Review of vertical take-off and landing fixed-wing UAV and its application prospect in precision agriculture

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Abstract: Compared with multi-rotor unmanned aerial vehicle (UAV) and fixed-wing UAV, vertical take-off and landing (VTOL) fixed-wing UAV has advantages such as good aerodynamic efficiency, high cruise speed and long flight duration, and has low requirements for the flatness and area of the landing site. Therefore, VTOL fixed-wing UAVs are widely used in many fields such as remote sensing, power line inspection, geological mapping and urban comprehensive patrol. However, there are still some problems in VTOL fixed-wing UAV, such as large aerodynamic interference of tilting propeller, high requirement of design strength of VTOL structure and complex power system matching in various flight states, which make it impossible to have a complete and reliable safety evaluation to guarantee the healthy development of VTOL fixed-wing UAV. In this paper, different types of VTOL fixed-wing UAVs are classified from aerodynamic layout and take-off mode, such as rotor, tilt-wing and tail-seat type. At the same time, the data of VTOL fixed-wing UAVs with certain representative design are compared, including maximum flight speed, maximum takeoff weight, range and flight time, etc. In addition, this paper also puts forward the application method and current situation of VTOL in precision agriculture. Finally, the future research direction and development suggestions are put forward to provide references for the performance improvement and further research of new VTOL fixed-wing UAV in the future.

Keywords: vertical take-off and landing, fixed-wing, unmanned aerial vehicle, tilt rotor, composite wing

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1 Introduction

With the rapid development of science and technology, UAVs is more and more widely used in various fields. From the perspective of lift components, UAVs are mainly classified into unmanned helicopter or multi-rotor UAVs with rotor as the main lift component and conventional fixed-wing UAVs with wing as the main lift component.

Among rotor-based UAVs, multi-rotor UAV can take off and land vertically and hover in the air without the need of runway. In addition, their structure is simple, flexible and convenient, so they are used more and more widely at present. However, because multi-rotor UAV needs to rotate through multiple propellers at high speed to obtain sufficient lift, its aerodynamic efficiency is low. Therefore, compared with fixed-wing UAVs, there are some disadvantages such as slow speed, short space time and small load. The corresponding fixed-wing UAV has the advantages of high lift-drag ratio, high aerodynamic efficiency, long stagnation time, fast speed and wide range of action in the cruising state. However, fixed-wing UAVs need a certain amount of open and flat ground for take-off and landing and cannot hover at any time, which results in the limited application range of fixed-wing UAVs and far less popularization of multi-rotor UAVs.

The definition of VTOL UAV is: it is capable of vertical take-off/landing, has hover capability, and can fly horizontally in the manner of fixed-wing aircraft[1]. In recent years, VTOL fixed-wing UAVs have been developed rapidly. It combines the advantages of the above two types of UAVs and greatly expands the application field of UAVs.

In this paper, the typical design of VTOL fixed-wing UAV at home and abroad is summarized. According to the switching mode from VTOL to fixed-wing flat flight mode, VTOL fixed-wing UAVs are divided into two categories: directional thrust and vector thrust. Different types of VTOL fixed-wing UAVs are different in terms of take-off mode, power, etc. Therefore, they are subdivided and compared to extract the key technology system. At the same time, the future research direction and development trend are predicted in order to provide reference for the performance improvement and in-depth research of the new VTOL fixed-wing UAV in the future.

2 Directional thrust type VTOL fixed-wing UAVs

Directional thrust means that all motors on the fuselage have fixed thrust direction and cannot be deflected. Generally speaking,

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multiple vertical ground motors are used as the thrust source of VTOL. At the same time, the horizontal motor (1~2) as the power is to switch to the fixed-wing mode of flat flight. Namely, N+1/N+2 mode (N is the number of motors providing vertical ground power, 1 and 2 are the number of motors providing horizontal thrust), also known as composite wing aircraft.

At present, the common VTOL fixed-wing UAVs at home and abroad usually adopt the 4+1 mode (4 rotors are used as the take-off and landing power and 1 horizontal thrust propeller to provide the flat flight power). Figure 1 is CW Dapeng series UAV of Chengdu Zongheng Automat Technology Limited Company. This series of UAVs all adopt the composite wing layout form of fixed-wing combined with four rotors, and have the quick-mounting structure. Its advantage is that when the UAV needs to work, it can be deployed in a short time. At the same time, the requirements for take-off and landing site are low. The two flight states of vertical take-off and landing and flat flight can be changed autonomously. With relatively low airspace restrictions on take-off and landing, it can successfully complete the operation tasks in mountainous areas, hills, jungles and other complex terrains and areas with dense buildings, greatly expanding the application scope of UAV[2]. Among them, CW-30 is a fixed-wing UAV with double-tail strut layout and push-back oil-moving vertical take-off and landing, which has been greatly improved during navigation.

a. CW-10

b. CW-20

c. CW-30

Figure 1 CW Dapeng series UAV (4+1 mode)

Figure 2 is the SF-D220 designed by Sanfei Aviation Technology Limited Company, which adopts the 4+2 mode (4 rotors serve as the take-off and landing power and 2 horizontal thrust propellers at the roots of both wings of the fuselage provide the flat flight power). Compared with the 4+1 mode, this model features two horizontal motors. This design can provide more forward pull power in fixed-wing flight mode. At the same time, the two motors are located at the wing root, so that the airflow generated by the propeller can be converted into lift efficiently by the wing. However, this design adopts the mode of multi-motors working together in the dynamic structure, which increases the waste weight of the aircraft in different flight modes to a certain extent, and also puts forward a test to its battery life capability.

