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Modular UAV Design for Rapid Assembly

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ABSTRACT
The modular UAV platform, designed using modular principles, allows for rapid assembly and reconfiguration of components such as fuselage, wings, and power systems. This flexibility enables the creation of UAVs tailored to various mission requirements. By leveraging lightweight 3D printing and advanced aerodynamic design methods, the platform expands design possibilities and supports potential automated customization. In addition, the platform integrates a flight control system for multiple configurations and employs a distributed swarm algorithm to improve operational efficiency. These capabilities allow the system to perform UAV, surveillance and strike missions.

KEYWORDS
Modularization; UAV; Combat system

1 Introduction

This paper introduces a modular UAV platform designed for rapid assembly and reconfiguration, offering flexibility for various mission requirements. By utilizing modular components for the fuselage, wings, propulsion, and control systems, the platform allows for adaptable drone configurations that can be customized to meet diverse operational needs. Moreover, the integration of knowledge-based aerodynamic design and 3D printing technology broadens the design possibilities, enabling potential automation and customization based on specific mission parameters.

Additionally, the platform features a flight control system compatible with multiple configurations and incorporates distributed swarm algorithms to enhance operational efficiency. This modular unmanned aerial system is specifically designed to support UAV-based surveillance and strike missions.

2 Problem Formulation

The UAV-based surveillance and strike system, composed of multiple drones, plays a crucial role in modern combat operations by providing comprehensive situational awareness and precise strike capabilities. These UAVs collaborate through information sharing and task coordination, assisting commanders in making informed, real-time decisions.

To enhance battlefield adaptability, the system requires the ability to quickly assemble and reconfigure drones to meet dynamic operational demands. This paper proposes a modular approach, wherein UAV components such as the fuselage, wings, propulsion, and control systems are designed as easily interchangeable modules. These standardized modules minimize assembly time and significantly improve system flexibility.

The UAV models adhere to modular aerodynamic designs and structural frameworks, which are optimized through the use of 3D printing techniques. Table 1 presents the key mission requirements for each UAV model, including payload capacity, flight speed, range, and endurance . The drones are equipped with electro-optical, infrared, and radar systems to facilitate target identification and real-time data transmission.

Table 1 Summary of UAV System Mission Requirements

Demand	UAV
Load mass (kg)	1.2
Cruising speed (m/s)	25
Range (km)	30
Flight time (min)	24
Maximum overload (g)	-1 / +2.5

Drones are equipped with infrared and visible light cameras with a field of view of 50m. Three drones flying at 25m/s can cover the battlefield in 15 minutes.

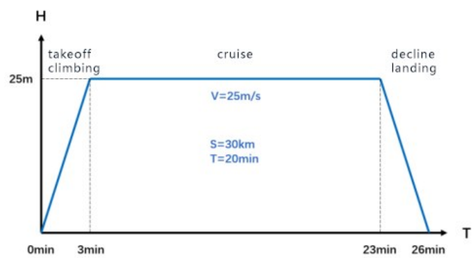


Figure 1 Mission profile of UAV configuration

A coupling CCD imaging system is used as the payload to monitor the drone[2]. Figure 1 shows the UAV covers the battlefield in 15 minutes, flying at 25 m/s and equipped with infrared and visible light cameras.

3 Method

In this paper, the UAV configuration is developed through an integrated process that incorporates aerodynamic, structural, and dynamic considerations. The design workflow proceeds as follows:

First, the initial configuration is assembled using modular components, and an electronic equipment model is selected, yielding an initial weight estimate. The configuration is then analyzed under various mission conditions using a panel method, with drag corrections applied based on empirical data. The maximum lift-to-drag ratio during cruise and the maximum lift during takeoff are determined.

If the maximum lift during takeoff is insufficient to support the total weight, or if the motor thrust is inadequate, the configuration is modified. The motor and propeller models are updated, and the required cruise thrust is recalculated. Energy consumption for each mission phase is estimated using the motor and propeller models, followed by the selection of an appropriate battery model.

