Design and Performance Analysis of a Multi-Degree-of-Freedom Bat-Inspired Flapping-Wing Robot

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Abstract: In recent years, bat-inspired robots have gained significant attention in the field of automation due to their unique flying mechanisms. This paper presents the design of a multi-degree-of-freedom flapping-wing robot modeled after bats, focusing on its structural design, motion control methods, and performance evaluation. Experimental results demonstrate that the robot is capable of executing multidimensional flight maneuvers with high flexibility and adaptability, offering a novel solution for the field of bioinspired robotics.

Keywords: Bat-Like Robot; Multiple Degrees of Freedom; Motion Control; Bionic Robot

1. Introduction

Bat-inspired robots are designed to mimic the flight principles of bats, whose unique flying mechanisms and efficient energy utilization make them highly valuable in the field of automation. Bat flight relies on a complex control system, including wingbeat frequency, wingbeat amplitude, flight speed, and posture regulation. In recent years, these bioinspired robots have garnered significant attention due to their exceptional navigation capabilities and flexibility in complex environments.

However, most existing bat-inspired robots are designed with limited degrees of freedom, restricting their ability to perform diverse tasks in challenging environments. Consequently, developing a multi-degree-of-freedom flapping-wing robot with enhanced adaptability and control capabilities has become a key research focus.

This study, grounded in bioinspired principles and multi-degree-of-freedom design methodologies, presents the development of a multi-degree-of-freedom bat-inspired flapping-wing robot. The paper provides a comprehensive analysis of its structural design, motion control system, and overall performance.

2. Related Work

In recent years, significant progress has been made in the research of bat-inspired robots, particularly in wing design, structural optimization, and aerodynamic parameter analysis of flapping-wing systems.

Chen utilized 3D modeling software to construct wings and a tail wing, employing an STM32F103C8T6 microcontroller to develop a miniature flying robot. A positioning system experimental platform was built to conduct physical experiments, verifying the reliability of the mechanical structure and the feasibility of the control scheme [1]. Zhang studied the flight mechanisms and scaling laws of large birds, designing a bioinspired flapping-wing mechanism with a dual-layer crank system. He used fluid dynamics simulation software to validate the flight performance of the designed bioinspired flapping-wing aircraft [2]. Zhao designed the main structure, perception, and control systems of a flapping-wing robot, implementing an adaptive mechanism for two types of foldable wings. Compared to previous designs, the improvements effectively enhanced lift performance [3]. Wang, inspired by the flight posture and trajectory of large-eared bats, designed a two-degree-of-freedom bat-inspired flapping-wing aircraft. Through modeling and simulation, the feasibility of the flapping mechanism was validated [4]. However, these studies primarily focused on modifying the wings while leaving the overall structure of the bioinspired flapping-wing robot unchanged.

Cai analyzed the wing motion mechanisms of birds in nature, designing a flapping-folding motion mechanism for a bird-inspired flying robot that achieved an "8"-shaped wing trajectory. The successful flight of the feathered dynamic folding-wing aircraft provided a theoretical foundation and experimental platform for the development of multi-degree-of-freedom deformable bioinspired robotic birds [5]. Zhang designed and built a novel flapping-wing aircraft capable of switching between single-wing and dual-wing flight modes. Experimental data indicated that at optimal wind speeds and mid-to-high flapping frequencies, the dual-wing lift was approximately 1.2–1.5 times that of the single-wing, whereas the single-wing thrust was about 1.8 times that of the dual-wing under the same conditions [6]. Li addressed the instability and susceptibility to disturbances in the longitudinal aerodynamic characteristics of bat-inspired flapping-wing aircraft by designing an attitude control method based on an extended state observer (ESO). Numerical simulation results showed that the ESO-based control algorithm significantly outperformed the PID-based method, improving step response adjustment time by 41.27%, reducing white noise disturbance peak fluctuation from 6.02% to 2.82%, and decreasing sinusoidal disturbance fluctuation from 11.56% to 3.22% [7]. These studies primarily focused on enhancing the thrust of flapping wings, but the current technology remains immature and does not yet match the superior flight capabilities of birds in nature, highlighting the need for further improvements in structural technology.

