Novel Portable Structure for Foldable UAV

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Abstract. UAV technology has realized rapid development in recent years, especially in foldable UAVs. The foldable UAV has numerous advantages, such as portability, compact storage, and easy to carry. This paper focuses on the structural optimization design of foldable UAV, aiming to improve its performance in practical applications while maintaining lightweight and portability. It starts with the analysis of the working principles and mechanical properties of UAVs, followed by the design and optimization of the foldable structure. The collapsible UAV has quadrotors that can be folded horizontally to reduce its footprint during non-operational states, making it easier to carry, less than 500g and a flight duration exceeding 20 minutes. The structural optimization includes a detachable frame and foldable arms, which not only improve its portability but also facilitate maintenance and upgrades. Through simulation, the mechanical performance under various flight conditions was analysed, confirming its structural integrity and flight stability. The results demonstrate that the optimized foldable UAV meets the requirements, offering a practical example for applications requiring portability and durability.

Keywords: UAV, Foldable Structure, Mechanical Simulation

1 Introduction

As the most common model of Unmanned aerial vehicle (UAV), four-rotor UAV has the advantages of simple operation, convenient take-off and landing, excellent aerial operation ability, safety and reliability, strong environmental adaptability, and long working time, and is the most important model in the world's UAV application. Therefore, four-rotor UAV has also become the most popular choice in the market and consumers. At present, UAV can be divided into military UAV and civilian UAV according to their application fields, of which civilian UAV can be further divided into consumer UAV and industrial-grade UAV [1-5].

With the rapid development of UAV, the need for lightweight, high-strength, and aerodynamically optimized drone structures is becoming increasingly important [6]. In the context of the continuous increase in the number of UAV in recent years, how to further optimize the structure of UAV has received a lot of attention, discussion and research [7,8]. The structural design of the UAV directly determines its flight performance, energy efficiency, and mission execution ability. Traditional drone design is very simple and intuitive, but it is difficult to meet the needs of modern drones for high performance, lightweight, and multi-function. With the improvement of

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computing power and the development of optimization algorithms, structural design methods based on numerical simulation and optimization theory have gradually become the mainstream. Through structural optimization, the weight of the UAV, the energy consumption can be minimized, and the aerodynamic performance of the UAV can be improved under the premise of meeting the requirements of strength, stiffness and stability. In addition, structural optimization can also help the drone maintain stable flight in complex environments. For example, in strong wind or turbulent conditions, the optimized structural design can effectively reduce the vibration and deformation of the fuselage, thereby improving the safety and reliability of the flight [9]. Under the condition that the drone is not working, the body of the drone is separated from the bracket, and the wings of the drone are folded horizontally, to greatly improve the portability.

In recent years, the structural optimization of four-rotor UAV has mainly focused on improving flight efficiency, stability, endurance and mission adaptability. The first aspect is the use of lightweight, high-strength materials such as composite materials (carbon fiber) or metal alloys to reduce weight and maintain structural strength [10]. Second, researchers can improve the energy and efficiency of four-rotor UAV by optimizing the rotor layout of four-rotors or improving the propeller airfoil shape of the four-rotor UAV's wings to reduce the airflow interference of the UAV's rotors and the drag of the fuselage [11]. The third aspect is to carry out modular and variable design of the four-rotor UAV, so that the four-rotor UAV can adapt to different mission requirements, and the foldable design of the arm, landing gear or body of the four-rotor UAV can realize the rapid replacement of the load module of the four-rotor UAV [12]. For example, combining design algorithms with additive manufacturing has huge advantages in creating lightweight structures for drone frames. For instance, one kind of framework that integrates multidisciplinary optimization has been proposed to improve the overall performance of the UAV. At present, most researchers mainly focus on the material and specific structure of the four-rotor UAV for the structural optimization of the four-rotor. To sum up, the following design requirements must be met: 1) the overall weight of the fuselage is within 500g, 2) four rotors and the rotors can be folded, 3) the fuselage can bear a certain weight.

