applications. The effectiveness of the controller in linear and nonlinear systems is verified through comprehensive computer simulations and detailed analyses, and the bounded input/bounded output (BIBO) stability properties of the controller are evaluated [8]. Despite its advantages in UAV flight management, traditional PID control has notable limitations in adapting to external changes. Rapidly evolving loads and wind conditions can overwhelm the PID controller’s response speed, leading to lag and suboptimal performance. UAV systems are inherently nonlinear, with factors like aerodynamics and motor dynamics complicating effective control, which limits PID's applicability in high-precision scenarios. Although the integral component is effective in eliminating steady-state errors, it can compromise the system’s response during rapid fluctuations, potentially resulting in integral windup and instability. Also, the linear combination of current, past, and future errors may be insufficient for capturing the complexities inherent in dynamic flight environments, which could ultimately result in a reduction in overall control effectiveness [9].

3. UAV Motion Principles and Control Challenges

3.1. Vertical Motion and Hovering Control

The basic motion modes of a UAV include hovering and vertical movement. As the UAV’s blades rotate, they generate lift while also experiencing a counteracting torque from the air, leading to the UAV's rotation. Its symmetrical design allows the motors on one side to rotate in the same direction, while the other two rotate in the opposite direction. By simultaneously increasing the speed of all four motors, lift can be proportionally enhanced, enabling the UAV to ascend when total lift exceeds gravity; conversely, reducing motor speed causes the UAV to descend vertically [10]. When total lift equals gravity and there are no external disturbances, the UAV can achieve a stable hover. Utilizing PID control, adjustments to motor speed can minimize the difference between the actual and desired height, resulting in smoother motion.

3.2. Yaw, Pitch, and Roll Motion

In yaw motion, the UAV counteracts the rotational torque of the rotors using two forward-propelling propellers and two reverse-propelling propellers, ensuring stable flight. Diagonal motors rotate in opposite directions, with their speeds adjusted by PID control. The rotor torque is proportional to speed [11]; when all motors operate at the same speed, the torques cancel out, preventing rotation. However, when motor speeds are inconsistent, an unbalanced torque is generated, leading to UAV rotation. For instance, increasing the speed of motors 2 and 4 while decreasing the speed of motors 1 and 3 creates a net torque around the z-axis, facilitating yaw motion. In pitch motion, PID control adjusts the speeds of motors 1 and 3 to alter the lift balance, causing the fuselage to tilt forward or backward for corresponding flight. Roll motion operates similarly, with the speed differential of

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motors 2 and 4 causing lateral tilt for sideways flight. Mk et al. proposed a novel quadrotor attitude control system, analyzing its stability and finite-time convergence using Lyapunov function techniques, with experiments demonstrating the method's effectiveness and robustness [12].

3.3. *Aerodynamic Disturbances and Control Challenges*

Under dynamic load variations, the attitude stability of quadrotors and the adjustment capabilities of PID control face numerous challenges [13]. UAVs must adapt to different environmental conditions during flight, such as balance control, wind disturbances, and speed adjustments, further highlighting the complexity of UAV operations [9]. In particular, the performance of traditional PID algorithms is significantly affected in turbulent environments and airflow disturbances, revealing their limitations. This necessitates ongoing improvements in PID control strategies or the exploration of alternative control methods to ensure the robustness and reliability of UAVs across various flight scenarios. For instance, integrating machine learning techniques allows the control system to make more adaptive adjustments based on real-time environmental data. Furthermore, by detecting information such as wind speed and airflow changes, PID control can dynamically optimize motor speeds, achieving stable flight in challenging conditions and enhancing the UAV's adaptability.

4. Adaptive and Self-Tuning PID Control for UAVs

4.1. *Self-Tuning PID Control*

The dynamic characteristics of unmanned aerial vehicles (UAVs) can undergo notable alterations when subjected to varying load conditions, which may subsequently affect flight stability. Self-tuning PID control employs built-in algorithms to monitor load conditions in real time and adjust PID parameters as necessary to maintain optimal control performance. For instance, when load increases, the control system may enhance proportional gain to accelerate response, while also adjusting integral and derivative gains to minimize steady-state errors and dynamic overshoot [14]. And self-tuning PID control demonstrates robust adaptability to unpredictable external factors, such as airflow disturbances. By means of continuous monitoring of key parameters such as attitude, speed, and acceleration, the control system is able to rapidly identify and rectify the impact of airflow on the flight trajectory. Timely adjustments to the derivative gain, in particular, assist in the prediction and counteraction of changes caused by disturbances, thereby ensuring flight stability and accuracy. The benefits of self-tuning PID control are derived from the sophisticated algorithms that intelligently select and optimize PID parameters based on real-time data and historical experience. This ensures efficient and stable operation of the control system under various conditions while also providing a learning capability to continually improve control performance and adaptability during flight [15].

