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An Overview of the Basic Structure and Flight Principles of UAVs

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Abstract

This study focuses on the basic structure and flight principle of unmanned aerial vehicles (UAVs), and systematically analyzes the core components of the UAV system, the flight control technology and its performance in different application scenarios. The UAV flight platform adopts lightweight and high-strength materials such as carbon fiber composites, and combines GPS/GNSS navigation, inertial measurement unit (IMU) and flight controllers to achieve autonomous flight and high-precision positioning. The ground control and communication system ensures real-time data interaction and remote control between the UAV and the ground station through standardized transmission protocols. The diversified and modularized design of payloads greatly expands the application boundaries of UAVs in agriculture, surveying and mapping, logistics, security and other fields. The study reveals the differences in flight principles between multi-rotor and fixed-wing UAVs, with multi-rotor UAVs being suitable for vertical take-off and landing and low-altitude fine operations, while fixed-wing UAVs have the advantages of long endurance and high-efficiency cruising. Through the optimization of structural design, control system and autonomous flight technology, UAVs are developing towards higher intelligence, longer flight time and stronger environmental adaptability, providing technical support for the construction of new infrastructure such as smart cities and intelligent transportation.

Keywords

Unmanned aircraft, basic structure, flight principle, autonomous flight, application scenario.

1. Introduction

In recent years, with the rapid development of multidisciplinary technologies such as aerospace, material science, automatic control, artificial intelligence, etc., the technology of Unmanned Aerial Vehicle (UAV) has made breakthrough progress. UAVs have become an important part of modern aviation due to their advantages of flexible structure, convenient operation, and lower cost. Especially driven by emerging technologies such as 5G communication, navigation and positioning, and intelligent perception, the performance and application scenarios of UAVs have been expanding, driving the rapid growth of the global UAV industry. UAVs not only play an irreplaceable role in national defense fields such as military reconnaissance, border patrol, and battlefield combat, but also show great application potential in civil and commercial fields. For example, in agricultural plant protection, geographic mapping, environmental monitoring, logistics and transportation, emergency rescue, film and television aerial photography, etc., UAVs have greatly improved operational efficiency and data acquisition capabilities, and have become an important force in promoting changes in the mode of social production. With the gradual improvement of policies and regulations and the continuous growth of market demand, the application scope of UAVs will be further expanded, becoming an important support for smart cities, intelligent transportation and other new infrastructures.

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2. UAV System Structure Composition

2.1. Flight Platform Core Components

As the core carrier of the whole system, the UAV flight platform, its structural design and the performance of its key components directly determine the UAV's flight capability, stability and mission adaptability. First of all, the material selection and design requirements of the fuselage structure are crucial. Modern UAVs commonly use carbon fiber composite materials as the main load-bearing components, which not only have extremely high specific strength and specific stiffness, but also can effectively reduce the weight of the airframe, and enhance the endurance and maneuverability. Carbon fiber materials have good corrosion resistance and anti-fatigue performance, and can adapt to complex and changing environmental conditions. In addition to carbon fiber, some UAVs also use lightweight polymer frames, such as polymer polypropylene and ABS, which are flexible in processing and lower in cost, and are suitable for the manufacture of small or disposable UAVs. The structural design of airframes needs to strike a balance between strength, weight and electromagnetic compatibility: it is necessary to ensure flight safety and impact resistance, while minimizing deadweight to improve the load ratio, and at the same time considering electromagnetic shielding and interference suppression for on-board electronic equipment to ensure stable system operation.