This paper refers to the modular design of the four-rotor UAV, and the foldable design of the arm of the four-rotor UAV is carried out, and the arm is folded up in the non-working environment of the UAV without affecting its take-off and landing, which greatly reduces its occupied space. In the working state of the four-rotor UAV, the arms of the UAV are unfolded, and the four arms are spaced 90 ° apart, and the UAV can take off normally. In its non-working state, its wings are retracted and retracted on both sides of the fuselage, which is conducive to carrying. four-rotor UAV are designed for small size, light weight, easy to carry and a certain flight life.

The follow-up parts of this paper are as follows: Chapter 2 focuses on the design and data display of the main body of the four-rotor foldable UAV and shows the specific structural optimization design and the results obtained; Chapter 3 introduces the analysis of the specific forces experienced by the four-rotor foldable UAV in flight and the corresponding formulas. The fourth chapter focuses on the static analysis of the four-rotor foldable UAV and simulates the force of each part of the foldable UAV in flight state. Chapter 5 draws conclusions based on the above data and analysis.

2 Design of the rotor and main part of UAV

In this paper, the rotor of the foldable four-rotor UAV is specifically designed, and the structural scheme is determined by considering its material quality and bearing capacity. To meet the needs of the wing, which can be folded and retracted on both sides of the fuselage, the total length of the rotor is about 187mm. The rotors of a foldable four-rotor UAV are spread out at 90-degree intervals in an X-shaped distribution. The foldable drone can be roughly divided into four parts: rotors, arms, body and base. The top of the UAV body is mainly used to place the UAV control system, including flight controller, GPS, and receiver. The fuselage is connected to the drone arm around it, and the rotor is connected to the arm through a connecting block, and the front and rear are connected by a rotating shaft. The battery is mounted on the bottom of the body.

The overall model of the four-rotor foldable UAV designed in this project is shown in the figure below, referring to the classic model of the UAV: F450, with four arms connected to the fuselage, and the base and the fuselage can be separated. The flight platform is made of ABS material. The overall mass of the drone is about 347g, the total length is about 511.7mm, the width is about 349.1mm, and the height is about 148.57mm, which meets the design requirements, as shown in Figure 1-2 below. Table 1 details the specific length, width and height of UAV, as well as total space occupied.

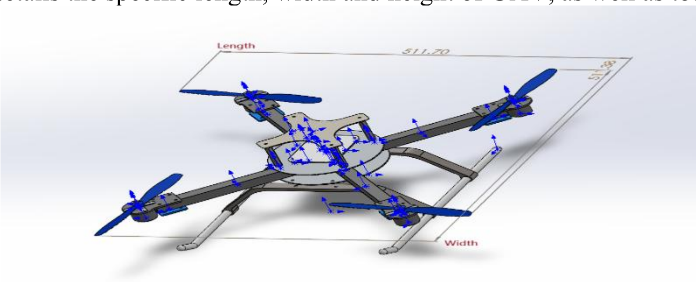

Fig. 1. Length and width of UAV (Picture credit: Original)

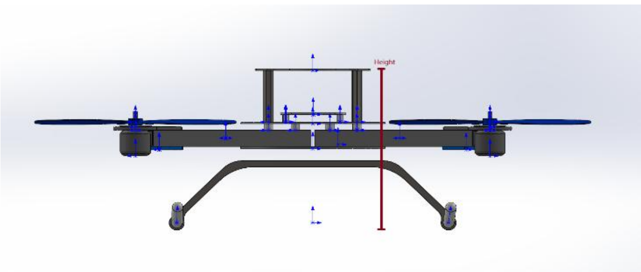

Fig. 2. Height of UAV (Picture credit: Original)

Table 1. The specific value of UAV

Parameters	value

Length	511.7mm
Width	511.38mm
Height	148.57mm
Total Space Occupied	38.876cm^3

The foldable rotor of the four-rotor foldable UAV adopts a transverse folding design, and in the non-working state of the UAV, the four arms with rotors can be retracted laterally on the four sides of the fuselage, which greatly reduces the space occupied by the four-rotor UAV in non-working conditions, which is easy to carry and transport, and can better protect the foldable rotor at the same time. At the same time, the main body of the fuselage of the drone and the landing gear of the drone can be disassembled. Figure 3-4 shows the shape of the UAV's folded arms. Tables 2 and Table 3 show the specific length, width and height of the folded UAV and the value of the space occupied by the UAV, and the specific length, width and height of the rack of the UAV and the space occupied

