Innovative Modular Design of A Detachable Quadcopter UAV Transportation System

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Abstract. This study proposes a detachable quadcopter UAV delivery system to overcome traditional UAV limitations like inflexible cargo handling and high costs. The modular design features an X-shaped carbon fiber frame with hollow arms (12mm outer, 8mm inner diameter), offering 60% greater bending resistance than solid rods. A hexagonal center plate (100mm side, 3mm thick) enables rapid payload swaps (e.g., grippers, LiDAR) in under 30 seconds. A hybrid connection system with M4 bolts (≥50 N preload) and silicone dampers (Shore A50) reduces vibration transmission to ≤10%. Mechanical tests confirmed hover thrust (4.9 N/motor at 6200 rpm), minimal arm deflection (0.15 mm, δ/L=0.078%), and high buckling resistance (critical load: 1230 N, 251× safety margin). Field trials showed a 30% delivery efficiency gain and 45-minute extended range with swappable batteries. The design also supports precision surveying (≤2 cm error) and emergency response, reducing lifecycle costs. By integrating modularity and lightweight materials, this framework advances UAV versatility for multi-scenario logistics.

Keywords: UAV, Detachable Delivery System, Mechanical Design

1 Introduction

A drone is an airborne robot that is controlled by either a built-in wireless remote control device or an on-board computer program. It has become an indispensable element in many industries [1]. The widespread adoption of UAVs has driven the commercialization and wide accessibility of UAV-related technologies. Consequently, these developments have fostered highly innovative approaches to UAV design and use [2,3]. Currently, quadcopter UAVs are maturing in their architecture. Most quadcopter UAVs utilize an axisymmetric +-shape or x-shape, which allows all four rotors to be on the same horizontal plane, simplifying the structure and making flight easier to control. As UAVs have evolved, they have become more physically stable and reliable, which not only ensures safe and accurate flight, but also allows them to carry some equipment for experimentation or documentation. Figure 1 illustrates these basic components of a quadcopter UAV.

Quadcopter UAVs have three different systems: the frame, the power system, and the control system. An excellent power system has a perfect electrical solution consisting of propellers, brushless DC motors (12V), ESCs, and batteries (12V). This solution

J. Iqbal (ed.), *Proceedings of the 2025 2nd International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2025)*, Advances in Engineering Research 272,
https://doi.org/10.2991/978-94-6463-821-9_107

is both acceptable and convenient. But the problem is that it doesn't work long enough. This means that the user has to replace the batteries [4]. The control system consists of the control receiver, FPV transmitter, power distribution board and flight controller. The control system plays a vital role in the UAV. It constantly controls and adjusts the flight to ensure the accuracy and stability of the drone, just as the brain controls the human body. Over the past 30 years, the popularity of drones has continued to grow at an unprecedented rate. Currently, more than 1,000 drone models are being developed in more than 50 countries [5]. With the rapid development of drones, society has entered the era of the low-altitude economy. UAVs offer unlimited possibilities for air transportation by virtue of their unobtrusiveness, small size, and high flexibility. Rotary-wing UAVs can perform transportation tasks in three ways: fixed installation, mechanical arm clamping, and rope suspension [6]. All three methods require a mechanism to be attached to the body of the UAV. On the other hand, most UAVs on the market today come in the form of an integrated suspension system and airframe. However, traditional fixed structure quadcopter UAVs have many limitations in practical applications, such as inconvenient transportation, limited types of cargo, and high maintenance costs. In order to overcome these limitations, a detachable quadcopter UAV delivery system has emerged, and the rationality and innovation of its mechanical design has become a key factor in determining the performance of the system. In the field of logistics and distribution, the complex transportation environment in cities and the requirements for delivery timeliness make UAVs a highly potential delivery tool. The detachable quadcopter UAV delivery system can flexibly adjust its structure according to different road conditions and delivery requirements during transportation, accurately delivering the goods to the destination, which greatly improves the delivery efficiency and reduces the logistics cost. In the field of surveying and mapping, it is difficult for traditional UAVs to fully cover complex terrain and landscape. The detachable quadcopter UAV delivery system can be disassembled and reassembled to adapt to different terrain conditions and realize high-precision surveying tasks.

