Integrated Frame Topology Optimization Design of Small Quadrotor UAV

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Abstract. In recent years, the development of UAV (Unmanned Aerial Vehicle) is rapid, but the development of structural design is slow, and the rack designed according to the experience of engineers still has great redundancy. With the rapid development of topology optimization and additive manufacturing, topology optimization design of integrated rack based on additive manufacturing is carried out. In the design process, manufacturing constraints are added and a variety of typical conditions to obtain the final optimization structure are considered. The influence of human empirical factors on the fuselage structure design is reduced scientifically and effectively by using this method. And the lightweight, topological and integrated design of the quadrotor frame is realized.

1. Introduction

UAV is a kind of unmanned aerial vehicle which can be controlled by remote control device and flies autonomously. [1-4] UAVs are generally divided into three categories, including fixed wing UAVs, single rotor UAVs and multi-rotor UAVs. Rotor UAVs can achieve a variety of flight posture, such as vertical lifting, hovering, backward, and turning flight action with small radius of curvature. It is suitable for more occasions comparing with fixed wing flying equipment [5]. Multi-rotor UAVs are generally divided into four-rotor, six-rotor and eight-rotor. Recently, the development of multi-rotor is mainly in control. However, the development of structural design and optimization is slow.

At present, UAV structural design methods still mainly rely on the engineering experience of designers. The design results are often higher than the expected structural strength. So the design results have mass redundancy frequently. The popular box frame is composed of plate, beam, tube, etc. [6]. The traditional structural design will produce stress concentration in the connection between the fuselage and the arm. And then fracture, fatigue and other failure phenomena appears [7]. In order to solve problems above, it is necessary to carry out lightweight design for the structure of the quadrotor.

Benefited from the rapid development on computing technology and finite element method, the traditional optimization method of trial and error has been gradually replaced by the optimization method of theoretical calculation and simulation. The structure optimization method of scientific system is formed gradually. Structural optimization is divided into size optimization, shape optimization and topology optimization [8]. Size optimization and shape optimization have been rapidly developed and verified in the past decades due to their consistency with traditional manufacturing methods. However,
because of limited design degree of freedom, the optimization result has a great limitation. Topology optimization is a method which is used to find the optimal material distribution in given design space. Benefit from scientific and efficient design characteristics, topology optimization replaces the traditional mode of relying on human design. Topology optimization becomes one of the mainstream development directions of structural optimization discipline [Eshenauer et al.2001, Guo et al.2010]. However, topology optimization is restricted greatly because of its large design freedom. The design results are difficult to be realized by traditional manufacturing methods. Compared with traditional material reduction manufacturing, AM (additive manufacturing) relies on layer deposition or solidification of materials, which greatly weakens the limitation of geometric complexity. Similarly, complex geometry does not have much impact on manufacturing efficiency and cost [9]. AM solves the problem that traditional topology optimization structure cannot be accurately manufactured from the underlying manufacturing mechanism. With the development of AM, it has been widely used in engineering [10-14]. Topology optimization has also begun to develop rapidly in recent years. It has been more widely used in structural lightweight. Based on additive manufacturing technology, Wang Xiangming proposed an innovative fuselage structure with large-scale integration, topology configuration, gradient compound and integration of structure and function [15].

Based on the above phenomenon, this paper adopts the method of topology optimization to optimize the topology design of the frame of the quadrotor. We propose an integrated, topological frame design process in particular. Firstly, the optimization method is determined. Secondly, the objective function and constraint conditions are determined. Thirdly, the initial design domain and mesh division are determined to prepare for finite element analysis. Fourthly, boundary conditions of multiple working conditions are determined to provide initialization parameters for finite element analysis. Finally, results and analysis are outputted after several iterations of optimization.

