# Structure Optimization and Implementation of a Lightweight Sandwiched Quadcopter

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**Abstract.** A three-layered sandwiched structure of quadcopter was proposed to lower the weight and rotary inertia, resulting in an increase in endurance time and payload in this present work. The framework was optimized with two carbon fiber layers on the surface and balsa in the middle. The weight was reduced to 148 g *via* the options of aluminum alloy, balsa and carbon fiber reinforced polymer (CFRP). Stress analysis shows that the stress and strain of this structure were within the safety range even when all four rotors are at maximum thrust with maximum payload which guarantees enough stiffness of the structure. A prototype controlled by an open source controller was used to run the tests. The flight tests indicated that endurance time was 29 min and the payload was 700 g, respectively.

**Keywords:** Quadcopter · Structure optimization · Sandwiched structure

## 1 Introduction

Research and development of unmanned aerial vehicle (UAV) and micro aerial vehicle (MAV) are getting high encouragement nowadays due to its broad potential applications in civilian and military areas [1]. Civilian applications of UAVs were initially considered for D3 (dirty, dull and dangerous) operations. For instance, the use of UAVs in radioactive contamination was documented after the Fukushima reactor damage [2, 3]. The use of UAVs for dull operations includes their use in frontier surveillance [4] and digital elevation model (DEM) creation [5]. UAV-based applications in dangerous situations include monitoring hurricanes and wildfire situations [6, 7]. Apart from the applications mentioned above, a number of remote sensing operations have tested the use of UAVs in the monitoring of wildlife, ice cover, weather phenomena, climate change, etc. [8]. The role of UAVs in daily life is predicted to grow in the next decade [9], which suggests the increased demand for the specialists in the fields of miniature UAV design and implementation. Scientific studies have been mainly concerned with the precursors of remote sensing flights using UAVs. They have shown the feasibility of UAVs and the advantages of using such platforms.

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Quadcopter (often also referred to as quadrotor) aircraft is one of the UAV that are major focuses of active researches in recent years. Design and implementation of a typical quadrotor system imposes some challenges, among of which are limited payload and flight time, fast and unstable dynamics, and tight integration of control electronics and sensors. However, the drift of inertial sensors leads to errors during time-discrete integration, making a steadily accurate estimation of the absolute pose nearly impossible. Recent development in quadcopters has made some achievements in control algorithm. In our previous work, control strategy based on the optimal control and subspace stabilization approach [10] and a flight controller with disturbance observer (DOB) [11] were developed to solve the two-point boundary value problem of a highly under-actuated quadrotor.

Although the control algorithms and sensors on quadcopters have made great progress, researches on structural design are rarely found in the existing literature. Structure of the quadcopter can be an essential factor in control model. Numerous aspects concerning the performance of the machine including endurance, maximum speed and acceleration are determined by the structural parameters of the frame.

In fact, the primary consideration is weight and rotary inertia. The quadcopter designs currently available in the market are almost identical. Most of them are made of plastic, aluminum alloy, and sometimes carbon fiber to lower the weight. But almost none of them managed to strike a balance between weight and strength.

The structure layout of a quadcopter is optimized with three layers based on the kinematics and dynamic models in this present work. To lower the weight and the rotary inertia of the framework, different materials are chosen, including carbon fiber reinforce polymer (CFRP) and aluminum alloy and a novel sandwiched structured material. Later the stress and strain of the optimized structure are analyzed, respectively. A prototype is built based on our design, which is controlled with a stable open source control board. The real time tests illustrate the flight time and the payload of the optimized structure.

## 2 Dynamic Model of the Quadcopters

### Kinematics Model

The quadcopter structure is presented in Fig.1 including the corresponding angular velocities, torques and forces created by the four rotors.

