

Structural Design and Simulation Research of an Air-Ground Amphibious UAV

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Abstract. Aiming at the problems that traditional unmanned aerial vehicles (UAV) can only operate in the air. An air-ground amphibious UAV platform with variable structure and dual-domain traffic capacity is designed to integrate the advantages of aerial flight and ground driving. An integrated wheel-arm structure with four steering gear motors independently controlled and gear transmission integrated is innovative designed. The mechanical model of the frame is established and optimized, and strength verification is carried out to verify the rationality and safety margin of the structure. Under hovering condition, the maximum stress of the frame is 3.002MPa and the maximum displacement is 7.956×10^{-3} mm. After the connector is fixed with the wheel, the maximum stress is 1.325MPa and the maximum displacement is 2.956×10^{-2} mm. Under static ground condition, the maximum stress of the wheel set is 0.5118MPa and the maximum displacement is 1.559×10^{-3} mm. The stress of each component is far lower than the allowable stress of carbon fiber and structural steel, meeting the strength and stiffness design requirements. Finally, prototype tests show that the platform can stably realize aerial hovering, ground driving and mode switching, with good air-ground dual-domain traffic capacity. The amphibious UAV designed in this study has both good aerial flight performance and ground mobility, providing a technical reference for the engineering realization of lightweight and high-reliability unmanned platforms in logistics distribution, emergency rescue and other scenarios.

Keywords: Amphibious UAV, Structural Design, Simulation Research, Prototype Experiment.

1. Introduction

Traditional UAV have aerial operation capability but there are difficult to enter narrow closed spaces such as indoors, with limited endurance. Traditional unmanned ground vehicles (UGV) have strong ground mobility but there are significantly limited by terrain obstacles and cannot cross gullies and complex barriers [1-4]. To break through the functional limitations of single-domain unmanned platforms, air-ground amphibious UAV integrating ground driving and aerial flight have become a research problem. They can switch operation modes autonomously according to the environment, combining the advantages of high ground endurance and aerial obstacle crossing, and have broad application prospects in emergency rescue, military reconnaissance, urban inspection and other fields.

Zhang Hua [5] employed a wheel-propeller integrated design with a swing-arm mechanism, utilizing planetary gear transmission for mode switching, and performed transmission hysteresis analysis using probabilistic statistical methods. Yang Wenliang et al. [6] improved ground traversability through an isosceles trapezoidal dual-rocker steering mechanism and conducted finite element strength verification on the rotor and linkages. Xia Zequn [7] employed a top-bottom docking and omnidirectional wheel structure, established a multimodal dynamic model, and designed a unified controller based on the ADRC algorithm. Zhang Zheng et al. [8] improved ground maneuverability through a retractable rotor and achieved stable dual-domain (land-air) operations based on ADRC control, providing a reference for military applications. Daler et al. [9] proposed a biomimetic multimodal flying and walking robot that achieves multi-domain propulsion using a single actuator. Hong Xianggong et al. [10] employed cascaded PID and optimal curvature methods to enhance mobility robustness, achieving stable control of the land-air amphibious robot in both modes. Huang et al. [11] constructed a dynamic model using a sliding mode control method and, by combining real-

time height estimation with segmented power control, achieved fast and stable control in ground mode. Li Qijun et al. [12] addressed the path planning challenges faced by land-air amphibious UAV in dense urban environments by proposing an improved A-algorithm (IA-AGPF) that integrates an artificial gravity potential field. Meng Qingjing et al. [13] optimized energy consumption by distinguishing between land and air mode energy consumption models and introducing mode switching and escape strategies. Zhu Hang et al. [14] established a kinematic model and employed fuzzy PID control, effectively enhancing motion control stability in complex environments. Lan Erbin et al. [15] achieved stable motion control through structural design and stress analysis, based on PID control, and demonstrated the advantages of such platforms in extending endurance and mission duration. Wang Zhengjie et al. [16] conducted research on the flight control system of land-air amphibious robots and verified the effectiveness of the control channels in the flight system through MATLAB simulation. Previous studies have proposed various mechanisms and control schemes for amphibious platforms, but most focus on control algorithms or mechanism innovation, lacking systematic research on statics characteristics, strength verification and lightweight optimization of key load-bearing components of variable structures.

Therefore, this study carries out the design, statics simulation, finite element analysis and prototype test of a variable-structure air-ground amphibious UAV to improve structural reliability and engineering practicability. The overall structure and integrated wheel-arm mechanism are designed, a mechanical analysis model is established, and statics simulation is conducted, structural parameters and configuration are optimized, and tests verify the air-ground traffic performance.