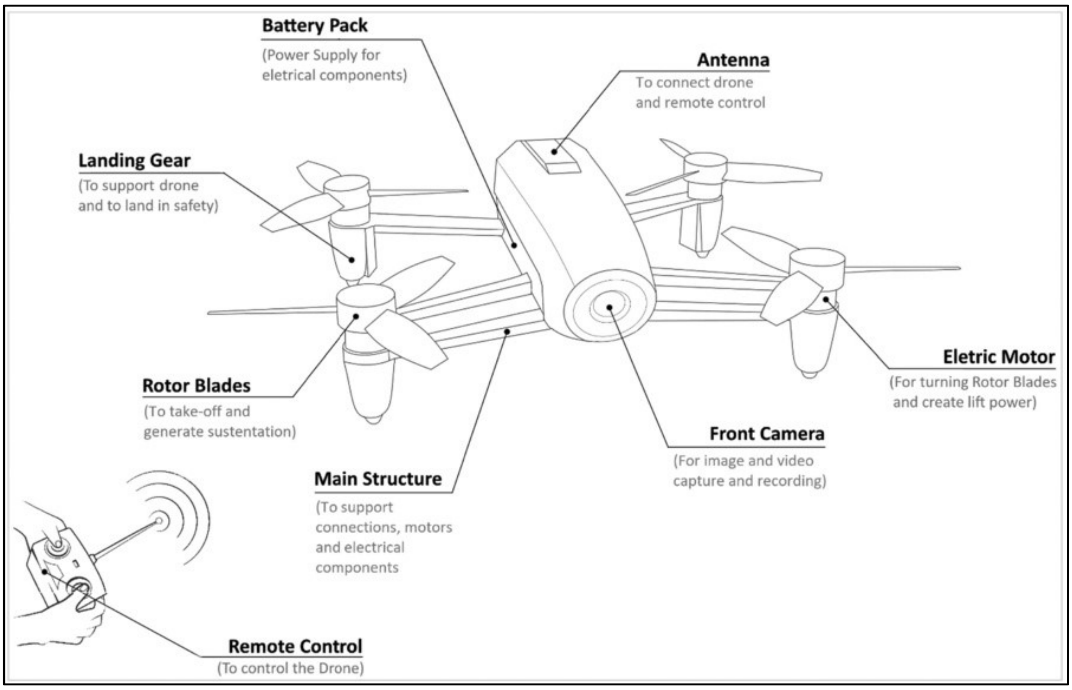

Figure 1. Fuselage structure

The navigation system is the key for UAVs to realize autonomous flight and high-precision positioning. Currently, mainstream UAVs generally integrate GPS or GNSS (e.g., BeiDou, GLONASS, etc.) positioning modules to realize real-time positioning and tracking of trajectories on a global scale. High-precision satellite navigation not only provides three-dimensional spatial coordinates for UAVs, but also supports intelligent functions such as automatic homing and fixed-point hovering. Meanwhile, the inertial measurement unit (IMU), as the core component of attitude sensing, usually consists of a three-axis gyroscope and a three-axis accelerometer, which can monitor the angular velocity and linear acceleration of the UAV in real time, and provide attitude estimation and dynamic compensation data for the flight control

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system. The flight controller, as the "brain" of the UAV, is responsible for fusing navigation and attitude information, running a real-time operating system, executing flight control algorithms, and generating control instructions for motors, rudders, and other actuators to achieve stable flight, path planning, and mission execution. The high-performance flight control system not only enhances the autonomy of the UAV, but also provides a solid guarantee for safe flight in complex environments.

2.2. Ground Control and Communication System

Ground Control and Communication System (GCS) is the core guarantee for UAV to realize remote control, mission management and data interaction. Ground Control Station (GCS) is usually composed of remote control, special computer, display terminal and other hardware, and with professional flight control software, it can carry out real-time monitoring of UAV flight status, route planning and mission parameter setting, etc. GCS not only supports manual remote control operation, but also has the functions of automated mission management, flight data analysis and emergency intervention, etc. It is an important support platform for safe and efficient operation of UAV. GCS not only supports manual remote control operation, but also has automated mission management, flight data analysis and emergency intervention, which is an important support platform for safe and efficient operation of UAVs. Through the ground station, the operator can remotely set the flight path, adjust the flight parameters, and obtain the position information, attitude data and load status of the UAV in real time, thus realizing precise control of complex tasks. The communication system is responsible for the transmission of commands and data between the UAV and the ground station, and the commonly used radio frequency bands include civil frequency bands such as 2.4GHz and 5.8GHz, as well as military frequency bands such as the L-band, which can satisfy the communication distance and anti-jamming requirements of different application scenarios, and the standardized transmission protocols, such as MAVLink, are widely adopted to achieve the two-way high-speed transmission of flight commands, telemetry data, images and videos, and guarantee the accuracy and precision of the flight process. MAVLink and other standardized transmission protocols are widely used to achieve two-way high-speed transmission of flight commands, telemetry data, images, videos and other information to ensure the real-time and reliability of the flight process. The efficient communication system not only enhances the autonomy and intelligence of the UAV, but also provides solid technical support for safe flight in long-distance and complex environments.