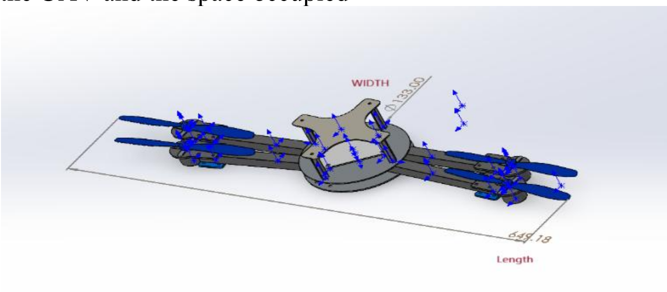

Fig. 3. Length and Width (Picture credit: Original)

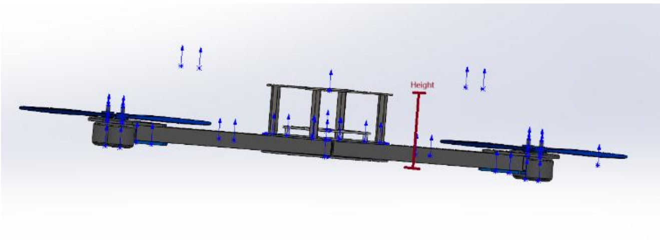

Fig. 4. Height (Picture credit: Original)

Table 2. The specific value of foldable UAV

Parameters	value
Length	649.39mm
Width	133mm
Height	72.85mm

Total Space Occupied	$6.292cm^3$

The detachable rack of the four-rotor UAV is shown in Figure 5 below.

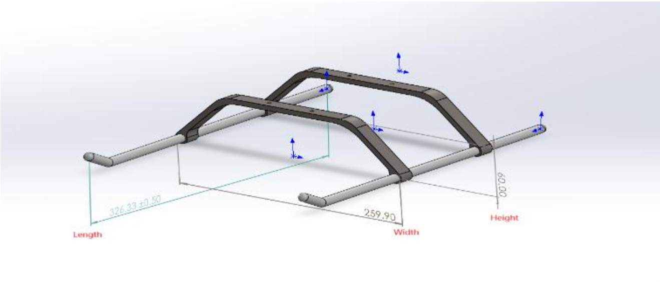

Fig. 5. Length, Width and Height of rack (Picture credit: Original)

Table 3. The specific value of rack

Parameters	value
Length	$326.33mm$
Width	$259.90mm$
Height	$60mm$
Total Space Occupied	$5.089cm^3$

From the data in the table, it can be intuitively seen that the four-rotor UAV occupies $38.876cm^3$ space under normal working conditions. It can be disassembled, and when the wings are folded, the fuselage body and frame are only $6.292cm^3$ and $5.089cm^3$, respectively. The space occupied by the four-rotor UAV in the non-working state is greatly reduced, the structural optimization of the four-rotor UAV in the non-working state is realized, and the convenience of its carrying is increased.

3 Force analysis of four-rotor UAV

During the flight, the drone is subjected to a variety of different forces, which affect the stability and control of the drone flight. These forces are lift, gravity, thrust and drag. Once the rotator rotates, the air velocity on the upper surface is greater than that on the lower surface, the air pressure on the upper surface is less than that on the lower surface, and the pressure difference between the upper and lower surfaces forms the lift. A schematic diagram of the lift force is shown in Figure 6.