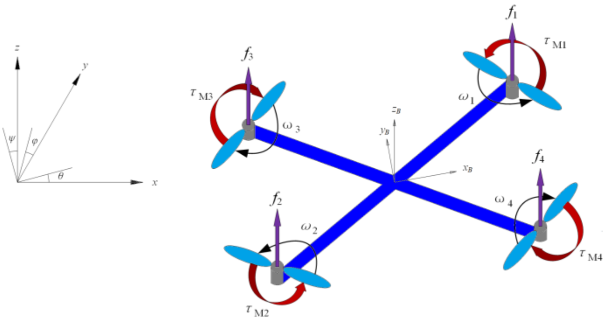


**Fig. 1.** The inertial and body frames of a quadcopter

The linear position of the quadcopter is defined in the inertial frame *x, y, z*-axis with a vector $\xi$ consisting three linear coordinates. The attitude (angular position) is defined in the inertial frame with a vector $\eta$ consisting three angles. Angle $\theta$, $\varphi$, $\psi$ determines the rotation of the quad around the *x, y, z*-axis respectively. Vector *p* contains linear position vector $\xi$ and angular position vector $\eta$.

$$\xi=\begin{pmatrix} x \\ y \\ z \end{pmatrix},\ \eta=\begin{pmatrix} \theta \\ \varphi \\ \psi \end{pmatrix},\ p=\begin{pmatrix} \xi \\ \eta \end{pmatrix} \tag{1}$$

The origin of the quadcopter is in the mass center of the frame. The linear velocity and the angular velocity are defined by vector *V* and $\omega$ respectively.

$$V=\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix}=\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix},\ \omega=\begin{pmatrix} p \\ q \\ r \end{pmatrix} \tag{2}$$

The rotation matrix between the body frame and the inertial frame is

$$R=\begin{pmatrix} \cos\psi\cos\varphi & \cos\psi\sin\varphi\sin\theta-\sin\psi\cos\theta & \cos\psi\sin\varphi\cos\theta+\sin\psi\sin\theta \\ \sin\psi\sin\varphi & \sin\psi\sin\varphi\sin\theta+\cos\psi\cos\theta & \sin\psi\sin\varphi\cos\theta-\cos\psi\sin\theta \\ -\sin\theta & \cos\varphi\sin\theta & \cos\varphi\cos\theta \end{pmatrix} \tag{3}$$

The angular velocity of rotor *i* creates force $f_i$ in the direction of the rotor axis. The angular velocity and acceleration of the rotor also create torque $\tau_M$ around the rotor axis

$$f_i=k\omega_i^2,\ \tau_{M_i}=b\omega_i^2+I_M\dot{\omega}_i \tag{4}$$

In which *k* is the lift constant, *b* is the drag constant, and $I_M$ is the inertia moment of the rotor. The effect of $\dot{\omega}_i$ is usually small and can be neglected.

The combined force of the four rotors create thrust ***T*** in the direction of the body *z*-axis. Torque $\tau_B$ consists of torque $\tau_\theta$, $\tau_\varphi$ and $\tau_\psi$ in the corresponding directions in the body frame.

$$T=\sum_{i=1}^{4} f_i=k\sum_{i=1}^{4}\omega_i^2,\ T=\begin{pmatrix} 0 \\ 0 \\ T \end{pmatrix} \tag{5}$$

$$\tau_B=\begin{pmatrix} \tau_\theta \\ \tau_\varphi \\ \tau_\psi \end{pmatrix}=\begin{pmatrix} lk(\omega_1^2-\omega_2^2+\omega_3^2-\omega_4^2) \\ lk(-\omega_1^2+\omega_2^2+\omega_3^2-\omega_4^2) \\ \sum_{i=1}^{4}\tau_{M_i} \end{pmatrix} \tag{6}$$

In the equations above, $l$ is the distance between the rotor and the center of the mass. Thus the attitude of the quadcopter can be controlled by controlling the angular velocity of the four rotors respectively.

### Control Model

Controlling the quadcopter based on the physical model discussed above is one of the most important jobs in designing the system. The design of the control model must consider its responding time, reusability and interoperability.

In this present work, the quad rotor employs a Proportional-Integral-Derivative control system. The PID controller is a closed-loop feedback system which sends a control signal and receives a feedback from the inertial sensors. The controller then calculates the difference between the set position and attitude and adjusts the output accordingly.

To test the performance of our designed framework, we choose Pixhawk, an open source controller. The control model of Pixhawk is shown in Fig.2.