2.3. Payload and Mission Adaptability

Payload and mission adaptability is an important driving force for the development of UAV technology, which directly determines the breadth and depth of its application field. Modern UAVs can be flexibly configured with various types of sensors according to different mission requirements, including high-resolution visible light cameras, infrared thermal imagers, LiDAR, multi-spectral sensors, etc. (see Fig. 2), and these devices are capable of realizing a variety of functions, such as environment sensing, target recognition, data acquisition, and so on. For example, agricultural plant protection UAVs equipped with multispectral cameras can carry out crop health monitoring, mapping UAVs equipped with LiDAR can realize high-precision three-dimensional modeling, and security UAVs integrated with infrared cameras can carry out surveillance tasks at night or under bad weather conditions [1]. In addition to sensors, UAVs can also carry a variety of mission equipment, such as logistics UAVs equipped with cargo pods that can carry 5kg-class goods for distribution, plant protection UAVs installed with spraying systems that can carry out accurate pesticide spraying, and rescue UAVs equipped with life-saving equipment that can provide assistance in emergency situations [2]. The diversified and modularized design of the load system greatly expands the application boundary of UAVs, expanding them from the initial military reconnaissance to agriculture, logistics, security,

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environmental protection, film and television, and other fields. With the continuous emergence of new materials, new processes and new technologies, the UAV load capacity has been continuously improved, and the mission adaptability has been further enhanced, providing strong technical support for the construction of new infrastructure such as smart cities and intelligent transportation, and promoting the rapid development of the UAV industry and the continuous enrichment of the application scenarios.

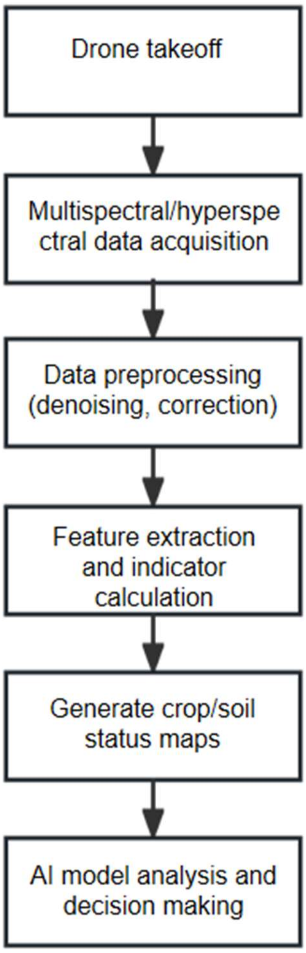

Figure 2. Flow of UAV spectral data acquisition and processing

3. Principles of UAV Flight

3.1. Fundamentals of Aerodynamics and Balance of Four Forces

Fundamentals of aerodynamics and balance of four forces are central to understanding the principles of UAV flight. UAVs are mainly subject to four basic forces during flight, namely lift, gravity, thrust and drag. Lift is a force perpendicular to the direction of the airflow generated by the movement of the wings or propellers in the air, and its magnitude can be expressed in the form of the formula:

$$L=\frac{1}{2}\rho V^2 S C_L$$

where ρ is the air density, V is the relative air velocity, S is the force area, and C_L is the lift coefficient. Gravity, on the other hand, is the product of the UAV's own mass and the acceleration of gravity, always acting vertically downward on the airframe. Thrust is mainly

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generated by propellers or jet engines, usually in the same direction as the UAV's forward direction, and is used to overcome in-flight drag and to maintain or change speed, and is expressed as:

$$T=K_n\omega^2$$

whereω is the propeller speed. Drag, on the other hand, is the reaction force of the air on the movement of the UAV, which is categorized into induced drag and parasitic drag, and its magnitude can be expressed by Eq:

$$D=\frac{1}{2}\rho V^2 S C_D$$

C_D is the drag coefficient. The mechanical condition for a UAV to realize stable flight is that the vertical upward force is equal to gravity (L=G), and the horizontal upward thrust is equal to the drag force (T=D), and only when these two sets of forces are balanced can the UAV maintain a stable flight state that neither rises nor falls, and neither accelerates nor decelerates. The precise understanding and reasonable distribution of the four forces is the theoretical foundation of UAV design and control, and the key to improving flight efficiency and safety.

3.2. Comparison of Multi-Rotor and Fixed-Wing Flight Principles

Multi-rotor and fixed-wing UAVs differ significantly in their flight principles, and each has unique structural advantages and application scenarios. Multi-rotor UAVs rely on the thrust of multiple propellers to realize vertical takeoff and landing (VTOL), without the need for a runway, and are able to take off and land flexibly in narrow or complex environments. Its attitude control mainly realizes pitch, roll and yaw by adjusting the rotational speed of each motor, and the flight control system can adjust the thrust distribution in each axial direction in real time, so as to realize precise hovering, spotting and maneuvering flight. However, multi-rotor UAVs consume high energy when hovering and flying at low speeds, and their endurance is usually limited by battery capacity, making it difficult to fly for long periods of time and over long distances (see Figure 3).

