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Design of a Small Bionic Butterfly Machine Under the Background of Innovation and Fusion

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Abstract: With the advancement of modern technology and the continuous development of science, research into flapping wing aircraft is becoming increasingly sophisticated. Addressing issues such as the large wingspan and heavy mass of existing bionic butterfly aircraft, this paper proposes the design of a lightweight lithium battery power supply, a chip integrated into a small circuit board, and a reference to the natural characteristics of butterfly wings. The wings are simulated using 0.125 mm polyethylene terephthalate (PET) film to replicate their movement. The driving structure employs a double motor and a four-bar mechanism to achieve natural and smooth wing vibrations. The control system features a lightweight motor, battery, and a high-performance low-power microcontroller for precise control. Using 3D printing technology, a lightweight design is realized, successfully simulating the structure and movement characteristics of a specific butterfly, demonstrating the principles of mechatronics. Furthermore, the design process incorporates multidisciplinary knowledge, and a workshop combining competitive discipline events with innovation and entrepreneurship has been established. This initiative fosters the deep integration of innovation and entrepreneurship education with professional training, effectively cultivating application-oriented technical talents.

Keywords: Bionic butterfly machine; 3D printing; Mechatronics; Specialized innovation integration

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1. Introduction

In the field of bionic butterfly aircraft research, Western countries have made remarkable achievements. For example, the German Festo's "emotion butterfly" bionic butterfly aircraft can simulate real butterfly flight, with a wingspan of 50 cm, a weight of 32 g, a flapping frequency below 3 Hz, a flight speed of 1–2.5 m/s, and a duration of 3–4 minutes [1]. In contrast, domestic research started late, but Leng Ye of Shanghai Jiao Tong University also made an attempt to design and manufacture an imitation butterfly flapping wing aircraft with a wingspan of 49.8 cm, weight of 32.2 g, and flapping frequency of about 1 Hz [2].

Despite these advancements, the design of flapping wing aircraft still faces certain deficiencies, such as large wingspans and heavy mass. These challenges, stemming from issues in control technology, materials, and structure, have yet to be fully addressed. As a result, the production of small bionic butterfly flapping wing aircraft remains problematic.

The small bionic butterfly designed in this paper utilizes a lightweight lithium battery for power and integrates the chip into a compact circuit board, continuously reducing the overall weight of the machine. Based on bionic butterfly technology, a movable and fully functional machine is created, reflecting the principles of mechatronics [3]. Furthermore, in the context of professional integration education, our team has established a workshop that combines discipline competition with innovation and entrepreneurship education. This initiative significantly enhances the quality of education and improves the talent development process.

2. Butterfly wing structure design

Butterflies have the super flying ability, which is closely related to their wing geometry, wing vein division, and mass distribution. Through an in-depth study of the bionics of butterfly wings, when the bionic butterfly flaps its wings at a high speed, the upward and downward flapping will be subjected to air resistance. The air resistance does positive work during downward flapping and negative work during reverse flapping [4]. To improve flight efficiency, we compared the material, performance, and characteristics of the wings of insects, and found that PET film has low cost, high surface density, and strong tension, which is the optimum choice. In the design of the wing structure, the PET film of 0.125 mm thickness is used, which has a longer flight distance in the experiment and better performance than other materials, and the film is not easy to deform under surface tension and has a certain flexibility. Based on the study of the motion morphology of butterflies, Hu *et al.* conducted numerous experiments on two types of butterflies: the monarch butterfly, known for its long-distance flight ability, and the winged papilio butterfly (Bird of Paradise). They concluded that butterflies with different shape characteristics produce distinct flow structures around them [5].

The leading edge of the monarch butterfly's wing is relatively straight, with a curvature much smaller than that of the Bird of Paradise wing butterfly. In a comparative study of the flow structure during flat flight without power, the front wing surface of the monarch butterfly performed better than that of the Bird of Paradise wing butterfly. Regarding the shape of the rear wing, the monarch butterfly has a smooth edge, similar to the oval wing design seen in fixed-wing aircraft. This wing shape exhibits excellent lift-to-drag characteristics at small to medium angles of attack, and good stall characteristics at large angles of attack. In contrast, the Bird of Paradise wing butterfly has a zigzag rear wing edge, which increases drag under low Reynolds number flying conditions. From an aerodynamic efficiency perspective, the rear wing of the monarch butterfly outperforms that of the Bird of Paradise wing butterfly.

