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Key technologies and application progress of civil unmanned aerial vehicle

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Abstract. This paper presents a comprehensive review of the key technologies and recent developments in the field of Civil Unmanned Aerial Vehicle (CUAV), systematically analyzing the latest developments in flight platform technology, propulsion and energy technology, and navigation and control systems. Special attention is given to the performance characteristics and application scenarios of fixed-wing, multi-rotor, and composite flight platforms, as well as to the advantages and limitations of lithium-ion and hydrogen fuel cells in terms of endurance, and the role of multi-sensor data fusion algorithms in navigation and control. By examining practical cases from typical fields such as aerial photography, logistics, and agriculture, this paper summarizes current technological achievements and application trends. Furthermore, it analyzes challenges in areas such as regulations and airspace management, safety, and technical limitations, while proposing future directions including technology integration, quantum communication, bio-inspired drones, and privacy and data protection. The research indicates that with the deeper application of emerging technologies like artificial intelligence and quantum communication, CUAV will achieve new breakthroughs in intelligence, autonomy, and safety, providing strong technological support for low-altitude economy and smart society.

Keywords: Civil Unmanned Aerial Vehicle (CUAV), flight platform, airspace management, low-altitude economy

1. Introduction

As the low-altitude economy becomes an integral part of national strategic emerging industries, Civil Unmanned Aerial Vehicle (CUAV), as a key technological carrier of this sector, are experiencing unprecedented development opportunities. In the logistics industry, CUAV are addressing the "last-mile" delivery challenge; in agriculture, they enable precision spraying and seeding; in the field of surveying and mapping, they offer high efficiency, cost-effectiveness, and accuracy; and in emergency response scenarios, CUAV play vital roles in disaster assessment and rescue operations. In recent years, the CUAV market has witnessed significant growth, driven by technological advancements, increasing market demand, and favorable policy environments. For example, data indicate that the scale of China’s CUAV market reached 160 billion yuan in 2024, with UAV-based logistics alone accounting for 30 billion yuan. This market is projected to continue growing at an annual rate of 20%, underscoring the vast development potential of the industry [1]. Key technological drivers behind this growth include advances in flight control, sensors,navigation systems, propulsion technologies and battery, communication systems, as well as increasing levels of intelligence and automation.

2. Key technologies for Civil Unmanned Aerial Vehicle

2.1. Flight platform technology

CUAV flight platforms are primarily categorized into three fundamental configurations: multirotor, fixed-wing, and hybrid layouts. Each configuration exhibits distinct aerodynamic characteristics, application adaptability , and control mechanisms. Fixed-wing UAVs generate lift through their wings, enabling sustained cruise flight with advantages such as extended range, high flight speed, and low energy consumption. These platforms are well-suited for large-scale mapping, border patrol, and agricultural monitoring. However, they require runways or catapult systems for takeoff and landing, impose higher demands on spatial conditions, involve more complex control, and generally lack Vertical Takeoff and Landing (VTOL) capabilities. Multirotor UAVs generate lift and control attitude through multiple rotors. They offer excellent hovering performance and maneuverability, with compact structures, strong adaptability , and rapid deployment. These advantages make them widely used in aerial photography, urban logistics, and emergency reconnaissance. Nevertheless, their endurance and payload capacity are relatively limited due to current battery technology constraints. Hybrid UAV configurations combine the strengths of fixed-wing and multirotor systems, achieving both VTOL and efficient cruising capabilities [2]. Common forms include tilt-rotor designs and convertible-wing models, which balance operational flexibility with long-range mission requirements. These platforms are particularly suited for long-distance logistics, mountainous operations, and inspections in complex environments. However, the structural design and control algorithms of hybrid UAVs are more intricate, and as such, they remain in a phase of rapid development and early-stage engineering application.

2.2. Propulsion and energy technology

The power system directly determines a UAV's endurance and operational efficiency. Currently, lithium batteries remain the dominant power solution due to their high maturity, moderate energy density, and low cost. They are widely used in small and medium-sized UAVs. However, limitations such as short flight time and poor environmental adaptability hinder further performance improvements. Hydrogen fuel cells, with their high energy density and zero-emission characteristics, emerge as a key candidate for CUAV [3]. However, their commercialization is constrained by high initial costs, complex hybrid power systems, and the continuous need for hydrogen fuel. These factors result in significantly higher deployment costs compared to lithium batteries. Additionally, their overall lifecycle economics are relatively weak, limiting adoption primarily to niche and high-end civilian markets.