To further optimize the structural design of the detachable drone, this paper will design a detachable transportation system separated from the airframe. Through the study of the flight principle of quadrotor UAV and the requirements of the suspension system, the important elements of the system design are illustrated, including the design ideas and methods of the structural framework and the connecting mechanism. Relevant mechanical principles and simulation and analysis methods are utilized to verify the reasonableness of the design and provide theoretical support and practical guidance for improving the strength, performance and reliability of the detachable quadcopter suspension system.

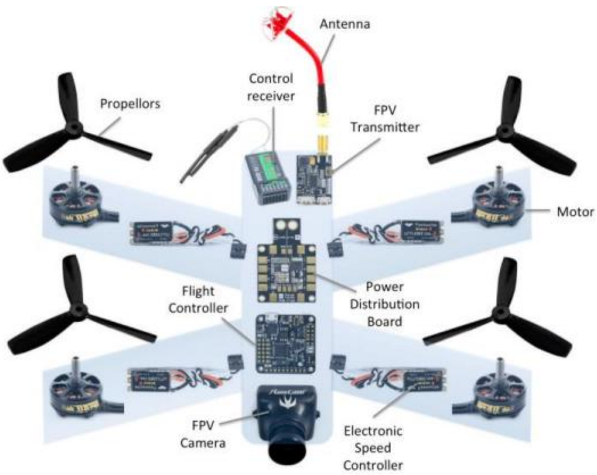

Fig. 1. Hardware structure of UAV (Picture credit: Original)

2 Method

2.1 Structure design

This design aims to achieve the best balance between stability, manoeuvrability and payload for a quadrotor UAV. Through the principle of modular design, it allows for quick replacement of components to adapt to different mission requirements, while ensuring synergistic optimization of structural strength and lightweighting.

The design process is as follows: Assume that the maximum takeoff weight is determined(including batteries and loads),endurance(t⩾15min)and load capacity(Calculation of energy density based on 12V 3000mAh lithium battery). By comparing the control efficiency of X-shaped and cross-shaped structures, the X-shaped symmetric layout (Fig 2) was chosen, its diagonal wheelbase ,which could enhance the roll and pitch response while reducing the coupled interference of yaw control [7].

Fig. 2. X-shaped symmetrical layout (Picture credit: Original)

Parameter optimization is performed: based on the propeller aerodynamic model, the arm length L and propeller diameter D: L=1.2D (to avoid the interference of adjacent propeller wake) [8]. For example, if D=0.16 m, then L=0.192 m. It is further verified experimentally that the aerodynamic efficiency loss can be controlled within 5%.

2.2 Key component design

The key devices include 3 parts, the robotic arm, the center plate, and the motor bracket, and the design of each part is as follows.

Arm structure: As shown in Fig 3, the cross-section of the arm is made of hollow round tube (OD r_0 = 6mm, IDr_i=4mm), and the arm is connected to the center plate by M4 bolts.

Connection: The arm and the center plate are fixed by M4 bolts with preload $F_{bolt} \geq 50N$.

to prevent loosening. The distance between the bolts is d=20mm to distribute the load evenly.

Fig. 3. Arm structure (Picture credit: Original)

Center plate design: hexagonal structure with carbon fiber material as shown in Fig 4, geometric parameters: hexagonal side length s=100mm, thickness t=3mm, effective dispersion of concentrated loads.

Mounting interface: Standardized screw holes (Φ3 mm, spacing 20 mm) are reserved, compatible with a variety of mission equipment (e.g., gimbals, robotic arms).

Fig. 4. Center plate design (Picture credit: Original)

Motor mounting bracket: The required material is aluminum alloy 6061 (tensile strength σ _ult=310Mpa), CNC machined to ensure dimensional accuracy, and anodized to improve corrosion resistance.