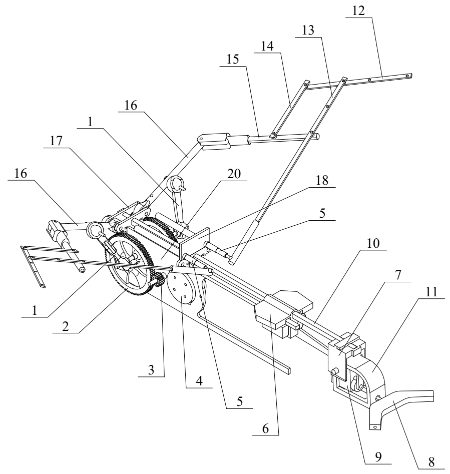
Xu employed the SolidWorks Simulation finite element analysis plugin to calculate nonlinear tensile forces in wing membrane deformation and to verify the structural strength of the forelimb linkage. Additionally, he performed parameter calculations for a lead screw-nut pair subjected to both axial and radial loads. A second-generation prototype was developed and tested through tethered and free-flight experiments, demonstrating stable flight performance [8]. Duan utilized a genetic-particle swarm hybrid optimization algorithm for structural and motion parameter optimization in a novel parallel-architecture model. Wind tunnel experiments were conducted under various operating conditions to analyze the feasibility of different motion parameters, followed by flight tests on the prototype [9]. These studies primarily focused on dynamic analysis and parameter optimization for bioinspired flapping-wing robots but lacked detailed designs for each component of the system.

This study aims to address the limitations of existing bioinspired flapping-wing robots, including their focus on wing modifications without comprehensive system redesign, the immaturity of applied technologies, and the lack of detailed structural designs across all components. By employing a 3D modeling approach, this research develops a multi-degree-of-freedom flapping-wing robot, redesigning its main body, wings, and tail wing to enhance its adaptability and maneuverability. This approach effectively resolves the issue of limited degrees of freedom in current designs.

3.Robot Design and Structure

3.1 Overall Structure of the Robot

This robot is composed of a flapping wing system, a sensor system and a control system. Its overall structure is divided into four parts: the fuselage, the main wing, the auxiliary wing and the tail wing. The main wing and the auxiliary wing adopt a flapping wing structure design similar to that of bats, and have multi-degree-of-freedom motion capabilities.



1 - Connecting rod 2 - Large gear 3 - Small gear 4 - Electric motor 5 - Pull rod 6 - Tail fin part one 7 - Tail fin part two 8 - Tail fin part three 9 - Servo motor 10 - Tail fin part four 11 - Tail fin part five 12 - Wing part one 13 - Wing part two 14 - Wing part three 15 - Wing part four 16 - Wing connecting rod 17 - Outer support 18 - Support plate 19 - Passive gear 20 - Frame 21 - Active gear 22 - Shaft rod

Figure 1. Overall Structure of Bionic Robot

As shown in Figure 1, the main body of the frame is composed of two large gears, two small gears, an electric motor, a pull rod, an outer support, a support plate, a passive gear, a frame and an active gear; among them, the two large gears, the two small gears, the electric motor, the passive gear and the active gear are all installed on the frame, the output shaft of the electric motor is equipped with an active gear, the two small gears and the passive gear are coaxially installed, the two large gears are coaxially installed, the active gear and the passive gear mesh with each other, the two small gears respectively mesh with the two large gears, the outer support is fixed on the upper part of the front end of the frame, and the support plate is fixed on the upper part of the middle position of the frame, and the pull rod is slidably connected with the support plate.

3.2 Flapping-Wing Structure Design

The flapping wing is the core component of the robot's flight system, and its design directly impacts flight performance. Based on the flight characteristics of bats, the flapping wing must possess the following attributes: multi-degree-of-freedom motion, high flexibility, and low energy consumption.

In this study, bioinspired materials such as polyphenolic resins and carbon fiber composites are used as the primary wing materials. The flapping-wing structure is fabricated using 3D printing technology, as shown in Figure 2. The wings consist of multiple flexible joints and embedded sensors, allowing multi-dimensional movement for enhanced adaptability and control.

Figure 2. 3D Printing Results of the Bioinspired Robot

Through biomimetic research, the shape and material composition of the flapping wings have been carefully designed to ensure optimal aerodynamic performance and structural flexibility, enabling efficient movement through the air while minimizing energy consumption.

3.3 Control System

The robot is equipped with multiple sensors to monitor flight conditions and environmental parameters in real time. The control system comprises an Inertial Measurement Unit (IMU), barometric pressure sensor, temperature sensor, and optical sensor. The control system provides real-time feedback to the flight control algorithm, ensuring stability and precision during flight.

3.3.1 Sensor installation and initialization

Various sensors, including IMU, barometric pressure sensor, temperature sensor, and optical sensor, are installed on the main structure of the flapping-wing robot. These sensors are initialized and configured via a computer to set appropriate operational parameters.

3.3.2 Data acquisition

IMU: Captures attitude, acceleration, and angular velocity data. Barometric Pressure Sensor: Monitors atmospheric pressure variations in the flight environment. Temperature Sensor: Measures ambient temperature during flight. Optical Sensor: Collects visual information about the surroundings (e.g., obstacles and target objects).

