

Comparative Analysis of Drone Stabilization Methods and Optimization Techniques

Yuxin (Yuliana) Zheng ^{1, *}, Zichen Zhao ^{2, a}

¹ Concord College, Shrewsbury, Shropshire, SY57PF, UK

² The Affiliated International School of Shenzhen University (AISSU), Shenzhen, Guangdong, China

* Corresponding author: Yuxin (Yuliana) Zheng (Email: yxzheng616@gmail.com),

^a 234484124@qq.com

Abstract. With the rapid expansion of unmanned aerial vehicle (UAV) applications in commercial, military, and scientific fields, flight stabilization has become a critical factor influencing both performance and safety. This study examined the significance of stabilization in UAVs and investigated various methods developed to achieve it. The primary objective was to identify the most effective and accessible optimization technique on improving the drone stability. Relevant literature was collected from IEEE Xplore, ScienceDirect, and SpringerLink databases, focusing on publications from 2000 to 2024. The study compared both traditional and modern stabilization approaches while exploring optimization techniques designed to enhance adaptability and reliability in complex real-world environments. The methodology involved theoretical analysis of the physical principles underlying UAV operations, followed by the integration of sensors and signal-conditioning circuits into the control system design. A proportional–integral–derivative (PID) control framework was modeled and evaluated, and its limitations under nonlinear conditions were analyzed. In contrast, sensor fusion combined with optimization algorithms significantly improved the system’s robustness and precision. The results demonstrated that integrating conventional control with intelligent methods provided superior stabilization performance. This research contributed to a better understanding of UAV stabilization mechanisms and offered valuable insights for future development of more reliable and adaptive drone control systems.

Keywords: Drone; Stabilization; Optimization; PID Control; Sensor.

1. Introduction

In recent years, the rapid evolution of embedded systems, lightweight materials and autonomous control technologies has driven more and more products towards greater efficiency, responsiveness and precision [1]. The most typical example is the Unmanned Aerial Vehicles (UAV), commonly referred to as drones which are aircraft that operate without human pilots which have experienced significant innovation and miniaturization from a remote-controlled aircraft to a highly sophisticated autonomous system, making them more accessible and practical for civil and commercial applications [2]. This includes precision agriculture, environment monitoring, and disaster management. Their ability to be able to operate in hazardous environments makes them irreplaceable tools for the modern industry and research [3].

Among the critical aspects of the UAV development, flight stabilization still remains a challenging area with considerable room for refinement. Stability refers to the systems’ ability to respond effectively rapidly to internal and external stimuli, including payload variations, sensor noise, wind disturbances and other aerodynamic perturbations [3]. It is fundamental for achieving the flights’ stability in the aspect of ensuring precise control over the drone’s position and orientation, which are the key requirements for accurate task executions.

Unlike fixed-wing aircraft that benefit from its aerodynamic stability, the multi-rotor UAVs are inherently unstable platforms, meaning that even small disturbances from the environment may cause drones’ deflections from their intended flight path. Their ability to remain airborne depends fully on the active feedback control. To address this, it is essential to implement advanced control

systems which can continuously interpret and analyze real-time sensor data from IMUs, barometers and GPS in order to apply corrections. These systems, often implemented using proportional interval derivative (PID) controllers, model predictive control (MPC) are critical for ensuring stable flight performance in the presence of both predictable variations and unexpected environmental disruptions [4].

In parallel with stabilization, optimization techniques play an increasingly important role in enhancing UAVs performances by adjusting details for control system parameters, algorithmic behaviors and mechanical configurations. Optimization seeks to achieve higher intelligence and accuracy to dynamic environments through techniques such as PID gain tuning, without optimization techniques, drones may exhibit issues such as sluggish response and not be able to perform advanced tasks like obstacle avoidance.

This essay aims to present the background knowledge for drones and a comparative analysis of various drone stabilization methods, ranging from traditional PID to modern MPC and artificial intelligence-based approaches in order to find out the most effective way to maintain stabilization. For the main text, it was divided into four aspects, including Physical Basis of UAV Operations, Drone Stabilization Methods, Optimization Techniques and Comparative Evaluation.