Figure 2 SF-D220

Figure 3 is the Cypher-1 bypass type fixed-wing UAVs developed by Sikorsky of the United States. This model is equipped with a rotor in the annular fuselage. On this basis, the wing and tail propulsion devices are added. This design is relatively simple[3] and belongs to the mode of 1+1 (1 vertical take-off and landing motor plus 1 horizontal thrust motor). The tension coefficient of this kind of aircraft is small in the state of small advance ratio flight. Due to the retardation of the fuselage, the power consumption of the rotor is lower than that of the single rotor. However, when the forward ratio is large, the power consumption of the rotor gradually approaches that of the single rotor[4-6].

Figure 3 American dragon warrior UAV

Figure 4 is the fixed-wing solar UAV of Hanerg. It adopts the combined 4+1 propulsion scheme of “vertical take-off and landing rotor + horizontal propulsion propeller”.

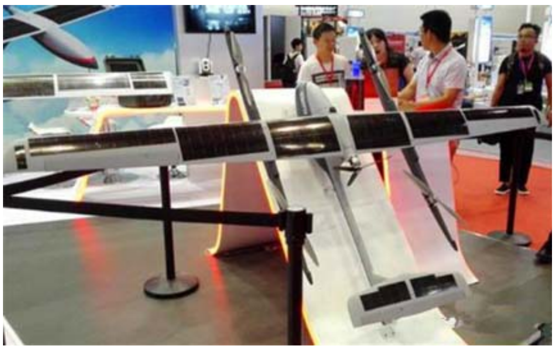


Figure 4 Hanergy solar-powered UAV

The UAV is using lithium batteries and solar battery hybrid mode. Its wings are covered with gallium arsenide thin-film solar cells, which are just 110 microns thick, so the added weight of the solar cells has little impact on the UAV's performance. When the UAV takes off, the higher electrical power required is powered by lithium batteries. When the UAV turns to horizontal flight, the power required is greatly reduced, and then the solar cell can meet the power supply demand[7].

In the actual flight effect, the directional thrust VTOL fixed-wing UAV can improve the horizontal flight speed in the rotor flight mode (similar to the helicopter flight mode) to some extent. In the case of large range, the power consumption is saved to a certain extent and the efficiency of rotor-type UAV is improved. In terms of overall layout and structure design, it is required to have strong anti-wind disturbance ability and attitude stability ability. Therefore, there is still much room for improvement in aerodynamic design, efficiency improvement and flight safety[8]. In addition, in practical applications, the power equipment used for vertical take-off and landing does not provide efficient power support when the UAV switches to fixed-wing flat flight mode, Thus increase the fuselage load and reduce aerodynamic efficiency.

3 Vector-thrust type VTOL fixed-wing UAVs

Vector-thrust VTOL fixed-wing UAVs can be divided into three categories according to the tilting mode: tilting rotor, tilting wing and tilting turning body (tail-seat type).

3.1 Tilt-rotor type

Figure 5 shows Bell Helicopter Company's Hawkeye UAV. It is a single oil engine driving providing power for the double helix pulp rotated rotor VTOL fixed-wing UAV. The middle single wing layout of the UAV is made of full composite materials, and the tail fin is designed with two vertical tail fins that tilt inward. There are two tilting nacelles at the wing tip. The nacelles are equipped with three-bladed propellers and driven by turboshaft engines[9].

Figure 5 Eagle Eye UAV

Hawkeye UAV adopts tilt-rotor design, and its rotor radius is smaller than that of ordinary helicopter. Therefore, the hovering efficiency of the rotor is relatively low when the Hawkeye UAV is hovering in the air. But when the rotor rotated to the level state, the design effectively improve the efficiency of the propeller propulsion[10,11], makes the UAV has the higher mobility.

Figure 6 shows a VTOL fixed-wing UAV developed by SONY Corporation. On the base of the double vertical stabilizer fixed-wing, the middle part of the fuselage is equipped with a common axis twin-propeller component to control the vertical take-off and landing of the aircraft. The lift component of the coaxial twin-propeller can be tilted around the axis, providing the power of forward push and attitude control for the aircraft when it is flying flat[12]. The drone has a top speed of 169 kilometers per hour and a range of up to two hours.

Figure 7 is a VTOL fixed-wing UAV designed by the Helicopter Design Institute of aviation Industry. The take-off and landing control power of the UAV consists of a main rotor located in the fuselage and two bypass motors located in the tail of the fuselage. In vertical take-off and landing, the main rotor inside the fuselage and two relatively small bypass motors at the tail of the fuselage are used as the source of take-off and landing lift. When entering the flat flight stage, the tail bypass motor tilts to the horizontal position to provide thrust for the fixed-wing mode, while the rotor openings on the fuselage are completely covered. It is conducive to maintaining the integrity of the fuselage and airfoil, and improving the aerodynamic efficiency and stability of the aircraft during flat flight[13].