4.2. *Fuzzy Logic-based PID Control*

The integration of fuzzy logic with PID control significantly enhances system performance in complex environments. This approach uses fuzzy logic as a dynamic regulator for PID controller parameters, enabling intelligent optimization of the proportional, integral, and derivative components. Fuzzy logic effectively handles imprecise and ambiguous information by defining fuzzy sets and membership functions, transforming system states into fuzzy variables. Then, leveraging a predefined fuzzy rule base, PID parameters are adjusted in real-time through fuzzy inference mechanisms. This dynamic and responsive adjustment allows for flexible optimization of PID controller performance to adapt to varying operational conditions [16]. In the context of sophisticated applications such as UAV flight control, this combination is of paramount importance. UAVs are subject to a variety of challenging conditions, including fluctuating loads, airflow disturbances, and uncertain environmental factors. These factors impose significant demands on the stability and accuracy of control systems. By dynamically adjusting PID parameters based on fuzzy rules, the control system can rapidly adapt to changes in the external environment, effectively mitigating disturbances during flight and ensuring stable operation in complex conditions. Moreover, the integration of fuzzy logic and PID control

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streamlines the parameter calibration process of conventional PID controllers, which frequently necessitates exhaustive manual testing and can be laborious. In contrast, fuzzy logic facilitates online adjustments of PID parameters, significantly improving both efficiency and accuracy [17].

4.3. Comparative Analysis of Traditional vs. Self-Tuning PID Control

Remote-operated vehicles (ROVs) exemplify a practical application of self-tuning PID control. Depending on the task, ROVs often need to switch operating tools and/or pick up and release loads, resulting in changes to their weight, buoyancy, and hydrodynamics, which can affect position tracking performance. Additionally, ROVs must navigate dynamic underwater environments, such as currents and waves in shallow waters, which complicate stable navigation and positioning. In such scenarios, when the system's dynamic characteristics are time-dependent or operating conditions change, recalibrating gains to achieve the desired performance can be a time-consuming and challenging process. In consequence, self-tuning PID control assumes particular importance in such dynamic environments. The system automatically adjusts control parameters based on real-time feedback, reducing the necessity for manual intervention and enhancing response speed, thereby ensuring that the ROV maintains robust operational performance and stability in complex conditions. Moreover, the flexibility of self-tuning PID control allows it to adapt in real time to varying working conditions and environmental changes, further enhancing the ROV's potential for diverse applications and enabling it to execute complex underwater operations more effectively [18].

5. Future Directions in UAV Control Systems

In the future, the development of UAV control systems will increasingly rely on artificial intelligence (AI) and machine learning technologies to enhance the system's adaptability and intelligence. Studies have shown that the use of a variety of AI algorithms to optimize PID control parameters can significantly reduce the vehicle's lateral and yaw motion errors, including the firefly algorithm (FA), particle swarm optimization (PSO), ant colony optimization (ACO), bat algorithm (BA), and imperial competition algorithm (ICA) [19]. By combining these intelligent algorithms with the UAV control system, the system can not only respond quickly in a dynamic environment but also automatically adjust the control strategy to achieve higher flight stability and autonomous decision-making capabilities. This intelligent control method will make UAVs more flexible and efficient in complex flight missions. In terms of hybrid control systems, the focus will be on integrating traditional control methods with modern optimization strategies, especially combining PID control with linear quadratic (LQ) control. PID control provides a stable flight foundation due to its simplicity and reliability, while LQ control enhances flight accuracy through performance optimization and rapid dynamic response [20]. Future hybrid control systems will not only emphasize basic functions but will also enable drones to self-learn and adapt to changing flight environments by introducing AI and machine learning technologies, achieving intelligent control and optimal energy configuration. Additionally, the combination of multi-sensor and data fusion technology will significantly enhance the perception and decision-making capabilities of drones, ensuring accurate navigation and obstacle avoidance in complex environments. Balancing the goals of efficiency and low power consumption will also become a development focus, with optimized control algorithms and battery technologies supporting drones in a wider range of application scenarios.

6. Conclusion

This paper systematically summarizes the application of PID control in unmanned aerial vehicles (UAVs) and the challenges it faces, particularly its limitations in dynamic environments. By analyzing the principles of UAV motion, we reveal the shortcomings of traditional PID control in responding to load fluctuations and changes in wind speed. This finding drives the exploration of more advanced control strategies. Self-tuning PID control and fuzzy logic PID control emerge as effective improvement methods, significantly enhancing UAV adaptability and stability in complex environments. Self-tuning PID control strengthens system intelligence through real-time monitoring and automatic parameter adjustments, while fuzzy logic dynamically optimizes PID parameters, boosting system robustness. These advancements not only optimize PID control algorithms but also lay the groundwork for achieving more precise flight control in UAVs. Looking ahead, research on hybrid control systems will become an important direction. By combining PID with other advanced control methods, such as Linear Quadratic (LQ) control, more efficient and adaptable UAV control systems can be developed to meet the growing application demands. Overall, this study provides essential theoretical support and practical guidance for the field of UAV control, highlighting the necessity for continuous innovation to address complex flight environments and task requirements, thereby driving further advancements in UAV technology.

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