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A Review of the Design, Development, and Application of Bio-inspired Unmanned Aerial Vehicles

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Abstract

This paper reviews the research achievements in the design, development, and application of bio-inspired Unmanned Aerial Vehicles (UAVs). Through the collection and analysis of relevant domestic and foreign literature, the design progress of bionic UAVs in the two major areas of airframe structure and control intelligence is summarized, and several possible future research directions are proposed. Research indicates that bio-inspired design significantly enhances the environmental adaptability, stealth, and energy efficiency ratio of UAVs. Future research will focus on power source optimization for long-distance flight, obstacle avoidance at extremely close range, and multi-source information fusion and autonomous decision-making.

Keywords

Bionic UAV; Design Development; Application Review; Airframe Structure; Control Intelligence.

1. Introduction

In today's society, UAVs have been widely used in many fields such as aerial photography, agricultural irrigation, logistics transportation, geographic surveying, and equipment inspection due to their low cost, portability, and high maneuverability.

However, traditional UAVs are limited by fixed-wing or rotary-wing structures, resulting in significant bottlenecks in terms of adaptability to complex environments, stealth, and energy efficiency. For example, most fixed-wing drones rely on runways for takeoff and landing, while rotary-wing drones have limited endurance, and both are insufficiently maneuverable in scenarios such as strong winds and confined spaces.

The rise of biomimetics has provided new solutions to these technological bottlenecks in UAVs.

By imitating the structure and behavior of organisms in nature, drones with superior performance can be designed. For example, studying the flight capabilities of hummingbirds can lead to the design of more agile flapping-wing aircraft; referencing the flapping-wing flight behavior of albatrosses can significantly improve the long-term loiter capability of fixed-wing drones; simulating the behavioral models of social organisms such as ant colonies and bee colonies can yield swarm algorithms suitable for drone swarm control.

Because bionics has diverse applications in the field of drones, researchers often find it difficult to choose a direction. Therefore, this paper aims to summarize the research results in the field of bionic drones and propose future research directions to provide a reference for the further development of drone technology.

2. Overview of Bionic Drone Design Development

Bionics has a wide variety of applications in the field of drones. To better summarize current research in bio-inspired UAVs, this paper categorizes the selected studies as follows: The first category involves bio-inspired design of airframe structures, such as fuselage shape and wing configuration. Based on the differences in drone lift modules, this category is further divided into four parts: rotary-wing drones, fixed-wing drones, flapping-wing drones, and other drone modules. The second category is the bionic design based on the drone control system, divided into four areas: attitude control, swarm control, path planning, and near-field obstacle avoidance.

2.1 Bionic Design in the Field of Drone Body Structure

2.1.1 Rotary-Wing Drones

Rotary-wing drones, as one of the mainstream drone types, are widely used in production and daily life due to their vertical take-off and landing and hovering capabilities. However, the noise and energy efficiency problems generated by traditional rotary-wing drones during flight have been a persistent concern. To solve these problems, researchers have begun to explore the bionic design of rotary-wing drones.

Currently, the biomimetic direction of rotary-wing UAVs mainly focuses on imitating the structure of bird feathers to reduce rotor disturbance noise. Several research teams at home and abroad have conducted research in this direction. For example, Lan Tian of the National University of Defense Technology, Wei Yuliang of the University of Science and Technology of China, as illustrated in Figure 1, Chen Weijie of Northwestern Polytechnical University, and Su Xin of Nanchang Aviation University have all studied and explored the feather structure of birds such as owls[1-4]. By mimicking their microstructures, they designed bio-inspired rotors with serrated leading/trailing edges to achieve noise reduction, which effectively improves the stealth of rotary-wing UAVs during flight.

Figure 1. Biomimetic noise reduction rotor structure (Source: Left [1], Right [2])

2.1.2 Fixed-wing UAVs

As another popular form of UAV, fixed-wing UAVs have significant advantages in long-distance flight; however, due to their take-off and landing capabilities being limited by the environment and their insufficient maneuverability in complex environments, they are still subject to many limitations in actual use. To address these issues, researchers have also explored biomimetic design for fixed-wing UAVs.

