Comparative Analysis of Rotary-Wing Drones, Fixed-Wing Drones and Compound-Wing Drones for Uavs

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Abstract. This article is mainly due to the rapid development of drones in today's society. It analyzes the characteristics and principles of the three existing types of drones for Unmanned Aerial Vehicle (UAV), namely fixed - wing drones, compound drones, and rotary - wing drones. Then, based on their anti - interference ability, endurance, and reliability in performing tasks, it analyzes their suitable application scenarios. Through chart comparison, it is concluded that rotary - wing drones are suitable for low - altitude economy such as low - altitude reconnaissance, agricultural plant protection, and aerial photography; fixed - wing drones are suitable for surveying and mapping, long - distance inspection, logistics transportation, and long - range strikes; compound drones are suitable for scenarios that require vertical take - off and landing and long - endurance, such as border patrol, emergency rescue, transportation, or experiments. It also elaborates on the existing drone technologies and then makes expectations and predictions for the future development of drones. The whole article provides a reference for the future application scenarios of drones.

Keywords: UAV; Rotary-wing; Fixed-wing; Compound-wing; Comparison.

1. Introduction

Since the dawn of the 20th century, global science and technology have advanced by leaps and bounds. In recent years, driven by China's rapid technological progress and sustained growth in manufacturing capacity, a series of high-tech products developed and manufactured in China have gained substantial traction in the global market, with UAVs being a prominent example. According to the 2024 Statistical Communique on the Development of Civil Aviation Enterprises released by the Civil Aviation Administration of China (CAAC), Chinese consumer-grade UAVs account for over 70% of the global market share, while industrial-grade UAVs hold more than 50% of the global market [1]. China has thus emerged as the world's largest supplier of UAVs and a core driver of the global low-altitude economy, with its UAV export volume on a steady annual rise. UAVs play a pivotal role across diverse sectors. Militarily, they are deployed for low-altitude transportation of heavy supplies, reconnaissance missions, and even precision strikes on military targets. In civilian applications, UAVs are utilized to collect meteorological data for weather forecasting, spray pesticides, irrigate farmlands, and conduct real-time agricultural monitoring [2]. They also prove invaluable in disaster relief efforts, aiding in the location and rescue of trapped individuals, inspecting hazardous structures, and executing high-risk tasks. In daily life, UAVs cater to recreational needs such as aerial photography and high-altitude live streaming. Evidently, UAVs have become deeply integrated into various aspects of our work and daily lives, boasting extensive untapped application potential.

With a history spanning nearly a century since their inception, UAVs have evolved into numerous types to address diverse operational requirements. Rotorcraft UAVs are the most commonly encountered by the general public in daily scenarios, while fixed-wing UAVs are predominantly used in military and transportation sectors. Additionally, hybrid-wing UAVs are specially designed for experimental research and military applications. Given the multifaceted prospects of UAV applications, exploring the structural advantages of different UAV types and their respective use cases holds significant theoretical significance and practical value.

This research also provides insights for the rational deployment of UAVs in the future. The structure of this paper is as follows: first, it explores the definition, structure, and historical development of UAVs; second, it analyzes the differences in airfoil designs, flight principles, and functionalities of various UAV types; third, it compares the application scenarios and typical advantages of different UAVs; finally, it discusses the challenges and prospects of UAV development amid advancing technological progress.

2. Theoretical basis and analysis

2.1. The definition, structure and history of UAV

UAV refers to a crewless aircraft operated by radio remote control equipment and an on-board programmed control device, or autonomously by an on-board computer. Simply put, a UAV is a powered, controllable, reusable unmanned aircraft capable of carrying various mission equipment and performing multiple tasks. Different types of UAVs vary significantly in structure. As the name suggests, a rotorcraft UAV is equipped with rotors. Its structure can generally be divided into three core components: the power system, the control system, and the mechanical system. The power system includes motors, electronic speed controllers (ESCs), batteries, and propellers; the control system comprises flight controllers, sensors, and ESC connection boards; the mechanical system consists of physical support components such as the frame, landing gear, and outer casing, which structurally sustain the entire UAV [3]. Each of these three systems is indispensable, serving as a critical prerequisite for the safe and stable takeoff of the UAV.

