DYNA
http://dyna.medellin.unal.edu.co/

UNIVERSIDAD NACIONAL DE COLOMBIA

Design and fabrication study of a small remote-controlled bionic butterfly flapping-wing flying machine

Yaozeng Mao, Fan Wu, Junjie Lao & Minglei Li *

School of Intelligent Manufacturing, Jiangnan University, Wuxi, China.
jyxy@jiangnan.edu.cn, 1046220226@stu.jiangnan.edu.cn; 13965192332@163.com; laojunjie126@126.com,
* *Corresponding author, lml18888071473@163.com*

Received: May 21st, 2024. Received in revised form: October 23rd, 2024. Accepted: November 18th, 2024.

Abstract
This research is devoted to simulating the flight characteristics of real butterflies, and a small remote-controlled bionic butterfly flying machine is designed and manufactured. We analyze the principle of butterfly wing flight, which provides a theoretical basis for bionic design. Then, through 3D modeling and finite element analysis, an innovative design scheme of small bionic butterfly flight vehicle was proposed and verified, and its lift force was analyzed after assembly. This study not only demonstrates the feasibility of the design and implementation of small bionic butterfly aircraft, but also emphasizes its potential application value in the execution of small space missions, providing a new perspective for the design and optimization of bionic aircraft in the future.

Keywords: flying machine; bionic machinery; butterfly flight characteristics; remote-controlled.

Estudio de diseño y fabricación de una pequeña máquina voladora biónica de alas batientes de mariposa teledirigida

Resumen
Esta investigación se dedica a simular las características de vuelo de mariposas reales, y se diseña y fabrica una pequeña máquina biónica teledirigida para volar mariposas. Analizamos el principio del vuelo de las alas de mariposa, que proporciona una base teórica para el diseño biónico. A continuación, mediante modelado 3D y análisis de elementos finitos, se propuso y verificó un innovador esquema de diseño de un pequeño vehículo biónico de vuelo de mariposa, y se analizó su fuerza de sustentación tras el ensamblaje. Este estudio no sólo demuestra la viabilidad del diseño y la implementación de pequeños aviones mariposa biónicos, sino que también pone de relieve su valor de aplicación potencial en la ejecución de pequeñas misiones espaciales, proporcionando una nueva perspectiva para el diseño y optimización de aviones biónicos en el futuro.

Palabras clave: máquina voladora; maquinaria biónica; características de vuelo de mariposa; teledirigida.

1 Introduction

Many of the current flight devices are based on the principle of bionics, modeled after the structure and flight mode of insects. Compared with fruit flies, mosquitoes, and other insects with flutter frequency above 100Hz, butterflies with flutter frequency below 10Hz have a more special way of fluttering, and this low-frequency fluttering feature gives it the advantages of low noise and low energy consumption. Therefore, in the implementation of narrow space reconnaissance and close-range monitoring tasks, imitation butterfly wing flapping machines can play an important role.

Most of the bionic butterflies developed so far have the problems of oversized design and limited path planning. Accordingly, we would like to control the size to about five times by improving the design and material, and at the same time control the movement path by remote control device and motor, to make it closer to the movement process of a real butterfly. Our research is based on the principle of bionics to design and fabricate a wing-fluttering flying machine that

How to cite: Mao, Y., Wu, F., Lao, J., and Li, M., Design and fabrication study of a small remote-controlled bionic butterfly flapping-wing flying machine. DYNA, 91(234), pp. 107-115, October - December, 2024.

mimics the way butterflies fly and looks in nature. It can integrate the process of climbing, propulsion, and hovering, and has high aerodynamic efficiency within a certain speed range, which prolongs the range and sailing time; at the same time, it has very low requirements for the environment of the take-off site, which is very convenient and has a very good prospect in military reconnaissance and environmental monitoring.

To further improve the performance of the current bionic butterfly flapping-wing aircraft, we designed and manufactured a new type of bionic butterfly flapping-wing aircraft. The contributions of this article are as follows:

- Based on the physiological characteristics of the butterfly itself, a new transmission mechanism was developed. This transmission mechanism enables the aircraft to achieve stable flight while keeping its size and weight as close as possible to that of a butterfly.
- Through simulation analysis of butterfly wing movements, specially distributed wing veins were designed. Experiments show that the wing veins are reasonably distributed and can achieve stable flight.
- Designed a high-performance, highly integrated, and intelligent flight control board, which allows for more subsequent application scenarios.

2 Related works

With the in-depth study of bionic machinery and the development of aerodynamic theory, it has been found that fluttering wing flight has the advantages of low noise and low energy consumption relative to other flight modes [1-5]. However, the inability to hover and the lack of a bird's broad tail for flight direction and attitude control are also obvious defects, which is also the current research direction of researchers on the bionic butterfly flyer. At the same time, due to the low-frequency characteristics of butterfly fluttering wings, it is difficult for researchers to design a bionic butterfly with 1:1 size and stable flight under the limitation of material and process.