Currently, biomimetic design for fixed-wing UAVs has evolved from simply mimicking bird wing shapes to systematically optimizing wing structures. In terms of airfoils, imitating the airfoils of efficient gliding birds like seagulls and albatrosses has significantly improved the UAVs' lift-to-drag ratio and endurance [5,6]. In terms of wingtip structures, winglet designs inspired by bird wingtip feathers can effectively reduce induced drag and improve aerodynamic and control performance[7,8]. In terms of adaptive structures, designs such as variable-sweep wings and biomimetic variant wings

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enable UAVs to dynamically adapt to different flight states[9-12]. Similar to noise reduction design for rotary-wing UAVs, biomimetic technology has also been widely applied in noise reduction for fixed-wing flight[13,14]. In addition, biomimetic technology has expanded the sources of design inspiration, such as mimicking the convex structure of humpback whale flippers, which can improve the stall characteristics of wings at low Reynolds numbers[15].

In addition to biomimetic designs based on biological aerodynamic structures, designs based on biological shapes also have a place. For example, agricultural bird-repelling drones designed based on the shape of birds of prey are more effective than traditional sound and light bird-repelling devices[16]; another example is cross-medium drones designed based on the shape of kingfishers, water beetles, etc., whose special aerodynamic structure can perform actions in both atmospheric and water media as the Figure 2 and 3 show[17-20].

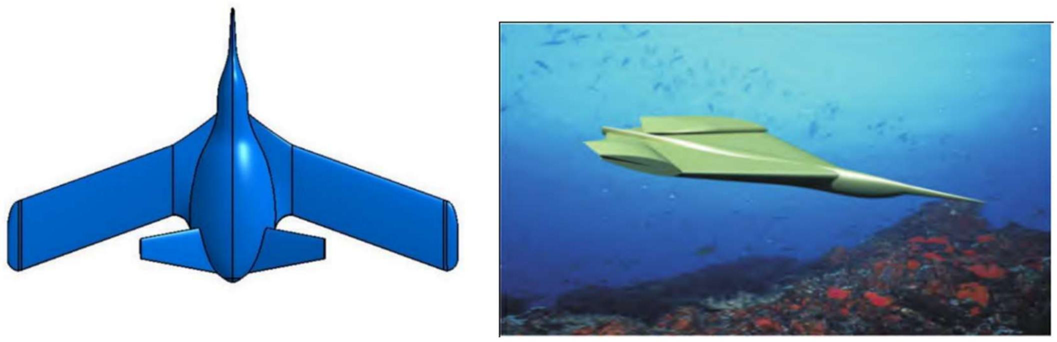

Figure 2. Aerodynamic shape design of cross-medium aircraft (Source: left[17], right[18])

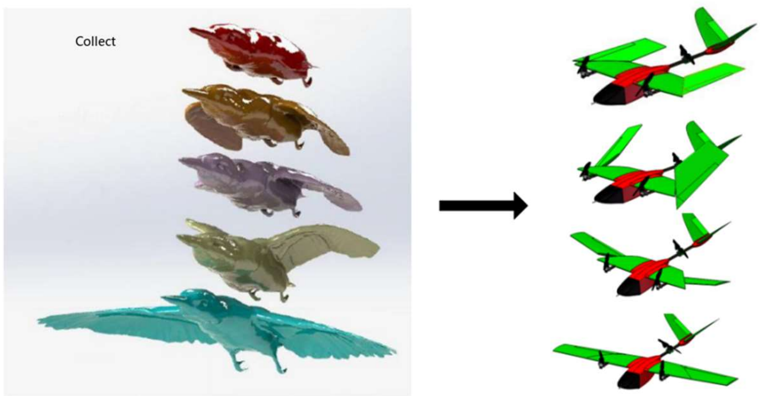

Figure 3. Bionic folding tri-rotor cross-medium drone design (Source:[19])

2.1.3 Flapping-wing Drones

Flapping-wing UAVs, as the type that most visually represents the "bio-inspired" concept of UAVs, are the easiest objects to consider when ordinary people or researchers think about the concept of "bionic drones". Based on the differences in their biomimetic flight mechanisms, flapping-wing UAVs can be divided into two structures: as shown in Figure 4, flapping-wing flight modeled after birds and bats and flapping-wing flight modeled after insects[21-26]. The two structures differ significantly in aerodynamic mechanisms, energy consumption, and noise. Due to the extremely complex unsteady aerodynamic characteristics, existing research focuses on flexible multibody dynamics simulation, aerodynamic analysis of flexible wings and tails, and dynamic modeling of tailless layouts to reveal the mechanisms of their high maneuverability and efficient flight[27-29].

In addition, researchers have attempted to combine the flight principles of flapping-wing UAVs with those of fixed-wing UAVs to obtain a new type of UAV that integrates the advantages of both[30].

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The special flight structure of flapping-wing UAVs has also inspired researchers to consider their application prospects in different environments, especially in the context of exoplanet exploration[31].