2.3. Navigation and control system

Navigation and control systems are central to ensuring stable flight and task execution for CUAV. Their performance directly impacts flight precision, safety, and adaptability to various environments. Currently, positioning systems based on Global Navigation Satellite System (GNSS) are widely used in most civilian platforms. However, in urban canyons, indoors, or environments with complex electromagnetic interference, these systems often suffer from signal blockage or distortion. Therefore, more reliable sensor fusion mechanisms are urgently needed. Multi-sensor data fusion technology enhances positioning robustness and accuracy by integrating information from Inertial Measurement Units (IMUs), visual sensors, Light Detection and Ranging (LiDAR), and ultrasonic sensors. Typical fusion strategies include Extended Kalman Filtering (EKF), particle filtering, and deep learning-assisted fusion. These methods enable real-time environmental perception and three-dimensional attitude estimation, particularly providing critical advantages in scenarios where GNSS signals are unavailable.

3. Technological progress and typical cases

3.1. Aerial photography: a new phase in image acquisition and spatial data integration

CUAV-based aerial photography technology has evolved from early-stage low-resolution image acquisition to the current phase of high-precision geospatial information capture, with widespread applications in geospatial surveying, urban planning, cultural tourism promotion, and film production. Equipped with high-performance electro-optical sensors and three-axis stabilized gimbals, CUAVs are capable of acquiring stable high-resolution images and videos even under complex flight conditions. In recent years, advancements in real-time image stitching, 3D reconstruction, and multi-source data fusion algorithms have driven a transition from two-dimensional image recording to three-dimensional spatial modeling in aerial photography. Meanwhile, the integration of AI-based image recognition and edge computing technologies enables real-time data processing and intelligent analysis, significantly improving operational efficiency [4]. In the domains of film production and new media communication, lightweight consumer-grade CUAVs—such as the DJI Air series—have further spurred the rise of "personal aerial photography" and the "mobile visual era."

3.2. Logistics: opening an aerial corridor for the "last mile"

CUAV logistics technology has experienced rapid development in recent years, progressively emerging as an effective solution to transportation challenges in remote areas and the “last-mile” delivery bottlenecks in urban settings. Leveraging autonomous flight control, precise navigation, and integrated ground dispatch systems, CUAVs can perform point-to-point deliveries with high efficiency, significantly reducing labor costs and transit time. This is particularly advantageous in the delivery of medical supplies, fresh goods, and during emergency logistics operations, where rapid response and minimal human contact are critical. Leading enterprises such as Meituan and SF Express have launched routine pilot operations across various domestic and international locations. Some platforms have further enhanced payload capacity and operational efficiency through the adoption of hybrid-wing configurations and intelligent scheduling systems. Meanwhile, the advancement of low-altitude airspace refinement and supporting infrastructure—such as unattended takeoff and landing platforms—is laying a practical foundation for the large-scale deployment of logistics CUAV [5].

3.3. Agriculture: precision farming driving the transformation to smart agriculture

As an integral component of smart agriculture, agricultural plant protection CUAV have been widely employed in scenarios such as pesticide spraying, seeding, fertilization, and crop growth monitoring. Compared to traditional manual operations, UAV-based workflows offer significantly higher efficiency and enable variable-rate application and precision control, thereby reducing pesticide usage and minimizing environmental impact. Multirotor plant protection CUAVs, represented by models such as those from DJI, are equipped with high-precision RTK navigation, intelligent terrain following, and multi-nozzle spraying systems, allowing them to operate effectively across complex terrains such as hills and terraced fields. Moreover, by integrating multispectral imaging, NDVI vegetation indices, and AI-based image recognition analytics, agricultural drones can provide refined agricultural data support, facilitating precise decision-making and yield optimization. As rural intelligent infrastructure continues to improve, agricultural CUAVs are becoming a key technological driver in promoting agricultural modernization and sustainable development.

4. Technical challenges and bottlenecks

4.1. Regulations and airspace management

At present, the regulatory framework for CUAV is still undergoing continuous refinement. Significant discrepancies exist across countries and regions regarding policies related to flight authorization, time-of-flight regulations, altitude restrictions, and airspace classification, with a lack of unified international standards. In particular, the issue of how to balance the commercial demands of CUAV operations with national airspace security in the context of low-altitude airspace liberalization has emerged as a pressing challenge. Moreover, existing airspace management systems are predominantly designed for manned aviation and do not adequately account for the unique characteristics of large-scale low-altitude CUAV operations. This mismatch has increased the potential risk of conflicts between unmanned and manned aircraft [6]. The underdevelopment of critical infrastructure—such as UAV identification systems, dynamic monitoring networks, and real-time sense-and-avoid technologies—further limits the safe operation of drones in urban low-altitude and complex airspace environments.

4.2. Safety challenges in drone operations

Safety is the most important core issue in the application of CUAV technology. Flight control system malfunctions,battery overheating or failure, and mechanical structure fatigue are the common failures when CUAV flight.Once these failures occur, they directly threaten the flight safety of the CUAV.External interference, signal obstructions, or malicious attacks are easy because CUAV rely on wireless communication for remote control and data transmission.These attacks may result in loss of control, data leakage, or even hijacking for illegal purposes.In urban complex environments, CUAV face challenges such as tall buildings, electromagnetic interference, and signal blockages. Achieving obstacle avoidance and collaborative path planning in a multi-UAV coordination scenario is also a significant safety challenge [7].

