Journal of Intelligent Systems and Control
https://www.acadlore.com/journals/JISC

Bio-Inspired Attitude Control in Flapping Wing Robots: Trends, Challenges, and Future Perspectives

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Received: 02-10-2025 **Revised:** 03-18-2025 **Accepted:** 03-25-2025

Citation: N. M. Mahdi and A. A. Shandookh, "Bio-inspired attitude control in flapping wing robots: Trends, challenges, and future perspectives," *J. Intell Syst. Control*, vol. 4, no. 1, pp. 48–67, 2025. https://doi.org/10.56578/jisc040105.

Abstract: Flapping wing robots (FWRs), inspired by the complex aerodynamics of birds, insects, and bats, have garnered substantial interest in recent years due to their ability to replicate agile and energy-efficient flight behaviors observed in nature. These biologically inspired aerial platforms are capable of executing sophisticated maneuvers, including stable hovering and rapid directional changes, which are typically unattainable by conventional rotary or fixed-wing aircraft. Attitude control systems, which are essential for ensuring flight stability across diverse environmental conditions, have undergone significant advancements with the integration of lightweight materials, novel actuation mechanisms, and miniaturized sensory technologies. Despite these developments, challenges persist in achieving robust, energy-efficient flight control under dynamically changing aerodynamic conditions. Bio-mimetic sensor technologies, such as gyroscopes, accelerometers, and tactile feedback systems, have been increasingly adopted to enable closed-loop feedback and real-time adaptive control. Both open-loop and closed-loop architectures have been investigated, with a growing emphasis on adaptive and learning-based control strategies to accommodate nonlinear flight dynamics. Recent research has explored the incorporation of artificial intelligence (AI) and machine learning (ML) algorithms to enhance autonomy, environmental adaptability, and decision-making capabilities. Despite these advances, limitations persist in power management, environmental robustness, and long-term flight endurance. Potential applications in surveillance, environmental monitoring, precision agriculture, and search-and-rescue missions underscore the transformative value of FWRs within autonomous aerial systems. Through continued interdisciplinary research in materials science, control theory, and computational intelligence, FWRs are anticipated to emerge as a pivotal class within the broader ecosystem of autonomous aerial systems.

Keywords: Bio-inspired; Flapping wing robots (FWRs); Attitude control; Autonomous flight; Aerial robots; Sensor integration

1 Introduction

Inspired by the natural world, more and more bio-mimetic designs have been developed to mimic the delicate mechanisms realized within biological systems. Apart from mimicking creatures with flapping wings, aerial robots have demonstrated more complexity than traditional flying vehicles. Therefore, they have drawn much attention. It is based on an extraordinary interest in insects, birds and bats with airworthy abilities that show excellent aerodynamic strategies and enhanced maneuverability. Consequently, bio-mimetic aerial robots have been created that have both esthetic appeal and increased functionality from these natural models [1]. This bio-inspired advancement uses FWRs, also commonly referred to as flapping wing micro aerial vehicles (FWMAVs). The flapping motions of these machines are done with great craft to provide stable hovering and agile directional changes similar to a number of species. There are associated challenges of understanding complex dynamics of insect flight for the purpose of creating effective control systems for micro aerial vehicles (MAVs). Scientists have studied these biological entities and applied the research to aerodynamics, structural design, and actuation fields, amongst others, to improve the performance and expand operational capabilities through the integration of sensors and their actuation [2].

The advancements in materials science allow for building lightweight yet strong structures mirroring nature's resilience. Payload capacity can be increased while maintaining the aircraft's agility during flight through such innovations. In addition, FWRs are evolving from experimentation to practical uses such as surveillance, environmental monitoring, as well as even agricultural pollination as they incorporate advanced technologies, such as onboard sensors for navigation with real-time feedback systems [3]. Furthermore, the need for mechanical advancements that complement attitude control mechanisms to maintain good stable flight performance is also being progressively felt by researchers. One important factor of the flight of an aerial robot is attitude control, that is, the capacity to sustain the orientation it has chosen. Then, based on these types of principles observed in nature in which organisms use their wings not only as a source of propulsion but also to maintain their balance and their direction with dynamic adjustments, various control strategies, both open-loop and closed-loop, have been developed [4]. Looking at the current research landscape, there is no lack of motivation to improve upon the limitations of traditional aerial vehicles, which are hounded by issues at low Reynolds numbers, a condition where the unique aerodynamics of flapping wing designs are so swift that they are unmatched. Through this innovative path inspired by biology, researchers have been seeking the performance of MAVs beyond what is possible and unlocking new potentials in autonomous aerial operations [4].

