Control Systems for Unmanned Aerial Vehicles: A Comprehensive Study

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Abstract. This paper provides a comprehensive exploration of Unmanned Aerial Vehicles (UAV) system architecture, focusing on the synergistic interplay between hardware and software components. The hardware system, comprising subsystems such as the aircraft platform, flight control, inertial navigation, information transmission, and mission execution, forms a robust foundation for stable flight and task performance. Complementing this, the software system incorporates critical modules including flight control, navigation and path planning, communication and data transmission, and mission management, enabling UAVs to operate with enhanced intelligence and autonomy. Furthermore, the study delves into adaptive control algorithms, such as Model Reference Adaptive Control (MRAC), robust adaptive controllers, and model-free adaptive control, which empower UAVs to autonomously adjust to dynamic environments, ensuring stability and overcoming limitations of traditional control methods. Despite the maturity and widespread adoption of UAV technology, key challenges remain, including limited endurance, precision, stability, and payload capacity. This paper highlights the need for targeted research to address these limitations, proposing advancements in adaptive algorithms, energy efficiency, and system integration as critical pathways for future innovation. By addressing these challenges, this study aims to contribute to the evolution of UAV technology, unlocking its full potential for applications in logistics, agriculture, disaster response, and beyond.

Keywords: Control System, PID Algorithm, Adaptive Algorithm, Application of UAV

1 Introduction

In the current era of rapid technological advancement, unmanned aerial vehicles (UAVs) have emerged prominently due to their unique advantages. Their compact size confers both concealment and flexibility. In comparison to manned aircraft, UAVs are significantly less expensive to produce, costing as little as 10% or even a mere fraction of the price of their manned counterparts. This feature of low cost facilitates their widespread application. With the progression of battery technology, the power consumption of UAVs has markedly decreased, leading to enhanced

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endurance performance. These attributes enable UAVs to play a pivotal role across various domains.

By Li M. and Du X.X. [1] highlights that in medical emergencies, particularly in remote areas with scarce medical resources and underdeveloped land transportation infrastructure, UAVs can rapidly deliver critical medical supplies. Meanwhile, Chen G.X. [2] notes that advancements in UAV technology enhance the accuracy and efficiency of power line inspections while reducing risks associated with manual inspections. In the agricultural sector, Wang Y.H [3] emphasizes that UAV technology plays a vital role in various stages, including crop monitoring, irrigation, and pesticide spraying. These studies collectively state the transformative potential of UAVs across diverse fields.

As a high-tech product resulting from interdisciplinary integration, unmanned aerial vehicles (UAVs) exhibit multidimensional classification characteristics that evolve with application scenarios and technological advancements. As highlighted in [4], UAVs can be categorized into the following four types based on their wing structures: multi-rotor UAVs, fixed-wing UAVs, hybrid UAVs, and flapping-wing UAVs. This classification reflects the diversity and adaptability of UAV designs to meet varying operational requirements.

During the execution of various tasks by unmanned aerial vehicles (UAVs), the role of their flight control systems is of paramount importance. To counteract disturbances caused by external airflow and adapt to complex and dynamic flight environments, UAVs must possess robust anti-disturbance capabilities. When performing mission-critical tasks, frequent adjustments to the UAV's flight attitude and the ability to follow diverse flight trajectories are required, necessitating a control system capable of accommodating complex dynamic characteristics. Furthermore, the rapidly changing conditions of mission scenarios demand that UAVs exhibit rapid response capabilities to ensure operational effectiveness and reliability.

This study provides a comprehensive exposition of UAV systems through meticulous deconstruction of critical hardware/software components and their functional interdependencies, thereby constructing a holistic framework that establishes coherent structural logic for researchers in this domain. Significantly, the investigation highlights adaptive control algorithms that play a critical role in enabling intelligence-oriented optimization, adaptability-oriented configuration, and robustness-enhanced performance in UAV operations.

2 UAV System Control Architecture

The UAV control system is composed of both software and hardware systems, which work in concert to enable the UAV's flight, movement, and execution of various tasks.

2.1 Hardware Systems

The hardware system of a UAV can be divided into the following subsystems: the aircraft platform system, the flight control system, the inertial navigation system, the data transmission system, and the mission hardware payload system. Fig. 1 shows the modules of hardware system and their key functions.