Figure 6 SONY UAV

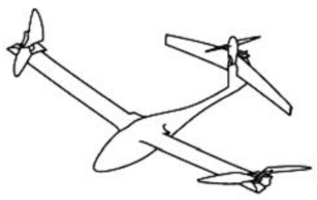
Figure 7 High speed and efficient UAV

Stoll et al. designed a VTOL fixed-wing UAV with a three-rotor tilting structure, Figure 8a and b respectively show the states of the three rotor motors when taking off and landing posture and flying posture. When the UAV becomes a horizontal flying attitude, the horizontal tail and propeller both tilt at the same time, with the tail propeller providing forward thrust. At the same time, the propeller at the two wing tips is folded into a specific Angle position through a special device, forming a special wing tip shape[14,15].

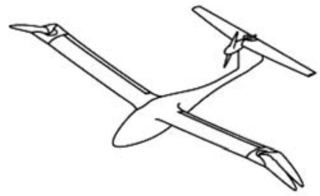
According to CFD flow field analysis in Figure 8c and d, this design makes the retracted propeller play the role of wingtip and winglet. It can effectively block the flow from the lower surface of the wing to the upper surface and weaken the strength of the tip vortex. Thus, the effective aspect ratio of the wing is increased[16,17], and the premature separation of the wing tip airflow is delayed. Increasing stall Angle of attack and induced drag is conducive to improving the lift-drag ratio of aircraft[18].

3.2 Tilti-wing type

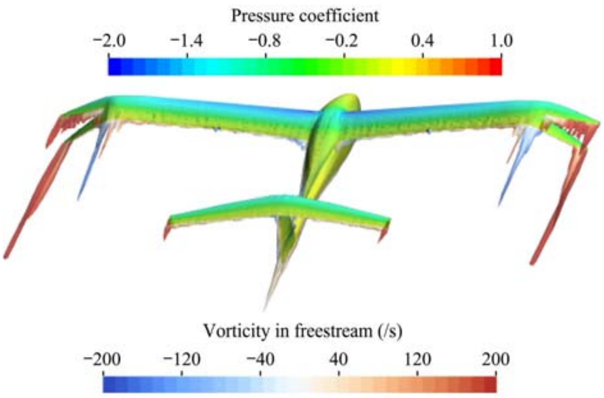
The representative type of tilt-wing VTOL fixed-wing UAV is “lightning strike” UAV[19]. It was developed by Aurora Flight Sciences based on the previous generation of the Holy Sword VTOL UAV, as shown in Figure 9. The electric power generated by the generator is distributed to 24 bypass fans in the whole machine, among which 3 bypass fans are installed on two canard wings and 9 bypass fans are installed on two wings[20]. By distributing thrust between the canard and the main wing and tilting the wing surface, the UAV can switch to horizontal flight without losing altitude[21]. However, the UAV need the wing root to the wing to provide more torque, dominated the whole force of the aircraft wing is complicated. Therefore, wings are required to have higher strength and stiffness[22].



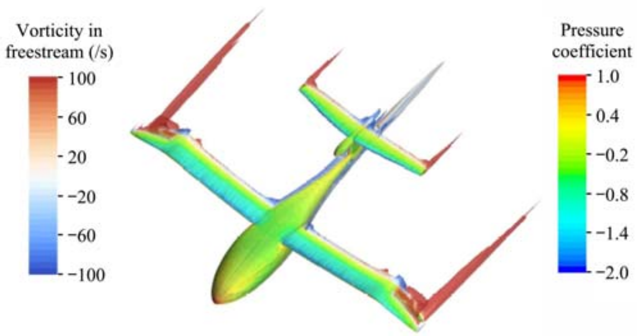
a. Landing posture



b. Flying posture



c. Equivorticity isosurface



d. Isovorticity and contour of pressure coefficient of model at 120 knots

Figure 8 Trirotor tilting structure

Figure 9 Concept of “lightning strike” UAV

Figure 10 shows the “Koker-1” fixed-wing UAVs developed by Iran. Its four rotor motors are respectively installed in the middle of two wings. During take-off and landing, the wing tilts vertically, with four rotors providing lift. In the flat flying attitude, the wing rotates in the normal direction. The flat flight thrust provided by the four rotors gives the UAV a 170 km mission radius and a range of three hours, while flying at an altitude of 3658 meters.

Figure 10 Koker-1

In the process of vertical take-off and landing with tilting wings, fixed-wing UAV is very beneficial to lift of the whole machine because the propeller’s slipstream flows through the streamlined shape of the wings[23]. However, it needs a large tilting driving force to change between the two states of vertical take-off and landing and flat flight. In the course of vertical take-off and landing touchdown, it is vulnerable to the influence of ground wind. How to solve the above flow field interference problem is the current research focus of tilting wing VTOL UAV[24].

3.3 Tail-seat type

Tail-mounted VTOL fixed-wing UAV adopts tail-mounted vertical take-off without tilting device. Therefore, when taking off to a certain height, the whole body should be tilted to realize the flat flight function of the fixed-wing. In the landing stage, after climbing to a certain height, the tail should be aligned with the landing area. With the reduction of thrust due to gravity, the landing should be done slowly. During take-off tilting, the motor needs to provide a huge torque to bring the entire fuselage forward into a horizontal flying attitude. Similarly, during the landing, the motor also needs to land the entire fuselage vertically. In this process, due to the large tilting volume of the whole machine, the flow model of this tilting mode is more complex than that of the previous two tilting modes[25].

