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Safety Adaptation Technologies and Management Strategies for Unmanned Aerial Vehicle Operations in Highland Mountainous Environments: A Case Study of Yunnan Province

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Abstract: With the rapid development of drone technology, its applications in fields such as geological exploration and emergency rescue in the plateau and mountainous regions of Yunnan Province are becoming increasingly widespread. However, special environmental factors such as low air pressure and strong radiation seriously affect flight safety, and the adaptability of the existing management system is insufficient. Taking Yunnan Province as a sample, this paper systematically analyzes the impact mechanisms of plateau and mountainous environments on drones, focusing on the safety adaptation technologies for core modules such as power systems, navigation, and positioning. Combining with the current management situation in the province, it proposes countermeasures from dimensions such as regulations, supervision, and talent, providing support for improving the safety of drone use in special environments.

Keywords: Plateau and mountainous regions; Drones; Safety adaptation technology; Management countermeasures; Yunnan Province

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1. Introduction

1.1. Research background and significance

Unmanned aerial vehicles (UAVs), with their advantages of high flexibility and low cost, are driving the digital transformation of various industries. In Yunnan Province, mountainous areas account for 88.64% of the total land area, with an elevation range spanning from 76.4 meters to 6,740 meters. The province boasts diverse climatic conditions, making transportation and resource exploration highly challenging. UAVs have found applications here in landslide monitoring, terraced field plant protection, and mountainous search and rescue operations, effectively overcoming environmental constraints.

However, the plateau environment frequently causes malfunctions in drones: low air pressure reduces engine power, strong ultraviolet rays accelerate equipment aging, and complex terrain blocks signals. According to data from the Emergency Management Department of Yunnan Province, there were 47 drone flight malfunctions across the province in 2023, with 32 of them related to inadequate environmental adaptability, resulting in direct economic losses exceeding RMB 2 million. Therefore, researching adaptive technologies and management strategies is of great significance for ensuring operational safety and promoting industrial development.

1.2. Current research status at home and abroad

In domestic research, Wang Jian et al. proposed a low-temperature preheating technology for drone batteries on the Qinghai-Tibet Plateau, maintaining a discharge efficiency of over 80% at -10°C; Li Juan et al. proposed a management system of "government supervision + corporate self-discipline + technological prevention and control" for the southwestern mountainous regions [1–2]. However, existing research mostly focuses on single environmental factors and lacks systematic studies on the composite environment of "high altitude, diverse terrain, and strong radiation" in Yunnan Province, with management strategies not closely aligned with local realities.

1.3. Research content and methods

Research Content: Firstly, analyze the environmental characteristics of the Yunnan Plateau and their impact on drones; secondly, develop core adaptive technologies such as power and navigation; thirdly, propose strategies based on the current management situation. Research Methods: (1) Conduct field surveys to collect drone operational data from six locations, including Kunming and Lijiang; (2) perform experimental analyses to test the effectiveness of technologies in simulated laboratories; (3) Conduct literature research to sort out relevant achievements and policies.

2. Environmental characteristics of plateau and mountainous areas in Yunnan Province and their impact on UAV flight

2.1. Core environmental characteristics

The plateau environment in Yunnan exhibits three major characteristics: First, there is a significant variation in altitude, with Meili Snow Mountain in northwest Yunnan exceeding 6,700 meters, while Hekou County in southeast Yunnan stands at only 76.4 meters. For every 1,000-meter increase in altitude, the air pressure drops by 10 kPa, and the oxygen content decreases by 12% to 15%. Second, the climate is complex, with some regions experiencing temperature differences of over 20°C between day and night, an average of more than 50 thunderstorm days per year, and annual precipitation reaching 2,000 millimeters in western Yunnan. Third, the terrain and radiation are unique, featuring numerous canyons and terraced fields, with dense vegetation that easily blocks signals, and an annual sunshine duration of 2,200 to 3,000 hours, with ultraviolet intensity 30% to 50% higher than that in plain areas.

2.2. Mechanisms of environmental impact on UAVs

2.2.1. Performance degradation of power systems

Fuel-powered UAVs experience reduced air intake and combustion efficiency at low air pressures. For a certain type of fuel engine, the maximum thrust decreases by 42% and the takeoff run distance increases by two times at an altitude of 5,000 meters [3]. Electric UAVs are more significantly affected by low temperatures; in winter in

Diqing (-5°C), the endurance of a mainstream model decreases from 30 minutes to 12 minutes, posing a risk of power failure.