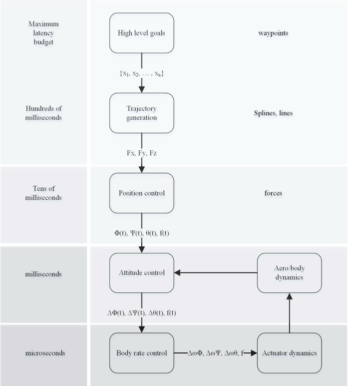


**Fig. 2.** Control architecture of Pixhawk. Different levels have different update and latency requirements [16].

## 3 Proposed Optimized Framework

The thrust $\boldsymbol{T}$ and the torque $\boldsymbol{\tau_B}$ can be controlled by rotors. The above-mentioned model showed that the acceleration matrix $\ddot{\xi}$ is determined by the mass of the frame $m$, and the angular acceleration $\ddot{\eta}$ is determined by the rotary inertia $\boldsymbol{I}$. To acquire greater agility, the mass and the rotary inertia of the frame have to be lowered.

A critical problem of quadcopter is its endurance. Usually, a quadcopter can fly about 20 min, and significantly less if they are carrying high payload. Thus, the lighter weight is, the longer battery life and the more payloads.

A typical quadrotor utilizes a four-spar method, with each spar anchored to the central hub. It consists of four rotors and electric speed controllers (ESCs), a control board, a battery, a radio transmitter and numerous sensors including GPS, compass, gyroscope, accelerometer, etc. The frame has to provide enough room for the equipment. The weight of the equipment attached cannot be lightened, so the only way to lower the rotary inertia is to move them as close to the center of mass as possible.

At present, mainstream quadrotors available in the market, such as DJI F450 and Hummingbird, have a single-layered popular frame. In the frame of DJI F450, all the equipment is jammed into a limited space. The battery is placed beneath the frame, which causes the frame not to stand on the ground without a high landing gear, resulting in the increase of the weight and rotary inertia. An overview of the DJI F450 is shown in Fig.3 (a).

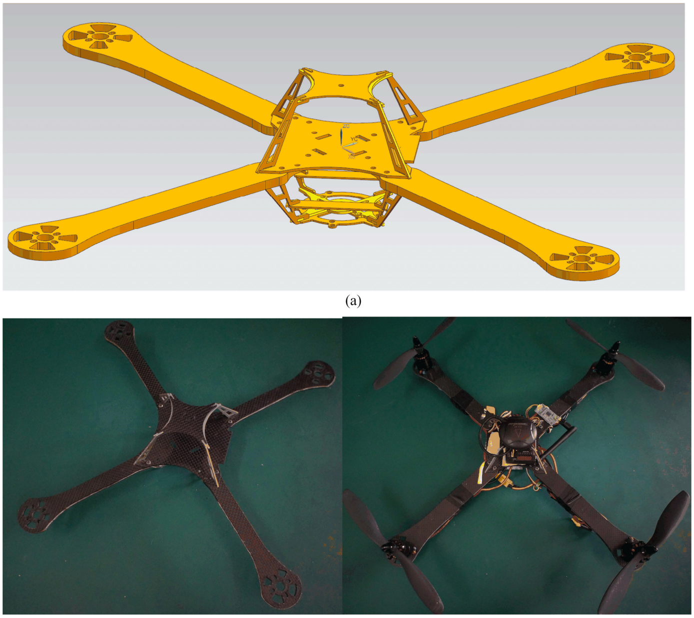
Hummingbird from Ascending Technology, which is widely employed type for indoor flights of quadcopter, is made of carbon fiber and magnesium alloy. Although Hummingbird weighs only 500g, its maximum payload is only 200g, which means it can carry nothing other than the battery. In addition, it does not have a GPS module. That is to say, it is not able to locate itself outdoors. These limitations greatly confine its application. The overview of Hummingbird is shown in Fig.3 (b).

(a) (b)

**Fig. 3.** Overview of DJI F450 and Hummingbird. (a) Actual physical picture of DJI F450 quadrotor, and (b) Actual physical picture of Hummingbird framework

Unlike them, our optimized design has three-layered sandwiched structure. In this sandwiched structure, the control board and most of the sensors can be placed on the middle layer. The top layer is designed for GPS, and the bottom layer is for battery. The battery can be locked with two carbon fiber panels to reduce oscillation. Compared to other conventional single-layered frames, the three-layered sandwiched structure makes it possible to spread the sensors to avoid electromagnetic interruption. The optimized design is also flattened so that it can access some narrower places. The overview of the optimized frame is shown in Fig. 4.