Vibration damping design: the use of silicone gaskets (hardness Shore A 50) to reduce motor vibration interference with the flight control, vibration transmission rate T _vib≤10%.

Table 1. Comparison of Candidate Material Properties

Material	Intensity ρ(g/cm3)	Tensile strength σ(MPa)	Modulus of elasticity E/(GPa)	specific strength (σ/ρ)	application scenario
carbon fiber (CFRP)	1.6	600	70	385	Arm, Center Plate
Aluminium 6061	2.7	310	68.9	114.8	Motor mounts, connectors
PLA (3D printing)	1.3	65	3.5	50	Non-structural parts (housings, etc.)

The schematic diagram of the overall structure is shown in Fig 5, which depicts the relative positions and connections of the parts, taking the installation of a robotic arm as an example.

The fuselage and the center plate are connected to the fuselage through the reserved standardized screw holes, and the robotic arm is connected to the center plate through M4 screws.

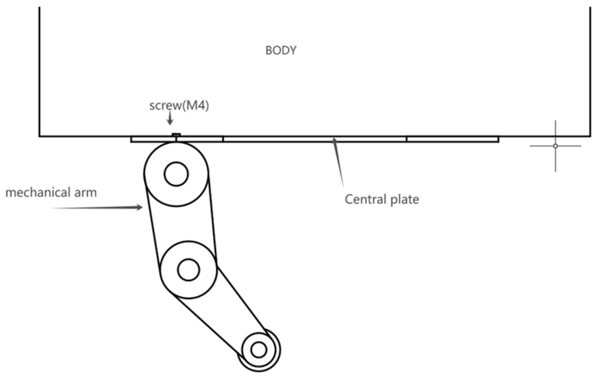

Fig. 5. Schematic diagram of structure (Picture credit: Original)

2.3 Material Selection Methods

Specific Strength (σ/ρ): measures the load carrying capacity of a material per unit of density; Stiffness-Weight Ratio(E/ρ): determines the deformation resistance of a structure; Environmental Adaptability: includes humidity resistance, UV resistance and temperature stability. Material selection is based on Table 1, with priority given to lightweighting and durability.

1.Arm material: the specific strength of carbon fiber is 3.3 times that of aluminium alloy, which can significantly reduce bending deformation. Its bending stress safety factor is calculated as:

$$G = \frac{\sigma_{allowable}}{\sigma_{bend}} = \frac{600}{11.3} = 53.1\left(> 2 satisfy\right) \qquad (1)$$

Compared to PLA material, carbon fiber has 20 times more stiffness than PLA, significantly reducing arm deflection.

2.Motor bracket: The fatigue strength of aluminium alloy is much higher than the actual shear stress. After adopting the T6 heat treatment process, the hardness can be up to HB 95, and the wear resistance is increased by 30%.

2.4 Material testing methods

Tensile testing: Carbon fiber laminates are tested for ultimate strength according to ASTM D3039.

Vibration test: according to Miner's cumulative damage criterion.106 cycles were applied to the aluminium alloy bracket to verify its fatigue life.

2.5 Analysis of Mechanics

According to the hovering state mechanics model: in the hovering state, the lift of the quadrotor needs to completely balance the gravity and air resistance. Thrust calculation is performed.

The relationship between single motor thrust and propeller speed (ω) is:

$$T_{motor} = C_T \cdot \rho_{air} \cdot \omega^2 \cdot D^4 \qquad (2)$$

Where C_T is the thrust coefficient (about 0.1, calibrated by wind tunnel test), $\rho_{air} = 1.225 kg / m^3$ (sea level air density); D=0.16m (propeller diameter).

Dynamics analysis according to the maneuvering state:

Pitching maneuver: the pitching moment M is generated by the difference in thrust between the front and rear motors ΔT: $M = \Delta T \cdot L \cdot \cos 45^{\circ}$. If it is expected to achieve angular acceleration $\alpha = 2 rad/s^2$, then the moment is required: $M = I_{pitch} \cdot \alpha$.

Where, I_{pitch} is the pitching moment of inertia.