In order to solve these problems, predecessors have conducted extensive and useful research. Yue Zhu et al. designed a new flap mechanism and conducted mathematical modeling to provide guidance at the theoretical level [6]. In addition, Yixin Zhang and others used high-speed photography to capture the butterfly's abdominal swing, wing movement and body pitching during free flight, further proving that there is a dynamic coupling effect between the wings and body of the butterfly in different flight modes [7]. In the field of manufacturing new structures, researchers have also made innovative attempts. Leng et al. conducted in-depth research on Festo's bionic butterfly and independently designed a new butterfly-shaped flapping aircraft structure scheme based on this prototype. The USButterfly produced by Huang Haifeng and others is a new milestone in bionic butterfly design, but its size is too different from that of a real butterfly [8]. In recent years, most bionic butterflies have been designed to be more than ten times the size of a butterfly, with wings proportionally larger to increase lift as much as possible without increasing mass.

In this design, the ailerons of the aircraft are cleverly designed as flexible hinge structures, with the main wings located above the ailerons. During downward flapping, the main wing drives the entire wing to complete downward flapping through the overlap with the aileron, maximizing the windward area; on the contrary, during the upward flapping process, the aileron is placed under the active wing and communicates with the active wing through a flexible hinge. The wings are connected, and a phase difference occurs between the main aileron and the active wing, which gradually reduces the windward area, eventually forming an upward net lift. This series of innovative designs further advances the research on bionic butterflies in aircraft structural design.The small bionic butterfly flapping wing aircraft is currently showing good prospects, but the rudder drive and other methods are very demanding on the hardware equipment, and so far there is no energy source with sufficiently high energy density or sufficiently efficient rudder to drive the small flying machine. The small imitation butterfly flier designed in this study uses a motor drive and an innovatively designed transmission mechanism that allows for greater energy efficiency.

3 Detailed program design and production

3.1 Bionic butterfly working principle

Based on biological research, butterflies mainly rely on the "principle of drag" to carry out flapping flight, and their lifting force to balance the gravity of the body and the thrust force to overcome the body resistance are mainly provided by the drag force generated by the wings. When the butterfly starts its downbeat movement, the left and right wings start flapping symmetrically from a small angle (about 50°) to both sides. At this time, strong leading-edge vortices and wing end vortices were formed at the leading edge and end of the two wings, respectively, while vortices formed during the downbeat and upbeat, respectively, of the previous beat cycle were also present downstream of the wings. In the subsequent flapping motion, the leading-edge vortex and the wing end vortex developed into a "vortex ring" in a short time, and a strong downward flow, i.e., jet, was formed in the area between the two wings under the action of the "vortex ring". Subsequently, the vortex on the wing surface starts to become loose and move backward and fall off due to the reduction of the flapping speed and the larger forward incoming flow. In the upbeat process, no new vortex formation on the upper fin surface, while the "vortex ring" generated in the downbeat continues to fall off backward, and gradually dissipates under the viscous effect of the fluid. After the start of the upbeat movement, the lower wing surfaces of the left and right wings also produce leading-edge vortices and wing end vortices, and they are obviously much weaker than the vortices produced on the upper wing surfaces during the downbeat. This is because the angle between the two wings at the beginning of the upbeat is larger (about 150°), and the angle between the direction of beat movement and the direction of incoming flow becomes smaller due to the upward tilt of the body. As a result, the peak in drag is much smaller in the upbeat than in the downbeat. Similarly, the vortex on the lower wing surface moves backward in subsequent motions and flips off from the end of the wing onto the upper wing surface as a result of the reduced flapping speed and the incoming flow.

3.2 Bionic butterfly total solution

Our bionic butterfly wing flutterer has an overall weight of 11.4g in a 30cm diameter circle, a double wing flapping rate of 4 Hz, and a full battery life of up to 4 min.

This small bionic butterfly flutter abandons less efficient drive methods such as rudders, chooses motors to control the wing movement, and increases the torque by gear reduction, and uses a linkage mechanism to convert the rotary motion of the gears into reciprocating oscillation of the wings. In addition, we simplify the principle of wing flutter and try to reduce the weight of the whole aircraft from the perspective of materials, batteries, etc., so that the lifting force is enough to overcome the gravity of the whole aircraft and the resistance of the flight, and at the same time, we can also reduce the power consumption and improve its stability and endurance during flight.

The small imitation butterfly aircraft designed in this study mainly consists of three parts: the main torso, the wing assembly, and the driving device. The wing assembly is divided into left and right parts, which are each mounted on the wing drive assembly on both sides of the front end of the main structure, and presents a mirror image symmetric layout. Each wing assembly consists of five parts: the outer profile bar, the main drive bar, the wing veins, the wing root connectors, and the elastic membrane. Specifically, the wing root connector adopts a fan-like cross-sectional structure; the outer contour rod forms the outer contour of the wing assembly, and the end of the main drive rod is connected to a blind hole. The structure sketch is shown in Fig. 1.