Based on this analysis, the small bionic butterfly designed in this paper features a front wing curvature similar to that of the Bird of Paradise wing butterfly. The rear wing, however, is designed with smooth edges, resembling the oval wing shape found in fixed-wing aircraft, while the wing skeleton mimics the distribution of the monarch butterfly's wings.

3. The butterfly drive structure design

3.1. Drive mechanism design

According to Wang's analysis and summary of typical flapping wing mechanisms, multi-degree-of-freedom compound flapping refers to the coordination of multiple motors to drive the flapping motion of the aircraft via a connecting rod mechanism. This flapping mechanism enables a higher degree of bionic wing movement [6]. Based on this conclusion, the driving mechanism of the small bionic butterfly designed in this paper employs a double motor and four-bar mechanism. The double motor design is superior to a single motor in terms of both power and efficiency, providing maximum lift for butterfly flight [7]. The four-bar mechanism can be adjusted by the length, position, and angle of the connecting rods to control the movement and frequency of the butterfly wings. This design allows the wings to produce natural and smooth vibrations, providing a more realistic simulation of the butterfly's flight motion [8].

3.2. The main body design

The two wings of the butterfly are connected to the motor via a rocker mechanism. The front wing consists mainly of three carbon rods, which are connected to the external outline. The middle part of the outer profile rod is connected to the four wings from front to back. The rear wing is primarily made of a carbon rod that forms a vortex ring structure. This structure allows the front and rear parts of the outer profile rod to become convex. The butterfly's pitch motion brings the leading-edge vortex closer to the wing surface and center of mass, while the up-and-down vibration of the body enhances the vortex, contributing to increased lift [9]. By simulating the average aerodynamic force of the front and rear wings of a dragonfly in each flapping mode, Yao *et al.* obtained the average aerodynamic coefficient of the cycle in different flapping modes of the dragonfly [10]. From this, it can be seen that both wings generate maximum lift when they flap simultaneously. Therefore, in the design of the small bionic butterfly machine, carbon fiber sheets are used to secure both the front and rear wings to enable simultaneous flapping.

A carbon rod is extended from the middle of the outer profile rod to connect to the main drive rod. The main drive rod is made of solid carbon fiber with a diameter of 1.5 mm and a length of 250 mm. One end is secured with a connector to hold the main drive rod in place, while the other end is threaded through a hole on the wing root connector and inserted into a specific blind hole on the motor rocker arm in the wing drive assembly to ensure fixation. Additionally, the wing root connector is designed to tightly fit the output end of the motor rocker arm. This configuration allows the main drive rod to transfer the motor's power to the wings, thereby driving the wing assembly to produce the fluttering motion.

Furthermore, the controller and battery are glued directly to the rear of the main rod and fixed securely to reduce the weight of the main rod, achieving a lightweight design. The rear wing bracket and the wing drive mounting bracket are adjustable along the main trunk axis, enabling the adjustment of the positions of the left and right wing assemblies, the micro-control system, and the power supply system.

3.3. 3D printing

In terms of 3D printing material selection, we use polylactic acid (PLA+), which is a new thermoplastic resin, but also a biodegradable plastic, with high strength, elastic modulus, good stretchability, and other advantages [11]. At the same time, Yang *et al.* obtained the 3D printing process parameters of the optimal mechanical properties through the PLA tensile specimen, which provided a theoretical basis for the best mechanical properties of the printed parts [12]. Based on the research results above, the components of the small bionic butterfly machine designed in this paper are made from PLA+ structural parts. Using SolidWorks modeling software, detailed diagrams of each part were created. In designing the bionic butterfly's drive structure, a comprehensive application of mechanical principles and knowledge from mechanical design courses was employed. Using 3D printing technology, a set of high-precision, lightweight transmission mechanisms was designed, paired with appropriate driving equipment. Additionally, a mechanical design platform was set up in the workshop, which effectively enhanced students' practical skills in structural assembly and fostered innovative thinking in mechanical design. This initiative stimulates students' creativity and helps better train professional talents in 3D printing.