When designing an autonomous quad rotor, material options must be considered according to the durability, machinability, and price. And in this case, weight is the ultimate concern. The materials in consideration for our design include aluminum, plastic, and carbon fiber. The thrust of the rotors and the vibration requires high strength. To make sure the control model keeps working, the deformation has to be small enough to be neglected. Based on the two factors, carbon fiber and aluminum alloy are chosen for their high strength, low density and acceptable price.



(a)

(b)

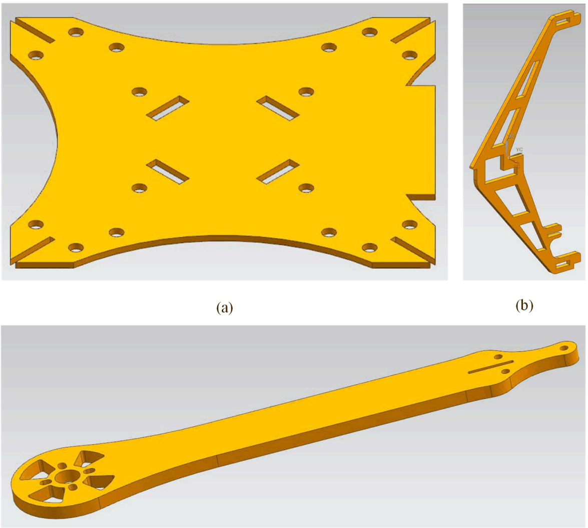
(c)

**Fig. 4.** Overview of our three-layered sandwiched structure. (a) The design model of framework; (b) Actual picture of our optimized framework; and (c) Actual picture of our quadrotor

The base is the center of the frame, which is made of carbon fiber reinforced polymer (CFRP). The control board is placed in the center of the base, with all the sensors around it and the GPS on the top. The base is large enough to avoid electromagnetic interference among the chips and onboard devices. This is essential because electric current can affect the accuracy of the sensors. To make the installation of the frame easier, several holes and slots are made on the base to allow wires pass through. Base of optimized design of the quadcopter is shown in Fig. 5 (a).

The supporting frame supports the panels on the top and bottom. To increase the strength of the frame with a relatively lower weight, the supporting frame is made of aluminum alloy. Several holes are designed to make the frame lighter. Supporting frame of optimized design of the quadcopter is illustrated in Fig. 5 (b).

The motor boom of the quadcopter is one of the most important parts of the frame. It has to stand great moment. Most of the quadcopters are using engineering plastics or carbon fiber to build the wings of the frame. The problem is that they are either too heavy or too crispy. In our design, the motor boom is made of composite sandwiched panel. The panel consists of two layers of carbon fiber on the surface and a wood layer in the center to increase the stiffness. The motor boom design is shown in Fig. 5 (c).


(a) (b)

(c)

**Fig. 5.** Base, supporting frame and motor boom of the optimized structure. (a) Base; (b) Supporting frame; and (c) Motor boom

# 4 Analysis and Test

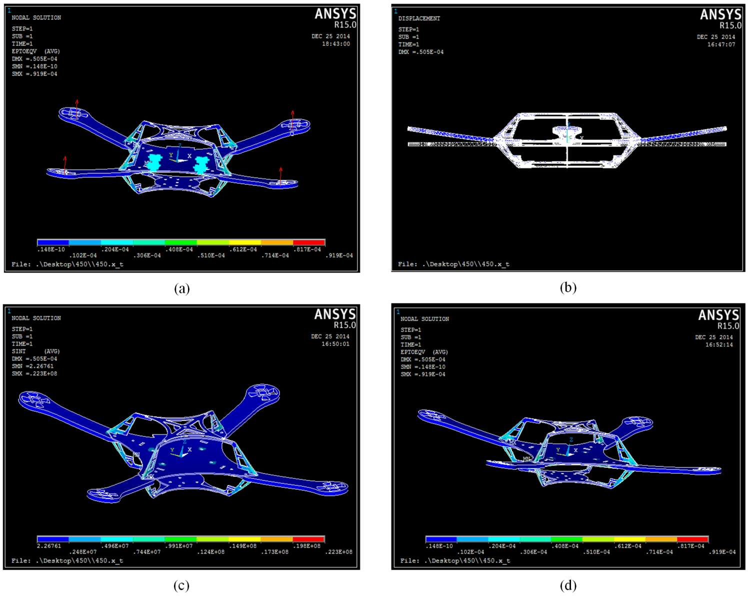
The mass of the frame weighs 148g. The comparison between our design and some mainstream frame designs is shown in Table 1. The weight of our frame was reduced by 45% to 51%, compared with the weight of some mainstream frame designs (with same wheelbase).