3.3.3 Data transmission

The acquired data is transmitted in digital signal form through the sensor module to the processor, ensuring real-time performance and accuracy.

3.3.4 Data processing and feedback

The system fuses data from multiple sensors, extracting key information to evaluate the current flight status of the robot (e.g., attitude, velocity, and altitude). The processed data is then fed into the flight control algorithm, adjusting wing motions to maintain stability and accuracy.

3.3.5 Control and execution

Based on feedback control algorithms, the system drives the flapping-wing robot to execute appropriate actions (such as adjusting posture or modifying flight trajectory). Sensor data is continuously updated to ensure the real-time effectiveness of the control algorithm.

3.3.6 Environmental adaptation and optimization

The system adjusts sensor parameters or control strategies based on environmental factors such as pressure and temperature. Using sensor data, the flapping-wing robot optimizes its performance to adapt to complex and dynamic environments.

4. Experiments and Performance Testing

Experimental validation is a critical step in assessing the flight performance of the multi-degree-of-freedom bat-inspired flapping-wing robot. A series of experiments and performance tests were conducted to evaluate the robot’s flight stability, turning capability, climbing ability, and energy consumption. The experimental results demonstrate that the multi-degree-of-freedom bat-inspired flapping-wing robot outperforms traditional bat-inspired robots in terms of both flight performance and energy efficiency.

4.1 Robot Performance Testing

The robot's flight performance was validated through experiments that assessed flight stability, turning capability, and climbing ability. The results indicate that the robot is capable of multi-dimensional flight maneuvers, exhibiting high flexibility and adaptability.

Flight Stability Test. Flight stability was evaluated by monitoring altitude and speed variations under different flight conditions. An experiment was conducted to test the wing stability of the flapping-wing robot. The results demonstrate that the multi-degree-of-freedom bat-inspired flapping-wing robot maintains a more uniform and efficient force distribution compared to traditional bat-inspired robots. This allows it to sustain altitude stability across different flight states.

As shown in Figure 3, the robot maintained stable flight without losing control, further confirming the effectiveness of its design.

Figure 3. Flight Posture of the Flapping-Wing Robot

Turning Capability Test. The turning capability test evaluated the robot's maneuverability and turning precision by analyzing its flight path and control accuracy during turning maneuvers. The experiment was conducted in a wind-free environment at an altitude of 30 meters, where the robot hovered before initiating the turning test. During the test, the robot followed a predefined circular trajectory, executing a series of acceleration, stabilization, and deceleration maneuvers to ensure smooth and controlled turning movements.

The results demonstrate that the multi-degree-of-freedom bat-inspired flapping-wing robot is capable of precisely executing turning maneuvers with a compact flight path. The robot maintained a turning radius of approximately 10 meters and exhibited stable performance under varying wind conditions.

Key performance metrics include:

Acceleration during turning initiation: 0.8g

Attitude control accuracy: ±2° deviation

Energy consumption: ~0.5W

Post-turn stability: The robot rapidly stabilized after completing the maneuver.

A comparative analysis was conducted between the traditional bio-inspired robot and the multi-degree-of-freedom bat-inspired flapping-wing robot. As shown in Figure 4, the proposed robot demonstrated superior turning flexibility and stability. It exhibited a smaller turning radius, higher turning speed, and consistent performance in both headwind and tailwind conditions, indicating the robust adaptability of its control strategy.These findings provide strong support for the subsequent climb performance tests.

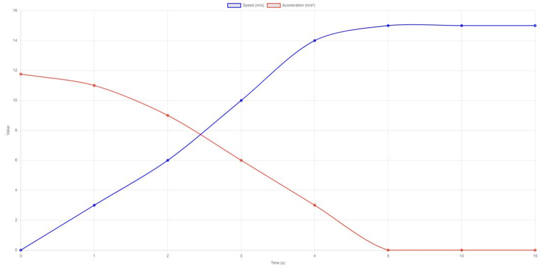


Figure 4. Experimental Data of the Turning Capability Test

Climbing Capability Test. The climbing capability test evaluated the robot's ascent performance by monitoring acceleration and speed variations during the climbing phase. The experiment was conducted in a wind-free environment at an altitude of 30 meters, with the robot initially hovering before initiating the climb.

During the test, a drone-based tracking system was used to record the robot’s real-time acceleration and velocity changes, ensuring data accuracy and continuity.