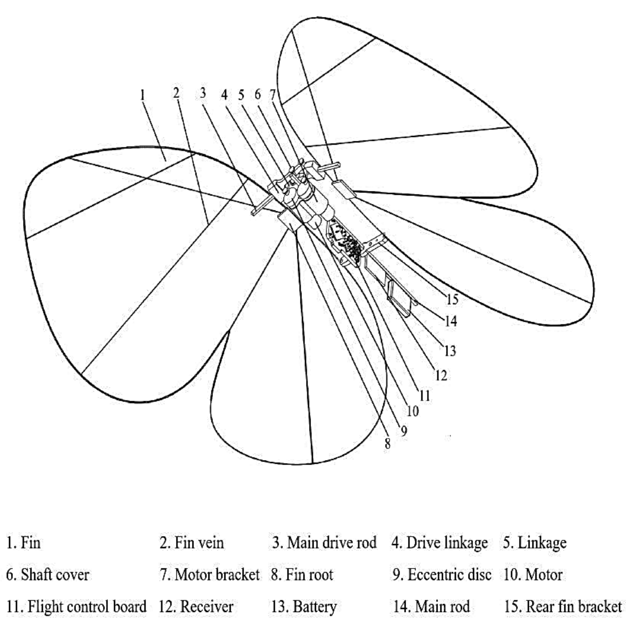


Figure 1. Bionic butterfly structure sketch.
Source: own elaboration

The middle section of the outer contour rod is fitted with a wing vein connection member along its length direction, so as to connect the wing veins and realize the concave in the middle of the outer contour of the wings through the wing veins, thus replicating the typical form of a butterfly wing. In addition, the front end of the outer contour rod is fitted with a main drive rod connector, one end of which is firmly connected to the main drive rod connector, and the other end of which passes through the through-hole provided in the wing vein connector and is ultimately secured to the drive motor rocker arm in the wing drive assembly. The trailing edge of the wing is connected to an articulating member in the center of the main body. Instead of a kite cloth, this flying machine utilizes a polyethylene terephthalate (PET) material, which covers the outer contour of the wings.

With the above construction, the small bionic butterfly flyer proposed in this study aims to achieve a more efficient and responsive flight performance by simulating the natural fluttering pattern of butterfly wings.

3.3 Bionic butterfly body torso design

The constituent elements of the main torso section include the carbon main rod, motor bracket, flight control board fixing bracket, battery connection bracket, and rear fin bracket as shown in Fig. 2. The main stem is a hollow carbon fiber rod with a cross-section of 1.5 mm side length and a length of 113 mm. the motor bracket, flight control board fixing bracket, battery connection bracket and rear fin bracket are all polylactic acid (PLA) structural components. The motor bracket has a bracket mounting hole in the center that matches the cross-section of the main rod, through which the bracket is set on the front end of the main rod to be fixed with a tight fit, and at the same time there are motor mounting holes designed along the axial direction of the main rod at the symmetric positions under the left and right sides, as shown in Fig. 3. The rear wing bracket is in a zigzag shape, with a mounting hole designed to match the cross-section of the main rod at the center, through which the rear wing bracket is put on the front of the main rod to be fixed in a tight fit, with the fixing position close to the center of the main rod, and at the same time there is a wing connecting hole designed for connecting the left wing assembly and the right wing assembly, respectively, as shown in Fig. 4. On this basis, the rear wing bracket and the wing drive mounting bracket are adjustable in the main torso axial direction to enable adjustment of the position of the left-wing assembly, the right-wing assembly, the flight control board, and the power supply unit. The adjustment is generally made with reference to a combination of factors such as the aerodynamic forces to which the left-wing assembly and the right-wing assembly are subjected and their own gravity.

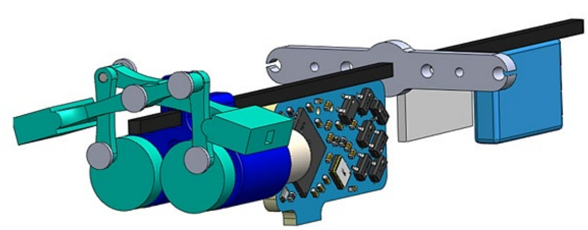


Figure 2. Main torso assembly drawing.
Source: own elaboration

Figure 3. Motor bracket.
Source: own elaboration

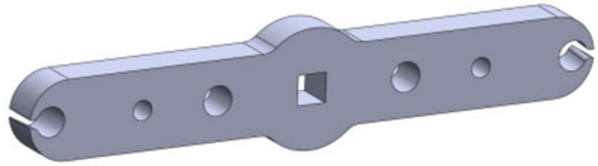


Figure 4. Rear fin bracket. (source: own elaboration)

3.4 *Bionic Butterfly Drive System Design*

The bionic butterfly drive system includes paired and symmetrically mounted motors and their transmission mechanisms on both sides of the main pole. The motors are 3V, 6mm, 242rpm hollow-cup motors with high precision, ultra-miniature, and lightweight metal cases. This motor can meet the speed and torque required for flight while dramatically reducing the overall mass of the machine.

To transform the rotation of the motor into the oscillation of the wing, we carefully designed a set of high-precision and lightweight drive mechanisms, as shown in Fig. 5. The motor is tightly connected to the eccentric disk through a D-shape shaft, the connecting rod is connected to the eccentric disk through an optical shaft and is positioned through the shaft cover, and the connecting rod is connected to the driving rod through an optical shaft to drive the wing movement. After the transmission mechanism, the wings swing at 63°. The axes of motor output axes of the two sets of wings are kept in the same plane with the axes of the main rods of the main torso of the bionic butterfly, toward the end of the main torso, and form an angle of 10° with the main rods, which is a key design parameter that determines that the forward swept angles of the left and right-wing assemblies are in a reasonable range.

The following is a detailed calculation description of the design of the four-bar mechanism of the drive system.