As for the impact of certain design principles derived from biological organisms on specific gain structures within FWRs, an inherent theme has emerged that pertains to the current cutting-edge technological advancement in the field of bio-inspired robotics, with implications in defense, agriculture, entertainment, and others [5]. Many review articles have focused on different matters of FWMAVs and bio-inspired robotics. As an example, Pan et al. [1] presented an overview of FWMAVs with only brief comments on the control approach to these vehicles. In a similar way, Zhou et al. [2] reviewed the landscape of the aerial robots; however, their analysis was focused mainly on the fixed-wing and rotary systems with very little reference to the flapping-wing platforms. Comparatively, Fang et al. [3] only paid attention to the high-level control strategy in bird-like flapping vehicles and did not provide much detail on bio-inspired sensor fusion or actuation principles. The paper by Park et al. [6] provides a vision-based obstacle avoidance system that applies mainly to flapping-wing robots, and it finds application in autonomous navigation. Their work also involves obstacle detecting and evasion algorithms that make use of visual feedback. The main area that they contributed to is the use of vision in small robotic aircraft control. Although Han et al. [7] investigated bionic aerodynamics and structural arrangements in flapping systems, they did not focus much on attitude control according to realistic disturbances in the real world.

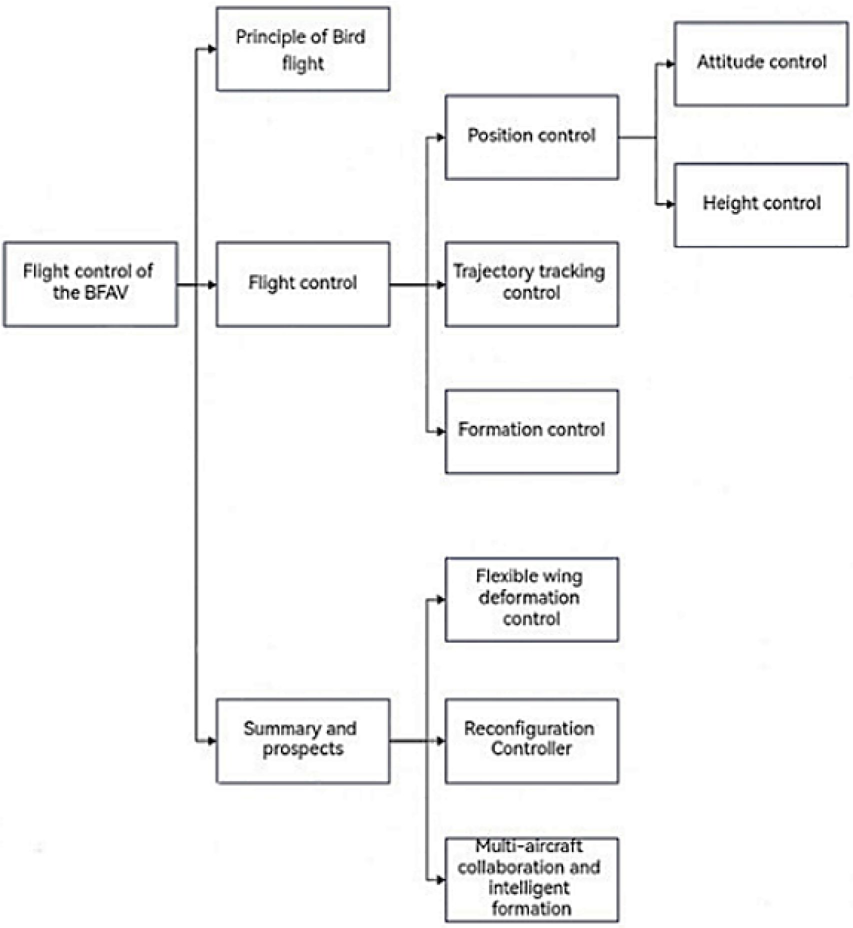


Figure 1. Flight control system of the BFAV [3]

Thus, this work aims to fill these gaps by providing an integrated and detailed review that takes into account not just the attitude control mechanisms (open-loop, closed-loop, and adaptive) but also bio-inspired sensor technologies, actuation systems, and applications of ML in the systems. In addition, this review further widens its focus in covering both recent issues in terms of technology and future research opportunities, thus catering to become a condensed source of information consisting not only of background knowledge but also of innovative possibilities in the field of bio-inspired attitude control with FWRs. Figure 1 shows the flight control system of the Bird-like Flapping-wing Air Vehicle (BFAV) [3].

