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Study on Bionic Fabrication and Morphology of the Two Wings of the Tiger Papilio

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Abstract: Based on research into bionic butterflies for environmental detection and ecological management, a scheme was proposed to develop and manufacture a bionic aircraft with two wings inspired by specific butterfly species. A flapping-wing aircraft with a simple structure was designed, and its two-wing design was optimized. The research focused on several key areas: the design and optimization of the wings, the development of the transmission mechanism, hardware design and fabrication, and 3D printing for component manufacturing. This resulted in the bionic replication of the wing shape and structure of the Tiger Papilio butterfly. The final bionic butterfly features a wingspan of 29.5 cm and a total weight of 13.8 g. This project integrates mechatronic principles and provides a valuable reference for advancements in the field of bionic butterflies. Future research could explore the aerodynamic characteristics of wings and innovative design approaches in greater depth.

Keywords: Bionic butterfly flying vehicle; Two wing design; Bionic design

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1. Introduction

Currently, there are specific research projects focused on bionic butterflies [1]. However, the application of bionic butterflies for environmental detection and ecological management remains in its early stages. Most bionic butterfly materials are lightweight, expensive, and technically demanding, limiting their widespread adoption in society. Despite these challenges, bionic butterflies hold significant market potential in areas such as environmental monitoring and biology education. However, their complex flight principles and the low Reynolds number aerodynamic mechanism have resulted in limited attention to their application in environmental supervision.

On the other hand, as traditional fixed-wing aircraft and rotorcraft technologies continue to mature, flapping-wing aircraft have demonstrated better adaptability to complex environments due to their superior maneuverability and control performance. These characteristics offer unique advantages in specific application scenarios [2]. As a result, a growing number of researchers have been drawn to the study of flapping-wing bionic butterfly aircraft, leading to significant advancements in recent years. However, despite their outstanding performance and development potential, flapping-wing aircraft face persistent challenges. Notably, insufficient lift remains a key issue, preventing stable flight over extended periods. To address these challenges and ensure the necessary flapping deformation and lift during flight, the design of the wings and the selection of appropriate materials have become critical areas of research.

2. Research and design of bionic butterfly wings

2.1. Two-wing design

Butterflies possess exceptional flight capabilities, which are closely related to their wing geometry, vein structure, and mass distribution [3]. Butterfly flight typically involves the periodic up-and-down flapping of their two wings, forming an arc shape. Based on studies of fluid-structure coupling in flapping-wing aircraft and butterfly flight dynamics, the Tiger Papilio butterfly was selected as the research subject for designing and analyzing the two-wing profile. Research into the Tiger Papilio's wings revealed the following: during unpowered level flight, the butterfly demonstrated greater stability in straight flight due to its flat front wing and pronounced arc shape. Additionally, its smooth wings exhibited favorable stall characteristics at high angles of attack and optimal lift-to-drag performance at small to medium angles of attack [4].

Accordingly, the front wing of the butterfly-inspired aircraft in this project is designed with a larger arc, similar to most natural butterfly wings, while the rear wing features a smoother edge, akin to an elliptical wing found in fixed-wing designs. The vein skeleton structure of the wings mimics the vein distribution of the Tiger Papilio butterfly. The experimental design will be further optimized and refined in future studies.

The model created in CAD software was imported into SolidWorks for preliminary simulation and optimization, resulting in a finalized three-dimensional model. The edge line of the two wings should ideally be parallel to the longitudinal axis of the torso or fall within an optimal range of -30° to +30°, ensuring that the trunk axis forms an acute angle relative to the wings. The inner edge line of the wing and the spar typically range between 70° and 110°, with the optimal range being between 80° and 100° [6].

2.2. The arrangement and distribution of carbon rods inside the two wings

Referring to the butterfly wing structure, this project uses carbon rods and lightweight film to simulate the butterfly wing veins and wing film. The wing film is made of polyethylene terephthalate (PET) film material, which has good stiffness and flight ability. In order to improve flight stability, this project designs three butterfly wing structures for experimental analysis.

In experiment 1, the carbon rods were distributed throughout the wing membrane, in experiment 2, the carbon rods were distributed throughout the wing membrane and longitudinally in the extended wing vein, and in experiment 3, the carbon rods were distributed longitudinally in the extended wing vein. The main object of structural analysis is the distribution of carbon rods on the wing surface. After preliminary modeling with SolidWorks, finite element mesh division is carried out with Ansys. Two kinds of materials were used for the wings, and material cards were established for experimental testing.

Through the experimental analysis, the three design schemes meet the allowable stress value, in which experiment 1 deformation is the largest, experiment 2 deformation is the smallest, and experiment 3 deformation is close to experiment 1, thus we choose design from experiment 2 as the final structural design.