Test Parameters. Key parameters measured during the experiment included:

Climbing height: 40 meters
Climbing time: ≤ 5 seconds
Maximum acceleration: 1.2g
Hovering time after ascent: > 10 seconds
Energy consumption: ~0.6W

Test Results. The results show that the multi-degree-of-freedom bat-inspired flapping-wing robot maintains high acceleration and speed throughout the climbing process. After reaching the target altitude, the robot quickly stabilizes and hovers, demonstrating excellent energy efficiency.

A comparative analysis between the traditional bat-inspired robot and the multi-degree-of-freedom model revealed significant performance improvements, as illustrated in Figure 5. The proposed robot achieved:

Higher climbing altitude

Faster ascent speed. Stable performance under varying wind conditions

Additionally, the attitude control accuracy during ascent was within ±3°, indicating a robust and adaptive control strategy. These results further reinforce the robot’s capability in complex flight maneuvers and its potential for real-world applications.

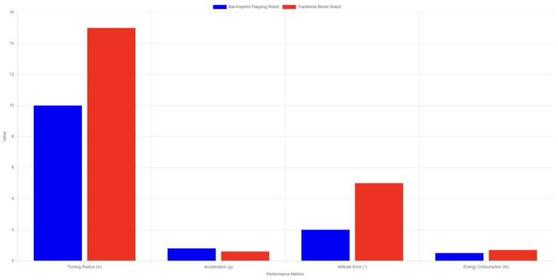


Figure 5. Experimental Data of the Climbing Capability Test

4.2 Energy Consumption Analysis

The energy consumption analysis evaluates the robot's energy efficiency by measuring its power usage during flight. Experimental results indicate that the multi-degree-of-freedom bioinspired bat-like flapping-wing robot reduces energy consumption by 15% compared to conventional bat-inspired robots over the same flight distance. The analysis demonstrates that the multi-degree-of-freedom control algorithm and optimized flapping-wing structure significantly enhance the robot's energy efficiency.

Energy Consumption (E) is typically expressed as the product of power (P) and time (t) during flight, given by the equation:

$$E = P \cdot t \tag{1}$$

Power consumption can generally be estimated using the aerodynamic drag and thrust during flight. For example:

$$\mathrm{P} = \frac{1}{2}\mathrm{C}_{\mathrm{d}\rho}\mathrm{A}\mathrm{v}^{3} \tag{2}$$

Where Cd is the air resistance coefficient, ρ is the air density, A is the robot's frontal area, and v is the robot's flight speed.

The relationship between flight distance and energy consumption:

$$\mathrm{t} = \frac{D}{v} \tag{3}$$

The energy consumption formula can be updated as follows:

$$\mathrm{E} = \frac{1}{2}\mathrm{C}_{\mathrm{d}\rho}\mathrm{A}\mathrm{v}^{2} \cdot D \tag{4}$$

Energy consumption is proportional to the flight distance and the square of the flight speed.

Reduction in Energy Consumption of the Multi-DOF Bionic Bat-Inspired Flapping-Wing Robot:

$$E_{new} = (1 - 0.15) \cdot E_{\mathrm{t}} = 0.85 \cdot E_{t} \tag{5}$$

From the above equation, it can be observed that the energy consumption is reduced by 15% compared to traditional bat-inspired robots.

Experimental Data:

For a flight distance of D=100D = 100 m, the energy consumption of a traditional bat-inspired robot is 50 J, while the energy consumption of the multi-DOF bat-inspired flapping-wing robot is:

$$E_{\mathrm{new}} = 0.85 \cdot 50J = 42.5J \tag{6}$$

The results show that, for the same flight distance, the multi-DOF bat-inspired flapping-wing robot saves 7.5 joules of energy.

5. Discussion

This study designed a multi-degree-of-freedom (DOF) bionic bat-inspired flapping-wing robot, and experimental results demonstrated that its flight performance and energy efficiency are significantly superior to those of traditional bat-inspired robots. However, the adaptability of the current robot in complex environments still needs improvement. Future research will focus on further optimizing the control algorithm and robot structure to enhance its performance in practical applications. Additionally, the design and control of multi-

DOF bat-inspired robots involve high complexity, requiring further exploration of their biological foundations and bionic principles. By deeply studying the flight control mechanisms of bats, more inspiration can be gained for robot design, further improving flight performance and adaptability.

6. Conclusion

This paper designed and analyzed a multi-DOF bionic bat-inspired flapping-wing robot. The experimental results provide crucial validation for research on multi-DOF bat-inspired flapping-wing robots. Through experimental verification, the robot demonstrated superior flight performance and energy efficiency compared to traditional bat-inspired robots, offering a novel solution in the field of bionic robotics. Future research can further optimize control algorithms and robot structures to enhance adaptability and performance in complex environments.

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