Research Article

PID Control and Alternative Control Approaches in UAV Systems

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Abstract
In the control of unmanned aerial vehicles (UAVs), proportional–integral–derivative (PID) controllers continue to play a central role due to their simplicity, rapid implementation, and low computational demand. However, the classical PID approach faces inherent limitations, including sensitivity to disturbances, complex tuning, and limited adaptability, which increasingly highlight the relevance of advanced control methods. Recent research has investigated adaptive, fuzzy, and fractional-order PID (FOPID) solutions, as well as methods based on artificial intelligence and predictive control techniques such as linear quadratic regulator (LQR), model predictive control (MPC), sliding mode control (SMC), and H∞ approaches, many of which provide improved robustness and performance. The purpose of this study is to review the application of PID control in UAV systems, to identify its limitations, and to present alternative control strategies that may become dominant in the future through the development of hybrid and intelligent systems.

Keywords: Unmanned Aerial Vehicle, PID Control, Robustness, Adaptive Control, Model Predictive Control (MPC), Fuzzy Logic, H∞ Control

1. Introduction

The application areas of unmanned aerial vehicles (UAVs) are continuously expanding worldwide. In agriculture, UAVs are employed for spraying and field monitoring, in transportation they are used for traffic monitoring and driver behavior analysis, while in maritime transportation their significance is also [1-7]. Furthermore, UAVs provide substantial benefits in building inspections, rescue missions, and infrastructure monitoring [1,8,9].

The growing range of applications requires the advancement of autonomous UAV operations, for example in area protection tasks where drones can automatically take off from drone nests and identify intruders [10-14]. Certain studies also suggest the use of autonomous precursor drones to support emergency vehicles by predicting and avoiding hazardous situations [15-17].

One of the main advantages of autonomous systems is the reduction of human-factor-related errors, such as the inattention or fatigue of remote pilots [18-19]. At the same time, the role of technical failures cannot be disregarded: in Australia, 60% of accidents were caused by such failures, while in the city of Hangzhou the most common issues identified from flight data included low battery charge and system malfunctions [20,21]. These factors have increasingly led to recommendations for the application of redundant systems. Moreover, the development of autonomous UAV technologies requires multidisciplinary expertise [22].

Among control solutions, proportional–integral–derivative (PID) controllers remain dominant, with their application share in UAV systems reaching 90–97% [23,24]. Their widespread adoption is attributed to simple structure and ease of parameter tuning. However, several studies highlight their limitations, including

weak disturbance rejection, stability issues, low robustness, and sensitivity to model uncertainties and environmental influences [25-28]. Consequently, current research is increasingly directed towards advanced and more robust control methods, such as sliding mode control (SMC) and model predictive control (MPC), which provide more effective performance in nonlinear systems and in the presence of disturbances [29,30].

The objective of this study is to provide a comprehensive overview of the application of PID controllers in UAV systems, with particular focus on their limitations. To this end, the review examines research findings that analyze the shortcomings of PID controllers and introduces solutions proposed to overcome these challenges in drone control systems.

2. Operation and Principles of PID Controllers in UAV Systems
PID controllers represent fundamental components of drone control, primarily responsible for stabilizing the three main axes—longitudinal tilt (pitch), lateral tilt (roll), and rotation (yaw)—as well as maintaining accurate altitude [31,32]. Their operation is based on the deviation (error) between the desired and actual values, which is corrected through the combined action of the proportional (P), integral (I), and derivative (D) terms. The P term provides fast response, the I term compensates for steady-state error over time, and the D term mitigates overshoot and improves stability by predicting expected changes (Shi, 2024) [31].

A PID controller utilizes onboard sensors such as accelerometers, gyroscopes, barometers, and the global positioning system (GPS) to calculate the required motor speeds, thereby enabling the intended motion and position control [23,33]. In practice, control relies on a multi-loop architecture: the inner loop (attitude control) operates with fast dynamics, while the outer loop (position control) provides slower but more accurate trajectory tracking (Lopez-Sanchez & Moreno-Valenzuela, 2023) [32].

The classical PID algorithm, due to its simplicity, can be easily implemented on microcontrollers such as Arduino or Pixhawk platforms. Owing to its low computational demand, it remains one of the most widely applied control methods in commercial UAV systems [32,34].

