A Review on the Application of PD and PID Controllers in UAV Attitude and Altitude Control

Yucheng Hua

King’s college London London, England

michaelhyc07@foxmail.com

Abstract. Unmanned Aerial Vehicles (UAVs) have become an essential component in civilian, industrial, and defense applications due to their high mobility, low operational cost, and ability to perform missions in dangerous environments. However, maintaining stability and accuracy during flight remains a critical challenge because UAVs are nonlinear, underactuated, and highly sensitive to environmental disturbances. Among the wide range of control strategies explored for UAVs, Proportional–Derivative (PD) and Proportional–Integral–Derivative (PID) controllers have retained their popularity because of their simplicity, reliability, and ease of implementation. This paper reviews the application of PD and PID controllers in UAV attitude and altitude control. It compares their fundamental design principles, implementation structures, performance characteristics, and recent advancements, including adaptive, fuzzy, and neural extensions. Through analysis of more than fifteen recent studies, the paper highlights that PD control provides fast transient performance suitable for agile maneuvers, whereas PID control ensures accurate steady-state tracking under persistent disturbances. The review concludes with a discussion of limitations in classical PID tuning and outlines future trends toward intelligent, hybrid, and AI-assisted PID architectures designed for next-generation UAV autonomy.

Keywords: UAV control, PID controller, PD controller, Intelligent and adaptive control.

1. Introduction

Over the past decade, unmanned aerial vehicles (UAVs) have emerged as one of the most dynamic research areas in control engineering. UAVs, ranging from micro quadrotors to fixed-wing drones, are now widely employed in mapping, logistics, agriculture, surveillance, and infrastructure inspection. Despite these advancements, flight control remains a major engineering challenge due to the nonlinear aerodynamic behavior, strong coupling between translational and rotational dynamics, and uncertainties arising from factors such as payload variation, battery depletion, and wind disturbances [1-3].

To ensure reliable operation under these uncertainties, UAV control algorithms must guarantee stable and robust flight performance. A typical UAV control system consists of two primary subsystems: attitude control (stabilization of roll, pitch, and yaw) and altitude or position control (maintaining or tracking a height or spatial trajectory). Achieving both simultaneously requires a controller that effectively balances responsiveness with steady-state accuracy [4-6].

Among various control strategies such as linear quadratic regulation (LQR) [7], model predictive control (MPC) [8], and sliding mode control (SMC) [9], the classical PID family continues to dominate UAV applications. Its enduring success stems from its intuitive structure, well-established tuning methods, and computational efficiency, which make it well-suited for real-time embedded implementation [10].

The PD controller uses proportional and derivative actions to minimize both instantaneous and rate-of-change errors, providing fast transient responses with limited overshoot. The proportional–integral–derivative (PID) controller extends this,
which eliminates steady-state errors, making it particularly effective for altitude regulation [11-13].

Traditionally, PID parameters have been tuned empirically using classical methods such as Ziegler–Nichols or Cohen–Coon [14]. Although these techniques perform adequately for linear systems, UAV dynamics are strongly nonlinear, prompting the development of adaptive and intelligent PID variants. Recent studies, including those by Zhou and Zhang (2020), Nguyen and Lee

(2021), and Kumar et al. (2022), have demonstrated that optimization-based and fuzzy-adaptive PID controllers significantly enhance stability and tracking performance under time-varying conditions. This review aims to:

(1) summarize the mathematical foundations of PD and PID control as applied to UAV dynamics;

(2) compare their performance in attitude and altitude stabilization; and

(3) identify emerging hybrid approaches that integrate PID control with artificial intelligence techniques to advance next-generation UAV autonomy.

2. Methodology and Control Principles

A UAV's motion can be described using Newton–Euler equations that capture both translational and rotational dynamics. This section provides a complete mathematical description of the UAV's dynamics, which forms the foundation for PD and PID control design.

2.1. Translational Motion (Linear Dynamics)

The translational equations describe the motion of an unmanned aerial vehicle (UAV) in three-dimensional space (x, y, z) under the combined effects of total thrust and gravity. These equations are derived from Newton's second law and expressed as:

$$m[\ddot{x},\ddot{y},\ddot{z}]^T = R[0,0,T]^T - [0,0,mg]^T \tag{1}$$

where m denotes the UAV mass, *T* is the total thrust produced by the propellers, *R* represents the rotation matrix transforming vectors from the body frame to the inertial frame, and g is the gravitational acceleration.

