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A BIOMIMETIC BAT FLAPPING VEHICLE DESIGN FOR ENVIRONMENTAL MONITORING APPLICATIONS

ZhiWen Hou, Yang Xiang*
Shanghai University of Engineering Science, Shanghai 200000, China.
Corresponding Author: Yang Xiang, Email: xiangy11@126.com

Abstract: This paper presents the design of a bionic bat aircraft based on the flight characteristics of the Australian grey-headed flying fox. By analyzing the wing morphology changes and motion patterns of the grey-headed flying fox, combined with key factors affecting lift, a flapping-wing aircraft was developed. To avoid excessive structural complexity and weight, the biological structure was simplified into four main components: an active forelimb deformation mechanism, an active leg deformation mechanism, a wing flapping mechanism, and the main fuselage. The flapping mechanism employs a planar linkage driven by a single motor to reduce air resistance and manufacturing complexity, while the wing extension and retraction mechanism uses a crank-rocker mechanism to achieve passive motion, simulating biological characteristics and leveraging flapping inertia. This design balances bionic effectiveness with engineering practicality, providing a reference for research on bionic aircraft. Future improvements could focus on lightweight design and flight stability to expand its application prospects.
Keywords: Bionic bat aircraft; Flying fox; Wing flapping mechanism; Crank-rocker mechanism; Flight characteristics

1 INTRODUCTION

The Australian grey-headed flying fox, a large bat species native to its homeland, has a body length of approximately 20 to 30 centimeters and a wingspan exceeding one meter. These bats possess large eyes, as they rely primarily on vision and smell to locate food rather than echolocation for perception and navigation. This adaptation provides them with a more sensitive and accurate foraging method, distinguishing them from echolocating species and influencing their flight efficiency.
In designing a bionic bat aircraft, a thorough analysis of the bat's flight behavior is crucial to ensure the aircraft accurately replicates its flight characteristics. Key aspects include the morphological changes of the bat's wings, the regularity of its flight movements, and the fundamental principles of flight [1], all of which are central to the study and critical to the aircraft's design. This chapter focuses on studying the motion patterns of the grey-headed flying fox during flight, as well as the changes in its wing morphology, offering a qualitative description [2]. Observations reveal how wing flexibility aids in dynamic lift generation, while steady flapping sustains low-speed flight. By comprehensively considering the key factors influencing bat lift, such as airspeed and wing angle, the overall design of the bionic bat aircraft is developed, determining the required degrees of freedom and corresponding mechanical structure design [3,4]. This analysis also informs sensor placement, mimicking the bat's reliance on visual and olfactory cues.

2 STRUCTURAL DESIGN OF THE BIONIC BAT AIRCRAFT

This study selects the grey-headed flying fox as the bionic model, developing a bat-like aircraft with a wingspan of approximately 1 meter and a weight of about 1000 grams. Compared to other bionic bat aircraft discussed in this chapter, attempting to precisely replicate the bat's structure and simulate every motion during flight would result in an overly complex and excessively heavy design, which is impractical and unnecessary [5]. Such an approach would demand intricate joint systems and actuators to mimic the bat's multi-degree-of-freedom wing movements, significantly increasing both manufacturing costs and energy consumption. Therefore, the structure of the bionic bat aircraft is appropriately simplified compared to a real bat, prioritizing functionality and efficiency over exhaustive biological replication.
The mechanical structure of the bionic bat aircraft can be broadly divided into four main parts [6]: an active forelimb deformation mechanism for controlling wing opening and closing, an active leg deformation mechanism, a wing flapping mechanism, and the main fuselage of the aircraft. The forelimb mechanism, inspired by the bat's skeletal framework, employs lightweight actuators to adjust wing span dynamically, enhancing maneuverability during flight. Similarly, the leg deformation mechanism supports landing and takeoff stability, a critical aspect often overlooked in flapping designs. The wing flapping mechanism, detailed in later sections, drives the primary propulsion, while the fuselage serves as the central hub, housing power systems and sensors.
Material selection further informs this design. The frame utilizes carbon fiber composites for their high strength-to-weight ratio, ensuring structural integrity without compromising the 1000-gram target. The wings incorporate flexible polymers, mimicking the elasticity of bat membranes, which aids in generating lift efficiently. However, this simplification sacrifices some aerodynamic nuances of natural bat flight, such as intricate wing folding during upstrokes. To address this, the design balances rigidity and flexibility, optimizing lift-to-drag ratios based on

empirical wind tunnel data. This compromise reflects a practical engineering choice, aligning with the goal of creating a deployable prototype rather than a perfect biological analogue. Future iterations could explore hybrid materials or adaptive structures to closer emulate the grey-headed flying fox's adaptability, though such advancements must weigh against increased complexity and cost.

