# Optimizing PID and Sliding Mode Control for Quadcopter UAV Stabilization

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**Abstract.** Quadcopter Unmanned Aerial Vehicles (UAVs) have seen widespread use in many industries recent years because of their versatility and efficiency in various applications. Integral components of the flight control system, such as PID (Proportional-Integral-Derivative) control and SMC (Sliding Mode Control) control, are extensively employed to make sure the robustness, stability and performance of these UAVs. This article provides a comprehensive overview of the current status and underlying principles of PID and SMC control methods as applied to quadcopter UAVs. It summarizes the latest research findings on the stability provided by these two control strategies and explores potential future developments. Emphasis is placed on enhancing the stability of quadcopter UAVs by integrating artificial intelligence with traditional control methods. The article also discusses the inherent challenges and limitations associated with PID and SMC control, offering insights into their optimization. Advantages and potential issues in the optimization process are highlighted, along with prospective directions for future research. By addressing both the current state and future possibilities, this article aims to contribute to the advancement of control methods for quadcopter UAVs, ensuring their reliable and efficient operation in increasingly complex environments.

**Keywords:** Unmanned Aerial Vehicle, PID Control, Sliding Mode Control, Artificial Intelligence, Quadcopter

## 1 Introduction

A quadcopter drone is a sort of Unmanned Aerial Vehicle typified by a four-rotor design. This design provides stability and maneuverability, making quadcopters popular for a variety of applications [1]. UAV technology has evolved over generations, from basic remotely piloted aircraft to the latest generation with full autonomy, smart sensors, and compliance with safety and regulatory standards, and nowadays quadcopters are utilized in a variety of industries and aspects, including military, commercial, logistic, environmental, and so on [2].

Y. Wang (ed.), *Proceedings of the 2024 2nd International Conference on Image, Algorithms and Artificial Intelligence (ICIAAI 2024)*, Advances in Computer Science Research 115,
https://doi.org/10.2991/978-94-6463-540-9_48

Modern quadcopter UAVs are sophisticated devices that employ a variety of technologies to achieve their functionality. These technologies enable quadcopter UAVs to perform complex maneuvers, remain stable and carry out tasks with high precision. The following are some of the main features and the technologies used to achieve them:

Stability and control: Modern quadcopters employ advanced flight control systems for precise maneuvering and stability in the air. These systems typically employ PID (Proportional, Integral, Derivative) controllers to maintain balance and orientation by regulating the speed of each rotor. A study by Wei Dong et al. discusses the modeling and control of quadcopter UAVs with aerodynamic concepts, focusing on high-performance flight control methods using improved active disturbance suppression techniques [3].

Autonomous flight: Many quadcopters are capable of autonomous flight, relying on technologies such as global positioning systems (GPS) for navigation, inertial measurement units (IMUs) for localization, and are equipped with a variety of sensors including accelerometers, gyroscopes, barometers, and sensors for obstacle detection and avoidance. These technologies enable quadcopters to perform tasks without direct human control, ranging from following preset waypoints to dynamically adapting their path to the environment [4].

Computer vision and pattern recognition: The integration of computer vision technologies enables quadcopter UAVs to recognize and interact with objects and environments in real time. This is critical for applications like search and rescue, surveillance and agricultural monitoring [5].

Energy efficiency and aerodynamics: quadcopter UAVs designs and materials are optimized for energy efficiency and aerodynamics to maximize flight time and performance. Lightweight materials (e.g., carbon fiber composites) are often used for the frame, while the aerodynamic design minimizes drag. This is critical to extend the operational range and flight time of quadcopters [6].

Real-time data processing and communications: Modern quadcopter UAVs can process data and communicate with other systems in real time. This includes transmitting video feeds, data of sensors, and receiving control orders. The ability to process and transmit data in real time is critical for applications that require immediate response or analysis [7].

To achieve these characteristics, modern quadcopter UAVs use a combination of hardware and software technologies. For example, they can employ advanced control algorithms including proportional-integral-derivative control or sliding mode control to maintain stability and maneuverability [7-9].

In the paper " A review on drones controlled in real-time", the author discusses the use of PID control in UAVs, stating that because of its simplicity and effectiveness, PID controllers are widely used control algorithms in UAVs field [7]. The paper also mentions the use of SMC control, which is of practical use in dealing with uncertainties and disturbances in UAV dynamics. This paper will focus on the application of PID control and SMC control for quadcopter UAVs.