2.2.2. Decline in navigation and positioning accuracy

Complex terrain causes satellite signal obstruction. In the canyon areas of western Yunnan, the number of visible GPS satellites drops from 12 to fewer than 4, and positioning accuracy degrades from the meter level to over 10 meters [4]. Ionospheric disturbances triggered by severe convective weather can cause brief interruptions in navigation.

2.2.3. Insufficient stability in communication transmission

Microwave communication is obstructed by mountain vegetation. In the rainforest areas of Xishuangbanna, the communication range of drones decreases from 5 kilometers to 1.5 kilometers, and latency increases from 50ms to over 200ms [5]. Strong ultraviolet radiation accelerates the aging of communication components, increasing the error rate of data transmission.

2.2.4. Vulnerability of airframe structure

The average annual wind speed in the northwestern plateau of Yunnan is 3-5 meters per second, with gusts exceeding 10 meters per second, which can easily cause fluctuations in the airframe's attitude; the large diurnal temperature variation causes material expansion and contraction, leading to cracks. Research indicates that the incidence of structural failures in drones in mountainous areas is 28% higher than that in plains, manifesting as propeller breakage, etc. [6].

3. Research and development of safety adaptation technologies for drones in plateau and mountainous environments

3.1. Power system adaptation technology

3.1.1. Adaptive adjustment technology for fuel engines

To address the issue of engine power degradation caused by low atmospheric pressure at high altitudes, an adaptive adjustment system based on real-time atmospheric parameter monitoring has been developed. This system utilizes pressure sensors and oxygen concentration sensors installed on the body of unmanned aerial vehicles (UAVs) to collect real-time atmospheric data from the flight environment. After analysis by the central processing unit, it automatically adjusts the engine's air intake and fuel injection ratio. By employing variable nozzle turbocharger technology, the system increases the engine's intake pressure, resulting in a 38% increase in air intake and a 25% improvement in combustion efficiency compared to traditional engines at an altitude of 5,000 meters. Experimental validation shows that UAVs equipped with this technology maintain power output stability above 90% of that at plain levels when operating in the Meili Snow Mountain region of Yunnan Province (at an altitude of 5,200 meters), meeting the demands of high-altitude operations [7].

3.1.2. Low-temperature protection technology for lithium batteries

To mitigate the impact of low temperatures on lithium battery performance, an integrated battery management system featuring "preheating-insulation-energy recovery" has been developed. Flexible heating films are installed within the battery compartment, and temperature sensors continuously monitor the battery temperature. When the temperature drops below 5°C, the preheating function is automatically activated, rapidly raising the battery temperature to between 15°C and 20°C. The battery compartment is wrapped with a vacuum insulation layer to minimize heat loss, maintaining the battery temperature above 10°C in -10°C environments. Additionally, energy recovery technology is introduced to convert the kinetic energy of the UAV during descent into electrical energy, supplementing the battery charge and extending flight time by 20% to 30%. This technology has demonstrated excellent performance in winter operations in the Diqing region of Yunnan Province, extending the UAV's flight time from 12 minutes to 18 minutes and meeting the demands of long-duration operations such as emergency rescue [1].

3.2. Navigation and positioning adaptation technology

3.2.1. Multi-source navigation fusion positioning technology

This technology integrates GPS, Beidou, GLONASS, and Inertial Navigation Systems (INS) to establish a multi-source navigation fusion positioning framework. It employs the Kalman filtering algorithm to fuse and process positioning data from various navigation systems. When satellite signals are obstructed, it automatically switches to an inertial navigation-dominated mode, utilizing sensors such as gyroscopes and accelerometers embedded in the unmanned aerial vehicle (UAV) to calculate flight attitude and position information in real time. Additionally, terrain matching navigation technology is introduced, which pre-stores Digital Elevation Model (DEM) data of the operational area and matches the real-time terrain data collected by the UAV with the pre-stored data to correct positioning errors. During testing in the western Yunnan canyon region, this technology maintained the UAV's positioning accuracy within 3 meters, representing a 60% improvement over single satellite navigation systems [4].

3.3.2. Anti-jamming navigation enhancement technology

In response to the issue of satellite signal interference caused by severe convective weather, a navigation anti-jamming module based on adaptive frequency hopping technology has been developed. This module can monitor the interference intensity of navigation signals in real-time, automatically switch operating frequencies to avoid interference bands, and employ signal enhancement algorithms to improve the reception capability of weak signals. In terms of antenna design for unmanned aerial vehicles (UAVs), multi-polarized antennas are adopted to enhance the reception capability of satellite signals from different directions and reduce the impact of signal blockage. Experiments have shown that in thunderstorm-prone areas of Yunnan Province, such as the Pu'er region, the interruption time of UAV navigation signals equipped with this technology has been reduced from an average of 8 seconds to less than 1 second, significantly enhancing the reliability of the navigation system [8].