Next, the center of gravity and moments of inertia are calculated [3]. If power consumption exceeds battery capacity, or if the configuration exhibits non-first-order dynamic modes[4], further adjustments are made. This iterative process continues until the design converges and satisfies the mission requirements.

Since the wing module's mounting angle is fixed, trimming is achieved by adjusting the horizontal tail surface[5]. After trimming, total power consumption for the mission is calculated based on aerodynamic performance[6], and dynamic stability is evaluated through modal analysis[4].

This process is repeated until the design criteria and mission requirements are met, or until the maximum number of iterations is reached. If convergence is not achieved, the mission requirements are re-evaluated. Final verification of the design is conducted using Computational Fluid Dynamics (CFD) simulations [5-8].

The detailed design process focuses on four key areas: modular design (addressing both aerodynamic and structural aspects), airborne system design 3D printing-based structural optimization, and swarm simulation for combat operations.3.1 Modular design

3.1 Modular pneumatic shape design

Due to challenging take-off conditions and unpredictable battlefield factors, the UAVs were designed to prioritize low-speed performance while maintaining adequate high-speed capabilities for mission success.

The module shape design was based on task requirements and design goals, with the modules divided into fuselage and wing components. This design was refined through iterative processes and data optimization.

The configuration was assembled using these modules, with key design variables outlined in Table 2.

Table 2 Table of configuration design variables determined by the module design

Design variables	UAV
Wing span/m	2.4
Wing area/m2	0.96
Aircraft length/m	1.2
Max take-off weight/kg	5
Wing loads/kg/m2	5.21

Since all configurations need to be launched by hand or catapult, the initial take-off speed is low, and a large maximum lift coefficient is required, as shown in Table 3. The XFLR5 liftingline method[9] was used for preliminary aerodynamic analysis. Firstly, a typical conventional layout configuration that can meet the requirements of strike missions is selected through aerodynamic analysis of different airfoils. NACA0012[10], CLARKY[11] and NACA 6412[12] are selected as the main airfoil and NACA0015 as the tail airfoil. Through the results of aerodynamic analysis, it can be seen that the three lift-drag ratios have little difference, and the selection of large curvature wing NACA6412 can achieve the required maximum lift coefficient and can have 20% lift redundancy to ensure safety.

Table 3 Maximum lift coefficient of take-off requirement for each configuration

Configuration	Take-off speed/m/s	Maximum lift coefficient	Consider 20% lift redundancy Maximum lift coefficient
UAV	10	0.83	1.00

Because the conventional configuration is relatively stable and the flight control technology is mature, the conventional configuration is selected for all three configurations. The UAV configuration is prone to aeroelastic problems due to its large wingspan[13], which adopts three-body layout and single-body layout for surveillance and strike configuration. The aerodynamic analysis results of initial configuration aerodynamic shape and surface element method are shown in Figure 2.

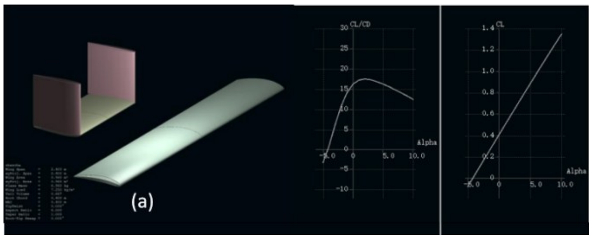


Figure 2 is used to illustrate the geometry and aerodynamic analysis of UAV. Figure 2 is the initial geometry and aerodynamic analysis of UAV configuration

Joint iterative design using joint design flow. When the design results meet the task requirements, the design variables of the tri-configuration geometry are shown in Table 4.