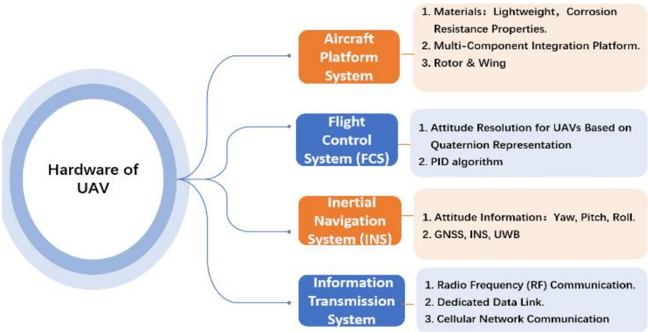

Fig. 1. Modules of Hardware system and their key functions

2.1.1 Aircraft Platform System.

Literature [4] states that it is proposed that the aircraft platform subsystem serves as the main body of a UAV, designed to enable its flight and mission execution. The structural framework of the UAV is essential for its expected operation, similar to the skeletal framework of the human body. The materials used primarily emphasize lightweight and corrosion-resistant properties. The literature [5] written by Wang L. P. introduces an advanced composite material as the preferred choice for UAV design. The lightweight and high-strength characteristics of composite materials significantly reduce the weight of UAVs, enhance flight efficiency, and extend endurance. Additionally, their corrosion resistance ensures the reliability of UAVs in harsh environments.

2.1.2 Flight Control System (FCS).

The flight control system (FCS) refers to the flight management system of an unmanned aerial vehicle (UAV). As proposed in the study [6] from Popular Science & Technology mentions that the UAV flight control system utilizes quaternion representation for attitude resolution and employs a cascaded Process Identifier (PID) control algorithm to achieve precise attitude control and automatic regulation of the UAV's flight position. Additionally, the system incorporates a ground-based host computer for data parsing, enabling the generation of real-time PID waveforms and the acquisition of the UAV's attitude information. This facilitates remote monitoring and control of the UAV from the ground, ensuring operational efficiency and stability.

2.1.3 Inertial Navigation System.

The UAV inertial navigation system is capable of acquiring the attitude information of the drone, such as roll angle, pitch angle, and yaw angle, and transmitting this attitude data to the main control unit in real-time to adjust the drone's posture. This system plays a critical role in ensuring the accuracy and stability of autonomous drone flight. Navigation systems are the mainstream navigation systems including the Global Navigation Satellite System (GNSS) and the Inertial Navigation System (INS). In addition, there are LiDAR systems suitable for industrial cruising and Ultra-Wideband (UWB) technology, which offers higher precision in indoor environments. In [7], Jiang Y.Q. and Chen P.P propose an indoor positioning system utilizing UWB technology, which prevents the loss of goods through real-time monitoring. This system employs microcontrollers (MCUs) such as STM32 as the main controller and integrates a UWB module to collect and then analyse positional data, therefore achieving precise indoor positioning functionality.

2.1.4 Information Transmission System.

Primarily utilized for data transfer and communication between ground stations UAV, the system encompasses several key technologies. These include wireless radio frequency (RF) communication, such as Wi-Fi, Bluetooth, Zigbee, and LoRa for short-range communication, as well as dedicated data links and cellular network communication. Satellite communication, mainly involving the Global Navigation Satellite System (GNSS) and low Earth orbit (LEO) satellite relay, enables UAV systems to integrate with relay satellite digital communication, as demonstrated in the literature [8] written by Xuan Y., Cheng D.S and Wang W.H.. Additionally, fee-space optical (FSO) communication, exemplified by NASA's Laser Communications Relay Demonstration (LCRD) project, has validated laser links between UAVs and satellites, achieving transmission rates of up to 10 Gbps.

2.1.4 Mission Execution System.

This system comprises a variety of hardware components designed to facilitate task execution, including Synthetic Aperture Radar (SAR) for acquiring object parameters, cameras for image capture, and electro-optical sensors, among others. These elements collectively enhance the system's capability to perform complex missions with precision and efficiency.

2.2 Software Systems

The unmanned aerial vehicle (UAV) software system constitutes a sophisticated integrated architecture, with its principal components encompassing: flight control software, navigation and path planning algorithms, communication and data transmission systems, as well as mission management and execution modules. This system architecture demonstrates rigorous hierarchical organization and functional modularity, reflecting the interdisciplinary integration of cyber-physical systems in contemporary aerospace engineering applications.