2 Bio-Inspired Design Principles in FWRs

2.1 Overview of Bio-Inspiration in Robotics

In robotics, particularly those related to the air, bio-inspiration has become a dominant strategy. The idea is to engineer such things as to mimic the natural traits of the organisms, including their adaptability and efficiency. Autonomous aerial vehicles with complex flight capabilities have been developed from the FWRs inspired by flight mechanisms of birds, insects and bats [1]. The first orders of operations in bio-inspired robotics' early history were to learn from and mimic the flight dynamics of larger animals, such as the oversized pterosaur replica proposed by Brooks et al. The inventions of smaller FWRs, however, are possible thanks to microtechnology. Such miniaturization, however, opens new applications in surveillance, search and rescue and exploration [1].

Substantial progress has been driven by interdisciplinary collaborations between the materials science, mechanical engineering, and fluid dynamics. Researchers are looking into how nature's flyers have gamed out remarkable aerodynamic performance in low Reynolds number environments, where traditional aircraft break down. Caltech Microbat is an example of an advancement in which birdlike aerodynamics combine with lightweight materials and sophisticated control systems [2]. An early example of a bio-inspired flying robot is the Caltech Microbat prototype MAV built at Caltech. This model simulates flapping mechanisms of a bat and was created to test unsteady aerodynamics in low Reynolds numbers. The Microbat has a wingspan of about 15 cm and a mass of 12 grams, including onboard electronics. The wings are made of carbon fiber spars and a thin polyester film membrane to come closer to the compliant wing structures observed in the chiropteran species. The Microbat contains two piezoelectric actuators that flap at approximately 3540 hertz to provide enough lift so that it has the ability to hover and move slowly forward indoors. The wings have a passive wing warping and elasticity to enhance their dynamic stability and aerodynamic efficiencies. Noteworthy, the Microbat has a suppleness transmission system with the ability to create a less rigid connection between the pitch and stroke motions, which is helpful in attaining the controllable maneuver, including pitching and rolling.

The Microbat with these traits features among the first attempts at proving full autonomy and free flight functionality of an insect-sized platform using flapping wings. The lessons of its development have a tremendous impact on what features should be included in the future flapping robots, pointing towards optionality of the compliant structure, resonance-based actuation and low mass integration of electronics as key points in the development of MAVs. Among these flapping wing designs are ones that are extremely maneuverable and possess excellent energy efficiency compared to more conventional drones, whose performance may fail in certain environments. These designs include the structural elements as well as kinematic strategies from biological systems with the use of flexible materials to respond to aerodynamic forces [6].

As stated in modern research on sensor integration, real-time data processing has been emphasized for improved flight control. Sensor technology can be relied on to be so innovative that robotic systems react dynamically to their surroundings, increasing autonomy. With continued research on advanced aerodynamics with bionic aerodynamics, issues pertaining to scaling and robustness have come up. Despite the availability of bio-inspired technologies with their advantages over traditional ones, the focus is to develop resilience to environmental factors [7]. For instance, bio-inspired flight technology can be applied to civilian uses, including military, agriculture and entertainment, for example, as aerial robotic performers. These systems replace each other with iterations, informed by nature, in order to transform our conception of what autonomous flying devices can or cannot be within webs of interactions [8]. The final point is that, in bio-inspired robotics, people look to replicate natural principles to gain innovative methods of robotic solutions. Recently, the study of biological locomotion, especially in flight, has resulted in the development of various platforms that allow emulating the agility and efficiency found in nature [8].