# 2 Related Control Principle in UAV

## 2.1 PID Control and Its Use in UAV Stabilization

In quadcopter UAVs, PID control is used to maintain the stability and reliability of the UAV. The adjustment of the altitude, attitude (roll, yaw, pitch) and translation of the quadcopter UAV is achieved by precise control of the PID control. This provides fine displacement control of the UAV and maintains UAV stability in the presence of wind and other external forces [10]. For example, the panning PID controller is responsible for moving the UAV to the desired position based on the current position estimated from GNSS data. It consists of a cascade of two controllers: a proportional controller that converts the position error to the desired velocity and a PID controller that converts the desired velocity to the desired acceleration. The desired acceleration is then converted to a tilt angle, which is passed to the stability PID controller to adjust the angle. The output of the stability PID controller is the torque to drive the actuator (motor) [10].

PID control can be responsible for controlling the trajectory and attitude of a quadcopter UAV. The practical application of PID control in quadcopter UAVs is altitude and attitude stabilization. The PID controller adjusts the speed of the UAV's motors to maintain the desired altitude and orientation. This is critical for tasks that require precise positioning, such as aerial photography or surveillance [11].

PID control can help with navigation and waypoint tracking for quadcopter drones. Navigation and waypoint tracking using a PID controller as shown in the Figure 1. And by computing the error between the current position and the set point, the PID controller can guide the UAV onward a predesigned path, which is critical for applications like delivery or search and rescue missions [12].

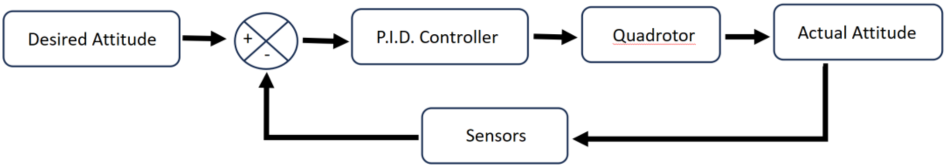

**Fig. 1.** Block diagram of the control flow of a quadcopter UAV by a PID controller

## 2.2 SMC Control and Its Use in UAV Stabilization

SMC (Sliding Mode Control) controllers also play a vital role in modern quadcopter UAVs to provide robust control and deal with uncertainties and disturbances. By continuously modifying the control inputs depend on the computation of the error between the expected state and the current state, SMC controllers are intended to maintain the attitude and trajectory of the UAV [13].

When there are disturbances, a quadcopter UAV's stable attitude control is the result of the SMC control. When the wind or other external disturbances affect the UAV's attitude control, the SMC control works effectively to maintain stable attitude control. The SMC can accurately maintain the required orientation by designing a sliding surface which considers both the disturbance and the UAV's dynamic model [14].

As seen in Figure 2, SMC control enables quadcopter UAVs to follow their trajectories more precisely. Additionally, by constructing the sliding mode surface and altering the control rule, it enables the UAV to precisely track complicated trajectories even in the face of model uncertainty or abrupt environmental changes. For missions requiring high maneuverability and high accuracy, this skill is essential [14].

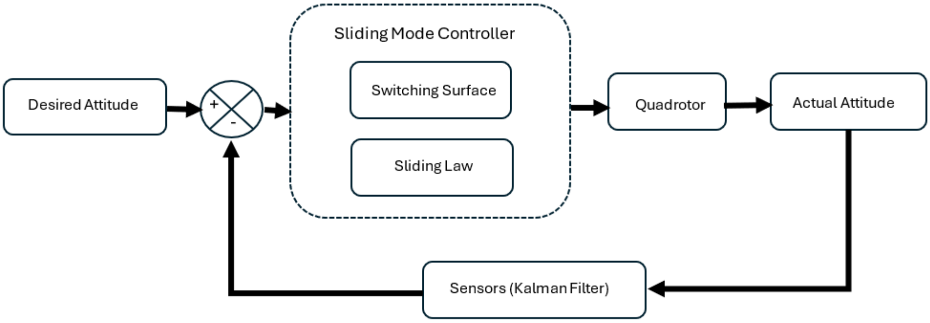

**Fig. 2**. Block diagram of the control flow of a quadcopter by a sliding mode controller

Both PID and SMC controls play an important role in the current UAV field, addressing different aspects of UAV control and stabilization. PID control is simple and effective in tasks such as altitude and attitude control and navigation. In contrast, SMC is characterized by high immunity to interference and precise trajectory tracking for applications requiring high reliability and performance under uncertain conditions. These practical examples emphasize the importance of both control strategies in enhancing the capabilities of UAVs and expanding their range of applications.