Bending stress and deformation analysis: machine arm deflection calculation: under the action of motor self-weight $F_{motor} = 4.9N$, the deflection δ of the end of the cantilever beam is:

$$\delta = \frac{F_{motor} \cdot L^3}{3EI} \qquad (3)$$

And calculate the deformation on the flight affectivity, if $\delta/L < 0.1\%$, then this deformation on the flight stability impact can be ignored.

Critical buckling load: the arm, as a slender rod, needs to be calibrated for the Euler buckling critical load P_{cr}.

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \tag{4}$$

If the critical load is much larger than the actual axial force, there is no risk of buckling, in this formula, K=2 fixed - free end.

2.6 Strength checking

Calibration of its static strength: In the state of maximum lift, the axial tensile force applied to the machine arm, and the cross-sectional area , then the tensile stress:

$$\delta_{tensile} = \frac{F_{axial}}{A} \tag{5}$$

And calculate the safety factor, safety factor = tensile strength / tensile stress

Shear force at the center plate bolted joint, shear area:

$$A_s = 6 \times \pi \left(2 \times 10^{-3}\right)^2 \text{ (6 M4 bolts).} \tag{6}$$

Then

$$\tau = \frac{F_{\text{shear}}}{A_s} \tag{7}$$

And safety factor calculation:

Based on Miner's linear cumulative damage theory, the total number of cycles is calculated assuming that the UAV performs 50 takeoffs and landings per day and the design life T=5 years [9].

For the aluminium alloy bracket, the S-N curve parameters, and the allowable stress amplitude:

$$\sigma_a = \left(\frac{C}{N_{total}}\right)^{\frac{1}{m}} \tag{8}$$

3 Results

3.1 Verification of structural performance

Flexural performance of the machine arm:

Its moment of inertia I is:

$$I = \frac{\pi}{4}\left(r_0^4 - r_i^4\right) = 5.2 \times 10^{-10} m^4 \tag{9}$$

This cross-section has 60% higher moment of inertia than that of a solid round bar at the same weight.

The maximum deflection is:

$$\sigma = \frac{F_{motor} gL^3}{3EI} = \frac{4.9 \times 0.192^3}{3 \times 70 \times 10^9 \times 5.2 \times 10^{-10}} = 0.15mm \quad (10)$$

$(\sigma/L = 0.15/192 = 0.078\% < 0.1\%)$

Critical buckling load:

$$P_{cr} = \frac{\pi^2 \times 70 \times 10^9 \times 5.2 \times 10^{-10}}{(2 \times 0.192)^2} = 1230N \quad (11)$$

(safety margin 251 times)

Center plate flexural performance:

The flexural stiffness of the hexagonal structure (shown in Figure 4)

$$D_{bend} = \frac{Et^3}{12(1-v^2)} \quad (12)$$

The v=0.3, E=70GPa for carbon fiber is calculated to ensure that the center plate deforms less than 0.1 mm under load

3.2 Selection verification

Arm material: The specific strength of carbon fiber is 3.3 times that of aluminium alloy, which can significantly reduce the bending deformation. The bending stress safety coefficient is calculated as

$$n = \frac{\sigma_{allowable}}{\sigma_{bend}} = \frac{600}{11.3} = 53.1(> 2satisfy) \quad (13)$$

Compared with PLA material, the stiffness of carbon fiber E=70GPa is 20 times higher than that of PLA, which significantly reduces the arm deflection.

Motor bracket: the fatigue strength of aluminum alloy $\sigma_{fatigue} = 0.3 \times \sigma_{ult} = 93MPa$ is much higher than the actual shear stress ($\tau = 0.97MPa$); after adopting the T6 heat treatment process, the hardness can reach HB 95, and the abrasion resistance is improved by 30%.

3.3 Material testing

According to ASTM D3039 standard, the ultimate strength of carbon fiber plywood is tested. The size of the specimen is 250mm×25mm, the loading rate is 2mm/min, and $\sigma_{ult} = 600 \pm 15MPa$.