2.3. Material selection of the two wings

Based on bionics research, it is found that the flexibility of butterfly wings in all directions is different, and it is precisely because of this that butterfly wings have good aerodynamic performance to meet flight needs [7]. The study found that most of the wings of simulated butterflies are made of thin film materials. To meet the lift requirements of the aircraft, the project studied different thin films. The performance of each material was analyzed and compared, and PET film with a thickness of 0.012 mm was selected to manufacture the two wing films, which have a longer flight distance in the experiment and better performance than other materials. Moreover, the PET film is not easy to deform under surface tension and has certain flexibility, meeting the flight requirements [8] .

3. Modeling analysis

As the core structure of the entire device, the main torso primarily consists of the carbon main rod, motor bracket, control board fixing bracket, battery connection bracket, and rear wing bracket. Among these components, the controller connection bracket is specially designed, with two such brackets included, along with one battery bracket. These brackets are made of Polylactic acid (PLA+), a material known for its good strength and moderate toughness, providing stable and reliable support and connections for all components.

The rear wing bracket and the wing drive mounting bracket have adjustable characteristics on the axis of the main trunk, which is of great significance. By adjusting the position of these brackets on the axis, the position of the left-wing assembly, the right-wing assembly, the micro-control system, and the power supply system can be accurately adjusted effectively. In the actual operation process, this adjustment function can be flexibly carried out according to many comprehensive factors such as the aerodynamic force of the left-wing assembly and the right-wing assembly, as well as its gravity. When the wing receives large aerodynamic force and its gravity distribution is unbalanced, the relative position of each component can be changed by adjusting the position of the support, to optimize the stress state of the entire device, ensure its stability and balance in the process of flight or movement in the air, so that the device can better adapt to different working environments and task requirements [9]. This greatly enhances the flexibility and reliability of the entire system.

4. The selection of other components

4.1. Transmission mechanism

The design of the transmission mechanism largely determines the aerodynamic characteristics of the bionic vehicle [10]. Nowadays, the common micro-aerial vehicles are divided into rotorcraft, fixed airfoils, and flapping airfoils. To make the bionic butterfly aircraft of aircraft more like the butterfly flying posture in the natural state, the project is designed and manufactured by the V-type flapping wing aircraft. Through various studies, the micro-flapping wing-type aircraft is based on imitating the biological flight mechanism, using the periodic movement of the two wings to generate the thrust and lift required for flight, and has the advantages of good maneuverability and less energy consumption during flight. The project research proposed CAM rocker design transmission mechanism. In the research, it is found that the CAM rocker mechanism has good bionic characteristics, and the down flutter accounts for 60% of the whole flapping process in the flapping cycle. In a certain range, it can obtain a large lift and thrust force [11]. The working principle of the designed flapping mechanism is that the circular CAM drives the guide rod to move up and down under the action of the motor. Thus, the rocker connected with the guide rod is driven to move up and down [2] .

4.2. Hardware design

The 8-bit AVR microcontroller ATMEGA328P-AU is selected as the main control chip of the small bionic butterfly flying machine. The chip is not only small in size, which can meet the requirements of lightweight design of the aircraft, but also powerful in performance. It can execute powerful instructions in a single clock cycle, and the throughput is close to 1MIPS per megahertz. Such characteristics enable us to optimize the power consumption of the whole machine while ensuring the processing speed [12]. To meet the trajectory requirements of remote control, the project reserves the pins required for remote control reception in the main control circuit. Through the experimental test of pitching attitude and propulsion efficiency, the bionic butterfly aircraft obtained the most efficient motion mode, that is, flapping wings at a frequency of 1–2 times per second, starting at a position with an angle of 60° from the horizontal plane where the main torso is located, descending to a position with an angle of -10°, and then flapping up and down in this form [13]. According to the formula calculation, the project can achieve the maximum speed of the bionic butterfly aircraft can reach 1.5 m/s, with a flight time of 3–4 minutes, and with an 80 mAh lithium battery of the power supply system that needs to be charged for 10 minutes.

4.3. Aircraft parts design

To better reduce the weight of the butterfly aircraft, part of the designed parts are made by Fused Deposition Modeling (FDM) 3D printing. Different from the traditional flapping wing flight, this project designed each bracket in the form of a clamping head, which can effectively reduce the weight and simplify the subsequent installation and debugging procedures. Taking the motor bin as an example, after the initial modeling in SolidWorks, the model was imported into Cura to establish support and passed into the printer for printing. Considering that the precision of aircraft parts production is difficult to control, and the impact of high-altitude air flow needs to be considered, the PAL+ material 3D printing technology is optimized in this project, and the printing layer thickness, printing angle, and printing temperature are studied and found that when the thickness of the printing layer is 0.2 mm ~ 0.3 mm, the printing angle is 700, and the printing temperature is 200°C, the mechanical properties of the printed parts are the best [14]. Under this condition, the motor bin and the connecting rod are manufactured.