# 3 Improvement of PID and SMC Control by Artificial Intelligence

## 3.1 Enhancement of Traditional PID Control by Artificial Intelligence

Most quadcopter UAV flight control systems use proportional-integral-derivative (PID) control systems. Traditional PID controllers are effective under steady state conditions but are difficult to adapt to the unpredictability of real-world environments. There exists a lack of precision in regulation, and it does not provide optimal performance. Integration of artificial intelligence techniques into the PID controller framework can bring substantial improvements, enabling it to adapt to changing environmental conditions in real time [15].

**Enhancement of PID Control using Neural Network (ANN).** Conventional PID systems are susceptible to dynamic changes and environmental disturbances. To address this challenge, authors Salman Bari et al. in " Artificial neural network based self-tuned PID controller for flight control of quadcopter." proposed a PID tuning algorithm that utilizes an ANN with a single hidden layer to continuously tune the PID parameters with the aim of minimizing the tracking error. tracking error. The ANN uses a sigmoid activation function and a back-propagation algorithm to optimize the weights. The study includes a comparative analysis of three training algorithms (Bayesian Regularization, Levenberg-Marquardt, and Scaled Conjugate Gradient) with different numbers of hidden layer neurons to minimize the mean square error (MSE). The effectiveness of the proposed control scheme is demonstrated by applying it to the altitude control, pitch, roll, and yaw of a quadcopter. The paper highlights the advantages of using ANN for PID regulation, emphasizing its ability to solve important problems and improve system performance under different conditions [16].

Authors Oualid Doukhi and Deok Jin Lee, in their research paper " Neural network-based robust adaptive certainty equivalent controller for quadcopter UAV with unknown disturbances", provide that they propose a new method for controlling quadcopter unmanned aerial vehicles (UAVs), with a special focus on dealing with unknown disturbances affecting the performance of UAVs disturbances. This controller generates the roll and pitch angle signals required for position control in the outer loop and applies them to the inner loop for attitude control. Its capacity to control uncertainties in UAV kinematic and modeling error, including external disturbances, inertia, mass, and nonlinear aerodynamic forces and moments, without requiring a correct dynamic model or prior knowledge of disturbances, is what makes it innovative. This methodology integrates an adaptive radial basis function neural network to approximate unknown nonlinear dynamics, in conjunction with a deterministic equivalent control technique. Stability and effectiveness of the proposed algorithm are validated using Lyapunov theory, demonstrating that tracking errors in altitude, position, and attitude converge to zero, thereby ensuring closed-loop stability even under extreme conditions. [17].

The authors suggest a decentralized PID neural network (PIDNN) control scheme in a different paper titled "Decentralized PID neural network control for a quadcopter UAV subjected to wind disturbance" with the goal of enhancing the stability and maneuverability of a quadcopter UAV that faces wind disturbances. Using the Newton-Euler formulation, a dynamic model of the quadcopter UAV that took wind disruption factor into consideration was first constructed in the study. Given that the quadcopter is more susceptible to turbulent wind fields when flying at low altitude, the study employs the Dryden model to simulate these conditions as the main source of disturbance for the quadcopter UAV. To address the stabilization and navigation challenges posed by wind disturbances, the authors introduce a nested loop control strategy. In order to stabilize the attitude angle, a decentralized PIDNN controller is designed for the inner loop, and a standard PID controller is used for the outer loop to create reference pathways for the inner loop. PID control theory principles are used to establish the initial weights of the PIDNN's connective weights, which are trained online by the error back-propagation approach. The stability of the system is guaranteed by choosing a suitable learning rate, which is guided by discrete Lyapunov theory. The simulation results highlight how well the suggested controller works to withstand wind disturbances from the outside, showing how the quadcopter UAV's stability, maneuverability, and resilience are enhanced under these circumstances. The main topics covered in the paper include the application of a PID neural network (PIDNN) to a quadcopter UAV, the effect of turbulent wind fields on flight dynamics, and controller design using discrete Lyapunov theory. This research contributes to the field of UAV control by providing a novel approach to enhance the performance of quadcopters under unfavorable environmental conditions [18].