3.3. Communication transmission adaptation technology

3.3.1. Relay communication and multi-link backup technology

To address the issue of communication blockage caused by complex terrain, a collaborative operation mode of "primary UAV + relay UAV" has been proposed. The relay UAV is deployed at a high altitude to serve as a communication relay node, enabling indirect communication between the primary UAV and the ground station, and extending the communication distance from 1.5 kilometers to over 8 kilometers. Meanwhile, a multi-link communication backup system has been constructed, integrating microwave communication, 4G/5G public network communication, and satellite communication. When one communication link is interrupted, the system automatically switches to other links to ensure communication continuity. In tests conducted in the tropical rainforest region of Xishuangbanna, Yunnan Province, this system reduced the UAV communication interruption rate from 25% to 1.2% [5].

3.3.2. Optimization of radiation-resistant communication modules

To address the impact of intense ultraviolet radiation at high altitudes on communication modules, radiation-resistant materials are employed to encapsulate the modules. A UV-resistant polytetrafluoroethylene material is selected for the outer casing, while reinforced chips are used for the internal electronic components to enhance radiation resistance. Additionally, the heat dissipation structure of the communication module is optimized by combining heat fins with a microfan to reduce the module's temperature in high-temperature environments, preventing damage to components due to overheating. After testing, the optimized communication module demonstrated a performance degradation rate of only 5% after six consecutive months of operation in Lijiang, Yunnan Province (with an annual UV radiation intensity of 3500 $\mu W/cm^2$), representing a 20 percentage point reduction compared to traditional modules [3].

4. Airframe structure reinforcement technology

The airframe structure is optimized using lightweight, high-strength materials. The main body of the airframe is constructed from carbon fiber composite materials, resulting in a 30% weight reduction and a 45% increase in strength compared to traditional aluminum alloy materials. To address airframe stability issues in strong wind conditions, the UAV's aerodynamic layout is optimized by adopting a delta-wing design to reduce wind resistance, while increasing the area of the tail fins to enhance flight attitude control accuracy. For propeller design, variable-pitch propeller technology is employed, enabling automatic adjustment of the blade angles in response to changes in wind speed, thereby improving propulsion efficiency. During testing in the strong wind regions of northwest Yunnan Province, UAVs equipped with this structure maintained stable flight at wind speeds of 8 m/s, with a 50% reduction in airframe vibration amplitude compared to traditional UAVs [6].

5. Current situation and existing problems in the use and management of unmanned aerial vehicles (UAVs) in Yunnan Province

5.1. Current management situation

Yunnan has issued documents such as the "Interim Measures for the Flight Management of Unmanned Aerial Vehicles", clarifying departmental responsibilities and establishing a "hierarchical and classified" regulatory framework. As of June 2024, 12 flight service stations have been established, with 86,000 UAVs registered, achieving a registration rate exceeding 90%. Detection equipment has been deployed in key areas, with 132 cases of illegal flights handled in 2023, and over 12,000 training sessions for operators conducted throughout the year.

5.2. Existing problems

5.2.1. Inadequate adaptability of the regulatory framework

The existing regulations largely draw on management experiences from plain regions, failing to fully consider the unique environmental characteristics of Yunnan's plateau and mountainous areas. For instance, the flight altitude limit for UAVs stipulated in the "Interim Measures for the Flight Management of Unmanned Aerial Vehicles in Yunnan Province" (120 meters below in general areas) renders UAVs incapable of performing tasks such as topographic mapping and disaster monitoring in some high-altitude mountainous regions (e.g., Diqing), where the terrain elevation exceeds 3,000 meters. Furthermore, the absence of standards for UAV environmental adaptability technologies leaves undefined performance indicators and modification requirements for UAVs operating in plateau and mountainous areas. Consequently, some enterprises, aiming to reduce costs, use UAVs not adapted to high-altitude environments for operations, thereby increasing flight risks [2].