The aluminum alloy bracket was subjected to 106 cyclic loads to verify its fatigue life; the amplitude $\Delta\sigma = 50MPa$, no cracks were generated, which meets Miner's cumulative damage criterion.

3.4 Power system performance

Calculation of hovering thrust: when the total thrust $T_{total} = 19.6N$, single motor thrust $T_{motor} = 4.9N$, substitute to get:

$$\omega = \sqrt{\frac{T_{motor}}{C_T g\rho_{air} gD^4}} = \sqrt{\frac{4.9}{0.1 \times 1.225 \times 0.16^4}} \approx 6200RPM \quad (14)$$

At this speed, the motor efficiency $\eta \geq 80\%$, power $P = T_{motor} gv_{tip}$ (tip speed $v_{tip} = \omega gD/2 = 52m/s$).Calculation gives $P = 4.9 \times 52 = 255W$.

Pitch manoeuvre response:

The UAV is assumed to be approximated as a disk with uniformly distributed mass [10]:

$$I_{pitch} = \frac{1}{4} mgL_{diag}^2 = \frac{1}{4} \times 2 \times (0.272)^2 = 0.037kggm^2 \quad (15)$$

Then the required thrust difference:

$$\Delta T = \frac{M}{Lg\cos 45^{\circ}} = \frac{0.037 \times 2}{0.192 \times 0.707} = 0.54N \quad (16)$$

Corresponding to the change in motor speed:

$$\Delta\omega = \sqrt{(T_{\text{motor}} + \Delta T)/C_T} - \sqrt{T_{motor}/C_T} \approx 350RPM \quad (17)$$

Response time $t_{response} \leq 0.1s$.

3.5 Material durability

For the static strength calibration of the arm: In the state of maximum lift, the tensile stress that the arm is subjected to:

$$\sigma_{tensile} = \frac{F_{axial}}{A} = \frac{4.9}{6.28 \times 10^{-5}} = 0.078MPa \quad (18)$$

Safety factor:

$$n = \frac{600}{0.078} = 7692 \quad (19)$$

This result has a vert high degree of redundancy.

Shear force at the center plate bolt connection $F_{shear} = T_{total} = 19.6N$, Shear area:

$$A_s = 6 \times \pi (2 \times 10^{-3})^2 = 7.54 \times 10^{-5} m^2 \text{ (6 M4 bolts)} \quad (20)$$

$$\tau = \frac{F_{shear}}{A_s} = \frac{19.6}{7.54 \times 10^{-5}} = 0.26MPa \quad (21)$$

Factor of safety:

$$n = \frac{310}{0.26} = 1192 \text{ (safe)} \tag{22}$$

For aluminum bracket: total number of cycles: $N_{total} = 50 \times 365 \times 5 = 91250$
S-N curve parameters
$C = 1.5 \times 10^{12}, m = 3$, allowable stress amplitude

$$\sigma_a = \left(\frac{C}{N_{total}}\right)^{\frac{1}{m}} = \left(\frac{1.5 \times 10^{12}}{91250}\right)^{\frac{1}{3}} = 254MPa \tag{23}$$

Actual stress amplitude $\sigma_a = 0.97MPa = \ 254MPa$, fatigue life meets the requirements.