As shown in Figure 11, V-BAT is a VTOL UAV that can be used for both military and civilian purposes. Its take-off and landing space only needs 36 m^2, and it has good operation convenience. It can take off multiple VTOL UAVs simultaneously in a limited space, such as from the helicopter deck of a frigate. Powered by a culvert fan, the drone is placed vertically on the ground before liftoff and then tilts. During the take off and landing process, ailerons on the wing can provide attitude assistance functions for the tilting process, but the larger plane area of the entire wing will depress airflow during the tilting process, which partially hinders the tilting process.

Table 1 Parameters of V-BAT

Name	Length/m	Wingspan/m	Height/m	Weight/kg	Load/kg
Value	2.4	2.74	0.6	31	2.26

Figure 11 V-BAT

Figure 12 shows the VD-200 UAV developed by Aviation Industry Corporation of China. It is driven by two propellers 2 meters in diameter and has a flying wing structure. The UAV can take off and land vertically and then fly horizontally after taking off. The VD200 was presented at the 2013 Chengdu International Trade Show and showed the basic data of the UAV as shown in Table 2.

The wing configuration of VD200 UAV adopts pre-power to pull and tilt the whole fuselage, and the whole design structure is compact. Tilting requires relatively little torque, which also reduces the complexity of air model in the tilting state. Sichuan Aoshi Technology Limited Company shows a VTOL fixed-wing

UAV to the public-Hawk as shown in Figure 13 X and X family members of the geek X-ray Hound a new generation of intelligent vehicle is shown in Figure 14.

Figure 12 AVIC VD200

Table 2 Parameters of VD-200

Name	Value
Wingspan	4.6 m
Length	1.8 m
Take-off weight	200 kg
Load	20 kg
Maximum flying speed	260 km/h
Voyage	150 km
Time	3 h

Figure 13 AOSSCI X-Hawk

Figure 14 AOSSCI X-Hound

Figure 13 is the Tail-mounted VTOL fixed-wing UAV X-Hawk developed by the AOSSCI team. It adopts the layout similar to the rhombic quadrotor UAV, and use the difference between the top and bottom motors on the short side to realize the overall tilting. This design successfully fills the technical defect of low vertical take-off and landing tilting efficiency of domestic tailstock fixed-wing UAV.

At the same time, AOSSCI also launched its educational version of the X-Hound drone for colleges and universities. UAV to make the string under the ratio sweep forward wing and tail v-shaped unconventionality design. The lower wing is designed so that when the fuselage is tilted, the horizontal Angle of the wing becomes smaller and the wing as a whole tends to be horizontal, giving it more lift than the upper. At the same time, the airflow change promoted the tilt of the fuselage, so as to accelerate the tilt and turn of the UAV, making X-Hound have excellent maneuverability and agility.

4 Comparison of VTOL fixed-wing UAVs

Multi-rotor UAV has short endurance time, so it cannot meet the requirements of long-range and long-endurance detection. Aiming at this problem, Ma Zhao et al[26] proposed a highway management operation mode based on VTOL fixed-wing UAV. They use VTOL fixed-wing UAVs as platforms. At the same time combined with the image recognition processing technology to design the system, simplify the work flow. The information management system of patrol inspection has been established to carry out the inspection of bridge slope diseases, and field tests have been carried out in The Shanghai section of Huchang Expressway.

Figure 15 is the Manta Ray of SF VTOL fixed-wing logistics UAV. It ingeniously “carries” the cargo during the transport flight, combined with the bionic streamline aerodynamic design of manta rays, greatly reducing the UAV's flight resistance. In addition to propeller power, it can also be driven by two bypass fans. The culvert fan has great thrust, safety and noise reduction ability. When the single fan fails, the UAV can still fly normally. In other emergencies, the UAV can automatically switch from fixed-wing mode to multi-rotor mode and actively hover. Manta Ray is made of a variety of lightweight composite materials, and a large number of carbon fiber composite materials are used in the bearing frame, which can meet the strength, stiffness and reliability requirements of UAV during normal operation. At the same time, the main operating rudder surface also adopts redundant design, which greatly improves the safety and reliability. The whole machine adopts modular structure design, which can be disassembled quickly to ensure efficient transportation and deployment.

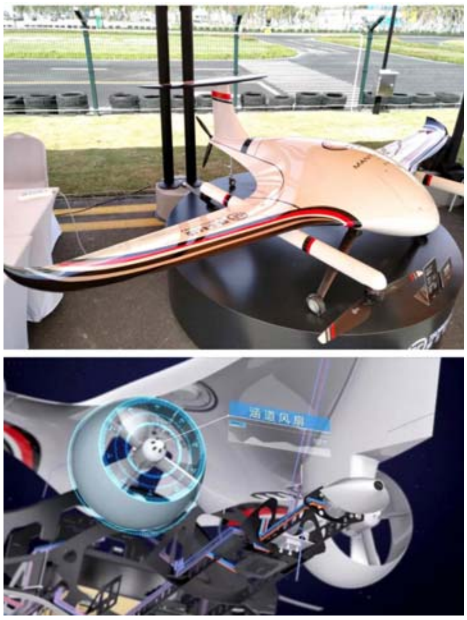


Figure 15 Sf Manta Ray fixed-wing VTOL UAV

Based on the above two application scenarios, as well as providing references for more possible application scenarios in the future, a representative VTOL fixed-wing UAV on the market is selected to compare their important parameters.