**Enhancement of PID Control using Machine Vision.** Machine vision has also been used to augment PID controllers to enable UAVs to detect and respond to obstacles in real time. In the paper " Autonomous vision-based target detection and safe landing for UAV" by Mohammed Rabah et al. the authors focus on target detection and safe landing of UAVs, especially in scenarios where the UAVs return to the UAV station during battery charging and maintenance. The study proposes a vision-based target detection method that utilizes an inexpensive Raspberry Pi (RPi) and a USB camera to detect the target, while a laser range finder (LIDAR) is used to measure the safe distance for landing. The study employed a fuzzy logic controller for safe landing and a PID controller for target recognition. Experiments on a testbed consisting of a quadcopter UAV and a target UAV station are used to validate the effectiveness of the created system. The outcomes of the experiment demonstrate how effectively the suggested system works for the quadcopter UAV's target detection and safe landing [19].

**Enhancement of PID Control using Deep Machine Learning.** Deep machine learning further optimizes the PID controller, allowing the UAV to learn from experience and adapt to new situations. Author Yalew Zelalem Jembre et al. in "Evaluation of reinforcement and deep learning algorithms in controlling unmanned aerial vehicles" examines the application and performance evaluation of reinforcement and deep learning algorithms in the control of unmanned aerial vehicles (UAVs). The research centers on configuring quadcopter UAVs to fly autonomously through the use of machine learning schemes (i.e., agents). These agents control the UAV from an initial location to a target location by learning about the virtual physical environment. In this work, two augmented learning models (Q-learning and

SARSA) and a deep learning model (deep Q-network) are employed as agents. The agents are rewarded when they bring the UAV close to the target location and are penalized otherwise. Integration of Gazebo and the Robot Operating System (ROS) enabled the application of learning algorithms and physical settings in simulations. The findings demonstrate that the deep Q-network model, with the Adadelta optimizer, represents the optimal configuration for navigating a quadcopter UAV from its initial to its target position. [20].

### 3.2 Directions for Improvement of Sliding Mode Control

Sliding Mode Control (SMC) is widely used in the control of unmanned aerial vehicles (UAVs) due to its robustness to uncertainties and disturbances. However, there are inherent drawbacks in the traditional SMC control, one of the main drawbacks is the chattering phenomenon, which leads to undesired high-frequency oscillations in the control inputs and causes wear and tear on the mechanical components of the UAV, heating of the components, and other unfavorable effects [21, 22].

Ahmed Eltayeb et al. proposed an improved Integral Sliding Mode Controller (ISMC) design aimed at solving the chattering problem and improving the robustness of trajectory tracking. The article begins with a brief description of the dynamics and kinematics equations of a quadcopter UAV, followed by the presentation of an improved ISMC that is applied to the inner loop control to stabilize the attitude of the Quadcopter UAV and track the desired values. By removing the chattering issue and preserving the stability of trajectory tracking, the design seeks to enhance the ISMC controller's performance. Tanh, error, saturation, and quasi-slip-film techniques are a few examples of approximation functions that are utilized in the ISMC control law and can be used in place of the switching function (sign(s)) that generates chattering in the design. The quadcopter UAV can track the desired location through a PD controller that is used by the outer loop controller. Using MATLAB/SIMULINK simulation, the suggested ISMC controller's resilience for trajectory tracking and chattering attenuation are examined. Ultimately, a comparison is done using the switching function (sign(s)) to demonstrate the superior performance of the suggested design performs [22].

Jairo Olguin-Roque et al. proposed a robust Fixed-Time Sliding Mode Controller (FTSMC) for Quadcopter UAVs. According to Lyapunov theory, the method ensures system stability and uses nonlinear error dynamics to precisely follow paths in the event of disturbances. The study also compares the performance of FTSMC with the typical non-singular terminal sliding mode controller (NTSMC) in order to evaluate the effectiveness of FTSMC. Numerical results show that FTSMC reduces disturbances more efficiently than typical NTSMC [23].

In their work, Sibo Huang and associates introduce an adaptive backward sliding mode control (ABSMC) technique intended to handle the quadcopter UAV's trajectory tracking control problem in the presence of actuator malfunctions and outside disturbances. The technique effectively mitigates the chattering effects associated with sliding mode control (SMC) through differential iteration by integrating the switching gain of adaptive sliding mode control into the backstepping design process. Initially, the authors present a dynamic model of a quadcopter UAV that accounts for actuator failures and external disturbances. Subsequently, a controller is developed using the adaptive backstepping sliding mode control (ABSMC) technique. Comparative trials demonstrate that the ABSMC method not only achieves superior control performance but also efficiently suppresses the chattering phenomena inherent in the standard SMC approach [24].