2. Topology optimization based on variable density method

2.1. Establishment of mathematical model

The variable density method, also known as SIMP method (solid isotropic material with penalty), is based on the isotropic material. And the relative element density of 0-1 is assigned to each element after discretizing the finite element of the continuum model. The material property is a function of the relative cell density and the original material property. The relative cell density tends to 0 and 1 by penalizing the intermediate density. Material property is expressed by the Eq. (1),

$$E_i = E_{\min} + x^p (E_0 - E_{\min})$$  \hspace{1cm} (1)

Where $E_{\min}$ is the minimum density to avoid singularity introduction of stiffness matrix, penalty factor $p$ is usually set to 3 according to experience, and $E_0$ is the characteristics of raw materials. $i$ is the number of the cell.

Manufacturing constraints is one of the factors that must be consider when we use additive manufacturing to manufacture the final result. Currently, additive manufacturing requires the use of support to ensure the construction of cantilever structures. And then the support is removed after manufacturing completed. It is obvious that the support of the internal closed cavity cannot be removed [16,17]. Therefore, it is necessary to add constraints to guarantee the final structure without internal cavity which is simply connected. VTM (virtual temperature method) [18] is adopted to avoid closed cavities in the structure and to determine whether the structure is simply connected by controlling the maximum virtual temperature of the structure.

Based on the above methods and constraints, we establish an optimized mathematical model, where the objective function is the minimum flexibility in Eq. (2).
\[
\min_{x} : c(x) = U^{T}KU = \sum_{i=1}^{n} E_i(x_i)u_i^{T}k_iu_i,
\]

subject to: \[
\frac{V(x)}{V_0} = f,
\]

\[
KU = F,
\]

\[
\bar{T}_{\text{max}} - \bar{T} \leq 0,
\]

\[
0 \leq x \leq 1.
\]

Where \(c(x)\) is the compliance, \(U\) is the global displacement vector, \(F\) is the global force vector, \(u_i\) is the element displacement vector, \(k_i\) is the element stiffness matrix, \(V(x)\) is the material volume, \(V_0\) is the volume of the design domain, \(f\) is the specified volume fraction, \(K\) is the global stiffness matrix, \(\bar{T}_{\text{max}}\) is the maximum temperature value of the temperature field, and \(\bar{T}\) is constant.

### 2.2. Integrated rack design process based on topology optimization

The whole design process is shown in Fig 1. Compared with traditional design, this process does not rely on manual experience. The final result is only related to the initial design domain, the loading of boundary conditions and the setting of volume fraction.

### 3. Topological optimization design of four-rotor integrated frame

Firstly, we establish the finite element model of topology optimization. Since the structure of quadrotor is axisymmetric, we just only optimize the design of half of the fuselage. Firstly, based on the power system, avionics, pod, etc. we selected, the space and position are determined, and the 3D model is built. The model is divided into 751,990 hexahedral elements. The AL 7050-T7451 material model is used. Young's modulus is 72.4Gpa and Poisson's ratio is 0.33. However, since we are optimizing the relative material density in the optimization process, the Young's modulus is set to 1.

It is very difficult to determine the boundary conditions of the quadrotor because of its complicated flying state in the air. The fuselage coordinate system is defined as following. The positive direction of \(Y\) axis is forward flight direction. The positive direction of \(X\) axis is right flight direction. And the positive direction of \(Z\) axis is climb direction. The common boundary condition is to hover as a single working condition and multiply by the safety factor. Such optimization results have high strength in the \(Z\) direction of the fuselage, but insufficient structural strength in other directions. Based on this situation, we disassemble the flight status of the quadrotor. Common quadrotor flight states are including hovering, climbing, flying forward, emergency stop, pitch, roll, yaw. According to the changes of the quadrotor' attitude, we divide the above states into two categories, such as attitude stability class and attitude change class. The first four flight states belong to category one, and the last three belong to category two. The attitude stability class is divided into seven typical working conditions, as shown in Table 1. The boundary conditions of these working conditions are the symmetrical constraints (3 degrees of freedom) which loaded on the symmetric plane. The other three degrees of freedom are constrained at the connection between the two arms and the motor. The acceleration field of the UAV is coupled with the gravity field during the flight of the payload, which is loaded on the airborne equipment in the form of a coupled acceleration field. When the attitude is stable, there is a definite mathematical relationship between the flight acceleration and the attitude angle \(\phi\). For the attitude instability class, the working conditions are limited by fixing six degrees of freedom of the symmetry plane and loading force and torque at the connection between the arm and the motor. Finally, three working conditions are summarized, as shown in Table 2. The volume fraction is set to be 0.03 for topology optimization.
**Table 1. Attitude stable flight conditions**