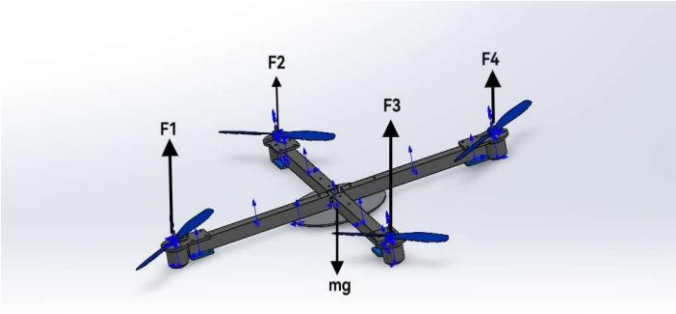

Fig. 6. Diagram of the total force of the drone (Picture credit: Original)

Gravity is the pull-down force of the drone's own mass due to the gravitational pull of the earth.

$$G = mg = 347.14g \times 9.8N / kg = 3.40N \quad (1)$$

Thrust is provided by the drone's electric motor and rotors, propelling the drone forward or upward. During vertical take-off and landing, the thrust direction is upward; In horizontal flight, the direction of thrust is forward. Thrust needs to overcome gravity and air resistance to maintain stable flight. The motor model carried by the four-rotor UAV studied in this project is 2212 920KV, and the thrust of a single motor is about 800-1000g. Resistance is the reverse force of air on the movement of the drone, which mainly comes from air friction and pressure difference.

$$D = C_D \times 0.5 \times \rho \times v^2 \times A \quad (2)$$

Thereinto:

D is the resistance

C_D is the drag coefficient (related to the shape, speed and flight attitude of the drone)

ρ for the density of the air

v for the flight speed

A is the windward area

The quadcopter UAV is equipped with a motor model of 2212 920KV, and the thrust of a single motor is about 800-1000g. The speed of the drone set in the simulation is 10 m/s and the motor speed is 60 rpm.

$$P_{MAX} = 150W \quad (3)$$

$$T = 9550P \div 60 = 23.875Ngm \quad (4)$$

Lift formula

$$L = 0.5 \times \rho \times \upsilon^2 \times S \times C_L \quad (5)$$

Resistance formula

$$D = C_D \times 0.5 \times \rho \times \upsilon^2 \times A \quad (6)$$

Where:

L for lift

S is the wing area

C_L is the lift coefficient

D for resistance

C_D is the drag coefficient (related to the shape, speed and flight attitude of the drone)

ρ for the density of the air

v for the flight speed

A is the windward area

The forces generated by the four blades are $F_1F_2F_3F_4$, d is the given torque coefficient and l is the arm length, respectively.

$$\tau_r = -F_1 \times d + F_2 \times d - F_3 \times d + F_4 \times d \tag{7}$$

$$\tau_p = -F_1 \times l + F_3 \times l \tag{8}$$

$$\tau_q = -F_2 \times l + F_4 \times l \tag{9}$$

4 Static analysis and simulation of a four-rotor foldable UAV

To simulate the flight of the foldable four-rotor UAV in the air, this paper conducted static analysis and simulation of the foldable UAV on SolidWorks.

4.1 Static analysis

Since the arm is long and the connection between the frame and the wing is a movable connection, the body bears a large torque, which may cause it to cause large deformation or even break failure. Therefore, the body module of the detachable drone needs to be statically analyzed. First, considering the complexity of the structure, the drone was first grid-based, as shown in Figure 7.

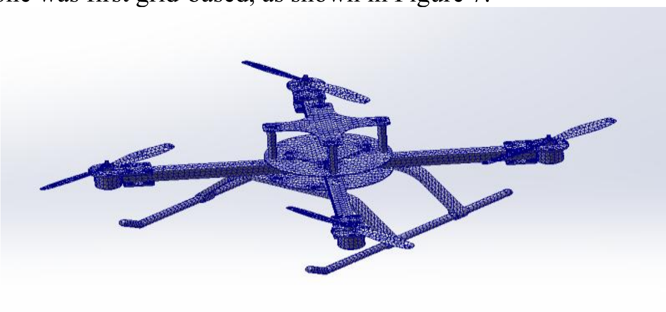

Fig. 7. Grid diagram of UAV (Picture credit: Original)

To test the overall static characteristics of the foldable drone frame in the flight state, a fixed support was applied to the center of the drone, and a vertical downward force of 50N was applied to the center of the drone's fuselage. The state of the drone during flight was shown, as shown in Figure 8.