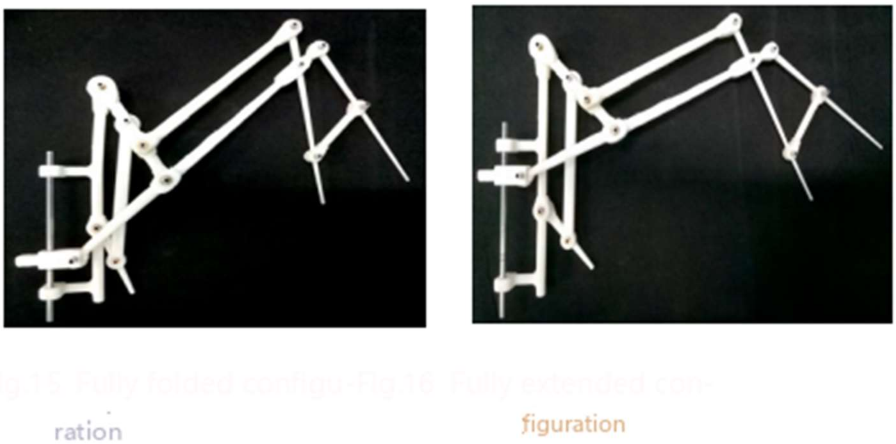

Figure 4. Bat-like flapping wing structure design (Source: [22])

2.1.4 Other UAV Modules

In addition to the airframe structure, the biomimetic design direction of UAV structure also includes the fuselage, sensor components, take-off and landing structure, etc. Among them, the UAV take-off and landing structure is a field that researchers focus on, and it can be further subdivided into multiple directions according to different research results. For example, the high-strength landing gear beam tube structure imitating bamboo, the UAV ejection system based on pneumatic tendons, the quadruped biomimetic folding landing gear suitable for multi-rotor UAVs, etc.[32-35]; as well as the bat-inspired inverted perching structures, the wall take-off and landing perching structure imitating insects, geckos, etc., the perching structure imitating bird claws, etc.(see Figure 5)[36-41].

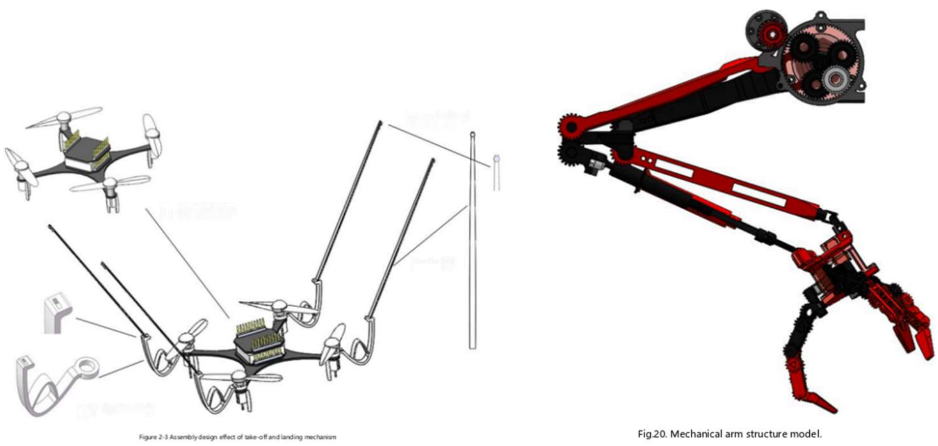

Figure 5. Bionic vertical take-off and landing structure design and eagle claw-like robotic arm structure design (Source: Left [38], Right [39])

In addition to the take-off and landing components, other structures are also considered by researchers. For example, a deformable bionic nose cone structure was designed based on the structure of the bee's abdomen,as the Figure 6 shows[42]; and a new type of UAV visual inertial positioning system was built by referring to the structure of the swan's neck[43].

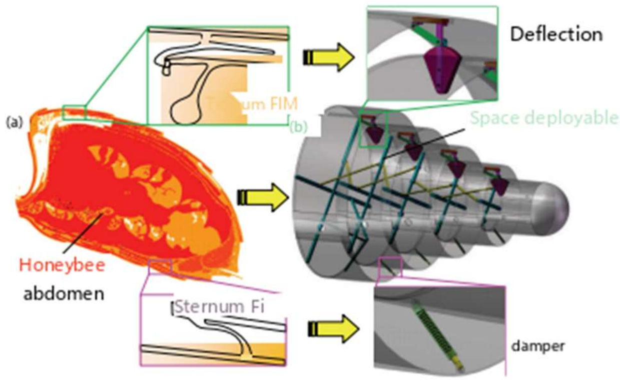

Fig.5 Bionic design of morphing nose cone for aerospace vehicle.
FIM: the intersegmental fold membrane.