Table 4 Final Design Variables

subassembly	Exhibit the length b/m	Chord length c/m	Location x/m	Mounting corners/°	Airfoil
UAV					
main wing	1.75	0.4	0	0	NACA 6412
Horizontal tail	0.575	0.4	0.8	0	NACA 0015
Vertical tail	0.4375	0.4	0.8	0	NACA 0015

According to the design results of the structure and electronic equipment, the final weight and center of gravity of each configuration are shown in Appendix 2, and the design results are shown in Table 5.

Table 5 Final Design Result Table

Design variables	UAV
Reference area s/m2	1.1
Aircraft length /m	1.8
Total weight WO/kg	5.5812
Wing loads /kg/m2	5.0739

The UAV configurations are divided into grids respectively, and the basic aerodynamic data and flow field are obtained by CFD simulation software. The CFD software used is CFL3D, RANS method[14] and SST turbulence model[15]. The calculation parameters of each configuration are shown in Table 6.

Table 6 Calculation parameters for each configuration

Calculate the parameters	UAV
Half mode reference area s/m2	0.48
Half wingspan L/m	1.375
Calculate the Reynolds number Re	658111
The location of the reference point m	(0.2169,0,0)

Figure 3-4 shows the aerodynamic analysis data of the monitoring configuration. When the cruise demand is 14m/s, the Angle of attack is 0.5°, CL=0.5, and the lift-drag ratio is 11.5. When the requirement is 20m/s, the attack Angle is -1°, and the lift-drag ratio is 8.5. When the cruise demand is 25m/s, the Angle of attack is -2.2° and the lift-drag ratio is 5. The maximum lift coefficient of the configuration is CLmax>1, and the configuration has a good ability to cope with low-speed accidents. It should be noted that the static stability margin of this configuration is small, and the slope of the torque curve is unstable due to the change of aerodynamic load. Flight control should be used to improve flight stability.

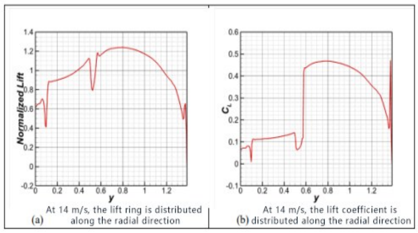


Figure 3 Aerodynamic analysis data of UAV

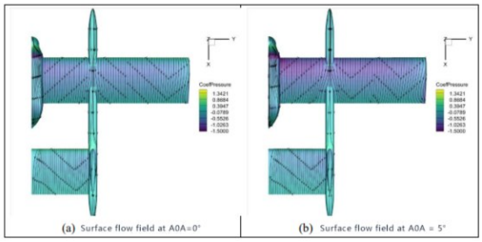


Figure 4 Surface pressure and streamlines of UAV in take-off condition

The results of CFD analysis show that the aerodynamic performance of the configuration has a certain deviation compared with the analysis results of the plane element method, and the design results meet the task requirements.

3.2 Modular structure design

The modular design of the UAV includes fuselage and wing modules, each engineered for ease of assembly and reconfiguration. The large fuselage module (Figure 5) connects to the main wing and houses critical equipment, supported by spacer frames and transverse columns, and secured with a latch mechanism (Figure 6). The transfer fuselage module (Figures 7 and 8) links the large fuselage to the motor, ensuring geometric continuity of the fuselage. One end of the transfer fuselage uses the large fuselage connector (Figure 9), while the other end connects to the small fuselage module (Figure 10).

The small fuselage module (Figure 11) features a girder structure that allows flexible positioning of the tail section. This module is connected using a system of protrusions and grooves (Figure 12), and secured in place with rotating pins (Figure 13).

The wing-body connection (Figure 14) attaches the two wing beams to the large fuselage, fastened securely with rotating handles (Figure 15). The main wing module (Figures 16 and 17), composed of fins, beams, and foam-filled structures, is reinforced with carbon tubes and assembled into the final wing (Figure 18). The tail module (Figure 19) follows a similar design and connection methodology.