2. Physical Basis of UAV Operations

2.1 Air-frame and Structural Design

The air-frame is the foundational mechanical structure of UAVs, acting as the physical skeleton which supports all onboard subsystems. Modern UAV airframes are predominantly constructed from lightweight materials such as Carbon Fiber Reinforced Polymer (CFRP) and aircraft-grade aluminum alloys in order to ensure both flight efficiency and mechanical reliability [5]. These material selections offer exceptional stiffness-to-weight ratios and intrinsic vibration resistance in order to minimize energy consumption and reduce high frequency noise. This is essential for sensitive instruments, particularly IMUs [6], whose readings can be easily skewed by structural oscillations.

Air-frame geometry is tailored to specific mission requirements. For example, H-frames and X-frames configurations are optimized for payload stability, thrust symmetry and the center-of-mass alignment which is often employed in the multi-rotor UAVs, while coaxial and hydride vertical take-off and landing (VTOL) designs enhance space and efficiency and operational versatility [6]. To address the engineering considerations, including moment of inertia and aerodynamic drag, this means the frame layout is carefully managed. Due to mechanical disturbances including motors and propellers, effective use of rubber grommets and silicon pads are protectable crucial electronics from mechanical fatigue and signal degradation [6].

As UAV systems evolve towards a higher level of autonomy and modularity, the role of the air-frame extends beyond structural support, but also accommodates other functions such as thermal management, EMI shielding, and plug and play reconfigurability in order to adapt well in the further complex and dynamic operational environment [7].

2.2 Propulsion and Actuation Systems

The propulsion and actuation subsystems are vital for enabling controlled flight and ensuring dynamic stability.

The main electric actuation architectures in drones include brushless DC motors (BLDC), electronic speed controllers (ESCs), and fixed-pitch propellers [8]. BLDC motors are preferred due to their high-torque-weight ratio and minimal mechanical wear, meaning the motors will provide significant rotational force relative to their mass by using a small amount of resources. Moreover, these motors do not operate autonomously; instead, their rotational speed is regulated by ESCs. They receive pulse-width modulated signals (PWM) from flight controllers and then convert these signals into corresponding voltage levels [9]. The induced current enables a real-time modulation of rotor RPM (revolutions per minute) to produce differential thrust across the rotors. Thus, this movement

also causes the spin propellers which impart momentum to the surrounding air and produce a downward airflow known as downwash. According to Newton's third law, the downward acceleration results in an equal and opposite upward force - thrust. Moreover, due to the special airfoil shape and pitch angle of the propeller blades, a pressure difference forms between the upper and lower blade surfaces which generate a lift and explained via Bernoulli's principle [9].

Without mechanical actuation, control in multi-rotor platforms is achieved through differential thrust. Pitch, roll and yaw are produced by asymmetrical modulation of rotor velocities with motor configurations determining the dynamics and fault tolerance of the system [7]. Together, the integration of differential thrust, and efficient power electronics provides a simplified mechanical design while enabling complex dynamics flight behaviors across various UAV configurations.

3. Drone Stabilization Methods

3.1 Attitude Control (PID)

Since differential thrust provides the basic mechanism for maneuvering, stabilization methods like PID control are applied to ensure that these movements remain accurate and well-balanced. PID control is used to adjust the attitude of drones like roll, pitch, and yaw which enables the drone to fly up, forward or spin.

First of all, Proportional-Integral-Derivative controller (PID) is a controller which is widely used in industrial control systems. It continuously calculates the errors to adjust the input signal of the system in the purpose of minimizing the error over time to ensure that the output of the system is close to the set value as precise as possible [10]. Letters in PID each represent a basic necessity—P for proportional, I for integral and D for derivative. The correction applied by PID is based on these three.

In these three parts, P is the major one, for it is needed in every PID system and can recognize the error immediately to produce the right signal that let the drone be stable. The greater value of the P is, the faster the system react [10]. Here is a formula that represent P.

$$P = K_p \cdot e(t)$$

K_p : proportional gain

$e(t)$: error(setpoint - measured value)

I is a bit similar to P, as both are aim to reduce and remove the errors [10], but I is used to eliminate the steady-state error which is the difference between the set-point and the measured value after the system has be stable. Integral algorithm eliminates this error by accumulating the past error and gradually adjust the control output to remove the steady-state deviation [7]. The formulae for I are different in continuous form and derivative form.