Fixed-wing UAVs are similar to conventional aircraft, consisting of five main components: wings, fuselage, empennage, landing gear, and powerplant. The wings serve as the core components generating lift, equipped with ailerons, flaps, slats, spoilers, and other control surfaces to maneuver the aircraft. The fuselage acts as the primary load-bearing platform, connecting all structural parts and providing space for housing avionics systems and other equipment. The empennage comprises a vertical stabilizer and a horizontal stabilizer [4]. The landing gear, typically composed of shock-absorbing mechanisms and wheels, facilitates takeoff, taxiing, landing, and shock absorption during touchdown. The powerplant, mainly consisting of engines, serves as the energy source for the UAV's flight.

Compound wing drones are hybrid-configured aircraft that combine the advantages of fixed-wing and multi-rotor drones. Their core components are designed around the dual-mode flight requirements of vertical takeoff and landing plus horizontal cruising [5]. They are still mainly composed of a power system, flight control structure, wing and fuselage structure, communication link system, power management system, and mission payload system.

The history of drones is quite long. It can be traced back to the First World War. In 1917, the UK successfully developed the first drone. Early drones were modified on the basis of decommissioned aircraft and could only fly on fixed orbits without autonomous response. Around the 1960s, with the rapid development of technologies such as radio technology and automatic control technology, drones began to adopt these emerging technologies. As a result, they no longer completely relied on ground control and became real drones. Since the 1990s, with the rapid development of information technology, materials science technology, satellite communication technology, etc., the application fields of drones have become more and more extensive, and the number has been increasing year by year. That's why we can see a wide variety of drones in large numbers today.

2.2. Types and functions of UAV wings

2.2.1 The wings of a rotary-wing UAV

The main feature of rotor drones is the propellers around them. There are also different types, including single-rotor with tail rotor, coaxial dual-rotor, tandem/transverse dual-rotor, and multi-rotor, etc. The lift of a rotor drone mainly comes from the rotors around it [6]. The core principle is to generate lift by rotating and cutting the air. At the same time, flight control is achieved by adjusting the attitude. When rotating, the air flow velocity on the upper surface is fast and the pressure is low, while the air flow velocity on the lower surface is slow and the pressure is high, forming a pressure difference between the upper and lower surfaces, thus generating lift, which is the Bernoulli principle.

2.2.2 The wings of fixed-wing UAV

Fixed-wing drones generate lift from the fixed wings on both sides. The principle of the wing's providing power is similar to that of fixed-wing aircraft. Historically, it mainly stems from the inspiration of bird flight aerodynamics for human flight. When the airflow blows over the wing at a certain angle of attack, a pressure difference will be generated due to the different airflow velocities above and below the wing surface [7]. Usually, the airflow velocity on the upper wing surface is faster, and that on the lower wing surface is slower, thus generating upward lift.

2.2.3 The wings of a compound-wing UAV

Most compound-wing UAVs are classified according to their airframe structures. They include the tilt-rotor type - the rotors on both sides of the wing and their engines can tilt as a whole, such as the U.S. V-22 Osprey UAV; the tilt-wing type - the entire wing tilts together with the propellers to switch flight modes; the vertical takeoff and landing fixed-wing type - after takeoff, it switches from the rotor mode to the fixed-wing level flight mode; the push-pull plus vertical takeoff and landing layout type - it mainly relies on the push-pull propellers to provide horizontal propulsion [8]. Its working principle is usually a combination of the fixed-wing and the rotor.