2. Structural Design of the Air-Ground Amphibious UAV

2.1. Variable Structure Design and Analysis

The air-ground amphibious UAV adopts a wheel-propeller integrated variable-structure configuration, mainly composed of four symmetrically arranged annular wheel-arm units and a lightweight frame. It switches between aerial flight and ground driving through mechanical transmission. The annular wheel-arm unit is the core component. Its outer ring serves as both a driving wheel and a propeller guard. In aerial mode, the propeller faces vertically downward to provide lift, in ground mode, the propeller is parallel to the ring to avoid interference and protect the blades. A deceleration motor and internal-meshing gear drive the outer ring for ground movement. The frame adopts a hollow lightweight plate structure, carrying four wheel-arm units with symmetrical layout, reducing weight while ensuring strength and reserving installation space for electronic systems. The two operation modes of the amphibious UAV are illustrated in Fig 1.

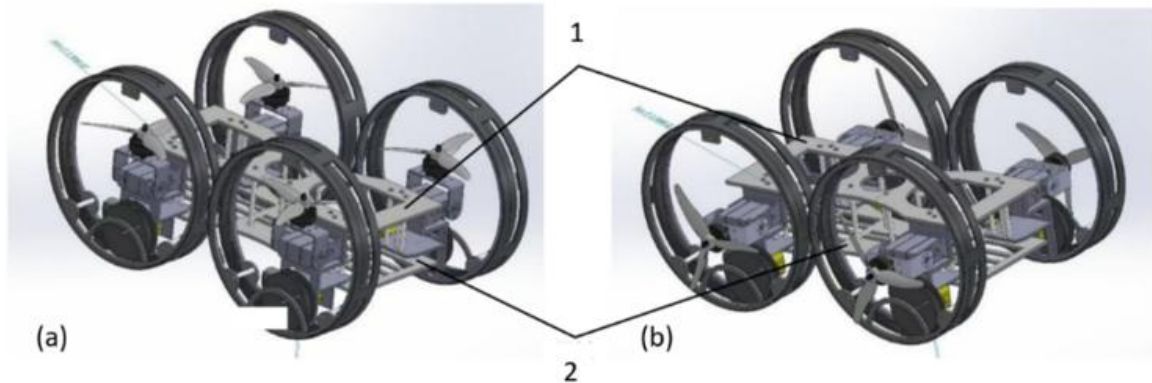


Fig 1. Two working states of the UAV(a) Aerial flight mode(b) Ground driving mode.

The detailed assembly structure of the wheel-arm unit is illustrated in Fig 2.

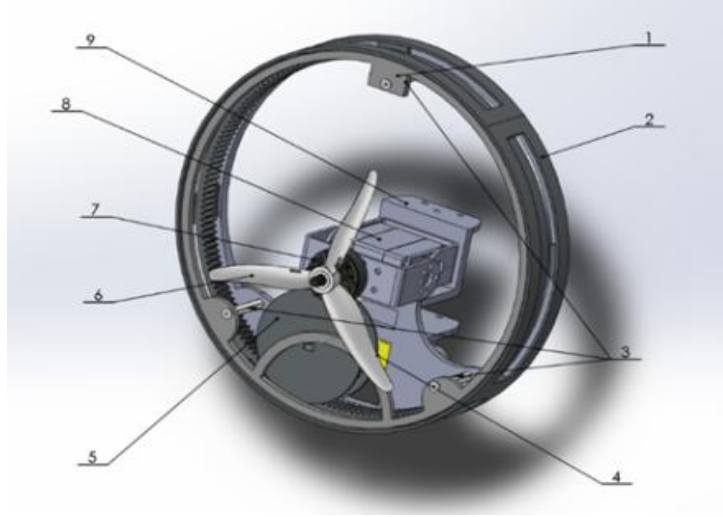


Fig 2. Wheel-arm structure of the amphibious UAV (1-hub, 2-outer ring, 3-connecting pillar, 4-DC gear motor, 5-inner gear, 6-propeller, 7-brushless motor, 8-steering gear, 9-connecting part).

2.2. Page Numbers Parameter Optimization and Selection of Key Components

2.2.1 Propeller Selection

The platform is equivalent to the hovering thrust of a single propeller.

$$T_{\text{hover}} = \frac{m_{\text{all}} \cdot g}{n_p} \quad (1)$$

Where m_{all} is the total mass of the platform, g is the acceleration due to gravity, and n_p is the number of motors and rotors. With $m_{\text{all}} = 1.5 \text{ kg}$, $g = 9.8 \text{ m/s}^2$, $n_p = 4$.