Figure 6. Bio-inspired Nose Cone Structure Design (Source: [42])

2.2 Bionic Design in the Field of UAV Control System

2.2.1 Attitude Control

UAV attitude control is a key factor in ensuring its stable flight. Traditional attitude control methods often rely on complex sensors and algorithms. In contrast, the rapidly developing field of bio-inspired attitude control achieves efficient and rapid adjustment by mimicking organisms' natural regulation mechanisms.

In terms of flight control strategies, many studies have shown innovative results. For example, the insect-type UAV flight strategy designed by imitating the flight of insects and using the principles of aerodynamics can automatically adjust its attitude and reduce its dependence on external sensors[44]; another example is the new coordinate system proposed by imitating the relationship between the wings and the center of mass when insects fly, which has lower requirements for yaw torque and better robustness than the traditional control framework[45]; in addition, there is a UAV attitude correction algorithm developed by imitating the principle of polarized light positioning of biological organisms, whose accuracy, anti-interference ability and other parameters are significantly improved on the basis of traditional methods[46].

2.2.2 Swarm Formation

In terms of swarm formation, biomimetic intelligent algorithms have shown great potential by simulating the cooperative mechanism of biological groups. Among them, algorithms based on navigation behavior (e.g., Pigeon-Inspired Optimization, PIO) simulate how pigeons use geomagnetism and landmarks for navigation, enabling coordinated group movement. Researchers have made various improvements to address the problem of it being prone to getting trapped in local optima[47-49]. Algorithms based on hunting-defense behavior (such as the wolf pack algorithm, eagle-rabbit game, etc.) simulate the hunting and escape strategies in nature and are suitable for multi-target tracking and defense tasks[50-52]. In addition, some studies have tried to integrate the advantages of different algorithms or combine them with consistency theory to improve the stability and adaptability of swarms in complex environments[53, 54]. Other swarm-related research includes a flapping-wing aircraft control system based on the leader-follower method, an algorithm suitable for flapping-wing aircraft to fly in swarms in noisy environments, and a swarm cooperative tracking strategy based on the principle of infection-immunity[55-57].

2.2.3 Path Planning

Path planning for long-distance flight is a critical aspect of UAV autonomous navigation. However, traditional path planning methods often rely on pre-set maps and algorithms, and their flexibility and reliability are often not guaranteed. Path planning using biomimetic principles draws inspiration from the excellent navigation capabilities of organisms, and its performance is significantly improved

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compared with traditional methods. For example, by imitating the homing behavior of pigeons, a long-distance navigation algorithm using natural beacons such as the Earth's magnetic field has been developed[58]. Various swarm intelligence algorithms (such as ant colony, wolf pack, whale optimization algorithm, etc.) have also been introduced and improved to solve the high-dimensional and multi-constraint problems in three-dimensional path planning[59-64]. Some studies have even attempted to model the navigation mechanism of grid cells in the animal brain or the pathfinding strategies of insects such as fruit flies, providing new ideas for navigation in GPS-denied environments[65,66].

2.2.4 Obstacle Avoidance

Rapid obstacle avoidance at medium and close ranges is crucial for the safe flight of UAVs. Traditional obstacle avoidance methods often rely on external sensors and complex algorithms, and their reaction speed is often unsatisfactory. However, obstacle avoidance methods designed by bionics are realized by imitating the natural obstacle avoidance mechanism of biological organisms, and their avoidance performance is often better than that of traditional methods.

In terms of near-range obstacle avoidance, the LGMD neurons of locusts have attracted much attention due to their rapid response characteristics to approaching objects. Researchers at Guangxi University developed a series of biomimetic vision algorithms based on this, which effectively improved the drone's ability to detect small obstacles such as power lines and its real-time obstacle avoidance by fusing with other neuron models (such as fruit fly LPLC2), introducing attention mechanisms, or optimizing warning logic[67-69].

In addition, breakthroughs in the field of bionic vision have also contributed to the obstacle avoidance problem. For example, the landing algorithm designed based on the principle of bionic eye vision can effectively avoid the blind spots and other problems caused by traditional binocular vision technology, thereby achieving zero blind spots and precise obstacle avoidance landing[70]; another example is the symmetrical interactive binocular linkage vision system composed of two unmanned aerial vehicle systems, which has significantly improved performance compared to the traditional binocular vision system[71].