Continuous Form:

$$I = K_i \cdot \int_0^t e(t) dt$$

Derivative Form:

$$I = K_i \cdot T_s \sum_{i=0}^k e(i)$$

K_i : integral gain

$\int_0^t e(t) dt$: integral of the error over time

$e(t), e(i)$: errors

T_s : sampling time

D is derivative which is used to predict the trend of future error and adjust the output based on the rate of the change of error [10]. It can make the value of proportion greater and play its role better [7], even can enhance the stabilization and reaction speed of the system through overcoming the oscillation. Here are formulae for derivative.

Continuous Form:

$$D = K_d \cdot \frac{de(t)}{dt}$$

Derivative Form:

$$D = K_d \cdot \frac{e(k) - e(k - 1)}{T_s}$$

K_d : derivative gain

$\frac{de(t)}{dt}$: the derivative of the error

$e(k) - e(k - 1)$: the difference in error

T_s : sampling time

As shown in the formulae of integral and derivative, PID control is divided into continuous form and derivative form. The reason for this is that the way the control system present in realistic is different, it needs to consider the reality condition. Here are the formula of each form, and Table 1 which shows the difference between the forms.

Continuous Form:

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt}$$

$u(t)$: control output

Derivative Form:

$$u_k = K_p e_k + K_i \sum_{i=0}^k e_i \Delta t + K_d \frac{e_k - e_{k-1}}{T_s}$$

k : current time step

Δt : time interval between samples

Table 1. Comparison of Continuous Form and Derivative Form

Aspect	Continuous Form	Derivative Form
Focus	Represents the entire system	Focus on the rate of change
Mathematical Tool	Continuous time, integral and derivative equations	Discrete time, difference equations
Application	Theoretical analysis, modeling	Local behavior, dynamics
Accuracy	Precise, but require numerical methods	Approximate, but simple to calculate
Sensitivity to Noise	Sensitive to high-frequency noise	Can reduce the impact through filtering

3.2 Sensor Fusion

Each sensor on a drone has its own strengths and weaknesses [11]. For instance, an accelerometer measures changes in velocity but is sensitive to vibration. A gyroscope provides angular velocity but can drift over time without correction. GPS gives location data but can be unreliable in areas with weak satellite coverage, such as cities or forests. Barometers help estimate altitude but can be influenced by weather conditions. Magnetometers, used to determine direction relative to Earth's magnetic field, can be distorted by nearby electronics. If a drone relied on only one of these sensors, its performance would be severely limited [11]. That's where sensor fusion comes in.

Sensors like IMU, GPS, LiDAR, infrared sensor, barometer can combine together to provide more precise position and attitude information for drones by conforming and processing the data they

detected. Some examples for this method are combination of IMU and GPS, infrared and visual sensor fusion, multi-modal sensor fusion.

3.2.1 Combination of IMU and GPS

This method is widely used in drones and auto-driving. IMU(Inertial Measurement Unit) is a sensor that be used to test measure the acceleration, angular velocity and the attitude. It is usually made up by gyroscope and accelerometer. GPS (Global Positioning System) works by worldwide positioning, navigation and timing via satellite signals.

Generally, IMU and GPS combined through Kalman Filter. The combination of these two sensor complement each other to achieve accurate position. This is because the low frequency absolute position produced by GPS can correct the accumulate errors in IMU, and IMU can still provide high frequency exercise data and navigation even if the GPS lose its signal [11].

3.2.2 Infrared and Visual Sensor Fusion

Infrared and visual sensor fusion is a technology that combine their searched data which aim is to enhance the system's environmental awareness and decision-making precision [11].

Infrared sensor works based on detecting the infrared radiation that the item emit. All the objects emit infrared radiation unless its temperature is lower than absolute zero(0K/-273°C), but this is rare [12]. Therefore, infrared sensor can detect almost all the items in this world, so it is widely used in many fields like drones and auto-driving car. Unlike infrared sensor which transfer radiation to signal, visual sensor transfer the visible light they catch to signal and useful information is then extracted through image processing technology [12].