The maximum thrust considering maneuvering acceleration is:

$$T_{\text{max}} = \frac{m_{\text{all}}(g + a_x)}{n_p} \quad (2)$$

Where a_x is the maximum design maneuvering acceleration. Taking $a_x = 0.5g = 4.9 \text{ m/s}^2$, and substituting this value into the calculation, we find that the maximum thrust of the single rotor is $T_{\text{max}} = 5.5125 \text{ N}$.

The blade element-momentum theory is used to model thrust and torque:

$$\begin{cases} T = \left(\frac{1}{60}\right)^2 C_T \rho n^2 D_p^4 \\ M = \left(\frac{1}{60}\right)^2 C_M \rho n^2 D_p^5 \end{cases} \quad (3)$$

Where C_T is the rotor thrust coefficient, C_M is the rotor torque coefficient, ρ is the air density, n is the rotor speed, and D_p is the rotor diameter. To measure the rotor's energy efficiency, the rotor thrust efficiency is defined by relating the hovering thrust to the rotor input power, as expressed by:

$$\eta_p = \frac{T_{\text{hover}}}{P_{pH}} = \frac{60T_{\text{hover}}}{2\pi M_H n_H} \quad (4)$$

Where P_{pH} is represents the input power of the rotor during hover, while M_H and n_H represent the drag torque and rotational speed of the rotor during hover, respectively. The measured performance data of the matching motor and propeller under different throttle signals are illustrated in Table 1. Based on measured data of 51466-3B 5-inch three-blade propeller, the thrust coefficient C_T is inversely calculated as about 0.12.

Table 1. Measured performance of motor and propeller.

Throttle	Thrust (g)	Current (A)	RPM	Efficiency (g/W)
100%	1601.1	33.2	28590	2.01
90%	1391.4	25.5	26734	2.28
80%	1024.9	17.8	24857	2.40
70%	822.5	12.1	22879	2.84
60%	590.2	7.4	19470	3.30
50%	347.5	4.1	16332	3.50

Determining the Rotor Drag Coefficient C_T Based on Experimental Data. By modifying the element-momentum drag model (Equation 3), the following expression for the drag coefficient C_T is obtained:

$$C_T = \frac{3600T}{\rho n^2 D_p^4} \quad (5)$$

Where T is the measured thrust of the rotor, $\rho = 1.225 \text{ kg/m}^3$, n is the measured rotational speed (RPM), and $D_p = 0.127 \text{ m}$.

Given the hover requirements for the entire system, the hover thrust of a single rotor must reach 375 g. Linear interpolation is used to determine the measured rotational speed and thrust corresponding to the hover condition.

$$n_{\text{hover, test}} = n_1 + (n_2 - n_1) \times \frac{T_{\text{hover}} - T_1}{T_2 - T_1} \quad (6)$$

Substituting the data yields $n_{\text{hover, test}} \approx 16686 \text{ RPM}$. Substituting $T_{\text{hover}} = 3.675 \text{ N}$, $n_{\text{hover, test}} = 16686 \text{ RPM}$, $\rho = 1.225 \text{ kg/m}^3$, $D_p = 0.127 \text{ m}$ into equation (5), we calculate $C_T \approx 0.12$. Thus, $C_T = 0.12$.

2.2.2. Motor Selection

The motor voltage balance equation is:

$$U_m = I_m R_m + \frac{n}{K_V} \quad (7)$$

Where U_m is the motor operating voltage, I_m is the motor operating current, R_m is the motor internal resistance, K_V is the motor speed constant, and n is the motor output speed. Motor efficiency reflects the effectiveness of the conversion of electrical energy into mechanical energy and is expressed as.

$$\eta_m = \left(1 - \frac{I_m}{U_m} R_m\right) \left(1 - \frac{I_{m0}}{I_m}\right) \quad (8)$$

Where I_{m0} is the no-load current of the motor. The motor and rotor are treated as a single integrated power unit for evaluating the overall power output performance, and the expression is:

$$\eta_{pm} = \frac{T_{\text{hover}}}{U_m I_m} \quad (9)$$

Substituting the hovering torque and torque efficiency into the equation yields an input power of approximately 108 W for the motor in hover mode. Combining this with the 4S battery voltage of 14.8 V, the hovering current is approximately 7.3 A, and the maximum operating current is approximately 12.1 A.