5. The production and debugging of the two wings of the bionic butterfly aircraft

5.1. Prototype production

According to the original bionic design scheme, the overall shape layout and partial parameters of the two wings of the aircraft can be obtained. The design of two wings from Computer-Aided Design (CAD) is exported to engineering drawings and printed. The two wings of the bionic butterfly aircraft were made of PET film with a thickness of 0.012 mm and carbon fiber rod. The PET film was placed in the engineering drawing and trimmed to produce the two-wing shape. The bionic butterfly flying machine was electrified for the flapping test, and the flight control was carried out by remote control. After turning on the power, the remote control is turned on and the throttle channel is established to control the flapping frequency of the two wings of the bionic butterfly aircraft. The flapping frequency is controlled by the throttle. When the default throttle is in the end, the two wings are stationary. As the throttle is pushed to the highest point, the flutter frequency of the wings gradually increases. When the throttle reaches the highest point, it can be simply tested that the flutter frequency of the two wings is 7 Hz, which meets the design requirements. The rolling rocker of the remote control can be used to control the deviation of the flutter angle of the two wings of the bionic butterfly aircraft. The default is when the rolling rocker is in the middle position and the left and right sides of the flutter angle are the same. When the rolling rocker is shifted left or right, the two wings will also complete the corresponding flutter angle change, to promote the aircraft to complete the direction turn operation [15].

5.2. The weight and physical display of the bionic butterfly flying machine

The final processed bionic butterfly aircraft has a wing size of 29.5 cm and a weight of 13.8 g. The two direct current (DC) motors weigh 2.5 g, accounting for 18.1% of the total weight of the machine. The two wings weigh 3 g, accounting for 21.7% of the total weight of the whole machine. The main control board weighs 0.9 g, 6.6% of the whole machine, and the receiving bag weighs 0.4 g, 2.9% of the whole machine. 3D printing parts (including all transmission mechanisms and all supports) weighing 3 g accounted for 21.7% of the weight of the whole machine. The battery weighs 4 g, which is the heaviest part of the machine, accounting for 29% of the machine.

5.3. Lift test

Let v be the speed of the butterfly when it swings on the wing, F_p is the thrust received by the wing, and F_f is the resistance received by the wing, according to the inclined plate effect Theoretically, we get:

$$F_q = 2\ sin\cos\theta\rho kV^2$$

$$F_f = 2C_C\sin^2\theta\rho kV^2$$

It can be seen from the formula that the thrust is close to the maximum and the resistance is close to zero.

$$\Delta V = V\sin\theta$$

$$v_a = \Delta V\cos\theta = V\sin\theta\cos\theta$$

$$v_c = \Delta V\sin\theta = v\sin^2\theta$$

$$\xi = \frac{V_a}{Vc}$$

Since different flapping angles correspond to different angles of attack , the angle of attack is a function of the flapping angle, and the total resistance after integration can be written as:

$$F_f = 2c\rho\int_{ro}^{R} k\int_{-\varphi}^{\varphi} V^2\sin\theta\cos\theta\, dr\, d\varphi$$

The total lift force is:

$$F = 2\,c\rho\int_{ro}^{R} K\int_{-\varphi}^{\varphi} kV^2 sin^2\, dr\, d\varphi$$

In summary, the lift force can be calculated:

$$F = 2\,c\rho\int_{ro}^{R} K\int_{-\varphi}^{\varphi} kV^2 sin^2\, dr\, d\varphi = 4c\varphi\left(R^2 - r_0^2\right)\rho kV^2\sin^2\theta$$

6. Conclusion

By simulating the wing structure and movement characteristics of a certain butterfly, that is, designing a reasonable wing shape and combining the structure of the bionic butterfly wing with the material of the imitation butterfly wing film and the flight control system, a movable and complete machine is made on the basis of the bionic butterfly technology, which fully reflects the idea of mechatronics. In recent years, the research of bionic butterfly flying machine has made rapid development, but due to the limitation of science and technology, most of the transmission mechanism still adopts the cumbersome transmission mechanism to realize the flutter of the two wings, and there is still a long distance from the real bionic butterfly. Therefore, future research will focus on the movement of multiple degrees of freedom, and further explore the impact of wing aerodynamic characteristics and novel design ideas on the bionic butterfly, in order to promote the continuous development of the bionic butterfly field.

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Disclosure statement

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