3. Advantages and Industrial Applicability of PID Control
One of the main strengths of PID control is system-level simplicity, which allows rapid implementation and makes it ideally suited for real-time drone control tasks (Shi, 2024; Lopez-Sanchez & Moreno-Valenzuela, 2023) [31,32]. The algorithm is transparent, programming is straightforward, and reliable operation can be achieved even with low computational demand, enabling effective application on low-performance microcontrollers such as the Arduino UNO platform [23]. As a result, PID control is present in approximately 97% of industrial control systems, including UAV stabilization and trajectory-tracking solutions [23,34].

Implementation of the PID algorithm can also be achieved using cost-effective and widely available hardware and sensor components. For instance, Ezhil et al. (2022) evaluated the performance of classical PID control on a UAV prototype equipped with a brushless DC (BLDC) motor, a 30 A electronic speed controller, an MPU6050 sensor module, and an Arduino UNO [23]. The experimental system was capable of stabilizing the roll and pitch angles, and following disturbances, the UAV restored equilibrium within 20 seconds. Stabilization efficiency reached 97% under minor disturbances and ranged between 70–80% under stronger wind effects, clearly demonstrating the practical applicability of PID control [23].

Another advantage lies in the ease with which PID controllers can be integrated with advanced control approaches such as fuzzy logic or optimization algorithms, making them suitable for the development of hybrid systems [25,35]. Although manual parameter tuning can be time-consuming, the simplicity of PID controllers ensures their role as the default control method in the early stages of UAV development [32].

4. Limitations of Classical PID Controllers in Drone Control
Although PID control is one of the most well-known and most frequently applied methods in drone control, it has several limitations, particularly in turbulent and nonlinear flight environments [31,32]. The dynamics of drones are highly nonlinear and mutually coupled, meaning that a single input variable can influence multiple output parameters. Moreover, system behavior changes over time, which classical linear PID controllers are unable to follow effectively. Shi (2024) highlights that PID is particularly disadvantageous during rapid load variations, wind gusts, and sudden maneuvers, since it possesses neither predictive nor adaptive capabilities [31].

A significant weakness of PID controllers is disturbance sensitivity. According to experiments conducted by Ezhil et al. (2022), an Arduino-based UAV prototype exhibited a stabilization time of approximately 20 seconds following disturbance: stability reached 97% under minor disturbances but decreased to 70–80% under stronger wind effects [23]. This clearly illustrates that although effective in controlled environments, PID is not always sufficiently robust under real external influences.

Parameter tuning represents another major challenge. It is not only time-consuming but can also result in unstable operation if performed incorrectly. The integral term (K_i) tends to accumulate the error signal (integral windup), which may cause instability or slow recovery after disturbance [31,35]. Reference dependency further complicates application in complex UAV operations. For example, Ma'arif & Setiawan (2021) compared integral state feedback (ISF) control with PID. Their results showed that ISF reached the desired value within 0.855 seconds without overshoot, while PID demonstrated slower response, overshoot, and oscillatory behavior [36].

The non-adaptive nature of PID represents an additional limiting factor. Mien et al. (2024) applied a cascaded PID structure to stabilize a six-degree-of-freedom quadcopter. Simulation results

indicated overshoot below 20% and nearly zero steady-state error [37]. However, the study also revealed that stability was guaranteed only under minor disturbances, while stronger external effects required retuning of parameters. The authors therefore recommended intelligent or nonlinear controllers to enhance robustness [37].

Similar conclusions were reached by Alrawi et al. (2024). In their investigation, PID resulted in 18% overshoot, 8 seconds of settling time, and 0.3 steady-state error, whereas a high-speed switching controller (HSSC) achieved stabilization within 1.1 seconds without overshoot. Their results demonstrated that PID cannot adequately handle rapidly changing load and environmental disturbances [38].

The review by Lopez-Sanchez & Moreno-Valenzuela (2023) also emphasized that PID systems with fixed parameters do not sufficiently adapt to variations during flight. Their analysis concluded that PID ensures stable operation only in disturbance-free environments, while nonlinear or time-varying dynamics require hybrid, adaptive, or intelligent extensions for long-term reliability [32].

These findings are further supported by the study of Çaska (2024), which compared the performance of classical PID and optimized fractional-order PID (FOPID) with a novel symbolic discrete controller synthesis (SDCS) method. PID-based controllers exhibited overshoot, longer settling time, and steady-state error, whereas SDCS achieved more accurate, faster, and overshoot-free control of a nonlinear quadcopter model. This clearly demonstrates the practical limitations of PID controllers in complex UAV environments [39].