The oversized fuselage (Figure 20) and large wing module (Figure 21) of the UAV are specifically designed to accommodate the installation of a target positioning pod. The overall structural design of the UAV, including the module layouts and connection methods, is illustrated in Figures 22.

3.3 Airborne system design

The main UAV modules are 3D printed using PLA material, chosen for its lightweight, high strength, and ease of printing. The printing direction and path are optimized based on load-bearing needs to ensure adequate stiffness and strength. The wing-body spar (Figure 23) includes grooves designed to break at stress points during emergencies, protecting critical modules. The print path is optimized using slicing software to balance quality and weight.

Figure 5-22 shows the modular structure design, and Figure 23 shows the 3D printing structure optimization

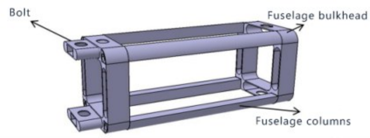
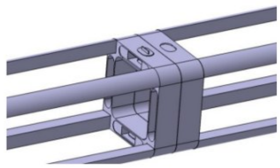
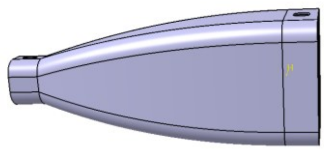
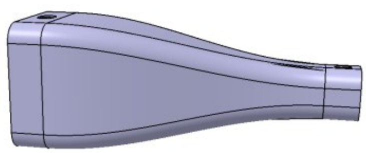
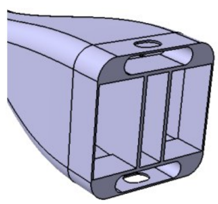
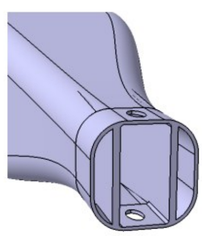
Figure number	Name	Figure
Fig 5	Large body module	
Fig 6	Large body module connectors	
Fig 7	Airframe module	
Fig 8	Rear transfer fuselage module	
Fig 9	Large connector	
Fig 10	Small connector	

Figure 5-22 shows the modular structure design, and Figure 23 shows the 3D printing structure optimization(Continued).