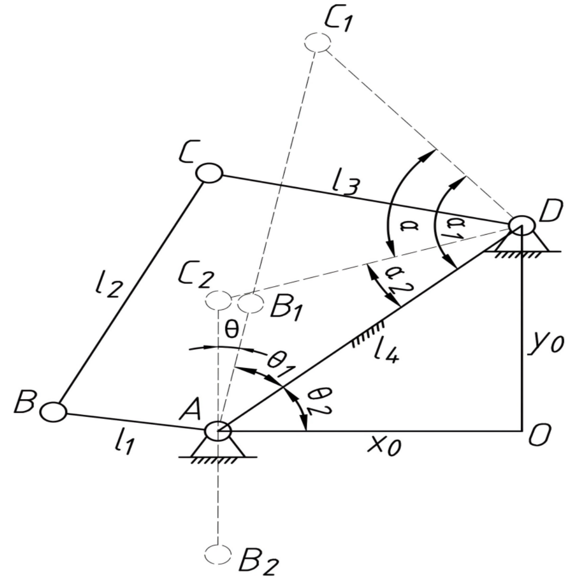


Figure 5. Schematic diagram of wing drive linkage mechanism.
Source: own elaboration

The schematic diagram of the wing drive linkage mechanism is shown in Fig. 8, where l_1=3mm, l_2=6mm, l_3=5.439mm, l_4=7.029mm, x_0=5.25mm, y_0=4.941mm.

When l_1 and l_2 coincide and $AC_1=AB_1+BC_1=l_1+l_2$=9mm, rod l_3 swings to the highest point.

In $\triangle AC_1D$, from the cosine theorem:

$$\begin{aligned}\alpha_1 &= \arccos\frac{(l_1+l_2)^2-l_3^2-l_4^2}{2l_3l_4}=\frac{9^2-5.439^2-7.029^2}{2\times 5.439\times 7.029}=88.493^{\circ}\\ \theta_1 &= \arccos\frac{l_3^2-(l_1+l_2)^2-l_4^2}{2(l_1+l_2)l_4}=\frac{5.439^2-9^2-7.029^2}{2\times 9\times 7.029}\end{aligned} \quad (1)$$

When l_1 and l_2 coincide, $AC_2=B_2C_2$-AB_2 =l_2-l_1=3mm, and rod l_3 swings to the lowest point.

In $\triangle AC_2D$, from the cosine theorem:

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

Therefore, the swing angle of one wing of the bionic butterfly is

$$\alpha=\alpha_1-\alpha_2=88.492^{\circ}-23.743^{\circ}=64.749^{\circ} \quad (3)$$

In Rt$\triangle ADO$

$$\theta_2=\arctan\frac{y_0}{x_0}=\arctan\frac{4.941}{5.25}=43.263^{\circ} \quad (4)$$

Therefore, the angle between the pole positions of the four-bar mechanism is

$$\theta=90^{\circ}-\theta_1-\theta_2=90^{\circ}-37.165^{\circ}-43.263^{\circ}=9.572^{\circ} \quad (5)$$

The emergency return characteristics are

$$K = \frac{180^\circ + \theta}{180^\circ - \theta} = \frac{180^\circ + 9.572^\circ}{180^\circ - 9.572^\circ} = 1.112 \quad (6)$$

This bionic butterfly has obtained the most efficient movement mode through experimental tests of pitch attitude and propulsion efficiency, that is, flapping its wings at a frequency of 4 times per second. The starting position of flapping is at an angle of approximately 40° with the horizontal plane where the main trunk is located. position, flutter down to a position with an angle of about -25°, then flutter up, and flutter up and down in this manner. After estimation, this design intends to achieve the effect: the maximum speed of the bionic butterfly aircraft can reach 1.5m/s.

3.5 Bionic butterfly wing structure design

The left fin assembly and the right fin assembly have the same structural and dimensional parameters and are set symmetrically on the left and right sides of the main torso. They consist of an outer contour bar, a main drive bar, a fin vein, a fin root connector, and a PET fin surface, as shown in Fig. 6. Among them, the wing root connectors adopt a fan-shaped structure with a thickness of 0.5 mm. the outer contours of the wings of the left-wing assembly and the right-wing assembly are formed by the bending of the outer contour rod, which is made of carbon fiber rods, and the front and rear ends of which are glued to the front and rear positions of the wing root connectors. The middle part of the outer contour rod is bonded to three wing veins in sequence from front to back, and the length of the three wing veins decreases in sequence from front to back, and the lengths of the three wing veins are all smaller than the length of the main drive rod. By means of the fin veins in the rear part, a concave structure can be formed in the middle part of the carbon fiber rod, and this structure can make the front part and the rear part of the outer contour rod convex. By means of the wing veins in the middle and the front portion, the middle structure of the outer contour of the wing can be stabilized and the transition between the front and the rear convex portions of the outer contour of the wing can be smoothed. The main drive rod connector with a blind hole structure fixed in the front part of the outer contour rod is located in the front convex part to connect the main drive rod. Through our optimized design, it is possible to make the output power of the drive motor, which is transmitted to the drive arm through the cam linkage mechanism, drive the wing assembly to realize the fluttering motion.