4.3. Technical limitations

The current insufficient endurance is a major bottleneck limiting CUAV from long-distance tasks and performing long-duration, especially in scenarios such as logistics delivery and long-distance surveying, where the battery capacity and energy density are inadequate, restricting effective operation time. Although new energy technologies like hydrogen fuel cells and hybrid power systems have made certain progress, their commercialization is still constrained by factors such as high costs and system complexity. Additionally, on the hardware level, key components such as high-performance sensors and dedicated chip processors are heavily reliant on imports, posing a potential "choke point" risk. On the software algorithm side, CUAV still have significant room for improvement in autonomous perception, path planning, and collaborative control in complex dynamic environments. In extreme situations involving dynamic obstacles or complex weather conditions, true high-robustness autonomous flight has not yet been fully realized.

5. Future development trends

Facing of the growing application demands and technological challenges of CUAVs, the future development will present new trends of multi-technology integration, intelligence, environmental sustainability, and standardization. Specifically, this can be explored from three aspects: technological integration, the application of new technology, and privacy and data protection.

5.1. Technological integration

Artificial Intelligence (AI) technology will be deeply embedded in every aspect of drone system, enabling end-to-end intelligence from perception, decision-making to control execution [8]. Technologies such as deep learning-based target recognition, path planning, and autonomous obstacle avoidance will further enhance CUAVs' ability to operate autonomously in complex environments. Intelligent algorithms like reinforcement learning and imitation learning are widely applied in CUAV autonomous flight and multi-drone collaborative control, enabling the efficient completion of multi-drone cooperation tasks. Moreover, AI's role in data processing is particularly crucial. Through edge computing and real-time data analysis, AI can significantly improve CUAVs' task response times and information processing capabilities in scenarios like agricultural monitoring and environmental surveillance. In the future, the deep integration of AI and UAVs will drive the shift from "controllable" flight to "autonomous" flight, from "task execution" to "intelligent decision-making," opening up new and innovative application scenarios.

5.2. Application of new technology

The intersection of emerging technologies will bring about breakthroughs in CUAV performance. The introduction of quantum communication technology is expected to fundamentally enhance the security and anti-jamming capabilities communication links, addressing issues such as interception and decryption that can occur with traditional wireless communication, making it particularly suitable for scenarios involving sensitive data transmission. On the other hand, biomimetic UAV design is gradually becoming a research hotspot. By mimicking the movement mechanisms of natural flying animals such as birds and insects, UAV can achieve more flexible and efficient flight patterns. For example, by imitating the wing-flapping flight and landing mechanisms of birds, UAV can gain superior aerodynamic performance and energy efficiency, making them suitable for tasks in confined spaces and complex environments. Biomimetic micro-drones show vast potential in fields such as military reconnaissance, indoor inspections, and disaster search and rescue. In the future, the collaborative development of new materials, lightweight motors, and intelligent control technologies will further push biomimetic drones from the laboratory to practical applications.

5.3. Privacy and data protection

As CUAVs are widely used in fields such as aerial photography, surveillance, and data collection, the potential impact on personal privacy and data security has increasingly attracted societal attention [9]. During large-scale CUAVs operations, vast amounts of image, video, and location data are collected and transmitted. Without effective regulatory and protective mechanisms, this could lead to risks such as privacy breaches and data misuse. Currently, the legal framework for CUAV data protection is incomplete, with unclear regulations regarding the scope of data collection, the purpose of its use, and storage duration. In the future, it is necessary to establish clear legal and policy boundaries for data collection, define responsible entities, and strengthen data security through encryption, edge computing, and access control measures. Additionally, public acceptance of the ethics of drone use and social norms will become key factors in the further expansion of drone applications. Legal, technological, and societal safeguards can help the healthy and sustainable development of the drone industry.

6. Conclusion

In recent years, CUAV has become a key technology driver for low altitude economy. For example, significant application achievements have been made in fields such as aerial photography, logistics, and agriculture, while also promoting breakthroughs in key technologies such as flight platforms, propulsion and energy systems, as well as navigation and control.However, problems such as incomplete regulations, complex airspace management, insufficient safety guarantees, and limited endurance still exist. In the future, the deep integration of artificial intelligence and drones will drive their transformation from automation to intelligent and autonomous systems. The application of new technologies such as quantum communication and biomimetic design will further enhance the security, adaptability, and stealth capabilities of CUAV. At the same time, it is necessary to strengthen the legal and policy framework related to privacy protection and social ethics. Only through technological innovation, policy support, and social collaboration can the healthy and sustainable development of the CUAV industry be promoted, and it can be more widely applied in fields such as smart cities, modern agriculture, and emergency rescue.

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