The formulas for calculating blade centrifugal force and allowable tensile force are as follows:

$$F_c = m_p \cdot \omega^2 \cdot r_c \quad (10)$$

$$F_{allow} = \sigma_{allow} \cdot A_p \quad (11)$$

Where F_c is the centrifugal force acting on the blade. m_p is the mass of a single blade (kg). ω is the angular velocity of the rotor (rad/s). r_c is the distance from the blade's center of mass to the center of rotation. F_{allow} is the allowable tensile force on the blade. σ_{allow} is the allowable stress of the blade material. for carbon fiber blades, $\sigma_{allow} = 3.5 \times 10^9 \text{ Pa}$, A_p is the cross-sectional area of the blade (m^2), for a 5-inch three-bladed propeller, $A_p = 2.5 \times 10^{-5} \text{ m}^2$.

Substituting the safety constraint $F_c \leq F_{allow}$ into $\omega = \frac{2\pi n}{60}$ yields the theoretical formula for the safe rotational speed.

$$n \leq \frac{60}{2\pi} \sqrt{\frac{\sigma_{allow} \cdot A_p}{m_p \cdot r_c}} \quad (12)$$

Where $\sigma_{allow} = 3.5 \times 10^9 \text{ Pa}$, $A_p = 2.5 \times 10^{-5} \text{ m}^2$, $m_p = 0.012 \text{ kg}$, $r_c = 0.06 \text{ m}$.

$$n_{safe} \leq \frac{60}{2\pi} \sqrt{\frac{3.5 \times 10^9 \times 2.5 \times 10^{-5}}{0.012 \times 0.06}} \approx \frac{60}{6.28} \sqrt{\frac{87500}{0.00072}} \approx 9.55 \times 3499 \approx 33420 \text{ RPM} \quad (13)$$

Taking into account factors such as air turbulence and fluctuations in rotational speed during actual flight, a safety margin of 70% is applied to determine the safe rotational speed of the rotor.

$$N_{safe} = 33420 \times 0.70 \approx 23390 \text{ RPM} \quad (14)$$

After determining the safe rotational speed, the operating speed range of the rotor is calculated in reverse using the blade element momentum model, and the rotational speed is then determined by substituting the values into the blade element momentum-drag model.

$$n = \frac{60}{D_p^2} \sqrt{\frac{T}{C_T \rho}} \quad (15)$$

Where T is the rotor thrust, $C_T = 0.12$, $\rho = 1.225 \text{ kg/m}^3$, $D_p = 5 \text{ inch} = 0.127 \text{ m}$. The maximum maneuvering condition is $T = T_{max} = 5.5125 \text{ N}$.

$$n_{max} = \frac{60}{(0.127)^2} \sqrt{\frac{5.5125}{0.12 \times 1.225}} = \frac{60}{0.016129} \sqrt{\frac{5.5125}{0.147}} \approx 3720 \times 7.10 \approx 22780 \text{ RPM} \quad (16)$$

After verification, the maximum operating speed is approximately 22,780 RPM, which is below the safe speed of 23,390 RPM and satisfies the structural strength constraints of the rotor. Derived from the motor voltage balance equation, the motor speed constant satisfies.

$$K_V = \frac{n}{U_m} \quad (17)$$

Substituting the operating speed and battery voltage into the calculation yields the following $K_V = \frac{16686 \sim 22780}{14.8} \approx 1127 \sim 1540 \text{ KV}$. Combined with speed and safety constraints, the motor KV is selected as 1850 KV, with maximum current not less than 20 A.

2.2.3. ESC and Battery Selection

The ESC continuous current should be no less than 30 A, supporting 3–6S lithium batteries. The battery is selected as 4S 14.8 V 4000 mAh 45 C to meet endurance and power requirements.

$$\sigma U_b = U_m + I_m R_e \quad (18)$$

Where σ is the ESC duty cycle, U_b is the battery voltage, and R_e is the ESC internal resistance. ESC efficiency reflects power transmission losses and is expressed as.

$$\eta_e = \frac{1}{1 + \frac{I_m}{U_m} R_e} \quad (19)$$

To ensure safe and reliable operation, the ESC's maximum continuous current must not be less than the motor's maximum operating current, i.e., it must satisfy the following constraint.

$$I_{e\max} \geq I_{m\max} \quad (20)$$

Based on the motor's maximum operating current of approximately 16 A and to ensure an adequate safety margin, ESC's continuous current rating should be no less than 30 A. It should also support a lithium battery voltage range of 3–6 S to accommodate the output requirements. Battery parameters directly determine the hover time and the maximum power output. The total battery output current is the sum of the operating currents of each motor and the currents drawn by onboard equipment such as the flight controller.