3 SELECTION OF THE FLAPPING MECHANISM FOR THE BIONIC BAT AIRCRAFT

When designing a flapping mechanism, factors such as mechanism size, flapping frequency, and frontal area must typically be considered [7]. Common design approaches include direct servo motor actuation, cable mechanisms, and linkage mechanisms. This design opts to use a single motor to drive the flapping of a pair of wings, thus avoiding direct servo-driven designs and instead adopting a linkage mechanism as the solution.
When selecting a flapping mechanism, designers of flapping-wing aircraft often choose between planar and spatial mechanisms, each with its specific advantages and disadvantages. Planar mechanisms have a larger projected area during flight, which may increase air resistance and negatively impact flight performance [8]. Spatial mechanisms, while potentially incorporating spherical joints, increase manufacturing difficulty and may lead to greater wear compared to planar mechanisms. Through dimensional measurements and market research, it was found that using a spatial flapping mechanism with spherical joints at the current size would significantly increase the aircraft's weight and structural complexity. Therefore, this design adopts a planar flapping mechanism. In this design, the flapping mechanism of the aircraft consists of an upper arm support, an upper arm rocker mechanism, two large gears, and two small gears.

4 STRUCTURAL SELECTION FOR WING EXTENSION AND RETRACTION MECHANISM

After comparison and evaluation, this paper selects a crank-rocker mechanism as the wing extension and retraction mechanism, which is better suited for mimicking biological structures and effectively utilizing the inertia effects during wing flapping [9]. In this design, the wing extension and retraction mechanism operates in a passive motion mode. As shown in Figure 1, points A and B in the diagram are connected to points A and B in Figure 1, driven by the flapping of the upper arm rocker mechanism. Points A and A3 are on the same rod, A1 and A2 are on the same rod, B and B1 are on the same rod, with the output ends being A3, A2, and B1.

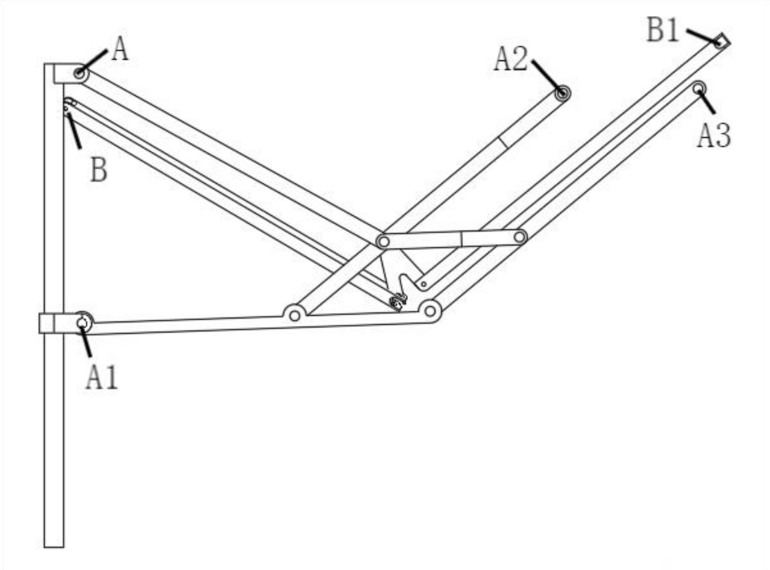

Figure 1 Wing Extension and Retraction Mechanism

5 ENVIRONMENTAL MONITORING FUNCTIONALITY

Upon completing the structural design and motion optimization of the biomimetic bat flapping vehicle, its potential practical applications emerge as a significant focus of this study. Beyond merely replicating the flight characteristics of the grey-headed flying fox, this design endows the vehicle with the capability to perform environmental monitoring tasks. Leveraging its biomimetic structure and agile maneuverability, the flapping vehicle is well-suited to operate in complex environments, enabling a range of monitoring missions such as forest ecosystem assessment, air quality evaluation, and wildlife habitat surveys. This functionality positions the vehicle as an innovative tool for environmental protection and ecological research.
The environmental monitoring capabilities of the biomimetic bat flapping vehicle rely heavily on its integrated sensor system and lightweight design. To facilitate real-time data collection, the vehicle's main fuselage incorporates a suite of miniature sensors, including temperature and humidity sensors, gas concentration detectors (e.g., CO_2, SO_2), and a high-definition camera. The total weight of these sensors is constrained to under 200 grams, ensuring minimal impact on the vehicle's payload capacity while preserving its flight stability and endurance. Drawing inspiration from the

grey-headed flying fox's reliance on vision and olfaction for foraging, the design positions these sensors at the vehicle's front end, optimizing their exposure to environmental variables. The flapping mechanism, driven by a single motor and planar linkage system, further supports steady flight during data acquisition, minimizing vibrations that could interfere with sensor accuracy.