2.2 Key Biological Inspirations for Flapping Wings

Birds and insects are nature's most agile and effective aerial navigators, which are a very rich source of inspiration in the field of FWRs. Thus, the basic design principles based on these animals serve as a base to build up bio-inspired robots which are able to perform complex flight maneuvers. The lightweight bodies and ability to swoop and sway of everyday insects give important insights into flight mechanics that can be mimicked in robotic designs [1]. One particular example of a fly is the fruit fly, or Drosophila melanogaster. These small flyers can do the equivalent of changing the stroke angle of their wings and stroke frequency to change the direction of flight and stabilize the aircraft.

Using these adjustments as a concept, robotic systems can achieve a large amount of agility and responsiveness. Miniature adjustments in the wing positioning that allow insects to rapidly change midflight orientation offer maneuverability at least tens to perhaps hundreds of times greater than that of traditional aircraft [7].

The model that is far more interesting again is the hawkmoth (Manduca sexta), famous for its amazing hovering ability. The creative wing motion inputs a unique figure eight with unique body movements to keep the stability while hovering. Designs based on this behavior have been inspired, which incorporate similar flapping patterns into robotic platforms and allow them to both hover and sustain at low energy expenditure [8]. Because their wings are so flexible, beetles also exhibit a variety of motion – either actively or passively as the wings actively or passively rotate during flight. The uses of this trait in bio-inspired robots frequently involve passive mechanisms to reduce actuator load that serve to guarantee adequate maneuverability. By allowing FWRs to more effectively use aerodynamic forces, such passive rotation makes it possible for beetles to create a stable flight with no constant motor input [9]. In this domain, dragonflies are noteworthy as they control each wing individually so vastly that each wing may independently adjust angle of attack. This capability enables highly accelerated and advanced aerial maneuvering capabilities, thus giving them the strength as predators in the air. This unique feature is currently being leveraged by robotics research to create systems in which individual wings can be controlled independently, enhancing maneuverability and responsiveness to flight like dragonflies [10].

The combination of various kinematic characteristics observed in natural flyers drives engineers to develop hybrid mechanisms that blend active actuation with passive stability components. These innovations result in designs that not only replicate natural movements but also enhance overall performance metrics such as efficiency and control precision [11, 12]. Additionally, soft actuators inspired by insect structures have been researched as a potential application using materials such as carbon nanotubes to obtain high flapping rates at a small scale while still maintaining the lightweight materials needed for small-scale flying robots. This translates well to engineered solutions with flapping wings that would make FWRs capable of navigating through a complex environment. However, as these creatures are further studied for their ability to master the flight dynamics, new possibilities for advanced functionalities that could be applied to environmental monitoring to search and rescue operations have appeared [13].

As an example, Drosophila melanogaster can adjust its stroke amplitude ($\sim$130°) and angle of attack ($\sim$40-50°) within the 100 ms required to reorient itself, and Manduca sexta carries out ducted or figure-eight strokes ($\sim$25-30 Hz), using its body-couple motions to stabilize during hovering [14, 15]. Although the biomimetic FWR has been designed based on various qualitative observations using biological flyers like the Drosophila and the Manduca sexta, the evolved quantitative wing kinematics of the biological flyers have the capacity to directly influence the engineering design parameters. The flapping frequency, the amplitude of each stroke, and the angle of attack, as well as wingbeat coordination, are important parameters that are given in Table 1.

Table 1. Comparative wing kinematics of Drosophila melanogaster and Manduca sexta

Parameter	Drosophila Melanogaster (Fruit Fly)	Manduca Sexta (Hawkmoth)
Flapping frequency	200–250 Hz	25–30 Hz
Stroke amplitude	$\sim$ 130°	$\sim$ 120°
Angle of attack range	30° to 50°	25° to 60°
Wingbeat coordination	Synchronous, two wings in phase	Near-synchronous, fine adjustments
Stroke plane orientation	$\sim$ 40° relative to horizontal	$\sim$ 20–30° relative to horizontal
Wing flexibility	Passive wing rotation at stroke reversal	Active and passive deformation
Lift coefficient (Cl)	$\sim$ 1.2–1.5 during peak stroke	$\sim$ 1.4–1.6 during hovering

2.3 Design Considerations Based on Biological Systems

The flight mechanisms of birds and insects have a large influence on the development of FWRs. Replicating biological flight principles is a key focus in their engineering. Therefore, the mechanical frameworks that make for good wing flapping need to be understood. The wings of birds are made of stiff structures and flexible membranes that allow complex maneuvering in air through a lightweight, strong construction [1]. Flexible materials and energy storage in nature are incorporated into FWRs to enhance durability. By absorbing impacts without failure during flight, this approach improves energy transfer and therefore improves robots' ability to navigate in crowded environments, governing applications [16].