$$I_b = n_p I_m + I_{\text{control}} \quad (21)$$

Where I_{control} is the operating current for the flight control system, sensors, and other equipment. Substituting the single-motor hover current and the equipment current yields a total hover current for the entire system of approximately 30.2 A, and a total current of approximately 49.4 A under maximum acceleration conditions. The battery terminal voltage satisfies the voltage balance equation.

$$U_b = U_e + I_b R_b \quad (22)$$

Where U_e is the ESC input voltage and R_b is the battery internal resistance. The expression for battery efficiency is expressed as.

$$\eta_b = \left(1 - \frac{I_b}{U_b} R_b\right) \left(1 - \frac{I_{\text{call}}}{I_b}\right) \quad (23)$$

Hover time is a key metric in battery selection. Assuming a 15% safety margin for discharge, hover time can be calculated based on battery capacity and total operating current using the following formula.

$$t_{\text{hover}} \approx \frac{0.85 \cdot C_b \cdot 60}{1000 \cdot I_b} \quad (24)$$

Where C_b is the battery capacity. To meet the design target of a hover time of at least 6 minutes, while also accounting for the maximum discharge current requirement, calculations indicate that the battery capacity should be 3775 mAh, with a discharge rate of at least 45C and a rated voltage of 4S 14.8 V. Additionally, the battery weight must comply with the overall system weight constraints.

$$(m_b + m^*)g \leq 0.85T_{\max} \quad (25)$$

Where m_b is the mass of the battery, and m^* is the mass of the platform excluding the battery. This constraint ensures a reasonable balance among hover time, battery capacity, and the total weight of the vehicle. After determining the motor and propeller combination based on the performance parameters specified in the design requirements, the specific design and selection parameters for each component of the propulsion system are illustrated in Table 2.

Table 2. Parameters of key components.

Component	Specification	Quantity
Propeller motor	AE2077, KV1850	4
Driving motor	12 V DC gear motor	4
Propeller	51466	4
ESC	30–35 A, 3–6S	4
Battery	4S 14.8 V 4000 mAh 45 C	1

2.3. Kinematic Analysis

Force balance equations are established for hovering, static ground, uniform driving and ascending conditions. The force analysis diagrams of hovering and static ground states are illustrated in Fig 3.

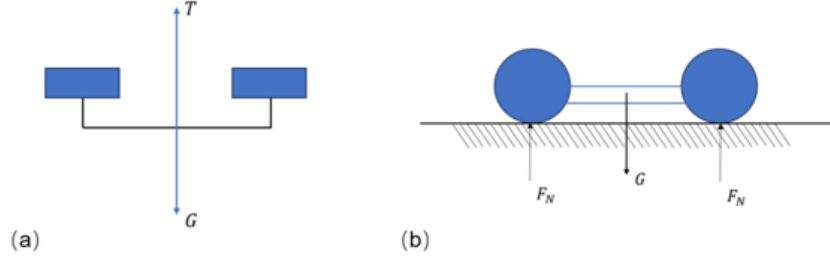


Fig 3. Force diagram in several conditions (a) Hovering quadrotor (b) Static ground state.

(1) Hovering. The following equilibrium equations can be established:

$$T = G \quad (26)$$

Where G is total weight of the drone. T is Lift provided by the rotors.

(2) At rest on the ground.

$$4F_N = G \quad (27)$$

Where F_N is Lift generated by the rotor.

The force diagrams of uniform ground driving and maximum acceleration ascent are illustrated in Fig 4.

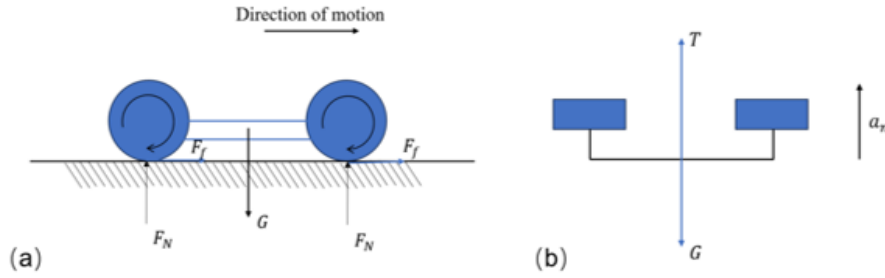


Fig 4. Force diagram in several conditions

(a) uniform ground motion (b) maximum acceleration ascent.