Compared with VTOL fixed-wing UAV, DJI multi-rotor UAV series has certain advantages in convenience and short time operation. However, due to its own aerodynamic design and endurance problems, it is difficult to be applied in the long-endurance industry. Table 3 and Table 4 show the weight flight distribution diagram of DJI UAV series and VTOL fixed-wing UAV in Figure 16 for intuitive comparative analysis.

In Table 5, for the application requirements of different industries, the current mainstream VTOL fixed-wing UAV has a large load design, which enables it to carry a variety of mission equipment and complete the mission more efficiently, quickly and accurately[27]. In addition, these models adopt modular design, which can be re-launched and applied to the new requirements only by replacing the mount module when the task requirements change, greatly reducing the purchase and use cost of users.

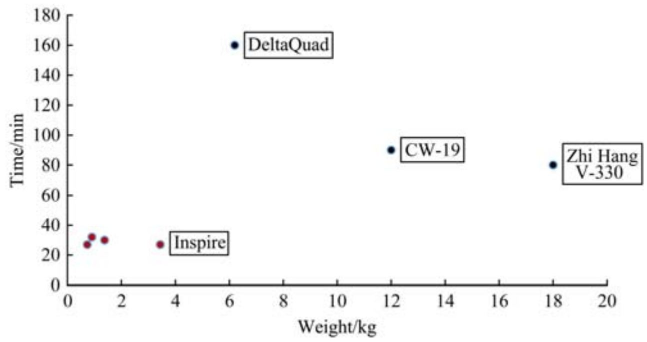


Figure 16 The weight and flight duration distribution diagram of DJI UAV series and VTOL

Table 3 Parameters of mainstream VTOL UAV

Name	Design type	Wingspan/m	Time/min	Voyage/km	Maximum flying speed/km·h^{-1}	Load/kg	Take-off weight/kg
CW-10	4+1	2.6	90	35	72	2	12
CW-30	4+1	4.0	360	100	100	6	34.5
CW-100	4+1	5.4	480	100	100	20	105
DeltaQuad	4+1	2.4	160	150	100	1.2	6.2
Zhi HangV-330	2+2	3.2	80	90	110	3	18
SF Manta Ray	4+2	3.55	90	100	94	10	38
Aoshi X-Hawk	tailstock type	/	90	150	120	3	/

Table 4 DJI UAV series parameters

Dji UAV series	MAVIC PRO	MAVIC 2 PRO	PHANTOM 4 PRO	Inspire 2
Size/mm Length×width×height	Folding: 198×83×83 Spread: 305×244×85	Folding: 289.5×289.5×196 Spread: 322×242×84	214×91×84	427×425×317
Take-off Weight/kg	0.734	0.907	1.375	3.440
Time/min	27	31	30	27
Graph transmission distance/km	7	8	7	7
Maximum flying speed/km·h^{-1}	65	72	72	94

Table 5 SMD-UAV and JoUAV CW series equipment function and application comparison

Name	Zhi Hang V330	Zhi Hang Z4	CW-10	CW-30
Difference mode	GPS/GLONASS Dual mode	GPS/GLONASS Dual mode	RTK/PPK	RTK/PPK
Take-off altitude	3500 m	3500 m	3500 m	4500 m
Wind resistance	6	6	6	7
Mount module	Sony-18 x optical zoom camera	121mp 5 lens tilt camera module	CA-102 Full-frame orthographic camera	Full frame five - lens tilting camera
	Infrared thermal imager	42.4 megapixel forward camera module	JR503 Five-lens tilt camera	CW-30LiDAR Lidar system
	Digital transfer station	24.3 megapixel forward camera module	MG-200S Double light pods	MG-200S Double light pods
	Strong light/Shout module	Digital transfer station	MicaSense Altum;High resolution multispectral	IXU-RS1000 / IXM-100 Medium format industrial camera
Industry application	Agricultural remote sensing ,Intelligent aerial,Intelligent security, Intelligent inspection, emergency relief, etc		Mapping,Power patrol,Police security,Emergency relief,Wisdom city,Agricultural remote sensing,etc	

5 Application of VTOL in precision agriculture

Rapid acquisition and analysis of farmland crop information is the premise and foundation for the practice of precision agriculture and the key to break the bottleneck restricting the application and development of Precision agriculture in China.Agricultural remote sensing UAV mainly monitors crop growth in a flexible and widely applicable way by carrying different remote sensing sensors to collect crop information. VTOL UAV makes up for the disadvantages of multi-rotor UAV such as short endurance time and low flight efficiency, solves the problem of difficult precise take-off and landing control of fixed-wing UAV, and can meet the increasingly complex requirements of agricultural low-altitude remote sensing tasks[28].