5. Alternative and Advanced PID-Based Approaches

To overcome the limitations of classical PID controllers, numerous advanced and alternative solutions have been developed in recent years, aiming to enhance robustness, adaptability, and control accuracy in dynamically changing UAV environments. One of the most widespread approaches is adaptive PID, where the gain parameters (Kp, Ki, Kd) are automatically adjusted in response to sensor data or external disturbances [31,33]. As a result, the system can react in real time to variations such as payload or wind strength, reducing the risk of instability and overcompensation.

Fuzzy logic–based PID approaches also provide significant improvements. Instead of relying on exact mathematical models, these methods employ rule-based inference, making them effective in handling uncertain, variable, or difficult-to-model environmental and system parameters [25]. In an agricultural UAV application, Amertet et al. demonstrated that fuzzy PID improved altitude, velocity, and lateral tilt control by 11–44% on average compared with classical PID [25]. Parameters were modified online in real time according to fuzzy logic rules, ensuring flexible operation even in noisy and disturbance-prone conditions.

Another direction of development is represented by fractional-order PID, which extends the integral and derivative actions to fractional orders. This enables finer tuning and greater control flexibility in nonlinear UAV systems [40]. Experiments conducted with a Tello EDU quadcopter showed that FOPID ensured faster and more stable recovery to the desired state under all disturbance scenarios compared with classical PID, even in cases such as propeller damage.

Artificial intelligence and machine learning methods—including long short-term memory (LSTM) neural networks, genetic algorithms (GA), the Firefly algorithm, and particle swarm optimization (PSO)—are also increasingly applied for PID parameter optimization. Yoon & Doh (2022) optimized PID using LSTM and NSGA-II (Non-dominated Sorting Genetic Algorithm-II), which reduced stabilization time from 64.99 seconds to 1.99 seconds, representing a 96.9% improvement. The optimized controller not only responded faster but also exhibited reduced overshoot and improved stability [35,41,42].

In real-time experiments, Noordin et al. (2023) applied an adaptive PID (APID) and a fuzzy-compensated variant (APIDFC – Adaptive PID with Fuzzy Compensator) on a mini-drone [33]. Tests revealed that these advanced approaches reduced energy consumption by 2–4% and improved response time by 45–46% under payload variations compared with classical PID.

Overall, these advanced PID-based controllers contribute significantly to achieving more stable, accurate, and reliable drone operation, particularly under variable environmental conditions and in scenarios requiring rapid and precise responses. In the future, PID is expected to play a dominant role not as a standalone method, but as a component of hybrid and intelligent systems in UAV control.

6. Comparison with Other Control Methods

Although PID controllers are reliable and easy to implement, they do not always provide sufficient performance, particularly in nonlinear and dynamically changing UAV environments. As discussed in Section 4, PID is sensitive to external disturbances, difficult to tune, and limited in adaptability.

In the study of Ma'arif & Setiawan (2021) mentioned in Section 4, classical PID was compared with integral state feedback (ISF) control in angular velocity regulation of a DC motor [36]. ISF achieved faster response time (0.855 s), 0% overshoot, and more stable operation, while PID performance fluctuated depending on the reference value and showed high sensitivity even to minor input changes. The advantage of ISF lies in considering all state variables, thereby providing a more complete representation of system dynamics.

Alrawi et al. (2024) compared classical PID with a high-speed switching controller in a UAV environment [38]. While PID achieved fast initial response (0.6 s), it produced 18% overshoot, 8 seconds of settling time, and 0.3 steady-state error. In contrast, HSSC stabilized the system within 1.1 seconds without overshoot, while responding effectively to disturbances and load variations.

These results indicate that HSSC offers a more robust and energy-efficient alternative to PID.

Several studies have highlighted that PID is not competitive with advanced methods such as linear quadratic regulation (LQR), model predictive control, sliding mode control, or artificial intelligence–based approaches. Methods such as MPC and machine-learning-based solutions can predict future system states and optimize complex objective functions. Consequently, they respond more robustly to environmental variations and provide higher accuracy, stability, and energy efficiency in UAV control [34,35].