(3) State of uniform motion on the ground. The driving force and driving torque for each wheel are expressed as follows.

$$4T = f_d = Gf_g \quad (28)$$

$$M = f_d R \quad (29)$$

Where f_d is road resistance. f_g is rolling resistance coefficient. here, the maximum rolling resistance coefficient for a bumpy road surface is taken as 0.05. Maximum acceleration during ascent. The following equilibrium equations can be established.

$$T = G + Ma_m \quad (30)$$

Where a_m is maximum acceleration.

3. Multi-Body Dynamics and Statics Simulation

3.1. Simulation Model Setup

3.1.1. Material Properties

The static analysis primarily uses simulation software to perform strength verification on key components of the amphibious UAV, including the airframe, ground mode airframe, connecting parts, and outer wheels. Prior to conducting the static analysis, the model was simplified by analyzing the UAV normal operating conditions, taking into account the model geometry and simulation conditions. Irrelevant and redundant structures were removed without affecting the simulation results. The material properties of the parts are illustrated in Table 3.

Table 3. Material properties of components.

Part	Material	Density (g/cm ³)	Elastic Modulus (GPa)	Poisson's Ratio
Frame, wheel arm	Carbon fiber	1.6	230	0.3
Connector	Structural steel	7.85	200	0.3

3.1.2. Meshing and Boundary Conditions

Structured hexahedral meshing is used with local refinement at stress concentrations. Binding constraints are applied between connected parts. Loads and constraints are set for hovering and ground static conditions. Lift is applied as uniform load on connectors; gravity is applied at the frame centroid. Rigid ground contact is set; vertical load is applied at wheel centroids. The mesh division effect of the frame and wheel-arm assembly is illustrated in Fig 5.

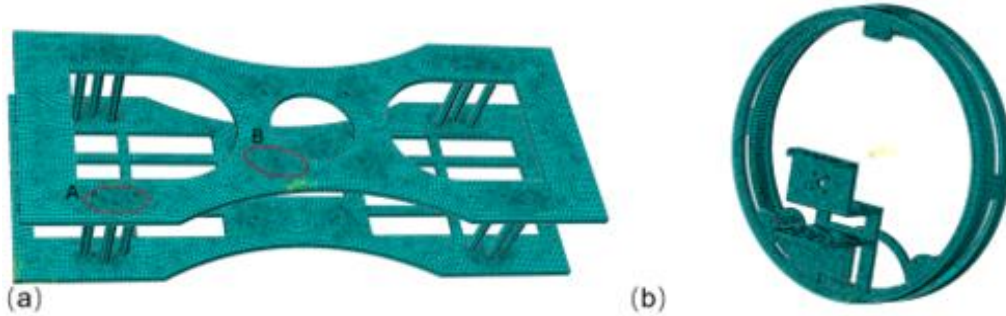


Fig 5. Mesh of key parts(a) UAV frame(b) wheel-arm.

The load application and boundary constraint settings under hovering condition are illustrated in Fig 6.

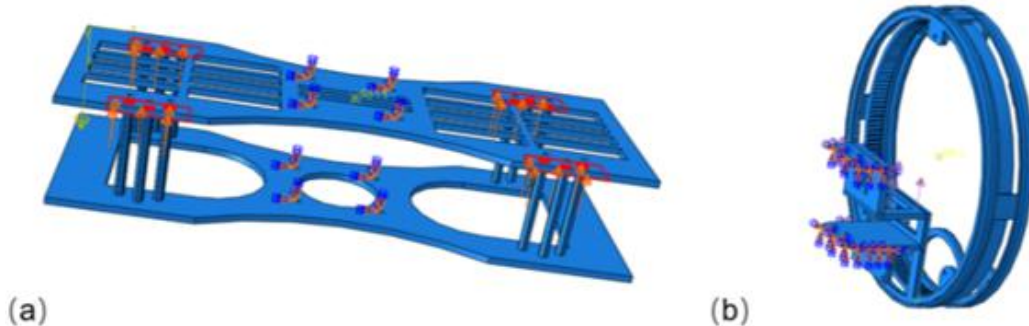


Fig 6. Load and boundary conditions under hovering(a) UAV frame(b) wheel-arm.

The contact constraint setup for static ground simulation is illustrated in Fig 7.