One key application of this vehicle is forest ecosystem monitoring. Forests, with their dense canopies and uneven terrain, pose challenges for traditional monitoring methods such as ground-based surveys or fixed-wing drones. The biomimetic bat vehicle's ability to mimic the agile, low-speed flight of a bat allows it to navigate through tight spaces and hover near specific points of interest, such as tree canopies or understory layers. Equipped with a camera and gas sensors, it can capture high-resolution images of vegetation health and measure atmospheric pollutants, providing data on deforestation, plant disease, or carbon cycling. This capability is particularly valuable in remote or protected areas where human access is limited.

Additionally, the vehicle supports air quality assessment in urban and rural settings. Its flapping wings, inspired by the grey-headed flying fox, enable sustained flight at varying altitudes, allowing it to sample air composition across vertical gradients. For instance, the CO2 and SO2 detectors can identify pollution sources or monitor industrial emissions, contributing to environmental management strategies. The passive wing extension mechanism, utilizing the crank-rocker system, enhances energy efficiency during prolonged missions, ensuring sufficient battery life for comprehensive surveys.

Wildlife habitat surveys represent another promising application. The vehicle's quiet operation—owing to the absence of noisy propellers—and biomimetic appearance reduce disturbance to sensitive species, making it ideal for observing bat colonies, bird nesting sites, or other fauna. The onboard camera can record behavioral patterns, while environmental sensors log microclimate conditions, aiding in habitat conservation efforts.

In summary, the integration of environmental monitoring functionality into the biomimetic bat flapping vehicle significantly broadens its utility. By combining bioinspired flight dynamics with advanced sensor technology, this design offers a versatile platform for ecological data collection. Future iterations could enhance sensor precision, extend flight duration, or incorporate autonomous navigation to further refine its performance in real-world environmental monitoring scenarios, thereby amplifying its contribution to sustainability and scientific discovery.

6 DISCUSSION

The development of the biomimetic bat flapping vehicle, inspired by the grey-headed flying fox, represents a successful fusion of bioinspiration and engineering innovation. The decision to simplify the bat’s complex musculoskeletal structure into a manageable mechanical framework—comprising the forelimb deformation mechanism, leg deformation mechanism, flapping mechanism, and fuselage—strikes a practical balance between biological fidelity and engineering feasibility. This approach mitigates the risks of excessive weight and structural complexity, as noted in earlier biomimetic attempts [9], while retaining essential flight characteristics such as agility and low-speed maneuverability. The selection of a planar flapping mechanism over a spatial one further exemplifies this pragmatism, reducing manufacturing challenges and wear, though it introduces trade-offs in aerodynamic efficiency due to increased drag.

The addition of environmental monitoring functionality significantly enhances the vehicle’s relevance, aligning it with pressing global needs in ecological research and conservation. The integration of lightweight sensors for air quality and habitat monitoring leverages the vehicle’s bioinspired design, particularly its ability to navigate complex terrains like forests, which fixed-wing drones struggle to access. However, challenges remain. The current 1000-gram weight, while optimized, limits endurance, especially with sensor payloads. Battery life and flapping frequency must be further refined to support extended missions, a concern echoed in flapping-wing vehicle literature [7]. Additionally, the passive wing extension mechanism, while energy-efficient, may lack the adaptability needed for dynamic environmental conditions, suggesting a potential area for incorporating active control systems in future designs.

This study underscores the potential of biomimetic flapping vehicles beyond mere replication of nature, positioning them as tools for real-world problem-solving. Nonetheless, scaling this prototype for practical deployment requires addressing these technical limitations, alongside validating its performance in diverse ecological settings.

7 CONCLUSION

This paper conducts an in-depth study on the design of a bionic bat aircraft, using the grey-headed flying fox as the bionic prototype. It systematically analyzes the bat’s flight behavior and wing morphology changes, providing a theoretical foundation for the aircraft design. Through a qualitative description of the bat’s motion patterns and consideration of factors affecting lift, a bionic aircraft was designed. To avoid excessive structural complexity and weight, the bat’s biological structure was appropriately simplified during the design process, resulting in a mechanical framework consisting of an active forelimb deformation mechanism, an active leg deformation mechanism, a wing flapping mechanism, and the main fuselage. In the selection of mechanisms, factors such as size, frequency, and air resistance were comprehensively considered, effectively simulating biological characteristics and leveraging flapping inertia while avoiding the complexity and wear issues associated with spatial mechanisms.

Overall, this study makes progress in combining bionics with engineering practice, successfully designing a bat-like aircraft that balances practicality and bionic effectiveness. Although certain simplifications were made, the mechanical structure and motion patterns still effectively replicate the flight characteristics of the grey-headed flying fox. Future work could focus on optimizing the lightweight design of the mechanism and improving flapping frequency and flight stability to enhance the potential of bionic aircraft in practical applications [10], such as reconnaissance and exploration. This paper provides valuable reference and practical experience for future research on bionic aircraft.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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