The review of Cetinsaya et al. (2024) emphasized that although most commercial UAVs still employ classical PID, adaptive, intelligent, and hybrid control solutions are gaining prominence [34]. While the number of studies on PID is decreasing, methods based on fuzzy logic, neural networks, reinforcement learning, and swarm intelligence are increasingly in focus. The trend points towards approaches emphasizing prediction, adaptability, and energy efficiency.

This conclusion is supported by the study of Çaska (2024), which compared the performance of classical PID and optimized fractional-order PID with symbolic discrete controller synthesis [39]. SDCS ensured faster settling in all tested motion directions (e.g., 1.4 s), zero overshoot, and no steady-state error, while even the best results with FOPID still exhibited overshoot (e.g., 0.965%) and several seconds of settling time (e.g., 2.374 s). These results clearly demonstrate that PID-based controllers, even in optimized forms, lag behind advanced methods in managing complex UAV dynamics.

Okasha, Kralev & Islam (2022) compared the performance of PID, LQR, and MPC on the Parrot Mambo mini-drone platform in both simulations and real experiments [43]. Their findings indicated that PID performed adequately in X and Y trajectory tracking but exhibited strong oscillations, particularly in altitude regulation, where significant overshoot occurred. LQR provided the best orientation maintenance, while MPC stood out in terms of stability and robustness, particularly in experimental results. The study demonstrated that while PID can be effective in single-input single-output (SISO) systems, multivariable systems require LQR or MPC as more efficient solutions, especially for disturbance handling and leveraging predictive control advantages.

Okulski & Ławryńczuk (2022) investigated the energy demand and performance of agile quadcopter flight by comparing PID with a modified MPC [44]. Experiments on a custom-built drone and within the ArduCopter environment employed a novel Trajectory Guessing Algorithm to reduce MPC computation time. Results showed that the modified MPC significantly improved maneuverability and reduced control delay (6 ms compared with 24 ms for PID).

Hui, Guo, Han & Wu (2024) developed an H∞-based dual-cascade MPC strategy to improve quadcopter flight stability in turbulent airflow [45]. The method separated two loops: attitude control was handled by an H∞ controller, while angular velocity control was performed by MPC using preprocessed data. This architecture reduced MPC computational load while enhancing robustness against disturbances. MATLAB simulations confirmed that the combined controller achieved smaller oscillations, shorter transients, and more accurate trajectory tracking than PID. The results indicated that the H∞–MPC combination is particularly effective in turbulent environments, providing rapid responses to stochastic disturbances and restoring drone attitude and position with minimal error.

Overall, the literature indicates that PID alone is insufficient for controlling complex UAV systems. While its simplicity makes it a valuable starting point, achieving higher levels of performance and robustness requires the application of advanced control strategies or integration with them.

7. Conclusions and Future Directions
As discussed in the previous sections, PID controllers continue to play a significant role in UAV control due to their simplicity, rapid implementation, and widespread industrial use [32,34]. However, recent research has made it clear that classical PID alone is insufficient for modern flight environments characterized by disturbances and dynamic variations [31,38].

Several studies emphasize that the future of effective UAV control lies in hybrid solutions, where PID is complemented with fuzzy logic, machine learning algorithms, or predictive control methods [35,46]. One of the key directions for future research is the integration of state estimation techniques—such as Kalman filters or neural networks—together with multi-objective control strategies that simultaneously optimize position, energy efficiency, and stability [25,36,40].

In summary, PID will remain a fundamental starting point in UAV control, but its future role will most likely be realized in intelligent, adaptive, and hybrid forms within complex UAV systems [34].

8. Conclusion
Based on the findings of the literature review, PID controllers remain widely applied and reliable tools in drone control, primarily due to their simplicity, low computational demand, and rapid implementation. At the same time, the reviewed studies clearly demonstrate that classical PID cannot effectively address nonlinear UAV dynamics, sensitivity to external disturbances, and varying environmental conditions. Advanced approaches—such as self-tuning PID, fuzzy-PID, fractional-order PID, and machine-learning-optimized controllers—offer significant improvements in terms of robustness, stability, and response time.

Current research focuses on the development of a quadcopter prototype designed for altitude control, providing an experimental environment for the practical comparison of different control strategies, including classical PID, gain-scheduled PID (GS-PID), model predictive control, and H∞ control. The evaluation

emphasizes robustness, stability, and performance, with particular attention to the extent to which each method can ensure accurate control while reducing energy consumption. The overall aim is to identify a control strategy that meets the requirements of modern UAV systems not only in theory but also under real-world conditions.

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