Because of these, using infrared and visual sensor fusion enhance the environmental awareness as infrared sensor can work during the night time and the visual sensor can provide high-resolution images if the light is sufficient [12]. The fusion of sensor also optimize the positioning and navigation as the visual sensor can provide visual location to supplement the locating ability of infrared sensor when there is no GPS. Fusion in data helps the drone fly in its intended path and reduce the error, improve the stabilization as well [11].

3.2.3 Multi-modal Sensor Fusion

Compare to multi-modal sensor, single sensor has a lot of limitations and can be affected easily, such as visual sensors can't work without light and infrared sensor can't transmit photograph [11]. Therefore, multi-modal sensor fusion makes up for the drawback of single sensor which let the sensors exploit their advantages to full.

Some drones in civil and industry field can just rely on sensors to achieve and maintain stable flight. For instance, a type of commercial drone which is usually used for photographing called the DJI Phantom series was made up of IMU, GPS, barometer and visual sensor. However, it is still loved by many consumers for its high shooting quality, ease of operation and stabilization.

3.3 Hardware Design

Update and design of the hardware structure is a direct way to improve the stability of drone [13] as the weight and the density of the structure material, the location of the components, the size and even the outlook of drones, all are the factors that affect the flying of the drone. Here are some places that usually be changed in stabilization methods.

3.3.1 Drone's Configuration

Structure is the basis of the drone as its design affect the flying capability and adaptability of the drone directly [13]. Better design of the configuration can lower the vibration and noise of the drone and improve the stability of the structure. For instance, choose a lighter and higher intensity material of the configuration [13] can greatly reduce the damage if collision occurs as the material improve the material strength.

3.3.2 Power Supply System

A long-lasting battery is crucial for drones as it increases the working time and flying scope of the drone so that it reduces the time of takeoff and landing which also improves the efficiency [13]. Safety is another part that can be considered by using the long-lasting battery. After improving the battery life, the drone can reserve enough power to fly back which lowers the risk of crash and damage.

Designing a proper and highly efficient circuit is useful as well. It ensures that the voltage passing through all components is the same and can provide constantly to avoid the errors produced by changes in voltage [14].

3.3.3 Modular Design

Like our body is made up of organisms which each has their own ability, the design of drone also needs to set the components separately for better management. So modular design means that to separate the system into several modules with specific functions independently. This greatly improves the producing efficiency as the components can be designed, produced, tested and maintained by part [14]. Finally these parts will form a complete system via connecting standardized interfaces.

For drones, using modular design helps adjusting the separation of components more flexible so that it can optimize the center of gravity and the distribution of weight to improve the stabilization. It also minimizes the cost of production and maintenance of drones. Factories can set a standard for each component to produce which enhances the reliability and efficiency [14]. In the other hand, when the drone is damaged or broken, modular design makes the maintenance faster and more convenient as probably it only needs to repair a little part of the drone, which also saves money.

4. Optimization Techniques

4.1 Advanced Control Algorithms

Optimization in the context of UAV stabilization refers to the process of reforming control parameters to enhance flight performance, robustness, and energy efficiency.

From the aspect of optimizing control algorithms, it is a crucial step in ensuring UAVs could respond precisely and stably to dynamic flight conditions. The most widely used traditional method is the PID control, which has been mentioned in the previous sections [10]. Optimization in PID involves gain-tuning three parameters (proportional, integral, and derivative) by adjusting the algorithm manually or automatically to observe the direct response. Thus, the UAV could correct its flight path smoothly without any delays or oscillations [4]. For more advanced control systems like MPC, optimization methods are embedded in the algorithm itself. MPC constantly solves an internal optimization problem in real time to determine the best control inputs over a prediction horizon, balancing multiple objectives such as trajectory accuracy and its stability. Hence, optimization isn't just a one-time process, it could be continuous, adaptive, and dynamic, allowing the UAV to make smarter decisions during mid-flight.

In essence, the optimization of control algorithms ensures that the UAVs could perform complex tasks in different environments, while maintaining smooth, reliable and energy-efficient flight [2] - all of which are crucial for high performance stabilization in the real-world operations.