Figure 3. Multi-rotor UAV

In contrast, fixed-wing UAVs have higher range and endurance by generating lift through the wings as they move forward and relying on aerodynamic principles to achieve efficient gliding. Its flight control relies on control surfaces such as ailerons, elevators and rudders, and attitude

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adjustment is achieved by changing the direction of airflow. Fixed-wing UAVs are suitable for missions such as wide-area cruising, mapping and long-distance transportation, but they usually require runways or catapults for takeoff and landing, and have limited maneuverability and low-altitude hovering capability (see Figure 4).

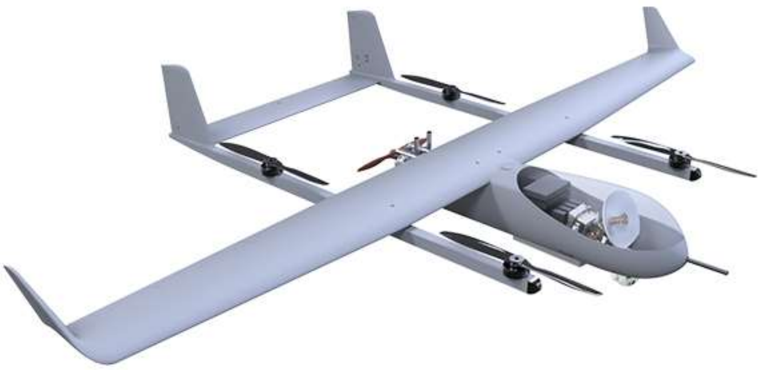

Figure 4. Fixed-wing UAV

Overall, multi-rotor UAVs are suitable for urban inspection, emergency rescue, aerial photography and other scenarios with high requirements for maneuverability and vertical takeoff and landing, while fixed-wing UAVs are more suitable for geographic surveying and mapping, border patrols, long-range monitoring, and other applications with high requirements for endurance and range. The limitations of the two also determine the need to rationally choose the type of UAV according to the task characteristics or adopt a hybrid configuration to take into account the advantages of both.

3.3. Analysis of Main Flight Control Methods and Energy Efficiency

The main flight control methods of UAVs are directly related to their flight stability, energy-efficiency performance and mission accomplishment quality. Current mainstream flight control algorithms include PID (Proportional-Integral-Differential) and LQR (Linear Quadratic Regulation), etc. PID control is widely used in real-time attitude and altitude adjustment due to its simple structure and rapid response, which can effectively suppress external perturbations and maintain the stability of the UAV in hovering and steering, etc. Modern control algorithms such as LQR improve the control stability in complex maneuvering and multivariable coupling situations by global optimization of the system states. global optimization of the system state, which improves the control accuracy under complex maneuvering and multivariate coupling, and is suitable for high-performance and highly autonomous UAVs [3]. Energy consumption and efficiency bottlenecks are important challenges in UAV design and application, especially when a multi-rotor UAV is hovering and flying at low speeds, the vast majority of the energy is used to fight gravity, resulting in limited endurance; whereas a fixed-wing UAV can make full use of aerodynamic lift in the cruise state, resulting in higher energy efficiency. For different flight states, UAVs adopt differentiated control strategies: when hovering, the thrust of each motor needs to be precisely adjusted to maintain balance; when cruising, the focus is on stable control of heading and speed; and maneuvering flights such as turning and climbing require dynamic distribution of thrust and adjustment of control surfaces [4]. Efficient flight control not only improves the flight safety and mission completion rate of UAVs, but also provides technical guarantee for energy consumption optimization and endurance enhancement. With the development of intelligent algorithms and adaptive control technology, the future flight control of UAVs will be more intelligent and efficient.