The wing vein connector, the main drive rod connector, the wing root connector, and the wing vein and main drive rod parts are all made of carbon fiber. In the design of the wing, the rear part of the outer contour is specially designed as a U-shape structure, which not only optimizes the stability of the wing but also the convex part of the wing at the rear, we cleverly fix it to the wing connection holes within the end of the middle and rear wing brackets of the main torso, which is an innovative innovation that makes the wing assembly securely fastened to the main torso part. Through this precise design, the stability of the wing assembly during the tumbling movement is finally realized, and the flopping phenomenon during the movement is avoided.

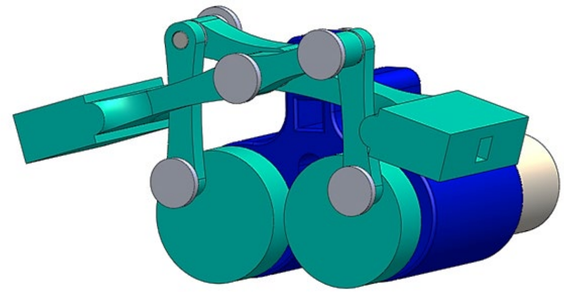


Figure 6. Transmission mechanism.
Source: own elaboration

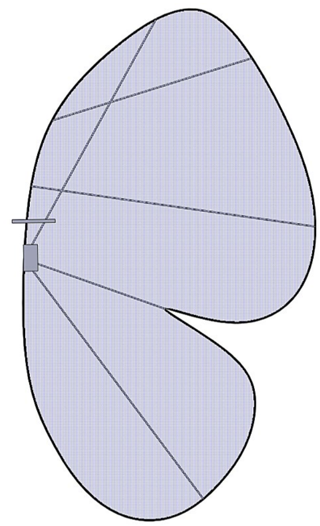


Figure 7. Butterfly wings design.
Source: own elaboration

3.6 Bionic butterfly control system design

The control circuit of our small bionic butterfly wing flutterer uses the STM32F401 microcontroller as the main control chip. The chip has a dynamic power consumption adjustment function, which can achieve a power consumption as low as 128µA/MHz in the operation mode, and at the same time, it has a strong performance and high integration degree, which enables us to ensure the processing speed and at the same time, reduce the burden of the whole machine and optimize the power consumption of the whole machine. The control circuit can independently control the speed of the two motors, and through mechanical transmission can realize the differential motion of the wings to realize the turn. The control circuit also integrates a voltage regulator circuit using a PW2057 voltage regulator chip to adapt to different specifications of the power supply. In order to meet the needs of the remote-control track, we have also reserved the pins required for remote control reception in the control circuit. Our solution provides a control circuit schematic diagram as shown in Fig. 8 and a PCB diagram as shown in Fig. 9.

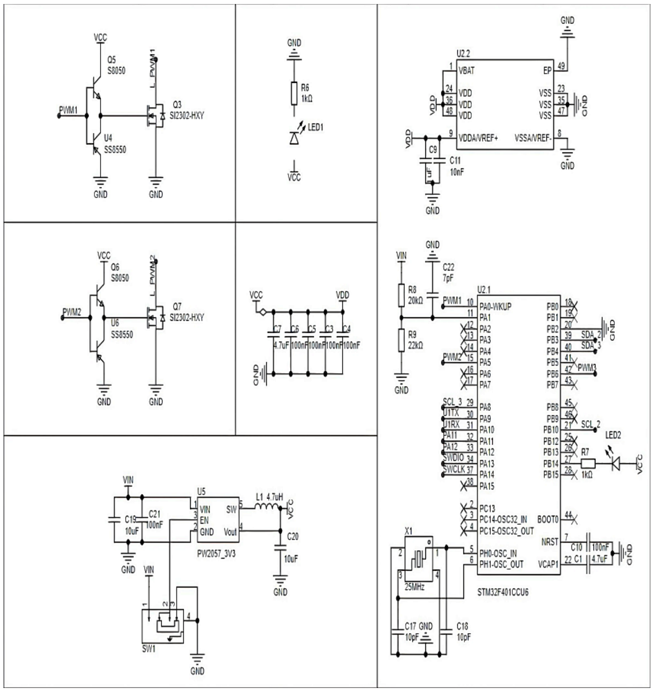


Figure 8. Control system schematic.
Source: own elaboration

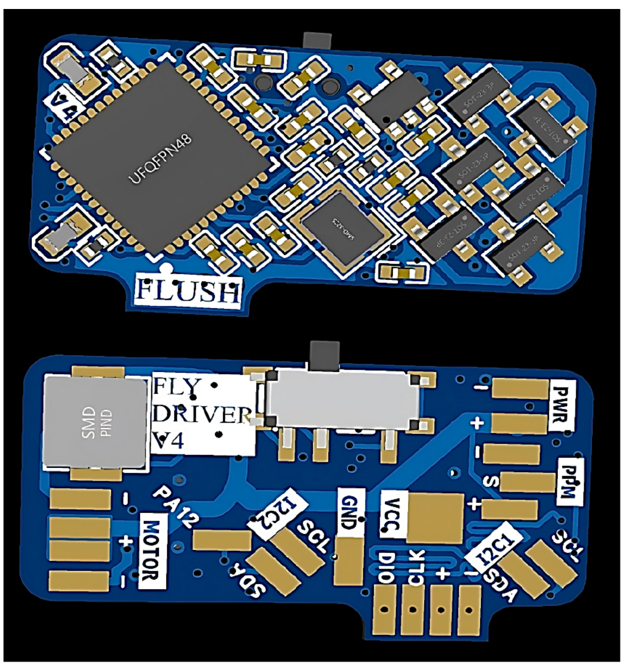


Figure 9. Control system PCB diagram.
Source: own elaboration

The flight control board is 25mm long, 12mm wide, and weighs only 0.9g, with redundant structures such as through holes and rows of pins removed, the integration level is quite high. It is worth mentioning that the flight control board also integrates a burn-in Debug interface and two IIC interfaces. The dual IIC interfaces can be interconnected with external modules such as WIFI/BT module, GPS module, IMU module, etc., reflecting the idea of intelligence.