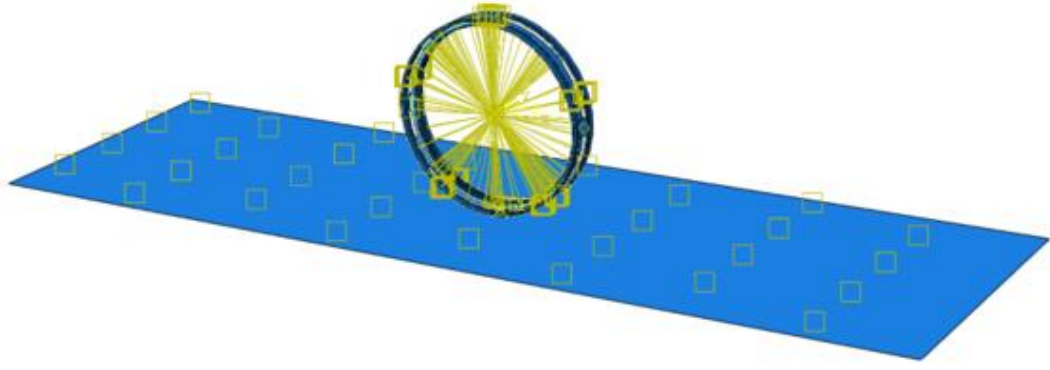


Fig 7. Contact setup for ground static condition.

3.2. Simulation Results and Analysis

3.2.1. Hovering Condition

All stresses are far below allowable values, meeting strength and stiffness requirements. Max stress is 3.002 MPa, max displacement 7.956×10^{-3} mm. Wheel-arm assembly: max stress 1.325 MPa, max displacement 2.956×10^{-2} mm. The stress, strain and displacement nephograms of the frame under hovering load are illustrated in Fig 8.

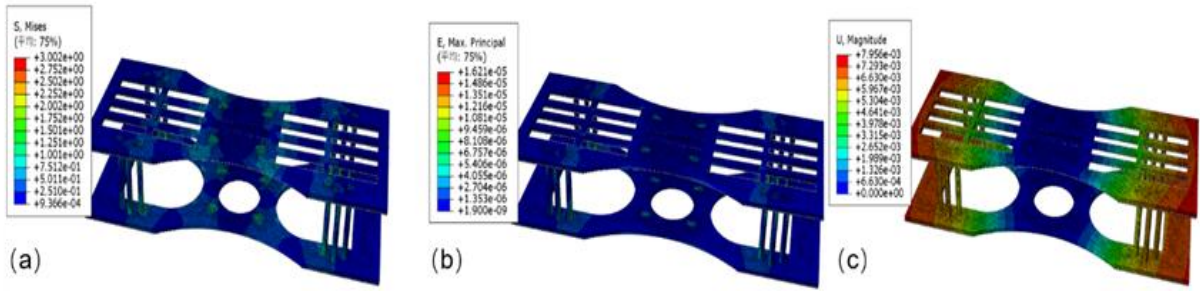


Fig 8. Simulation results of frame under hovering
(a) Stress distribution (b) Strain distribution (c) Displacement distribution.

The statics simulation cloud charts of wheel-arm assembly under hovering condition are illustrated in Fig 9.

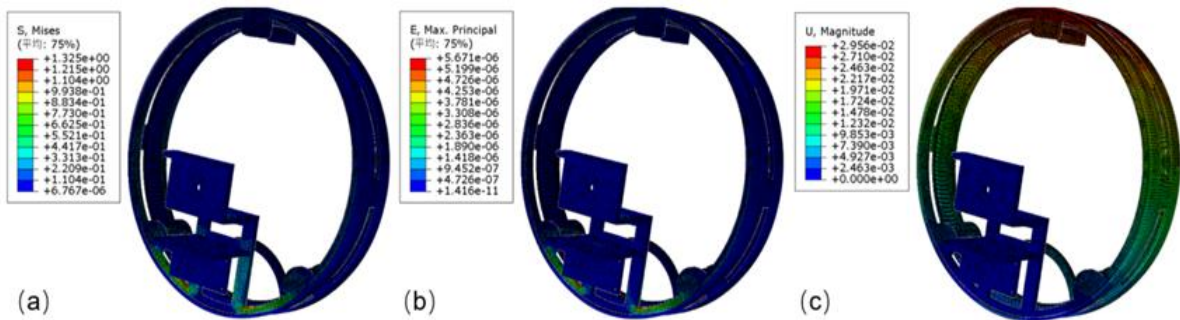


Fig 9. Simulation results of wheel arm under hovering
(a) Stress distribution (b) Strain distribution (c) Displacement distribution.

3.2.2. Ground Static Condition

The structure is safe with small elastic deformation. Max stress of outer wheel is 1.278×10^{-2} MPa. Max stress of connecting part 0.5118 MPa, max displacement 1.559×10^{-3} mm. The Mises stress distribution result of the outer wheel under ground static load is illustrated in Fig 10.