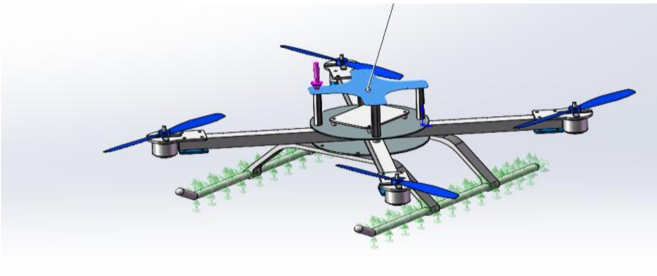

Fig. 8. The force applied (Picture credit: Original)

A constraint was added to the bottom of the drone, as shown in Figure 9.

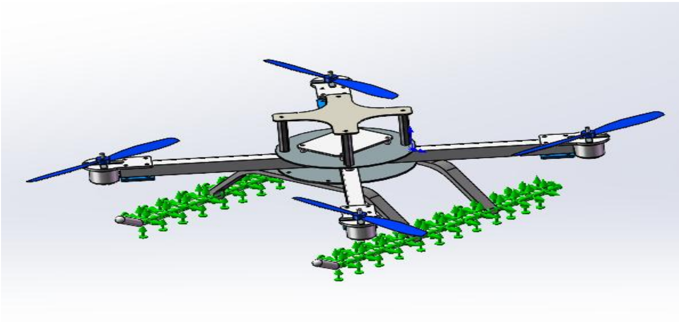

Fig. 9. Added constraints (Picture credit: Original)

In this case, the displacement, strain and stress cloud diagram of the drone is obtained, as shown in Figure 10-12.

Fig. 10. Static displacement (Picture credit: Original)

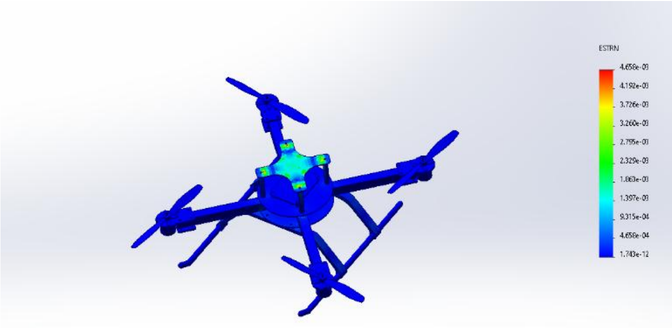

Fig. 11. Static strain (Picture credit: Original)

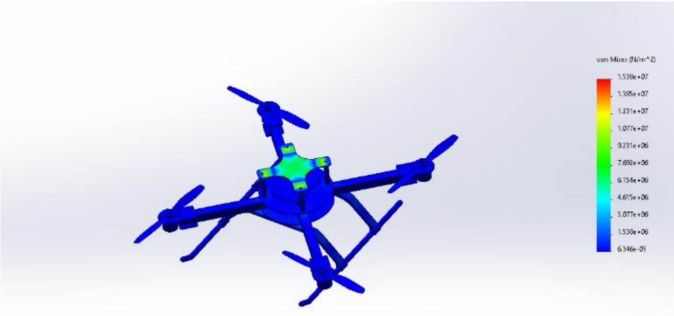

Fig. 12. Static stress analysis (Picture credit: Original)

Based on the data obtained from static stress analysis, this paper analyzes the stress, displacement and strain of the foldable UAV structure in simulated flight state.

(1) Stress cloud graph analysis (von Mises, N/m²)

The data ranges from 6346 to 15380000 N/m², showing that stress values increase significantly with changes in conditions. The highest stress value appears at 15380000 N/m², which may correspond to the maximum stress point or critical area of the foldable UAV, at the top of the drone body where it connects to the four pillars.