At the level of the control algorithm, we use pulse width modulation (PWM) output to achieve accurate and stable control of the motor.

The power supply unit of our Bionic Butterfly Puffer is a 100mAh, 3.7V Li-Polymer battery, which operates at 15C and up to 30C. It can ensure excellent performance and sufficient endurance under a lighter mass and can be used for the Bionic Butterfly Puffer to fly for 3-4 minutes.

4 Simulation

4.1 Stress analysis

The Abaqus finite element numerical simulation technique was used to investigate the bending performance of the butterfly wing model under the reaction force as the point force, in which the material properties were assigned to the wing membrane and the wing veins separately. According to the results in Fig. 10, the butterfly wings have the most concentrated stress at the wing root, which suffers the most serious load damage, and the stress is transferred from the wing root to the wing edge along the wing vein; the load application position obviously affects the stress distribution of the wings, with the load at the edge of the wing vein, where the overall stress is more uniform, and the load in the middle of the wing vein, where the stress is concentrated in the application position with the position of the wing root; and the stress distribution increases with the increase of load.

According to the simulation results, we carry out several iterations of the wing structure, and the main optimization directions are the strengthening design of the wing root connection, the effect of different wing vein distribution on the stress distribution, the effect of spraying and dispensing process on the stress distribution of the wing, and the selection of the wing vein and wing surface materials.

4.2 Flow field analysis

The motion analysis of our bionic butterfly flutter aircraft is carried out using the Fluent module of ANSYS. The transient overlapping mesh method is used, and the simulation parameters are as follows: the wing flapping frequency is 4Hz, the flight speed is 0.3m/s, the air inlet velocity is 1m/s, and the gravitational acceleration is 9.81m/s. After the simulation analysis, the pressure and velocity clouds on the yz-plane at different moments in a cycle are obtained as in Fig. 11. It can be seen in Fig. 10 that when the wing is flapping down, the lower surface pressure of the fin is greater than the upper surface pressure of the fin, and there is a wing end vortex generated. surface pressure is greater than the upper surface pressure of the fin, and this pressure difference generates the lift of the fin, and there is a vortex generated at the end of the fin. The velocity of the flow field on the upper surface of the wing is greater than that on the lower surface of the wing, and a vortex is formed on the upper surface of the wing. The flow field generated by the fin during uptake is just the opposite of downtime, there is drag generated to provide forward thrust, and the vortices generated at the end of the wing are weaker than during downtime.