**Utilizing AI Techniques to Mitigate Chattering phenomenon in SMC Controller.** Ping Li et al. proposed the use of radial basis function neural networks (RBFNNs) to develop a sliding mode control (SMC) strategy for a quadcopter UAV, with the objective of enhancing control performance in the presence of unknown disturbances through an optimized control approach. The paper addresses the challenge of unknown external disturbances in the dynamic model of the controlled quadcopter by constructing a comprehensive dynamic model that incorporates these disturbances and applying SMC for both attitude and position control. To manage the unknown disturbances in the derived controllers, RBFNNs are utilized to approximate the unknown components of the controllers. Furthermore, to enhance the performance of these controllers, a particle swarm optimization (PSO) algorithm is employed, which focuses on minimizing the absolute approximation error. A significant contribution of the paper is the demonstration of the convergence of the quadcopter's state tracking error, ensuring that the proposed control strategy achieves the desired outcomes. To validate the superiority of the proposed control strategy, the differences between RBFNN-based SMCs with and without PSO are compared. The results show that the strategy integrating PSO can achieve faster and smoother trajectory tracking, thus verifying the effectiveness of the proposed control strategy [25].

Fuzzy logic control (FLC) and sliding mode control (SMC) are combined in Y. Deia et al.'s research to propose a fully decentralized fuzzy sliding mode control (FDFSMC) approach for quadcopter UAV attitude. Reducing the chattering phenomena (energy consumption) and the material need (building cost) are the primary goals. In order to accomplish this, chattering is minimized by the use of a fuzzy logic controller in fully decentralized SMC and the system is broken down into smaller components. The system's tracking performance and stability are satisfactory, according to simulation findings, and the fully decentralized fuzzy SMC that has been suggested can accomplish good performance [26].

The primary contribution of the paper by Wang, Q et al. is the proposal of a novel approach to mitigate the chattering phenomenon in quadcopter UAV sliding mode control while enhancing tracking performance through the integration of reinforcement learning. The paper employs a reinforcement learning approach to identify the optimal nonlinear function for reducing chattering. It departs from the conventional reference model of sliding mode control by directly incorporating the network output into the controller computation, circumventing any limitations. Furthermore, a two-step validation methodology is proposed, which includes simulations under input delays and external disturbances, as well as practical experiments using a quadcopter. For comparison, two classical chattering reduction methods are also implemented in the experiments [27].

# 4 Discussion

This paper argues that in the current technological field of quadcopter UAVs, adaptive autonomy control systems with the addition of artificial intelligence technology are the most epoch-making and practical. Adaptive autonomy allows UAVs to dynamically adjust their behaviors and strategies in response to changing environmental conditions and mission requirements, thereby improving operational efficiency. This capability is particularly beneficial in complex or uncertain environments where pre-programmed responses may not be adequate. For example, in the case of a UAV used in the battlefield, the battlefield situation, enemy position, and troop deployment may change at any time during the mission, and the UAV's adaptive control system should be able to make optimal choices to change or reset the priority of the mission, and reset the flight control parameters, to prioritize the more valuable tasks, mission.

Artificial Intelligence algorithms can also optimize flight paths and control strategies in real time to minimize energy consumption and extend the range and flight time of UAVs. This is particularly important in the field of logistics and express delivery, i.e., how to arrange the UAVs to pick up the goods ordered by the customer from the warehouse and deliver them to the designated location with the shortest path, the lowest flight cost, including the shortest flight time, and the lowest energy consumption, which requires the involvement of AI algorithms in the setup.

Since artificial intelligence technology is developing rapidly and traditional UAVs technology has matured, considering that the UAVs field should rapidly embrace artificial intelligence technology and transform it from a traditional vehicle operated remotely by personnel via a remote control to a revolutionary intelligent vehicle, including and not limited to the use of the following technologies:

1) Predictive Maintenance and Fault Tolerance: By combining Artificial Intelligence with PID/SMC devices in flight control, and by reading and comparing parameters in real time, the UAV can predict and compensate for system failures or malfunctions before they occur, thus improving reliability and safety. The effective combination of AI and UAV control should be able to determine system failures or malfunctions that may occur under certain climatic and environmental conditions. For example, energy loss, weather anomalies, and making rational decisions and behaviors to prevent "Crash".