4. Butterfly control system design

4.1. The choice of motor and battery

The small bionic butterfly machine designed in this paper uses a 3-stage, 300 rpm, 6 mm hollow cup planetary gear motor, which offers several advantages, including lightweight, compact size, sensitive control characteristics, and stable operation. These features help effectively reduce the aircraft's weight. Considering the small wingspan of the bionic butterfly, we selected a lightweight 80 mA lithium battery to ensure sufficient lift. This battery design further reduces the vehicle's weight, thereby improving its flight efficiency. The choice of these motors and batteries contributes to minimizing the overall size of the bionic butterfly, bringing it closer to the real butterfly.

4.2. Main control board design

The aircraft selected uses an 8-bit AVR microcontroller ATMEGA328P-AU as the main control chip [13]. 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 1 MIPS/MHz. It is a microcontroller with high performance and low power consumption, which can ensure the processing speed and reduce the energy consumption of the whole machine. The regulator is AMS1117-5.0, it provides a fixed output voltage, and the output voltage accuracy is high, to ensure the stability and reliability of the power supply. The 16 MHz crystal oscillator provides the reference clock signal for the system. To meet the needs of the remote-control track, the pins required for remote-control reception are reserved when designing the main control circuit.

4.3. Transmission structure design

The flight mode of butterflies differs significantly from that of other insects. During flight, the butterfly's aerodynamic force is primarily directed perpendicular to its body's vertical axis. When the butterfly flaps its wings downward, its body pitch angle decreases, generating a larger aerodynamic force that is directed upward and slightly backward. This aerodynamic force not only provides the vertical lift to support the butterfly's weight but also creates a smaller horizontal force directed backward. In contrast, when the wings flap upward, the body pitch angle increases, generating less aerodynamic force, which is directed forward and slightly downward. This force mainly provides horizontal thrust to overcome the backward horizontal force created by the body during the downstroke. By adjusting the body's pitch angle, the butterfly can control the direction of the aerodynamic force to suit its flight needs [14]. This unique flight mechanism allows the butterfly to display a high degree of flexibility and control in flight. Based on the above principles, the wing-driven linkage mechanism is derived, in which,

$l_1 = 3$ mm, $l_2 = 6$ mm, $l_3 = 5.439$ mm, $l_4 = 7.029$ mm, $x_0 = 5.25$ mm, $y_0 = 4.941$ mm, When l_1 and l_2 coincide, $AC_1 = AB_1 + BC_1 = l_1 + l_2 = 9$ mm When the rod l_3 swings to the highest point. In △AD, from the law of cosine C_1 :

$$\alpha_1 = arccos\frac{(l_1+l_2)^2 - l_3^2 - l_4^2}{2l_3l_4} = \frac{9^2 - 5.439^2 - 7.029^2}{2 \times 5.439 \times 7.029} = 88.493°$$

$$\theta_1 = arccos\frac{l_3^2 - (l_1+l_2)^2 - l_4^2}{2(l_1+l_2)^2 l_4} = \frac{5.439^2 - 9^2 - 7.029^2}{2 \times 9 \times 7.029} = 37.165°$$

When l_1 and l_2 coincide, $AC_2 = B_2C_2 - AB_2 = l_2 - l_2 = 3$ mm, the bar l_3 swings to its lowest point. In △AD, from the law of cosine C_2 :

$$\alpha_2 = arccos\frac{(l_1-l_2)^2 - l_3^2 - l_4^2}{2l_3l_4} = \frac{3^2 - 5.439^2 - 7.029^2}{2 \times 5.439 \times 7.029} = 23.743°$$

Therefore, the swing angle of the bionic butterfly's unilateral wings is:

$$\alpha_1 - \alpha_2 = 88.493° - 23.743° = 64.749°$$

In Rt△ADO:

$$\theta_2 = arctan\frac{y_0}{x_0} = arctan\frac{4.941}{5.25} = 43.263°$$

So the angle between the poles of the four-bar mechanism is:

$$\theta = 90° - \theta_1 - \theta_2 = 90° - 37.165° - 43.263° = 9.572°$$

The quick return characteristic is:

$$K = \frac{180° + \theta}{180° - \theta} = \frac{180° + 9.572°}{180° - 9.572°} = 1.112°$$

Based on the above research, we designed a micro-flight control board that highly integrates the remote-control circuit, the voltage regulator circuit, and the motor control circuit. This design demonstrates the concept of integration and intelligence of mechanical and electrical products and integrates the knowledge of single-chip microcomputers, electronic and electrical engineering, Programmable Logic Device (PLD) combined logic circuits, and other related courses. In the design of small bionic butterfly machine, in order to ensure the in-depth practice, we established the mechatronics integration technology workshop, the purpose is to improve the overall quality from the practical level through engineering training tasks and discipline competition training.