3. Comparative analysis of UAV application scenarios

3.1. Rotor UAV

Rotor drones take off by means of rotors, so they can take off and land vertically and have a certain load capacity. When flying at low altitudes, they have the advantages of high operation efficiency, automatic or autonomous flight, good maneuverability, and no need for a dedicated take - off and landing airport. Therefore, they are often used in tasks such as large - field pesticide spraying operations. This is because they can take off and land vertically in the fields, and the interaction between the rotating rotors and the air provides lift for the airframe, which can also wrap around the airframe. At the same time, the sprayed droplets are carried and squeezed onto the crop canopy for pesticide spraying [9]. At the same time, multi - rotor drones have the advantage of low - altitude stability. In addition, they have a simple structure and are light in weight. They don't need a complex site to take off. Coupled with a mature flight control system, they can perform precise hovering. Although their endurance is relatively low, even so, the DJI MATRICE 600 PRO six - rotor drone can still stay stationary in the air for 20 minutes with a load of 5 kg. With these advantages, it can also be used for emergency rescue. It can be located in narrow alleys and other spaces to accurately deliver supplies and scout for trapped people [10]. However, at the same time, the literature suggests that because rotor drones are small in size, light in weight, and prone to severe body shaking, they are prone to control failure in complex environments such as at sea or in strong winds. Although increasing the fuselage size and upgrading the configuration can enhance the wind - resistance performance, it will increase the load, reducing the drone's flexibility and endurance. Therefore, existing rotor drones are not suitable for operations in complex environments such as strong winds [11]. At the same time, the literature shows that the endurance of rotor drones is generally less than 30 minutes. The low energy density of the battery and insufficient motor conversion efficiency are the main reasons [12]. The endurance of rotor drones will also be significantly reduced in high - altitude, low - temperature and low - pressure environments. Even when the battery weight is twice that of the non - battery part of the drone, and the endurance can reach the maximum value, it still cannot carry out long - term tasks [13]. From the above, rotor drones are currently only suitable for low - altitude economic operations and cannot perform long - distance, high - altitude and complex - environment tasks.

3.2. Fixed-wing UAV

Fixed-wing drones take off with their fixed wings. Compared with multi-rotor drones, fixed-wing drones have longer endurance, greater payload capacity and better flight efficiency. They can greatly improve work efficiency and save time costs. At the same time, fixed-wing drones with a fuselage-integrated layout structure have a high lift-to-drag ratio, a relatively small overall mass and longer endurance. This also prompts some fixed-wing drones to be widely used in military reconnaissance, military strikes, agricultural remote sensing monitoring, etc [14]. Meanwhile, due to the above advantages and their unique advantages in many aspects such as airspeed and longer range resulting from lighter batteries and greater energy release, they are capable of completing tasks in environments where multi-rotor drones cannot adapt. For example, they are used in fields such as obtaining geographical information data, power line inspection, communication restoration, precision agriculture, logistics transportation, environmental monitoring, remote sensing monitoring, rescue and search. There is even a branch of solar-powered drones that can achieve even longer endurance. The Zephyr S set a continuous flight record of 25 days, 23 hours and 57 minutes in 2018, with a day - and - night flight altitude of 21 - 16.7 km [15]. However, at the same time, the unique fuselage structure of fixed-wing drones makes them unable to hover in the air like rotor drones, and their fuselage flexibility is insufficient. Also, since they need the fixed wings on both sides to generate lift, fixed-wing drones require a runway of a certain length to assist take - off, that is, they need an airport and cannot take off anytime and anywhere like rotor drones. Moreover, compared with rotor drones, fixed-wing drones have higher costs and maintenance costs. For example, the unit price of entry - level plant protection fixed-wing drones on shopping platforms starts at about 200,000 yuan, while the unit price of consumer - grade plant protection rotor drones is between 5,000 and 50,000 yuan.