5.1 Technical architecture

The complete technical architecture of UAV remote sensing system is shown in Figure 17. It mainly includes UAV platform, micro-sensor, crop growth analysis, crop fertilization decision model and variable fertilization operation. Among them, UAV platform is the carrier carrying flight control, navigation and positioning system, sensors and other equipment. Common UAV platforms include multi-rotor UAV, fixed-wing UAV and hybrid wing UAV. However, multi-rotor UAV has problems such as low aerodynamic efficiency and short endurance time, while fixed-wing UAV is limited by the need for open and flat ground for take-off and landing. VTOL fixed-wing UAV can make up for the shortcomings of the above two types of UAV[29,30]. The XingChen-05 UAV (Figure 18) is capable of VTOL and fast air cruise, greatly improving its portability and safety in use. It can not only carry surveying and mapping camera to carry out accurate measurement of farmland and provide precise positioning information for plant protection UAV, but also carry multi-spectral camera to carry out monitoring of farmland diseases and insect pests and realize precision agriculture.

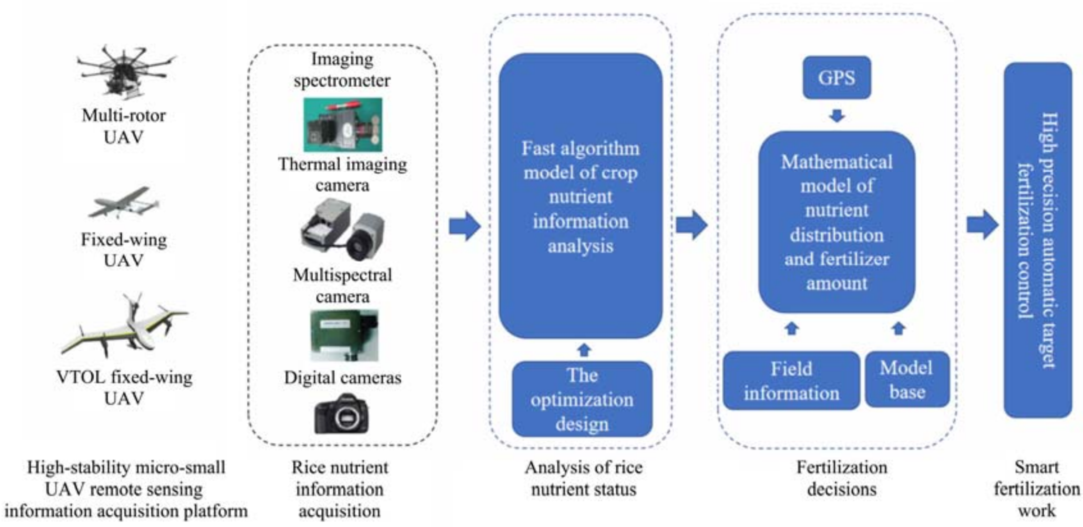


Figure 17 Technical architecture

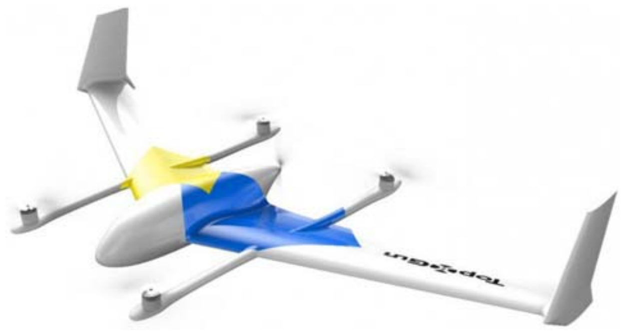


Figure 18 XingChen-05 UAV

Rice nutrient information is mainly obtained by imaging spectrometer, multi-spectral camera, thermal imager, digital camera and other sensors mounted on VTOL fixed-wing UAV. Digital camera can quickly obtain gray or color images in visible band. Its biggest advantages are low cost, high pixel number and simple operation. VTOL fixed-wing UAV can acquire agricultural information of large area rapidly due to its fast cruising speed and long flight time. According to the different spectral methods, the multi-spectral camera can be divided into single-lens plus spectral system and multi-lens spectral system[31,32]. Among them, multi-lens spectroscopy is realized by setting narrow-band interference filters with different spectral segments at the front end of multiple imaging focal plane sensors. Depending on the sensor, the multispectral sensors can be divided into Charge coupled device (CCD) and Complementary metal oxide semiconductor (CMOS) cameras. CCD is superior to CMOS in image quality and other aspects, while CMOS has the characteristics of low cost, low power consumption and high integration.

The multi-spectral flight data includes independent small-range photographs of each band, and images of large dimensions with definite reflection information can be obtained after photogrammetric processing and radiometric calibration processing. Photogrammetric processing includes automatic splicing of a large number of single-band UAV multi-spectral images into seamless multi-spectral orthophoto, and then geometric correction and geographic registration. Radiometric correction use the transfer function to convert the Digital number (DN) value of the sensor into the radiant brightness of the sensor, which is used to overcome the influence of solar Angle, bidirectional reflection distribution function (BRDF) effect, cloud shadow, camera gain, exposure time and other factors on the measured value of the sensor. The processed multi-spectral image data can be used to generate normalized difference vegetation index (NDVI), digital surface model (DSM) and other information[33-35].