5.2.2. Shortcomings exist in the regulatory system

Firstly, the regulatory coverage is limited. Most mountainous areas in Yunnan Province are located in remote regions where unmanned aerial vehicle (UAV) regulatory equipment has not been deployed, resulting in regulatory blind spots. Among the 47 UAV malfunction incidents that occurred across the province in 2023, 28 took place in mountainous areas without regulatory coverage. Secondly, the inter-departmental coordination mechanism is inadequate. The information sharing among civil aviation, public security, emergency management, and other departments is not timely, leading to insufficient dynamic regulatory capabilities for UAV flights. For example, when emergency rescue UAVs fly beyond the designated airspace at disaster sites, ground stations are unable to promptly transmit flight information to air traffic control departments, which may result in conflicts with manned aircraft flights. Thirdly, technological regulatory means are lagging. The existing regulatory equipment is primarily designed for medium and large-sized UAVs, and lacks the detection capabilities for small and micro UAVs, making it difficult to meet the regulatory needs for the large number of small UAVs operating in mountainous areas [9].

5.2.3. Weak talent and technological support

Yunnan Province faces a shortage of UAV professionals, particularly compound talents who possess both UAV technology expertise and familiarity with the characteristics of plateau and mountainous environments. Among UAV-related enterprises across the province, less than 30% of operators hold professional qualifications. Some operators have not undergone systematic training and lack proficiency in UAV operation techniques and emergency response capabilities in plateau environments. In terms of technological support, there are few UAV research and development enterprises within the province, which mainly rely on technology introduction from outside the province. The research and development capabilities for adapting technologies to Yunnan's specific environmental conditions are weak, with low technology transfer efficiency, making it difficult to quickly meet market demands.

5.2.4. Inadequate safety responsibility system

Some users operate in violation of regulations, such as an agricultural company in Pu'er illegally modifying batteries, which led to a drone crash. The determination of accident liability is ambiguous, making it difficult to define the responsibilities of multiple parties [4].

6. Countermeasures for the safe management of drone use in Yunnan Province

6.1. Improve adaptive regulations and standards

Revise the "Interim Measures for the Administration of Drone Flight," implementing restrictions based on "reference altitude plus relative altitude," with a relative altitude limit of 120 meters in general areas, and clarifying priority flight rights in special fields. Introduce the "Safety Technical Standards for Drones in Plateau and

Mountainous Regions", stipulating that the engine decay rate should be ≤15% below an altitude of 5,000 meters, and battery endurance at -10°C should be ≥60% of that in plain areas, establishing an adaptation certification system [3].

6.2. Establish a comprehensive supervision system

Deploy portable detection equipment in disaster-prone areas to establish a data link among "drones, ground stations, and supervision platforms." Set up a hotline for reporting violations to encourage public participation. Establish an inter-departmental joint meeting system and build an information-sharing platform to achieve real-time synchronization of emergency flight information. Develop AI recognition technology to enhance the detection capabilities for small and micro drones, and use big data to predict flight risks [5].

6.3. Strengthening talent and technological support

Yunnan University and other higher education institutions have established unmanned aerial vehicle (UAV) majors and offered specialized courses on high-altitude flight. They have implemented an integrated "training-assessment-certification" training program, attracted high-end talent, and provided subsidies. Special research and development funds have been set up, and technological transformation platforms have been constructed to facilitate the implementation of technologies such as low-temperature protection. Additionally, university-enterprise cooperation has been strengthened to introduce and adapt advanced technologies [4].

6.4. Improving the safety responsibility system

The primary responsibilities of user entities have been clarified, and a safety credit evaluation system has been established to deduct points from or blacklist violators. The "Measures for Handling UAV Flight Accidents" have been formulated, and a multi-departmental investigation team has been established to define the responsibilities of manufacturers, user entities, and others, as well as establish an accident compensation mechanism [2].

7. Conclusion and outlook

7.1. Research conclusions

Factors such as low air pressure and low temperatures on the Yunnan Plateau have led to issues such as reduced UAV power and decreased navigation accuracy. Technologies such as adaptive adjustment of fuel engines and multi-source navigation fusion developed to address these challenges have effectively enhanced flight safety. Regarding management issues such as inadequate regulatory compliance, proposed countermeasures such as improving standards and strengthening supervision hold practical value.

7.2. Future outlook

In the future, drone adaptation technology will evolve towards intelligence, such as AI-powered autonomous obstacle avoidance and improved communication stability through 5G. In terms of management, blockchain can be utilized for data certification, while digital twins can support training and planning. The research achievements in Yunnan can serve as a reference for other plateau regions, and it is necessary to strengthen cross-regional cooperation to promote the unification of technical standards and management norms.

Disclosure statement

The authors declare no conflict of interest.

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