(2) Displacement cloud graph analysis (URES, mm)

The displacement data ranges from 1.000e-30 mm to 3.278mm, indicating the amount of deformation generated by the foldable UAV when it is subjected to its own gravity, external lift and air resistance in flight. The maximum displacement of 3.278mm occurs under the highest stress conditions and is the part where the top of the drone body is connected to the four pillars and is also the part that is most likely to fall apart during flight.

(3) Strain Cloud Map Analysis (ESTRN)

The strain data range from 1.743e-12 to 4.658e-03 reflects the degree of deformation of the materials used in foldable UAV under stress. The strain is consistent with the first two changes, and the highest value corresponds to the maximum stress and displacement conditions. This article focuses on structural optimization design, so it does not conduct more analysis on the material.

By comparing three sets of data, it is clear that when the foldable four-rotor drone is under the working state, the foldable arm and the disassembled frame in the drone do not cause deformation or displacement, which verifies that the structural optimization of the foldable UAV does not affect its normal flight work.

4.2 Motion Simulation

A rotating motor is set in the four blades of the four-rotor UAV, and the speed is set to 10 m/s, so that it rotates, generating lift into the air. Two linear motors were set on the fuselage to pan it in the air. The take-off, flight and landing simulation effects of four-rotor UAV are shown in the Figure 13 below.

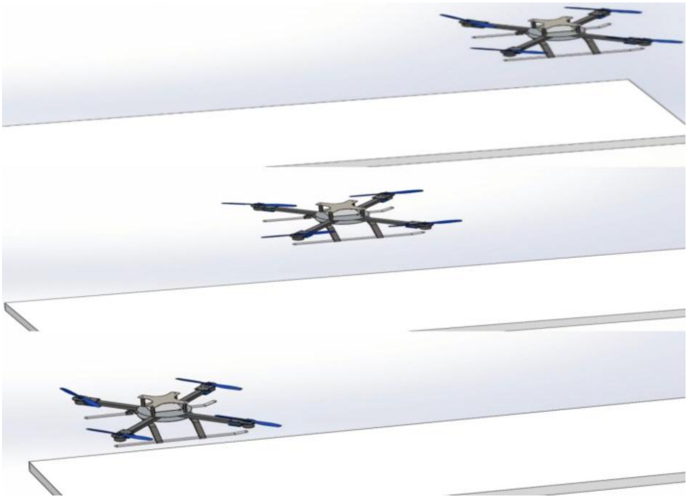

Fig. 13. Simulation of UAV in the air (Picture credit: Original)

The first stage in the figure is the takeoff of the foldable UAV, and the rotary motor operates to lift it off; the second stage in the figure is the translation of the foldable UAV in the air, and the linear motor generates force to make it glide in the air; the third stage in the figure is the landing of the foldable UAV, and the rotary motor generates force in the opposite direction, causing it to fall.

5 Conclusion

This paper optimizes the structure of the four-rotor foldable UAV, sets the connection between the wing and the body part into a movable connection, and disassembles the frame. This reasonable foldable design scheme broadens the idea of solving the structural optimization problem of the four-rotor foldable UAV. This structural optimization method will foldable design of a complete four-rotor drone, and when the product needs to be upgraded or repaired, it only needs to replace or redesign the corresponding body or wing, greatly reducing the maintenance time. Static analysis results show that the maximum deformation of the foldable drone body structure is 0.003278mm, and the mechanical properties of the structure meet the design requirements. Through the motion simulation analysis of the drone, the four-rotor foldable UAV successfully took off and hovered and landed, all meeting the design requirements. A series of optimized designs for the structure do not affect its normal working conditions. Through the foldable and disassembled design of the foldable drone, the floor space of the foldable drone is greatly reduced, making it more convenient to carry.

At present, most researchers mainly focus on the selection of lightweight materials, the specific layout design of the drone and the bionic structure of the drone, involving a series of topological optimizations and 3D printing and other new technologies. This article focuses on the improvement of the structure of the four-rotor drone itself. Compared with these more professional studies, this article only provides a relatively economical and simple improvement. The next step should be to consider replacing the composite material of the four-rotor drone arm, so that its performance will be better under working conditions.

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