By expanding the rotation matrix R, the component-wise translational dynamics can be written as:

$$\begin{aligned} m\ddot{x} &= T(\cos\phi\sin\theta\cos\gamma + \sin\phi\sin\gamma) \\ m\ddot{y} &= T(\cos\phi\sin\theta\sin\gamma - \sin\phi\cos\gamma) \\ m\ddot{z} &= T(\cos\phi\cos\theta) - mg \end{aligned} \tag{2}$$

These equations describe the linear accelerations of the UAV along the x, y, and z axes as functions of the total thrust T and the attitude angles (φ, θ, ψ). They are particularly important for altitude control, since the vertical motion (z) is directly determined by the balance between the thrust and gravitational forces.

2.2. Rotational Motion (Angular Dynamics)

The rotational dynamics describe how the body of an unmanned aerial vehicle (UAV) rotates about its three principal axes—roll (φ), pitch (θ), and yaw (ψ). Using Euler's rotational equations, the general form of motion can be expressed as:

$$\begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} - \begin{bmatrix} (\dot{\theta}\dot{\psi})(I_z - I_y) \\ (\dot{\phi}\dot{\psi})(I_x - I_z) \\ (\dot{\phi}\dot{\theta})(I_y - I_x) \end{bmatrix} \tag{3}$$

where $I = \mathrm{diag}(I_x, I_y, I_z)$ denotes the inertia matrix, and τ_φ, τ_θ, and τ_ψ represent the control torques generated by differential rotor thrusts. The second term accounts for cross-coupling effects arising from gyroscopic and Coriolis forces, which become significant during rapid rotational maneuvers.

Under small-angle assumptions or in linearized flight conditions, the equations can be decoupled into:

$$\begin{aligned} I_x\ddot{\phi} &= \tau_\phi \\ I_y\ddot{\theta} &= \tau_\theta \\ I_z\ddot{\psi} &= \tau_\psi \end{aligned} \tag{4}$$

2.3. Summary of UAV Dynamics Equations

Most unmanned aerial vehicle (UAV) controllers employ a cascaded control architecture consisting of two primary loops. The outer loop regulates altitude and position using a PID controller, while the inner loop stabilizes the attitude through PD or PID control. The outer loop generates desired attitude commands based on altitude or position errors, and the inner loop translates these reference signals into corresponding motor thrusts and torques [15].

As shown in Table 1, the performance of PID controllers is highly dependent on the accuracy of parameter tuning. Traditional approaches, such as the Ziegler–Nichols method, provide approximate gain values derived from the system's oscillatory response. In contrast, heuristic optimization algorithms—including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Differential Evolution (DE)—can automatically determine optimal gains by minimizing objective functions such as the Integral of Time-Weighted Absolute Error (ITAE). More recent developments integrate fuzzy logic systems to adapt the proportional, integral, and derivative gains (K_p, K_i, K_d) in real time according to the magnitude and rate of the control error.

Table 1. Translational and Rotational Dynamics of UAV Motion

Motion Type	State Variables	Governing Equation	Control Input
Translational	x, y, z	$m\ddot{x} = RT - mg$	Total Thrust (T)
Rotational	φ, θ, ψ	$I\dot{\omega} + \omega \times (I\omega) = \tau$	Control Torques (τ_φ, τ_θ, τ_ψ)

3. Results and Discussion

Attitude stabilization ensures that a UAV maintains its desired roll, pitch, and yaw orientations under external disturbances. Proportional–Derivative (PD) controllers are widely employed for this purpose because of their fast response and effective damping characteristics. In comparative simulations conducted by Kim and Lee, a PD controller achieved a 40% shorter rise time than a standard PID controller. However, the steady-state error remained approximately 0.12 m, indicating a persistent bias when external torques were applied [5].

In contrast, Proportional–Integral–Derivative (PID) controllers exhibit slower transient responses but provide superior steady-state accuracy. Li and Wang reported altitude deviations within ±0.05 m using PID control, compared with ±0.12 m for PD control. Experimental tests confirmed that the integral component effectively compensates for long-term drift caused by asymmetric propeller thrusts [3].

A comparative summary indicates that PD control favors agile maneuvers and rapid stabilization after disturbances, whereas PID control excels in accurate hovering and steady flight. For example, Singh implemented a real-time PID algorithm in the thrust command loop, reducing altitude deviation by 30% compared with PD control under gusty wind conditions [6]. Zhao and Chen proposed a hybrid PID–MPC controller that combines predictive control with conventional PID feedback [10]. Simulation results showed improved disturbance rejection and smoother actuator outputs, achieving rise times comparable to PD control while maintaining PID-level accuracy.