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4. The Correlation and Development Trend of Structure and Flight Principle

4.1. Influence of Structural Design on Flight Performance

Structural design, as a core element of UAV system engineering, has a decisive influence on flight performance. The choice of fuselage configuration is directly related to the aerodynamic characteristics and application efficiency of UAVs. For example, fixed-wing UAVs need to weigh the lift coefficient and induced drag in the design of the wing chord ratio, and high chord ratios increase the weight of the structure even though they improve the lift efficiency; the choice of the wing profile is also critical, and laminar flow airfoils can reduce the cruising drag, while multi-point airfoils can be adapted to a variety of flight states. Material selection is also decisive in structural design. Carbon fiber composites are used in the main fuselage with high strength-to-weight ratio to reduce weight and ensure structural rigidity; the roughness of aerodynamic surface skin material affects the flow and drag characteristics of the boundary layer, and the new type of nano-coating can realize intelligent de-icing and self-cleaning to enhance the capability of all-weather operation. The suitability of take-off and landing modes and structural design should not be overlooked. Vertical take-off and landing configurations need to enhance structural strength to cope with load variations, and the design of the power system and the center of gravity needs special consideration; traditional runway take-off and landing UAVs need to optimize the landing gear design to ensure the aerodynamic efficiency and mission load capacity. In actual design, aerodynamic efficiency, load capacity and reliability need to be considered comprehensively. For example, multi-rotor UAV arm design needs to take into account stiffness and lightweight, and multi-objective optimization is often realized with the help of modern engineering tools such as CFD and FEA.

4.2. Control System and Autonomous Flight Technology

The UAV control system adopts a layered architecture, integrating the navigation, attitude and actuation layers to synergistically realize flight control. The navigation layer obtains position information based on GPS/INS combined navigation, plans global paths and makes decisions in combination with preset waypoints, and provides the system with the basis for flight trajectories. The attitude layer receives the navigation commands and realizes the pitch, roll and yaw control through attitude solving to ensure the flight stability, which is the key interface between the navigation and execution layers. The execution layer directly manipulates motors, servos, etc., and transforms the control commands into actual actions to complete the flight mission [5]. In terms of key technologies, the gravity compensation algorithm estimates and compensates for the influence of gravity in real time to improve the attitude control accuracy; Kalman filter and adaptive control strategy effectively suppresses wind disturbance, airflow turbulence and other external interference. Robust control and model predictive control technology enhance the adaptability of the system to model uncertainty and parameter changes. Autonomous flight relies on the closed-loop control system, which utilizes sensor feedback to construct a state observer and realizes position-velocity-attitude nested closed-loop control. Vision-based SLAM technology and obstacle detection system give the UAV the ability to perceive the environment, combined with deep learning algorithms to realize autonomous navigation and obstacle avoidance in complex environments, while fault detection and fault-tolerant control mechanisms guarantee the basic flight ability when some of the functions of the system are degraded, and improve the overall reliability [6].

4.3. Future Directions and Technical Challenges

The future development of UAV technology faces multidimensional challenges and opportunities. In the energy field, solid-state battery technology is expected to break through the energy density limitations of existing lithium batteries while providing higher safety

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performance, while hydrogen fuel cell systems offer new possibilities for long endurance flights, but their system integration and replenishment infrastructure still need to be improved. In the field of intelligent control, control algorithms based on deep learning and reinforcement learning are gradually replacing the traditional PID control, enabling UAVs to have the ability of autonomous decision-making and environmental adaptation, but the real-time and interpretability of the algorithms still need to be improved [7]. In the field of aerodynamic design, new composite materials and bionic design are promoting the improvement of flight efficiency, while the development of redundancy design and fault diagnosis technology enhances system reliability. With the continuous expansion of UAV application scenarios, especially operations in urban airspace and complex environments, the formulation of relevant regulations and standards faces challenges in various aspects such as technical feasibility, safety and privacy protection, and requires the joint efforts of all industrial parties to establish a perfect regulatory system.

5. Conclusion

This study reveals the intrinsic correlation between the structural design and flight principles of UAVs by systematically analyzing the two, and finds that the synergistic optimization of the airframe configuration, material selection, and control system is the key to enhancing the flight performance. The study shows that different types of UAVs have their own characteristics: multi-rotors are suitable for low-altitude fine operations, fixed-wings have advantages in long endurance and high-efficiency cruising, and hybrid configurations show unique value in specific application scenarios. Looking ahead, UAV technological innovation will continue to make breakthroughs in areas such as new battery technology, intelligent control algorithms and composite materials, promoting the development of UAVs in the direction of higher intelligence, longer endurance and stronger environmental adaptability. In order to promote the healthy development of the industry, it is recommended to focus on the research and development of ultra-long endurance technology, the integration of interdisciplinary technology, and the exploration of new application scenarios, and at the same time, accelerate the improvement of the relevant regulations and standards system, so as to provide institutional safeguards for the technological innovation and industrialization and application of UAVs. These efforts will jointly promote UAV technology to play a greater value in military and civil fields.

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