4.2 AI and Machine Learning

Machine learning (ML) as a branch of artificial intelligence, has also played an important role in advancing the stabilization and control systems of UAVs [15]. One thing that makes this method stand out is its ability to mimic human intelligence by learning and adapting in real time, rather than relying solely on fixed mechanical operations. During its training, the model is fed with a large dataset of flight scenarios, and it learns the correct motor commands which result in stable flight. These models are trained to predict the future flight path but also minimize the prediction errors. Once trained, they can deduce the appropriate motor speeds or control surface deflection in real time. As a result, this enables drones to respond intelligently to dynamic and uncertain conditions [16].

Another method is Reinforcement Learning (RL), instead of feeding dataset, this method allows the UAVs to learn through interaction with a simulated or real environment. The drones start up with zero prior knowledge. They will perform random actions towards disturbances and receive feedback from the manipulator in the form of rewards or penalties based on the results of these actions [15]. Over time, this approach enables the UAVs to adapt to new environments or unexpected disturbances [16]. In conclusion, these AI-driven techniques represent a shift from the fixed-rule control to adaptive, self-improving systems that continuously optimize and adapt the flight stability under varying conditions.

4.3 Structure Design Optimization

Optimization of the mechanical structure in UAV design is a critical engineering process aimed to achieve the ideal balance between strength, weight, aerodynamics, and modularity. As mentioned in the previous sections, the airframe must be rigid but also light weighted [17]. To accomplish this, structural optimization often begins with the finite element analysis (FEA), allowing engineers to know the mechanical stress distributions across the whole airframe under different loading conditions. By using this technique, engineers could identify areas of the structure that experience high stress while simultaneously removing unnecessary material from low-stress regions to reduce overall mass. This whole process, known as topology optimization. Furthermore, the weight distribution for drones is carefully managed where its center of gravity needs to be in the right place to hover in the air [4]. Otherwise, the flight controller must work harder, using more power and potentially reducing its performance.

Engineers also use the Computational Fluid Dynamics (CFD) to design shapes that reduce air resistance. This means that adjusting the drone's arm angles, motor placement, or even the shape of the body to help it cut through the air smoothly, meaning that less drag force is required from the motor, causes the aircraft to fly longer [17]. The cleaner aerodynamics make the UAV more responsive to control inputs [4], and also less disturbances mean less work for the controller in order to achieve better stability.

5. Comparative Evaluations

5.1 Stabilization Methods

As mentioned previously, the methods that be compared are attitude control, sensor fusion and hardware design. Table 2 clearly shows their advantages and disadvantages.

Table 2. Comparative Analysis for Different Methods

	Advantage	Disadvantage
Attitude Control	<ul style="list-style-type: none"> - Easy to implement - High efficiency which satisfied the real-time control - Reliable / low cost 	<ul style="list-style-type: none"> - Limited adaptability - Hard to optimize parameter - Lack of robustness - Can't handle complex systems
Sensor Fusion	<ul style="list-style-type: none"> - Good robustness - High-precision estimation - Adapt complex environment - Can reduce error 	<ul style="list-style-type: none"> - Intricate algorithm - Difficult calibration - Computationally intensive - Rely on quality
Hardware Design	<ul style="list-style-type: none"> - Basis of stabilization - Boost performance directly - Good adaptability - Reliable 	<ul style="list-style-type: none"> - Costly - Low flexibility - High requirements for production - Balance between capability and weight

The comparison in Table 2 shows that each stabilization methods play different roles in improving UAV performance. Attitude control is one of the most commonly used approaches because it is simple to apply, inexpensive, and capable of handling real-time adjustments. However, it struggles to

adapt to changing flight conditions and tends to lose effectiveness in complex or nonlinear systems. Moving on to sensor fusion, on the other hand, provides more accurate and stable control by combining data from multiple sensors, which helps reduce errors and improves adaptability in unpredictable environments. Still, this method often requires precise calibration and high computational power, which can be difficult for smaller or low-cost drones. Hardware design offers another perspective by improving the physical structure of the UAV itself, directly enhancing stability and reliability. Yet, it usually increases production costs and limits flexibility because of the need to balance performance, weight, and manufacturing precision.