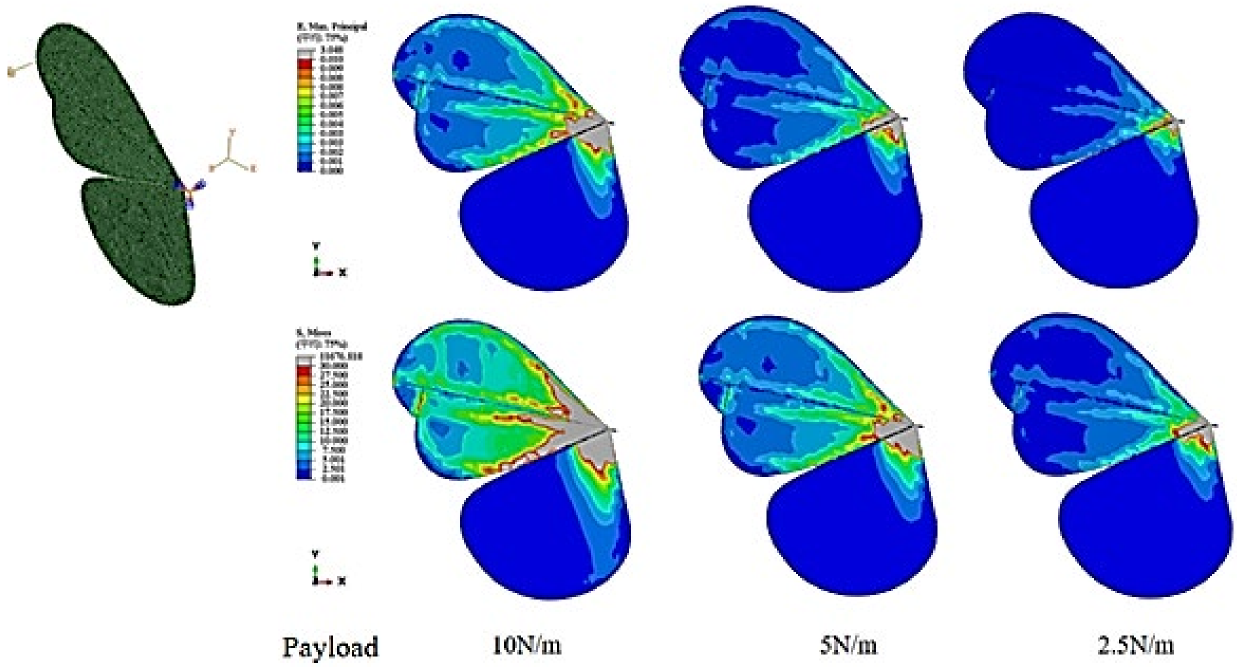


Figure 10. Stress analysis.
Source: own elaboration

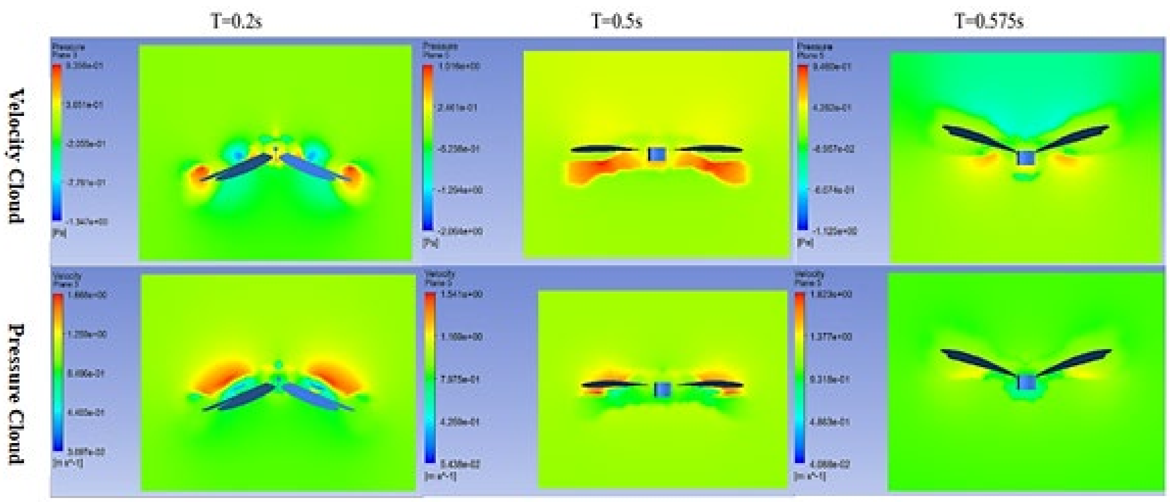


Figure 11. Flow field analysis.
Source: own elaboration

1 Data computation and analysis

v is the velocity of the butterfly as it swings its wings upward, F_q is the thrust on the wings, and F_f is the drag on the wings, according to the theory of the swashplate effect:

$$F_q = 2C_c \sin\theta \cos\theta \rho k v^2 \quad (7)$$

$$F_f = 2C_c \sin^2\theta \rho k v^2 \quad (8)$$

From the equation it can be seen that θ is near maximum thrust at about 45°, and drag is close to zero.

$$\Delta v = v \sin\theta \quad (9)$$

$$v_a = \Delta v \cos\theta = v \sin\theta \cos\theta \quad (10)$$

$$v_c = \Delta v \sin\theta = v \sin^2\theta \quad (11)$$

$$\xi = \frac{v_a}{v_c} \tag{12}$$

Since different beat angles φ correspond to different headway angles θ, the headway angle is a function of the beat angle, and the total resistance after integration can be written as:

$$F_f = 2c\rho\int_{r0}^{R} k\int_{-\varphi}^{\varphi} v^2 \sin\,\theta \cos\,\theta drd\varphi \tag{13}$$

Total lift is:

$$\begin{aligned} F_q &= 2c\rho\int_{r0}^{R} k\int_{-\varphi}^{\varphi} rv^2 \sin^2\,\theta drd\varphi \\ &= 4c\varphi(R^2 - r0^2)\rho k v^2 \sin^2\,\theta \end{aligned} \tag{14}$$

where, c is the air viscosity coefficient taken as 17.9×10^{-6}, flapping angle $\varphi = 75°$, distance from the tip of the wing to the symmetry plane of the butterfly's body R = 285mm, distance from the root of the wing to the symmetry plane of the butterfly's body r_0 = 40mm, wing area k=10563, and θ is the angle of approach taken as 30-45°.

When the flight speed is v=4m/s, F_p is about 0.34N, and this lift is the lift that a single wing can provide, so the total lift F=0.68N.