2.2.1 Flight Control Software.

This software serves as the core of the entire UAV software system, encompassing flight control algorithms, sensor fusion mechanisms, and power management systems. The flight control algorithms typically employ software-based PID controllers or more sophisticated adaptive control software controllers.

2.2.2 Navigation System.

This system integrates GPS with visual SLAM (for GPS-denied environments). According to [9], visual Simultaneous Localization and Mapping (SLAM) technology enables autonomous environmental perception, self-localization, and map construction, establishing itself as a predominant research trend in robotic autonomous navigation under complex conditions. The Dijkstra algorithm, characterized by relative simplicity and widespread applicability, represents a foundational path-planning approach. It is extensively utilized in time-sensitive and precision-critical scenarios such as logistics and food delivery operations. The communication and data transmission subsystem comprises three principal components: the remote- control link, video transmission system, and ground station interface.

2.2.3 Mission Management and Execution.

They focus on software-driven implementation of predefined operational tasks. In topographic surveying applications, UAVs demonstrate unique advantages in accessing dynamic and hazardous environments that pose challenges or risks to human field investigators. Furthermore, UAVs play a pivotal role in power line inspection through automated tracking mechanisms. In agricultural applications, integration of multi-sensor systems with targeted path planning enables precision pesticide spraying in designated areas, exemplifying the system's operational versatility.

3 UAV Adaptive Control System

The adaptive control technology for unmanned aerial vehicle (UAV) systems is designed to achieve intelligent and autonomous operations during flight missions. Particularly in complex and dynamically changing environments, this technology enables real-time adjustment of control strategies through continuous feedback, thereby enhancing system robustness and operational flexibility. It effectively mitigates the instability inherent in conventional control systems under environmental disturbances. Based on current research advancements, adaptive control implementations primarily include: Model Reference Adaptive Control (MRAC) [10], Robust Adaptive Control [11] and Model-Free Adaptive Control [12].

3.1 Model Reference Adaptive Control (MRAC)

Model Reference Adaptive Control (MRAC) technology dynamically adjusts controller parameters by establishing error feedback between the reference model and the actual system, thereby enabling system output to track the ideal model. The study [10] investigates attitude adaptive control algorithms for UAVs operating in various environments, proposing an adaptive control law. Experimental results demonstrate that the adaptive algorithm exhibits significantly enhanced capability to mitigate wide-range persistent disturbances compared to conventional control methods.

When UAV flight systems encounter uncertainties, voltage outputs of motors fluctuate accordingly, deviating from set reference values in the control system and amplifying system errors. To compensate for disturbance-induced effects, both error outputs and reference model outputs are fed into an adaptive mechanism. Through real-time online adjustment of adjustable parameters within this adaptive framework, the system progressively minimizes performance metrics, achieving superior tracking accuracy and regulatory stability. This methodology has been validated in power management applications as documented in [13]. Fig. 2 shows the flowchart of MRAC.

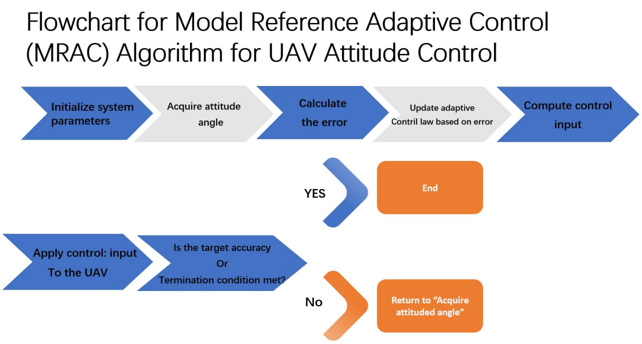

Fig. 2. Flowchart of MRAC Algorithm for UAV attitude control

3.2 Robust Adaptive Control

The study [11] highlights that the nonlinear dynamics, strong coupling effects, and susceptibility to external disturbances inherent in quadrotor UAVs significantly complicate controller design. Robust Adaptive Control (RAC) enhances system stability by incorporating predefined compensation terms that account for environmental parameter perturbations. Unlike Model Reference Adaptive Control (MRAC), the robust adaptive controller does not dynamically adjust its parameters. Instead, it embeds potential parameter variations into the controller's initial design framework, ensuring the maintenance of predefined performance characteristics and disturbance rejection capabilities under dynamically changing environmental conditions.