3. Future Research Discussions

As can be seen from the above, in the current research on bionic unmanned aerial vehicles, researchers often conduct bionic design based on the characteristics of a certain organism or a certain type of organism. This design mode is highly targeted and can effectively avoid detours that may be encountered in the research and development process, speed up the process and reduce risks; however, at the same time, the lack of integrated design also leads to the neglect of synergistic effects within biological systems. For example, the flapping-wing aircraft designed to mimic the flapping of insects will not have the support of corresponding sensor and control system design, and its final flight flexibility and other effects will be far inferior to the original version.

As can be seen, if biomimetic design can be integrated from two or more aspects, the advantages brought by bionics can be better utilized. This is also a relatively minor aspect involved in biomimetic drone design to date. The following are some biomimetic drone design ideas for reference.

3.1 Power Source Optimization for Long-Distance Flight

To address the problem of insufficient power source for drones during long-distance flight, the process of birds ascending by hovering with the help of near-ground hot air can be simulated. Birds can use the rising air currents of hot air to save energy during flight, achieving long-distance unreplenished flight. This behavior can be applied to drone trajectory planning tasks. By using infrared sensors to detect the location of near-ground warm air, the drone can actively seek out and utilize these air currents to climb to high altitudes for gliding. This method can significantly reduce the energy consumption of drones and extend their flight distance and time.

In specific implementation, high-precision infrared sensors can be installed on the drone to detect the temperature distribution of the surrounding environment in real time. By analyzing near-surface temperature data using algorithms, potential areas of rising hot air currents are identified. The UAV then adjusts its flight path planning based on this information, actively seeking out and utilizing potential hot air currents along its path for ascent and gliding. Simultaneously, corresponding biomimetic flight attitude control algorithms need to be developed to ensure the stability and safety of the UAV when utilizing hot air currents, such as when entering or exiting hot air current cyclones.

3.2 Instantaneous Obstacle Avoidance at Extremely Close Range

Insects such as mosquitoes rely on receptors on their antennae to sense the minute air currents created by human movement, thus avoiding being slapped by a human hand. This sensitive airflow perception allows mosquitoes to quickly avoid obstacles at extremely close range. By mimicking this sensitive airflow sensor and supplementing it with flexible UAV flight mechanisms such as flapping wings, a UAV capable of avoiding high-speed moving obstacles at extremely close range can be designed.

In specific implementation, airflow sensors mimicking mosquito antennae can be installed on the UAV to detect real-time changes in the surrounding airflow. Algorithms analyze the airflow data to identify potential obstacles and their directions of movement. The drone adjusts its flight attitude and path based on this information to quickly avoid obstacles. Simultaneously, it needs to be combined with flapping-wing and other flight mechanisms to improve the drone's maneuverability and evasion capabilities at extremely close range.

This obstacle avoidance technology at extremely close range is of great significance for drone operations in complex environments. For example, in future military conflicts, near-ground reconnaissance drones are frequently targeted by enemy interception fire, such as anti-aircraft guns and enemy air-to-air missiles. If the aforementioned maneuvering and evasion technologies can be applied to the drone platform, emergency evasion can be performed before incoming missiles are about to collide. Due to their high-speed movement, the missiles will have a high probability of missing their target, thus better protecting our military resources while also depleting the enemy's supply lines to some extent.

4. Conclusion

This paper systematically reviews recent research on the design, development, and application of bio-inspired unmanned aerial vehicles (UAVs). By analyzing over 70 relevant studies, it summarizes progress in two main areas: airframe structure and intelligent control.

Bionics has significantly enhanced UAV performance. Structurally, bio-inspired designs-such as feather-based rotors for noise reduction, bird-like wing shapes for improved lift-to-drag ratios, and flapping-wing mechanisms for agility-have optimized aerodynamic efficiency, stealth, and adaptability. Innovations like cross-medium drones and specialized landing gear further expand operational scope.

In control systems, biomimetics has enabled breakthroughs in attitude stability, swarm coordination, path planning, and obstacle avoidance by emulating natural regulatory and navigational mechanisms. These advances improve autonomy and reliability in complex environments.

Future research should focus on integrated biomimetic approaches, such as optimizing long-endurance flight using thermal updrafts and achieving extreme close-range evasion through airflow sensing inspired by insects. Multi-source information fusion and autonomous decision-making will also be critical to enhancing UAV intelligence and operational effectiveness in diverse scenarios.

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