**Table 1.** Comparisons between our design and some mainstream frame designs (with same wheelbase)

| Model | DJI F450 | Q450 V3 Glass Fiber | Hobbyking SK450 | Our Design |
|---|---|---|---|---|
| Weight (g) | 282 | 270 | 300 | 148 |

## Stress Analysis

Stress analysis of the optimized design using ANSYS is shown in Fig.6.



(a) (b)

(c) (d)

**Fig. 6.** Stress and strain analysis. (a) Abridged view of the simulation; (b) Deformation distribution; (c) Stress Distribution; and (d) Strain Distribution

With four rotors all at maximum thrust, the maximum deformation is small enough to be neglected. The maximum stress and strain are also within safe range.

The stiffness of the optimized framework is illustrated in Fig.7. The stiffness is approximately 74222N/m under the force of one rotor, and the stiffness is approximately 145608N/m under the forces of four rotors. When controlling a quadcopter, the forces are relatively small, and the stiffness is big enough to ensure the safety of the vehicle.

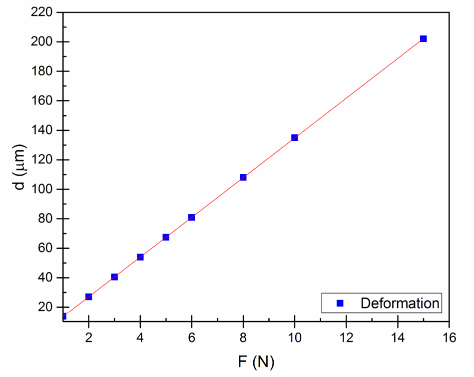


**Fig. 7.** The stiffness of the optimized framework

### Endurance and Payload Test

The main goal of our optimization is to increase the endurance and payload of the quadcopter. The endurance and payload of our design are compared with those of DJI F450 and Hummingbird shown as in Fig. 8.

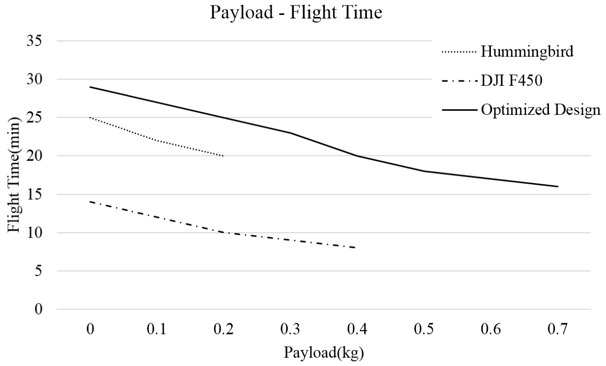


**Fig. 8.** Payload vs. flight time for different designs. (With same battery)

As is shown in Fig.8, the flight time of our optimized model is prolonged to 29 min, which almost doubles 14.5 min of DJI F450 with the same wheelbase. It also flies longer than Hummingbird which is much smaller than our design. In the viewpoint of payload, our optimized design can carry as much as 700 g, while the maximum payload of Hummingbird is only 200 g, and that of DJI F450 is not more than 400 g. At maximum payload, the optimized design can still fly longer than DJI F450 without any payload.

## 5 Conclusion

In summary, the design of a lightweight quadcopter is optimized by employing a sandwiched structure. With applying carbon fiber, aluminum alloy, and composite materials, the weight of our optimized framework was reduced by 45% to 51% compared with typical quadcopter available in the market. The optimized design allows the control board and the sensors to be placed more dispersedly, and the frame can be flattened. The stress analysis shows that the framework is safe even when all four rotors are at maximum thrust. And the deformation is small enough so that the control model can be utilized. Flight tests indicate that the flight time of the optimized model is prolonged to 29 min and the payload is increased to 700 g, respectively.

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