2) Enhanced environmental monitoring and navigation planning: The combination of new technologies such as artificial intelligence, machine vision and UAV control will allow

for more sophisticated environmental monitoring and navigation strategies, even in complex environments where the UAVs can autonomously develop more rational monitoring flight paths. This combination of technologies will be very beneficial for agriculture, forest, environment, and traffic monitoring. We should invest in advanced machine vision algorithms in the field of UAVs to get accurate and detailed monitoring data in the fastest time and shortest flight paths, reduce the number of reciprocal flights, and reduce the frequency of ineffective data collection, which will greatly improve the efficiency of UAV monitoring.

3) Learning-based control adjustment: With the introduction of artificial intelligence technology, especially reinforcement learning and online learning, flight control such as PID and SMC parameters can be automatically adjusted, reducing the need for manual calibration and improving control accuracy. Adapt the UAV to changing environmental conditions, payload changes and other uncertainties.

Although AI techniques have helped so much in developing UAV PID control/SMC control, the author are also aware of the multiple challenges that the current development may have, and the author propose the following questions for future open research and study:

1) Complexity of AI algorithms: While AI offers significant advantages, the computational complexity of the algorithms can be a limiting factor. Research is needed to develop lightweight and efficient AI models suitable for airborne UAV (limited onboard resources) computing systems. In the process of referencing other papers, the authors found that researchers rarely address the computational strain their new algorithms place on the current UAV's on-board equipment; whether the new equipment that would need to be added would result in additional host processing workloads, and energy loss, never sacrificing the UAV's battery efficiency.

2) Data security and privacy: As UAVs collect and process large amounts of data, ensuring the security and privacy of this information is a serious challenge. This includes preventing data leakage and unauthorized access. This is a real issue, for example, in the use of machine vision, whether the protection of the privacy of the person being photographed will be considered, especially under commercial applications. This designs both regulatory and ethical considerations: the increased functionality of UAVs raises questions about their use, including privacy concerns and the potential for misuse. It is crucial to develop ethical guidelines and regulatory frameworks that keep pace with technological advances.

3) Human-AI interaction: As AI assumes more control responsibilities, it becomes critical to define the role of the human operator and ensure effective human-machine collaboration. That is, to what extent can UAVs be "autonomous" under the management of AI, and in special circumstances, do they require "human" intervention. How humans can know the current "state" or "thoughts" of the UAV in real time and be able to intervene in a timely manner is a matter that requires research to explore the interfaces and communication protocols that would support such interactions.

4) When AI-assisted UAVs formulate their routes, should consideration be given to avoiding flying overcrowded areas or special scenarios, such as schools and special buildings, as far as possible. To avoid the frequent flights of a large number of UAVs to bring impact and disturbance to the life of human society.

## 5 Conclusion

The integration of quadcopter UAVs into various industries, including disaster management, logistics and courier services, agricultural monitoring, and public entertainment, has sparked significant interest in enhancing their capabilities. The fusion of Artificial Intelligence (AI) with conventional control techniques such as Sliding Mode Control (SMC) and Proportional-Integral-Derivative (PID) opens new avenues for improving the efficiency, autonomy, functionality, and stabilization of quadcopters. AI-enhanced control methods enable quadcopters to perform more robustly and adaptively, thereby facilitating their ability to navigate complex tasks and dynamic environments with greater precision.

In conclusion, the combination of AI with PID and SMC control strategies is a promising direction for advancing the capabilities of Quadcopter UAVs. This approach has the potential to develop UAV systems that are more intelligent, flexible, and efficient. However, to fully realize the potential of AI-enhanced UAVs, it is essential to address several challenges and explore open research questions. These include improving the reliability and safety of AI algorithms, ensuring robust performance under varying conditions, and minimizing computational and energy constraints.

The future of Quadcopter UAV technology lies in the creation of intelligent systems that can autonomously perform complex tasks in diverse environments. Continued research and development in this area will likely result in UAVs that are not only more capable but also safer and more reliable. By overcoming the current limitations and leveraging the power of AI, we can unlock the full potential of Quadcopter UAVs, paving the way for their widespread adoption and integration into various sectors, ultimately transforming the way we approach tasks and challenges in numerous fields.

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