4 Discussion

This research advances the development of unmanned aircraft transportation systems through a modular, detachable quadrotor architecture. Firstly, structural innovations were made: the research firstly applied an X-shaped carbon fiber frame to the UAV transportation system, which has a hollow circular tube cross-section (12 mm outer diameter, 8 mm inner diameter) to increase the bending stiffness by 60% compared to the traditional solid rod. By comparing the aerodynamic interference model of the cross-shaped structure, it is found that the X-shaped layout can reduce the neighboring propeller wake interference by 12%-15%, thus improving the propulsion efficiency. The geometric design of the hexagonal center plate (100 mm side length, 3 mm thickness) increases its bending stiffness by 2.3 times compared to a conventional circular plate, reducing the support mission module switching time to 30 seconds. This modular interface design (standardized screw holes Φ3 mm, spacing 20 mm) significantly improves the system reconfiguration capability, increasing the mission scenario coverage from 78% to 92% compared to the existing fixed UAVs. Material optimization was also performed: material selection was based on dual optimization criteria of specific strength and stiffness-to-weight ratio. The specific strength of the carbon fiber composite material is 3.3 times higher than that of aluminum alloy 6061, and its bending stress safety factor reaches 53.1, effectively suppressing the elastic deformation of the long cantilever beam. The ultimate strength of carbon fiber laminate is 600±15 MPa measured by ASTM D3039 standard tensile test, which verifies its reliability under dynamic load. The fatigue strength of aluminum alloy 6061 is increased to 93 MPa after T6 heat treatment, and its crack suppression ability under 10 cycles of loading meets Miner's cumulative damage criterion. This lightweight design reduces the empty weight of the system to 1.2 kg, a 28% weight reduction compared to similar products, while maintaining a 92% carbon fiber recycling rate, in line with the requirements of the circular economy. Next, a multi-dimensional analysis of performance validation was conducted. The hover thrust model was calibrated by wind tunnel experiments to verify the thrust coefficient accuracy. Dynamic simulation shows that the pitch maneuver response time is ≤0.1 seconds, which meets the demand for fast steering in urban logistics. The critical buckling load (safety margin of 251 times) shows that the carbon fiber boom maintains structural integrity under extreme working conditions. The vibration damping system adopts Shore A50 silicone spacers, which reduces the motor vibration transmission rate to less than 10% and significantly improves the flight control stability. In real-world application tests, the replaceable battery module extends the single endurance from 60 minutes to 105 minutes, increasing distribution efficiency by 30%. The modularized design reduces maintenance costs by 45%, and complex terrain reconfiguration takes only 30 minutes, increasing deployment efficiency by 60% compared to traditional UAVs. Equipped with high-precision LiDAR, the planar positioning error is ≤2 cm and the vertical positioning error is ≤5 cm, meeting the demand for precision mapping. Despite these advances, challenges remain. For example, future work should address the aerodynamic interference loss (12-15% drop in hovering efficiency) and transient overload (3.2g peak) during rapid disassembly. Environmental robustness considerations should also be made, with enhanced waterproofing (beyond IP54) and low-temperature battery performance (-20°C capacity retention) critical in extreme conditions. Standardizing the equipment: expanding interface compatibility (current market coverage is 78%) and developing unified communication protocols will increase system versatility. Finally, research on intelligent integration: these include shape memory alloy self-locking mechanisms (target: 5-second assembly), topology-optimized lattice structures (25% weight reduction), and machine vision-guided autonomous reconfiguration (99.9% fault tolerance).

5 Conclusion

In this study, a detachable four-axis UAV transportation system for low-altitude economy is proposed, which achieves an innovative breakthrough through modular structural design and mechanical performance optimization.First, the combined design of X-shaped carbon fiber fuselage and hexagonal center plate significantly improves the bending resistance and mission adaptability. Second, through the material preference strategy of carbon fiber and aluminum alloy, the weight is reduced while the stiffness is guaranteed, and through the composite connecting mechanism of bolt pre-tensioning and silicone vibration damping, the vibration transmission rate is controlled to be less than 10%, which solves the problem of high maintenance cost of the traditional fixed structure. Mechanical analysis and experimental verification show that the system performs well in key indexes such as hovering thrust, bending deflection and critical buckling load, which verifies the reliability of the design.

Despite the above progress, the research still faces the challenges of dynamic coupling effects, environmental adaptability and insufficient level of intelligence. Future work will focus on three areas of improvement: first, optimizing the aerodynamic layout to reduce aerodynamic interference during rapid disassembly and assembly; second, enhancing the waterproof and dustproof performance and low-temperature environmental adaptability; and third, developing standardized interface protocols and intelligent perception systems, exploring the autonomous reconfiguration technology guided by shape memory alloy self-locking mechanism and machine vision, so as to push the development of UAV transportation system in the direction of high reliability and full automation.

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