The formulae of variable fertilization could be obtained by using the generated vegetation index and digital surface model. Variable rate technology (VRT) is required for site specific fertilization. The use of VRT can not only minimize the use of fertilizer and fertilizer pollution, but also improve work efficiency and reduce production costs[36,37]. The variable-rate decision process, mainly includes the logic of the target position and target fertilizer application rate. Within the decision process, once the coordinates of the granular fertilizer spreader (GFS) were input, the target application rate could be used to calculate the target discharge rate and then the rotational speed. By adding travel speed and routing space into the decision-making process, the target fertilizer application rate can be converted into an executable target emission rate signal of the metering device, so as to realize variable fertilization operation.

5.2 Application case in rice precision agriculture

In March 2019, South China Agricultural University and Luoding Daoxiangyuan Agricultural Development Limited Company carried out a demonstration of micro-UAV remote sensing information acquisition and rice nutrient management technology in Taiping Town, Luoding city. The demonstration area was 144.64 hm^2, and Meixiang No.2 was selected as the rice variety. In the process of fertilizing rice in the demonstration area, advanced variable fertilization technology was used. At the fertilization node, the rice growth situation was first obtained by remote sensing using VTOL fixed-wing UAV, and the operation prescription map was generated according to the remote sensing fertilization decision-making model. Then, the fertilization amount in hm^2 of the prescription map was executed by variable fertilization UAV, the prescription map as shown in Figure 19 and 20. After more than three months of growth, the field test results of Yunfu Municipal Bureau of Agriculture and Rural Affairs in Guangdong Province on July 9, 2019 showed that compared with traditional fertilization, the average yield per hm^2 increased by 9.27% under the condition that the amount of fertilizer applied to rice in the demonstration area of remote sensing information acquisition and rice nutrient management technology decreased by 28.34%. The results show that the application of remote sensing technology in rice nutrient management can achieve remarkable results, and the experts suggest to further expand the application area.

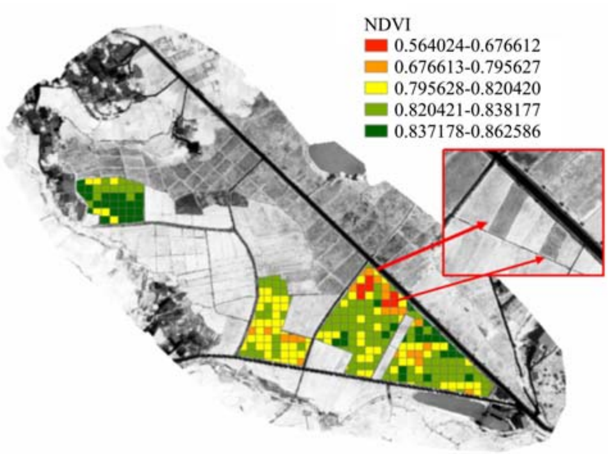


Figure 19 Thematic map of growth

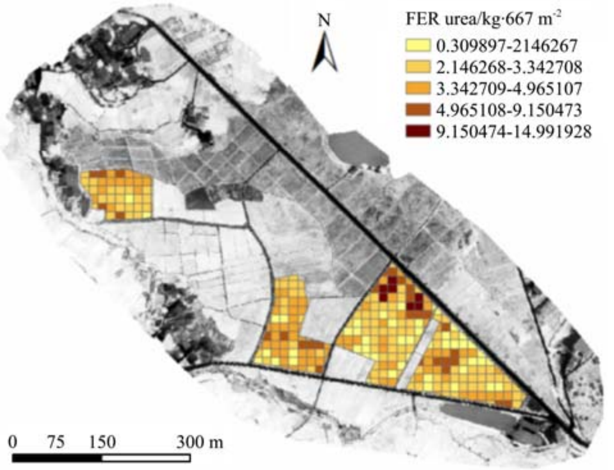


Figure 20 Fertilization Prescription Chart

6 VTOL fixed-wing UAVs require further breakthroughs in technology

Since the advent of VTOL technology, its application in UAV is very flexible, and many strange VTOL design schemes have emerged. However, the 4+1/4+2 mode fixed-wing UAV design is a relatively stable VTOL solution. In this scheme, the lift required for VTOL is provided by the quadrotor system, the pull or thrust for forward flight is provided by the horizontal motor during flat flight, and the lift is provided by the wing. As a result, the designed UAV has both vertical take off and landing performance and high-speed flight capability, and has good technical realization[38,39]. The above mentioned VTOL fixed-wing UAVs all have high detachable capability. This design is convenient for component module maintenance and replacement, which enables UAV to have a longer overall life cycle and lower user cost. When working outside, users can easily carry, quickly install and disassemble, and the disassembly process does not need tools. In practical application, this 4+1/4+2 mode design will make the power equipment used for vertical take-off and landing unable to provide efficient power support after the UAV switches to the fixed-wing flat flight mode, thus becoming an unnecessary load on the fuselage. Therefore, compared with the design scheme of tilt-rotor UAV, the quality and efficiency of this design scheme are not high.

At present, the structure of directional thrust VTOL fixed-wing UAV is relatively simple and the technology development is complete. However, the design structure of tilt-rotor UAV is complex, and there are the following technical difficulties at the present stage[40].