Despite its widespread success, classical PID control has several limitations: (1) fixed gains perform poorly when system dynamics vary; (2) integrator windup during actuator saturation leads to overshoot; and (3) derivative action amplifies sensor noise. To address these issues, anti-windup compensators and filtered derivative terms are often introduced, though their tuning remains dependent case.

Recent research has introduced intelligent PID variants to overcome these challenges. Fuzzy-PID controllers adjust gains based on fuzzy rules relating the error (e) and its rate of change (de/dt) [7]. Neural PID controllers use neural networks to approximate optimal gain mappings [11], while adaptive PID controllers continuously update parameters using gradient or recursive least-squares algorithms [9]. Zhang et al. demonstrated that an AI-enhanced PID controller reduced energy consumption by 15% and improved tracking accuracy by 25% in simulations [14].

The essential trade-off between PD and PID control lies in speed versus accuracy. PD control minimizes transient time by responding directly to the error rate but lacks integral correction, whereas PID control incorporates accumulated error, improving robustness at the cost of slower dynamics. Modern UAV systems increasingly adopt hybrid loop structures, such as PD for inner attitude stabilization and PID for outer altitude regulation.

From a computational perspective, PD and PID algorithms are highly efficient, typically requiring less than 2% CPU usage on STM32 microcontrollers. Their simplicity and low processing demand make them well-suited for small UAVs with limited onboard computational resources, compared with more complex approaches such as model predictive control (MPC) or reinforcement learning-based controllers.

4. Conclusion

This paper reviewed the applications and comparative performance of PD and PID controllers in UAV attitude and altitude control. PD controllers provide fast transient response, suitable for aggressive maneuvers and disturbance recovery. PID controllers deliver superior steady-state accuracy and robustness against constant disturbances. The integration of fuzzy, neural, and optimization techniques marks a clear trend toward intelligent and adaptive PID systems capable of real-time self-tuning. Hybrid architectures that cascade PD and PID loops remain the most practical for current UAV implementations due to their balance of performance and simplicity. Future work should focus on embedding adaptive PID algorithms into hardware-constrained UAV platforms, developing standardized tuning benchmarks, and validating AI-assisted PID frameworks under real flight conditions.

References

[1] I. Sadeghzadeh, et al., “PD and PID-based attitude control of quadrotor UAVs,” IEEE Trans. Aerosp. Electron. Syst., 2019.

[2] L. Zhou and H. Zhang, “Ziegler–Nichols tuning of PID controller for UAV stabilization,” Control Eng. Pract., vol. 102, p. 104526, 2020.

[3] J. Li and X. Wang, “Altitude control of quadrotor UAV using improved PID control,” Aerosp. Sci. Technol., vol. 99, p. 105704, 2020.

[4] Q. Nguyen and J. Lee, “Genetic-algorithm-based PID optimization for drone systems,” Appl. Sci., vol. 11, no. 3, p. 1142, 2021.

[5] D. Kim and S. Lee, “Comparative performance of PD and PID controllers for UAV attitude stabilization,” Sensors, vol. 21, no. 12, p. 4179, 2021.

[6] A. Singh, “Disturbance rejection in UAVs using PID-based control,” Int. J. Control, vol. 93, no. 5, pp. 1045–1059, 2020.

[7] R. Kumar, et al., “Fuzzy adaptive PID for UAV flight control,” ISA Trans., vol. 120, pp. 183–192, 2022.

[8] I. Al-Mashaqbeh, “Neural-network tuning of PID controllers for UAVs,” IEEE Access, vol. 10, pp. 78512–78522, 2022.

[9] S. Rahman and K. Park, “Adaptive PD controllers for quadrotor attitude control,” Control Theory Technol., vol. 20, no. 4, pp. 514–528, 2022.

[10] M. Zhao and Y. Chen, “Hybrid PID–MPC control for UAV trajectory tracking,” Aerosp., vol. 10, no. 2, p. 211, 2023.

[11] J. Alvarez and P. Ruiz, “Neural PID control in nonlinear UAV systems,” J. Intell. Robot. Syst., vol. 108, no. 7, p. 411–426, 2023.

[12] Y. Tang, et al., “A comparative survey of classical and intelligent PID controllers in UAVs,” Appl. Sci., vol. 13, no. 5, p. 2905, 2023.

[13] T. Zhang, et al., “AI-enhanced PID controller design for quadrotors,” Robot. Auton. Syst., vol. 173, p. 104456, 2024.

[14] H. Zhang and J. Xu, “A review of PID control applications in UAVs,” Aerosp. Res. J., vol. 12, no. 1, pp. 65–78, 2024.

[15] P. Mohanty, “Performance analysis of PID tuning methods for UAV flight control,” IEEE Access, vol. 9, pp. 31211–31222, 2021.