In summary, there is no single method that works best in all situations. The most effective approach is usually a combination of attitude control and sensor fusion, supported by a well-designed hardware system. This hybrid setup brings together the fast response of control systems, the accuracy of data fusion, and the reliability of solid mechanical design, allowing UAVs to maintain stable flight even in challenging conditions.

5.2 Optimization Techniques

Proportional-Integral-Derivative (PID) algorithms remain foundational due to their mathematical simplicity and low computational costs - traits particularly advantageous for the embedded systems with constrained resources such as processing power. For example, a well-tuned PID controller reduces the steady-state error by up to 90% thus, it stabilizes the Quadra rotors within only a few milliseconds, which is essential for the high-frequency attitude correction and the precise trajectory tracking. However, PID's fixed parameters (K_p , K_i , K_d) do limit the adaptability to dynamic flight conditions, such as varying payloads or wind gusts [20]. Consequently, the modern control methodologies often integrate techniques such as the gain scheduling, model predictive control. Nonetheless, the PID remains widely used as a baseline or inner-loop controller within the hierarchical frameworks due to its stability guarantees and the ease of integration.

Adaptive control algorithms do address this limitation by dynamically adjusting the controller parameters from different perspectives in real-time based on sensor feedback. Research has shown that adaptive controllers could improve the disturbance rejection by 30-40% compared to the PID in a turbulent environment [20]. However, these programs are way more mathematically complicated and demand greater onboard processing capabilities and sophisticated sensor fusion techniques. MPC, which has been mentioned before, represents a further advancement, employing an internal model of the drone to predict the future states and optimize control inputs over a prediction horizon. Its control accuracy is high - often achieving the trajectory tracking errors below 2cm. However, the MPC requires a high computational power, which has limited its deployment to drones equipped with specialized processors or off-board computation.

Moving on to the structural optimization, the mechanical design of the drone directly impacts the stabilization performances. Studies indicate that rigid, lightweight frames made from the carbon fiber composites reduce the vibration transmission by nearly 50%, significantly improving the sensor accuracy [19]. However, it could be argued that after optimizing the drone, there is an average increase in the product weight of 18%, with a declined weight capacity of -14% [18].

Artificial intelligence further revolutionizes drone stabilization through sensor fusion, autonomous navigations and control parameter optimization. Kalman filters enhanced with neural networks offer reliable state estimation by effectively filtering the unnecessary data from the Inertial measurement Units(IMUs) and GPS, to achieve the outdoor positioning accuracy which is 10 cm even in GPS-denied environments. Reinforcement learning enables drones to autonomously develop specific flight surgeries in complex and dynamic settings and be able to reduce energy consumption around 15%. However, on the downside, the drone spends longer time on training and learning with the data, roughly 310 hours [19].

Among the compared methods, evolutionary algorithms are the most accessible and cost-effective, providing efficient controller tuning with the minimal computational cost. By using both Kalman

filters and reinforcement learning to offer a high accuracy and adaptability which makes it ideal for the low-budget drone optimization projects.

6. Conclusion

This study explored and also compared different stabilization methods that are used in unmanned aerial vehicles (UAVs), aiming to identify the most effective and accessible techniques for optimizing flight stability. UAV stabilization plays a vital role in ensuring flight safety, control accuracy, and system reliability, especially as drones are increasingly employed in people's daily life and even in research applications

The analysis focused on several major control strategies, including PID control, sensor fusion, hardware-based solutions such as differential thrust mechanisms, and also algorithms. The findings showed that while traditional PID control remains widely used due to its simplicity, low cost, and high efficiency in real-time applications, it lacks adaptability in nonlinear and unpredictable environments. Differential thrust and hardware optimization improved physical stability and maneuverability, however, they were limited by cost, flexibility, and design constraints.

These results suggest that algorithm-based stabilization methods, particularly those integrating intelligent optimization with classical control frameworks, provide the best balance between performance, reliability, and adaptability. Such hybrid approaches are well-suited to meet the growing demands of modern UAV applications, where both precision and environmental adaptability are essential.

Despite the progress demonstrated in this study, current stabilization research still faces limitations in real-time adaptability, computational efficiency, and scalability. Future research should focus on developing lightweight, adaptive algorithms, improving onboard computing efficiency, and expanding integration between control systems and hardware design to support more autonomous and resilient UAV operations.

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