| Flight Condition                  | Accelerated Speed(X) | Accelerated Speed(Y) | Accelerated Speed(Z) |
|----------------------------------|----------------------|----------------------|----------------------|
| Hover                            | $0$                  | $0$                  | $-g$                 |
| Climb                            | $0$                  | $0$                  | $-g - \alpha$        |
| Acceleration, deceleration       | $0$                  | $0$                  | $\frac{-g}{\cos \varphi}$ |
| Forward flight                   | $0$                  | $g \sin \varphi$    | $-g \cos \varphi$    |
| Back flight                      | $0$                  | $-g \sin \varphi$   | $-g \cos \varphi$    |
| Left flight                      | $-g \sin \varphi$   | $0$                  | $-g \cos \varphi$    |
| Right flight                     | $g \sin \varphi$    | $0$                  | $-g \cos \varphi$    |

**Table 2. Unstable attitude flight conditions**

| Loading Conditions               | Front Arm             | Behind Arm            |
|----------------------------------|-----------------------|-----------------------|
| Full speed of front motor        | $F_z = 40N, M_z = 2N \cdot m$ | $0$                   |
| Full speed of behind motor       | $0$                   | $F_z = 40N, M_z = -2N \cdot m$ |
| Full speed of both motors        | $F_z = 40N, M_z = 2N \cdot m$ | $F_z = 40N, M_z = -2N \cdot m$ |

4. **Interpretation of result**

Since the relative density of each cell is a number between 0 and 1, we output the cell with the relative density greater than 0.2, and smooth the boundary to output it in STL. The result is shown as Figure 2. The maximum stress and compliance under each working condition are obtained by substituting the material parameters into the calculation. As shown in the Table 3, it can be seen that topology optimization based on multiple operating conditions ensures the stiffness and strength of the frame in each operating condition, and leaves enough margin on the maximum stress to ensure the service life of the frame in various flight states of the quadrotor.
The establishment of the initial design domain

Initialization

FEA, VTM

Sensitivity analysis

MMA

Whether the convergence

No

Yes

Output result

Figure 1. Design cycle

5. Conclusion
In this paper, a method of UAV structure design is proposed, which integrates and lightweight UAV frame design by means of topology optimization. This design method has several advantages:

- In the design, the identification of closed holes is added to ensure that the design results can be achieved through additive manufacturing.
- The design method effectively eliminates the influence of artificial empiricism and avoids the stress concentration phenomenon.
- The stiffness and strength requirements of UAV under various flight conditions are met. The design, simulation and optimization are mutually verified, which confirms the feasibility, reliability and scientific nature of the design method.
Table 3. Compliance and maximum stress under various working conditions

| Condition                  | Compliance  | S(MPa)  |
|----------------------------|-------------|---------|
| Full speed of front motor  | 3.3357407e-3| 0.6029 |
| Full speed of behind motor | 3.3328275e-3| 0.6029 |
| Full speed of both motors  | 3.3169835e-3| 0.5612 |
| Hover                      | 3.8618360   | 9.055  |
| Climb                      | 1.3620711e+1| 18.11  |
| Acceleration, deceleration | 1.8175413e+1| 15.68  |
| Left flight                | 4.0593495   | 7.541  |
| Right flight               | 4.0593495   | 8.150  |
| Forward flight             | 3.5229051   | 17.58  |
| Back flight                | 3.3155718   | 9.498  |

Figure 2. Final optimization result

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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