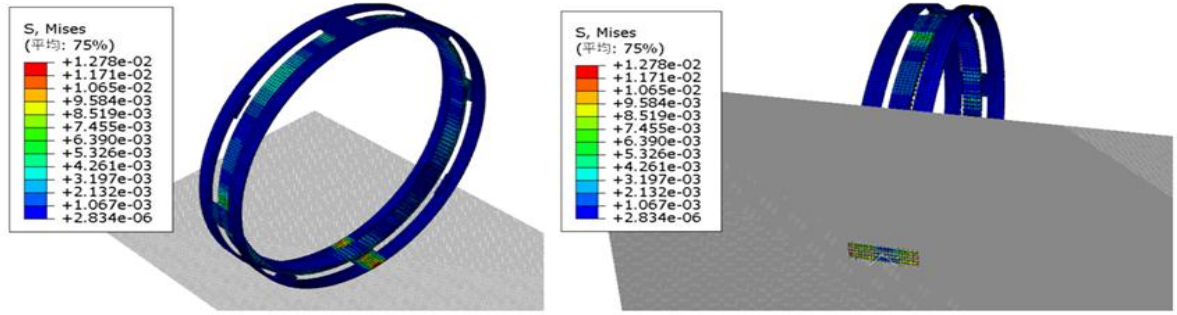


Fig 10. Simulation results of outer wheel under static ground.

The stress, strain and displacement simulation results of the connecting piece under static ground state are illustrated in Fig 11.

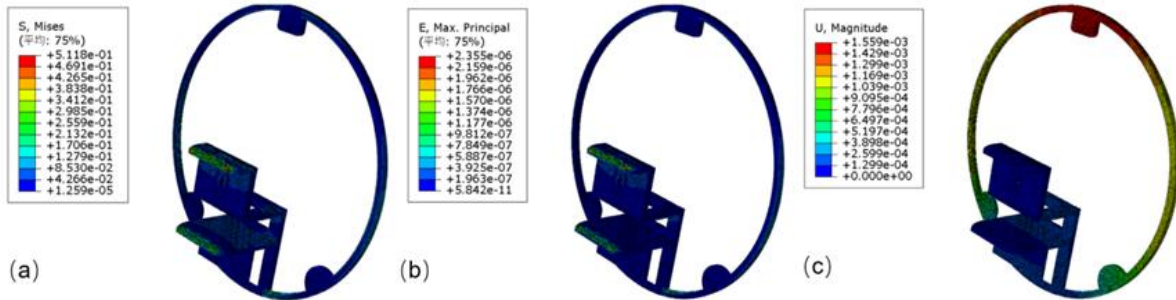


Fig 11. Simulation results of connectors under static ground
(a) Stress distribution(b) Strain distribution(c) Displacement distribution.

4. Prototype Manufacturing and Performance Experiment

The prototype total mass is 1.5 kg. The length is 405 mm, width is 311 mm (ground), 232 mm (air), height is 195 mm. Outdoor tests are conducted. The overall dimension parameters of the prototype under two operation modes are illustrated in Table 4.

Table 4. Prototype dimensions in two modes.

Mode	Length (mm)	Width (mm)	Height (mm)	Mass (kg)
Ground driving	405	311	195	1.5
Aerial flight	405	232	195	1.5

4.1. Simulation Results and Analysis

The prototype realizes smooth start, straight driving, differential steering and braking on flat ground, with good stability and no skidding or jamming. The field ground driving test scene is illustrated in Fig 12.



Fig 12. Ground driving experiment of the UAV.

4.2. Simulation Results and Analysis

The prototype completes stable takeoff, hovering and translation. The structure is locked reliably, and mode switching is smooth. The aerial flight test effect of the prototype is illustrated in Fig 13.



Fig 13. Aerial flight experiment of the UAV.

Test results show that the prototype meets design expectations in both modes.

5. Conclusions

This study enhances the structural reliability and engineering practicality of the platform through structural design, design and static simulation of a transformable land-air amphibious UAV, finite element analysis, and prototype testing.

(1) A wheel-arm integrated structure with hidden propellers is designed to improve ground trafficability. Key parameters of propeller, motor and battery are selected.

(2) Static simulation results show that the maximum stress under hovering conditions is 3.002 MPa, and the maximum displacement is 7.956×10^{-3} mm, under stationary ground conditions, the maximum stress in the wheel assembly is 0.5118 MPa, and the maximum displacement is 1.559×10^{-3} mm. Both structural strength and stiffness meet the design requirements.

(3) Prototype tests confirm stable operation in air and ground modes and smooth modes switching.

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