5. Conclusion

This paper successfully simulates the structure and movement characteristics of a specific butterfly wing, resulting in a fully functional, movable mechanical bionic butterfly. The butterfly has a wingspan of 29.5 cm, weighs 13.8 g, can reach a top speed of 1.5 m/s, has a flight time of 3–4 minutes, and requires 10 minutes to recharge. During the design process, the team also leveraged relevant knowledge and experience, establishing online and offline learning workshops for students with no prior foundation or those with some experience but no systematic training. These workshops aimed to foster learning through competition and promote the integration of innovation [15]. However, although this research has successfully designed and manufactured a small bionic butterfly machine, the scope of the study remains relatively limited. The flight speed and endurance of the bionic butterfly still need improvement. We believe that with advancements in science and technology, these challenges can be addressed in the future. We also look forward to optimizing the design, improving material performance, enhancing the intelligence of the flight control system, and achieving more efficient and durable flight performance.

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Disclosure statement

The authors declare no conflict of interest.

References

[1] Zhang Y, Li S, Wang X, et al., 2024, Butterfly Flying Mechanism and Summarized Research Progress in Imitation of Butterfly Flapping Wing Flight Vehicle [J]. Journal of Engineering Science, 46–48(9): 1582–1593. https://doi.org/10.13374/j.issn2095-9389.2023.10.11.002

[2] Leng Y, Zhang W, Zhou S, et al., 2019, Bionic Butterfly Aircraft Design Analysis. Journal of Mechanical Design and Research, 35(4): 32–35 + 42.

[3] Gao Y, Zhong S, Xiong Z, et al., 2019, Design and Analysis of Bionic Butterfly Robot. Mechanical and Electrical Engineering Technology, 53(08): 97–100 + 123.

[4] Sun W, Feng C, 2016, Imitation Dragonfly Flapping Wing Flight Vehicle Design and Aerodynamic Research. Journal of Flight Mechanics, 2016(5): 21–25 + 29.

[5] Hu Ye, Wang J, Zhang C, et al., 2010, The Influence of Butterfly Wing Surface Shape on the Flow Structure. Journal of Aerodynamics, 28(02): 138–142.

[6] Wang L, 2018, Design and Aerodynamic Analysis of Bionic ornithopter, thesis, Beijing Jiaotong University.

[7] Lu Z, Tian G, Li R, et al., 2024, Single and Double Electric Machinery Transmission Direct Comparative Study on the Performance of the System. Journal of Automobile Engineering, 46–48(02): 310–319.

[8] Xu B, Zhu W, 2017, Based on Four-Bar Linkage of Flapping Wing Drive Mechanism Design and Motion Simulation. Journal of Chongqing Institute of Technology (Natural Science), 12(5): 63–66.

[9] Huang S, Shen G, Wei L, et al., 2010, Flow Display Experiment for Hovering Flight of Mechanical Butterfly Model. Experimental Fluid Mechanics, 24(02): 59–64.

[10] Yao D, Shen G, Zhu B, et al., 2011, Experimental Study on Aerodynamic dynamics of a Mechanical Dragonfly Hovering. Journal of Experimental Fluid Mechanics, 25(01): 69–75.

[11] Li H, Wang H, Liu X, 2024, The Response Surface Method to Optimize the PLA Material Mechanical Properties of 3D Printing Specimens. Journal of Plastic Science and Technology, 52(10): 130–135.

[12] Yang L, Meng J, Xue T, 2021, Effect of 3D Printing Process Parameters on Tensile Strength of PLA Specimen. Plastics Industry, 49(05): 73–77 + 142.

[13] Yan H, Xu K, ZhuJia X, 2015, Based on the Four Rotor Aircraft MEGA328P Design. Value Engineering, 2015(29): 141–142.

[14] Sun M, 2015, Aerodynamics of Insect Flight. Chinese Journal of Mechanical Mechanics, 47(02): 384.
[15] Jin H, Meng L, Liu Z, et al., 2019, Innovation Curriculum Reform and Practice in the Context of Specialization Integration. Journal of Electrical and Electronic Teaching and Learning, 46(03): 208–210.