3.3 Model-free Adaptive Control

Model-free adaptive control is a distributed direct-form model-free adaptive PID control algorithm based on controller dynamic linearization. According to [12], it performs controller parameter tuning solely using the input-output data of the controlled system and the topological structure relationships between agents, without being constrained by the mathematical model of the controlled system. This introduction maintains academic rigor.

4 Key Technologies and Limitations of UAV Applications

4.1 Key Technologies

In recent years, unmanned aerial vehicle (UAV) systems, leveraging their high precision, high flexibility, and modular payload capabilities, have achieved technological breakthroughs across multiple domains. In the field of precision agriculture, the study [14] proposes a UAV equipped with multispectral sensors for NDVI (Normalized Difference Vegetation Index) analysis, enabling real-time monitoring of crop health status and significantly reducing pesticide usage. In the field of disaster emergency management, the study [15] highlights that UAV-based earthquake disaster monitoring systems offer advantages such as cost-effectiveness, operational flexibility, and strong exploration capability in high-risk zones. These advantages position UAVs as a revolutionary solution for spatial information acquisition. By integrating dynamic cruising and intelligent sensing technologies, the system can rapidly construct centimetre-level precision 3D real-scene models, providing high-temporal-resolution and high-accuracy spatial data support for post-disaster assessment and rescue decision-making. In the field of environmental protection, the study [16] addresses the efficiency bottlenecks in remote sensing monitoring of large-scale forest areas, proposing that UAV technology offers an innovative method to enhance forest ecological monitoring. This technology, characterized by flexible deployment, broad-area coverage, and long-term sequential monitoring capabilities, integrates predefined flight path planning with high-resolution sensors to systematically acquire precise spectral data. Compared to traditional remote sensing methods, its low-altitude operation capabilities significantly reduce interference from atmospheric layers and micro-terrain environments on the multi-dimensional spatiotemporal analysis of monitoring data. In logistics and transportation, large-scale civilian UAVs can transport bulky and heavy cargo, leveraging extended endurance and range to serve domains such as freight delivery and material supply. These systems provide faster, safer, more convenient, and lower-cost transportation services compared to land-based alternatives.

4.2 Limitation

In practical applications, as unmanned aerial vehicles (UAVs) become increasingly prevalent, their limitations have also emerged, which partially constrain the full realization of their functional potential. Conducting an in-depth analysis of these limitations holds significant importance for fostering sustainable industry development and achieving technological breakthroughs. For instance, small delivery UAVs face range limitations, confining their operational scope to localized urban areas typically spanning hundreds of meters to several kilometers. Their flight altitudes remain relatively low, generally within tens to hundreds of meters in low-altitude airspace, making them only suitable for short-distance deliveries in urban neighbourhoods. Additionally, single-unit UAVs exhibit constrained payload capacities, encountering practical challenges such as hardware resource limitations, restricted energy supply, and communication bandwidth bottlenecks.

5 Conclusion

Unmanned aerial vehicles (UAVs), as high-tech products integrating multidisciplinary advancements, exhibit exceptional advantages and transformative potential across diverse fields through their dual-system architecture of hardware and software. The hardware system combines airframe platforms, flight control modules, inertial navigation systems, data transmission units, and mission-specific payloads to form a robust operational foundation, while the software system employs intelligent algorithms for flight control, path planning, communication management, and mission execution to enable autonomous decision-making. To address dynamic environmental challenges, UAVs utilize adaptive control methodologies including Model Reference Adaptive Control (MRAC), robust adaptive controllers, and model-free adaptive systems, which dynamically adjust flight parameters through real-time feedback to overcome traditional control limitations and ensure stability under variable conditions. Despite significant global progress in UAV technology, critical constraints persist in endurance, positioning accuracy, operational stability, and single-unit payload capacity. Future advancements must prioritize energy-efficient propulsion systems, AI-enhanced navigation algorithms, fault-tolerant control architectures, and modular payload designs to expand UAV capabilities in complex scenarios. Addressing these challenges will not only improve reliability in existing applications like surveillance, logistics, and emergency response but also unlock novel uses in urban air mobility and precision agriculture. The convergence of adaptive control systems with emerging technologies such as 5G networks, edge computing, and swarm intelligence is poised to redefine UAV operational paradigms, necessitating coordinated research efforts across aerospace engineering, materials science, and artificial intelligence to achieve next-generation autonomous aerial systems capable of sustained, precision-oriented missions in increasingly demanding environments.

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