3.3. Compound wing UAV

Compound-wing drones are usually composed of fixed wings and rotors. In specific environments, they are prone to be affected by disturbances such as air currents and wind speeds. However, compared with rotor drones, they still show significant improvements. Compared with traditional fixed-wing drones, compound-wing drones have the ability of vertical takeoff and landing and superior endurance. Moreover, their flight mode switching is stable, which highlights the remarkable advantages of compound wings in terms of stability and lift performance [16]. Meanwhile, according to the simulation in the paper, after adding disturbance factors such as gravity and wind, the attitude control error of the tested compound-wing drone is within only 0.05 degrees, and it can stably and quickly hover at the target position. These experimental data directly indicate that compound-wing drones have far stronger anti-interference ability and flight stability than fixed-wing drones and rotor drones. Therefore, they can be used in windy scenarios such as agricultural and maritime work [17]. At the same time, for some tilt-rotor drones, such as the US V - 22 Osprey drone, due to its unique structure, it can perform some long-distance delivery tasks. In this task, it has a fast speed and requires less runway space. It also has good controllability, as well as the performance of vertical takeoff, landing, and low-altitude hovering. The only drawback is that compared with rotor drones and fixed-wing drones, because of its unique and complex tilt structure, the development, maintenance, and use costs are relatively high [18]. Moreover, it is prone to breakdowns. For example, the US Osprey, a helicopter using a compound wing, often crashes due to its complex structure.

3.4. Comparative analysis

As stated in the table 1, in our daily lives, rotor drones are still the most common.

Table 1. Comparative analysis

	Rotor UAV	Fixed-wing UAV	Compound wing UAV
Wing types	Rotor (propeller)	Fixed-wing	Compound wing
Structural characteristics	It has a simple structure and takes off by relying on rotors.	It has a regular structure and flies by means of fixed wings and propellers or jets.	A structure combining a rotor and a fixed wing
Range	Short	relatively long	relatively long
mobility	Hoverable and flexible	It can fly at high speed and high altitude but cannot hover.	It has both the ability of vertical hovering and high-speed level flight.
Application scenarios	Low-altitude economy such as low-altitude reconnaissance, agricultural plant protection, and aerial photography	Surveying and mapping, long-distance inspection, logistics transportation, long-range strikes, etc.	Scenarios that require vertical takeoff and landing and long endurance, such as border patrol, emergency rescue, transportation, or experiments.

Their main tasks include low - altitude missions such as aerial photography and agricultural reconnaissance, as well as serving the low - altitude economy. With their flexible maneuverability, they can easily shuttle through big cities for photography. However, their endurance and anti - interference capabilities still need further optimization. Fixed - wing drones are rarely seen in daily life. They are often used for experimental purposes, monitoring and mapping, or military strikes. They have a long endurance, but their maneuverability is poor, and they are expensive to build and maintain. Therefore, they cannot be popularized among the general public and are mainly used in the military and mapping fields first. Compound - wing drones combine almost all the advantages of the previous two types. However, due to their complex structure, they require higher costs for construction and maintenance. Also, because of the complex structure, they have a relatively high failure rate and are prone to accidents. But with the development of technology, these problems will be gradually solved.

4. Conclusion

Due to the rapid development of technology, drone technology is also iterating and updating at an amazing speed, showing disruptive potential and application capabilities in many fields. However, such a future also faces challenges. Just like the problems with a large number of drones, their endurance is not strong, or rather, it is relatively short. Generally, the endurance of drones is about 30 minutes to an hour. However, with the innovation and development of power technology and engine technology, drones are expected to operate continuously for days or even weeks in the future. Moreover, drones still lack intelligence and still need to be manually controlled. But in a complex urban environment, the effect of manual control may depend on the upper limit of the operator. In the future, the in - depth integration of AI algorithms will enable drones to have stronger environmental perception and decision - making capabilities. They can better cooperate to complete tasks such as large - scale disaster relief in complex urban environments. At the same time, in the face of high - intensity and harsh environments, the materials of drones also need to be innovated. Lighter and stronger composite materials can make them have stronger anti - interference ability and a more lightweight fuselage, thus bringing longer endurance. The innovation of drone technology will enable them to undertake tasks that cannot be completed today, such as in the high - intensity logistics field and the fully intelligent agricultural field.

All in all, the future development prospects of drones are very broad. They will promote social progress and improve the quality of human life. At the same time, humans also need to face the challenges in the development process with a rational and responsible attitude, such as environmental issues and airspace management issues. Only in this way can drone technology truly benefit and serve humanity.

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