6.1 Aerodynamic interference

Aerodynamic interference of tilt-rotor UAV is mainly caused by the downwash flow of the rotor[41]. When the UAV is hovering, most of the downwash flow generated by the propeller ACTS on the wing surface, which makes the wing bear a large amount of download. At the same time, the direction of airflow is changed so that it turns to the propeller, reducing the overall efficiency of the rotor and affecting the hovering performance and stability of UAV[42]. In the transition mode, the underwash flow of the rotor will still impact the wing surface, generating downwing load and affecting flight safety[43]. Therefore, determining the aerodynamic characteristics of tilt-rotor UAV in its vertical, hover and transition state is one of the key technologies to promote its development, so as to improve its safety and improve the spraying accuracy brought by the rotor wind field. A great deal of work needs to be done in aerodynamic design. Numerical analysis and wind tunnel test are combined to analyze its multi-mode aerodynamic characteristics[44,45].

6.2 Tilting structure design

Tilt-rotor UAV is equipped with an extended carbon tube supporting tilt-rotor device on the wing root, so the wing root will be subjected to concentrated loads in various aspects, which puts forward high requirements for the strength, flexural stiffness and torsional stiffness of the wing structure. At the same time, there are complex gas-elastic coupling problems between wings and rotors, which also bring great difficulties to aerodynamic dynamics analysis[46,47]. In addition, since the tilting mechanism needs to switch between the flight mode of rotor and fixed-wing, the tilting wing UAV will generate certain thrust during vertical take-off, which makes the force on the entire wing more complex. Therefore, the rotated strength and structural reliability of the system is also put forward higher design requirements.

6.3 Power system matching

As for the exploration of power system matching methods of electric VTOL fixed-wing UAV, most researchers conduct independent tests by referring to the existing matching methods of fixed-wing[48-50] and multi-rotor[51]. They then use experience and trial and error to determine which system meets the requirements. Therefore, the selection and matching of the power system of VTOL fixed-wing UAV lacks corresponding theoretical methods[52]. Tilt-rotor UAVs need to be switched between multi-rotor and fixed-wing modes. In the state of vertical take-off and landing and hovering, the airflow lift generated by the propeller needs to overcome the full gravity of the aircraft and the downward load of the propeller wash flow on the wing[53]. In fixed-wing mode, the thrust generated by the propeller only needs to overcome the horizontal resistance generated by the aircraft. Under these two conditions, the power demand of UAV for power system is quite different. It is difficult to realize the optimal power matching between the two modes because of the great difficulty in the design of power system matching under different modes. Solving this problem can improve the endurance and benefit the application of VTOL in precision agriculture.

7 Future development trend

From the perspective of technology development at home and abroad, VTOL fixed-wing UAVs have the following development trends:

(1) The flight stability problem of VTOL fixed-wing UAV must be solved by perfect flight control system. Existing VTOL fixed-wing UAVs (including tilt-rotor type and tilt-wing type, etc.) all have poor stability in the transition stage[54,55]. With the development of intelligent flight control technology, advanced sensor technology and information processing technology, the flight control system of VTOL fixed-wing UAV will be more stable and intelligent[56]. With the steady application of VTOL fixed-wing technology in UAVs, it will also be used in manned aircraft.

(2) At present, the power modes of VTOL fixed-wing UAVs include electric, oil-powered and oil-electric hybrid. As the market has higher and higher requirements for UAV endurance, it is especially obvious in remote sensing UAV operation. These three power modes require further improvement in energy distribution and utilization efficiency[57]. In terms of aircraft structure, more lightweight and reliable design[58,59] should be pursued to achieve the purpose of reducing weight and increasing endurance. In terms of power energy, designers should closely combine the application research of solar energy, fuel cell, liquid fuel and other new energy sources[60]. Only by combining the development of energy, materials, aerodynamics and other disciplines can the structure of aircraft be further optimized and the endurance capability of UAV be enhanced[61].

(3) With the increasing demand for large-scale air operations, such as agricultural situation monitoring and variable fertilization in precision agriculture, monitoring of people and vehicles on the scene of security, atmospheric and water environment treatment, the operation capability of a single VTOL UAV has certain limitations. Therefore, the collaborative flight research of multiple VTOL UAVs is more suitable for the future market development trend of VTOL UAVs[62-64]. In the future, VTOL UAV multi-aircraft operation mode can be a multi-aircraft three-dimensional execution of a mission, or multiple aircraft carrying different equipment and performing multiple types of tasks on the target area at the same time. These two kinds of operation modes will make the operation area more extensive, and the acquisition of regional comprehensive information will be more rapid and three-dimensional.

8 Conclusions

Although there are still many technical problems to be solved in the development of VTOL fixed-wing UAVs, the development of VTOL fixed-wing UAVs is in the rising stage. Its development has a great promotion effect on aerodynamic layout optimization technology, structural optimization design, control theory and energy management technology. With the development of science and technology, the performance of VTOL fixed-wing UAV will be further improved, and new VTOL fixed-wing UAV will be developed and launched one after another. The stability and reliability of VTOL fixed-wing UAVs are constantly improved, and its application in precision agriculture and other fields will be more and more extensive. Meanwhile, frontier disciplines related to VTOL, such as energy, materials, aviation, artificial intelligence and big data, will also be developed synchronously. Therefore, VTOL fixed-wing UAV will be an important development direction of future aircraft.

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