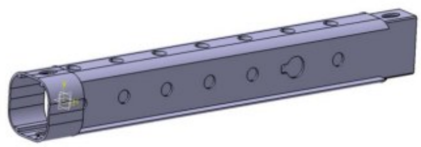
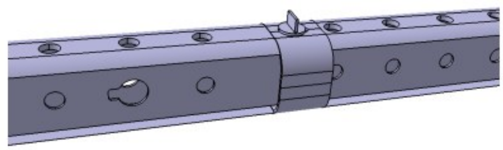
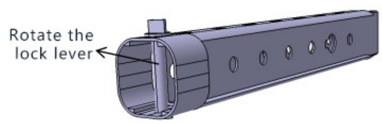
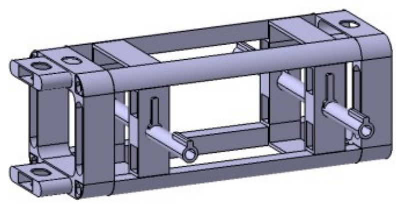
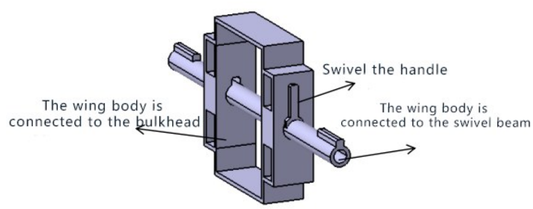
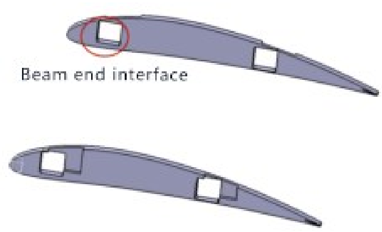
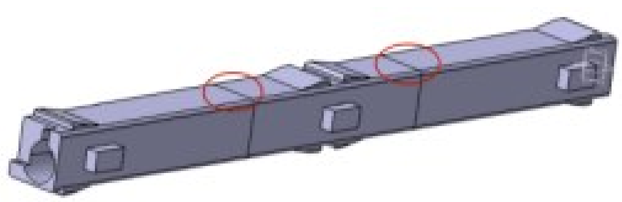
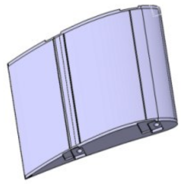
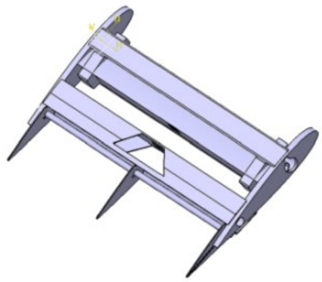
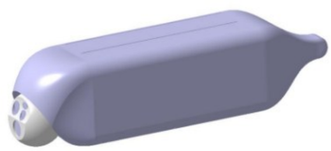
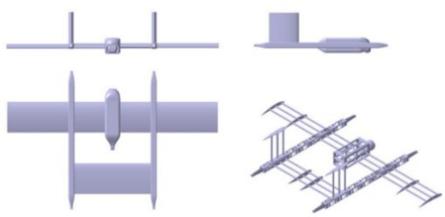
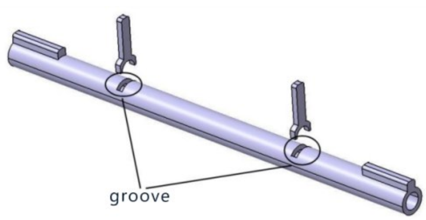
Figure num - ber	Name	Figure
Fig 11	Small body module	
Fig 12	Small body module connec- tion	
Fig 13	Small body connection part	
Fig 14	Wing-body attachment	
Fig 15	Detail of the wing-body con- nection	
Fig 16	Diagram of the ribs of the main wing	
Fig 17	Wing spar model drawing	

Figure 5-22 shows the modular structure design, and Figure 23 shows the 3D printing structure optimization(Continued).

Figure num - ber	Name	Figure
Fig 18	Main wing module assembly diagram	
Fig 19	Diagram of the tail module	
Fig 20	UAV configuration with cam- era body module	
Fig 21	UAV configuration wing module	
Fig 22	Diagram of the structure of the supervision diagram	
Fig 23	The wing body attaches the grooves on the screw beam	

4 Results

After completing the modular design, the components were 3D printed using Raise3D E2 and Raise3D Pro3 Plus printers, which are renowned for their high printing precision. Once printed, each component was carefully weighed using high-precision electronic scales to ensure adherence to the design specifications, including the accurate positioning of the center of gravity.

The UAV was then assembled according to the design models. Some parts required minor adjustments, such as polishing, to ensure a tight fit during assembly. To preserve the airfoil shape, reduce aerodynamic drag, and protect the surface, a transparent film was applied to the wing.

The final weight of the modular UAV was 1565g, in line with the expected design parameters. During flight tests, the UAV performed well, successfully executing takeoff, climbing, turning, and other essential maneuvers. The motor thrust and control surfaces operated as expected, confirming that the UAV was ready for operational deployment.

5 Conclusion

The UAV combat system based on a modular platform offers significant advantages in battlefield adaptability, cost-effectiveness, reduced logistical burden, and enhanced capabilities. The modular design enables rapid assembly and reconfiguration of drones, allowing for customization to meet diverse mission requirements.

Future work will focus on optimizing the aerodynamic design through multi-objective optimization methods, aiming to enhance performance across various flight parameters. Additionally, structural designs will be refined to achieve lighter and more efficient configurations using finite element analysis and optimization techniques. To ensure the system's effectiveness in real-world scenarios, live testing of flight control systems will be conducted, validating their performance and suitability for operational deployment.

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