2 Photograph of the real object

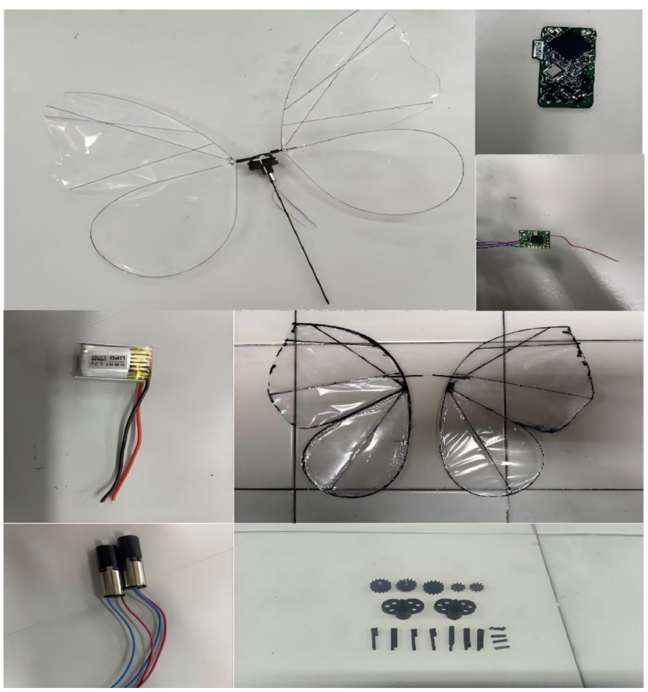


Figure 12. Photograph of the real object.
Source: own elaboration

3 Conclusion

Inspired by the excellent maneuverability, agility, and adaptability shown in the flight of butterflies, this study proposes the design of a small remote-controlled bionic butterfly flyer. This paper is devoted to simulating the flight characteristics of butterflies, including maneuverability and adaptability. At the theoretical level, the forces on the wings in the flapping and gliding states are analyzed in detail, and the lift force in the gliding state is calculated. Subsequently, the design proposal was modeled by 3D modeling software, and the strength of the wing was verified using finite element analysis software to ensure the reasonableness of the design. Further, a prototype of a small remote-controlled bionic butterfly flyer was fabricated by selecting appropriate materials and designing the drive structure and hardware circuit. The prototype is controlled by a remote controller to control the flight path and driven directly by a servo, with a wingspan of 29.8 cm, an overall length of 17.9 cm, and an overall weight of 11.4 g. The experimental results show that the lifting force of the prototype reaches 0.68 N, and the flapping frequency is stable at about 4 Hz, with a maximum flapping angle of 65°.

References

[1] Huang, H., He, W., Fu, Q., He X., and Sun, C., A Bio-Inspired Flapping-Wing robot with cambered wings and its application in autonomous airdrop, in: IEEE/CAA Journal of Automatica Sinica, 9(12), pp. 2138-2150, 2022. DOI: https://doi.org/10.1109/JAS.2022.106040.

[2] Fu, Q., Wang, X., Zou, Y., and He, W., A miniature video stabilization system for flapping-wing aerial vehicles, Guid. Navigation Control, 2(1), 2022. DOI: https://doi.org/10.1142/S2737480722500017.

[3] He, W., Mu, X., Zhang, L., and Zou, Y., Modeling and trajectory tracking control for flapping-wing micro aerial vehicles, in: IEEE/CAA Journal of Automatica Sinica, 8(1), pp. 148-156, 2021. DOI: https://doi.org/10.1109/JAS.2020.1003417.

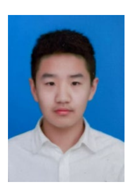
[4] Huang, H., Wu, X., Wang, T., Sun Y., and Fu, Q., Reinforcement learning control for a flapping-wing micro aerial vehicle with output constraint, Assem. Automat., 42(6), pp. 730-741, 2022. DOI: https://doi.org/10.1108/AA-05-2022-0140

[5] Qiao, H., Wu, Y.-X., Zhong, S.-L., Yin P.-J., and Chen, J.-H., Brain-inspired intelligent robotics: theoretical analysis and systematic application, Mach. Intell. Res., 20(1), pp. 1-18, 2023. DOI: https://doi.org/10.1007/s11633-022-1390-8

[6] Zhu, Y., Huang, H., Wang, Y., Han Z., and Zhong, J., Structure design and mathematical modeling of bionic butterfly flapping wing aircraft, in: 2021 IEEE International Conference on Mechatronics and Automation (ICMA), Takamatsu, Japan, 2021, pp. 1249-1254. DOI: https://doi.org/10.1109/ICMA52036.2021.9512601.

[7] Zhang, Y., Wang, X., Wang, S., et al., Kinematic and aerodynamic investigation of the butterfly in forward free flight for the butterfly-inspired flap wing air vehicle[J]. Applied Sciences, 2021, 11(6), pp. 2620. DOI: https://doi.org/10.3390/app11062620

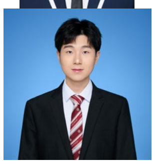
[8] Huang, H., He, W., Zou, Y., and Fu, Q., USTButterfly: a servo-driven biomimetic robotic butterfly, in: IEEE Transactions on Industrial Electronics, 71(2), pp. 1758-1767, 2024. DOI: https://doi.org/10.1109/TIE.2023.3260355.



Y. Mao, is currently pursuing the BSc. degree in Robotic Engineering at Jiangnan University, Wuxi, China. His research interests include computer vision and robot control.
ORCID: 0009-0000-2842-1761

J. Lao is currently pursuing the BSc. degree in Mechanical Engineering at Jiangnan University in Wuxi, China. His research focus on motion simulation and mechanics.
ORCID: /0009-0003-5749-6297

F. Wu, is currently pursuing the BSc. degree in Mechanical Engineering at Jiangnan University, Wuxi, China. His research interests include exoskeletons, robot control, and bionic devices.
ORCID: 0009-0005-6454-2540



M. Li, is currently pursuing the BSc. degree in Robotic Engineering at Jiangnan University, Wuxi, China. His research interests include SLAM, autonomous driving, and robot control.
ORCID: 0009-0007-3454-8073