Another point to be considered is the strength of integrating bio-inspired sensors and actuators. Although researchers have improved FWRs' ability to monitor their flying conditions with sensors that mimic biological mechanoreceptors, these systems are still limited to real-time measurements and do not yet allow for the detailed analysis of parameters such as airflow within the wings, wind speed, or angle of attack. Moreover, materials have been advanced to mimic feather structures in order to improve sensory capabilities without dramatically increasing weight [17]. Inspiration from biology is also applied to actuation techniques, which are handed over to biomimetic actuators in place of traditional motor systems. The innovative designs convey the precision and high speed with which living organisms control their wing movements, concentrating upon high-frequency flapping and energy efficiency based on the study of avian flight dynamics [18].

Hierarchical organization of natural wings can be explored as multi-dimensional design strategies for FWRs. Natural wings are integrated systems that are capable of changing their overall performance based on the action of small structures, and using multi-layered materials can enhance aerodynamic efficiency as well as maneuverability for robotic counterparts. Wings need to be shaped and configured the way they are for lift and stability. Flexible wing designs have been studied in light of varying shapes and stiffness, as those insects change wing angles at different flight phases [18]. In bio-inspired designs, it is becoming more important for environmental adaptability to evolve. In a similar way as birds change their flight according to weather or terrain, FWRs should have the flexibility of reconfiguring the wing shape and flapping patterns according to external conditions. Overall, the development of advanced aerial robotics demands a multifaceted and biological principle-based approach [19]. Table 2 shows the comparison between bio-inspired and biohybrid soft robots.

Table 2. Comparison between bio-inspired and biohybrid soft robots [15]

Aspect	Bio-Inspired Soft Robot	Biohybrid Soft Robot
Materials	-They are made of non-natural materials (e.g., elastomers and polymers) -Regulated, predictable properties -Can be compatible with existing fabrication techniques	-Add to have biological cells or tissues -Provide regenerating or self-healing potential -Have high biocompatibility
Advantages	-Robust in severe conditions -Strength design of structures -Versatile in size	-Receiving signals of the outside world -Ability to heal itself and to compensate where damaged
Disadvantages	-Not biodegradable -Not much variety in biological mimicry	-Have to demand particular conditions (vapidity and nutrition) -Require intricate assimilation and manufacture
Motion & control	-High controllability -Repeatability of actuation pattern -External control tools	-Great plasticity -Natural adaptability -Prospects of self-conduct (e.g., chemotaxis)
Challenges	-Cannot copy sophisticated embodied motion -Cannot adapt easily to new situations	-Living systems are hard to control and to predict -Performance hinges on biological viability
Applications	-Robotics in industry -Medical robots -Mining in severe environments	-Biomedical engineering -Smart implants -Interaction with vivo tissues

Table 3. Performance comparison of actuation materials for FWRs

Actuation Type	Strain Range (%)	Power Density (W/kg)	Response Time	Efficiency	Operating Frequency	Suitability for FWRs
Piezoelectric (e.g., PZT)	<0.2	∼ 300–500	<1 ms	High	Up to 150 Hz	Excellent for micro FWRs
SMA (NiTi)	3–8	∼30–100	50–200 ms	Low – moderate	<10 Hz	Suitable for slow flapping or morphing
DC motor (with linkage)	N/A (rotational)	100–300	5–20 ms	Moderate – high	10–50 Hz	Common in macro - scale FWRs
EAP	5–300	∼ 5–50	10–50 ms	Moderate	<20 Hz	Experimental, not yet field - deployed

Table 3 shows a comparison of typical actuation materials to flapping systems in order to support the mechanical design of FWRs better. It compares piezoelectrics, shape memory alloys (SMAs), direct current (DC) motors, and electroactive polymers (EAPs) to parameters of relevance, such as strain capability, the power-to-mass ratio, response time, and the ability to flap at a high frequency. Figure 2 shows the design schematic of a biohybrid FWR.

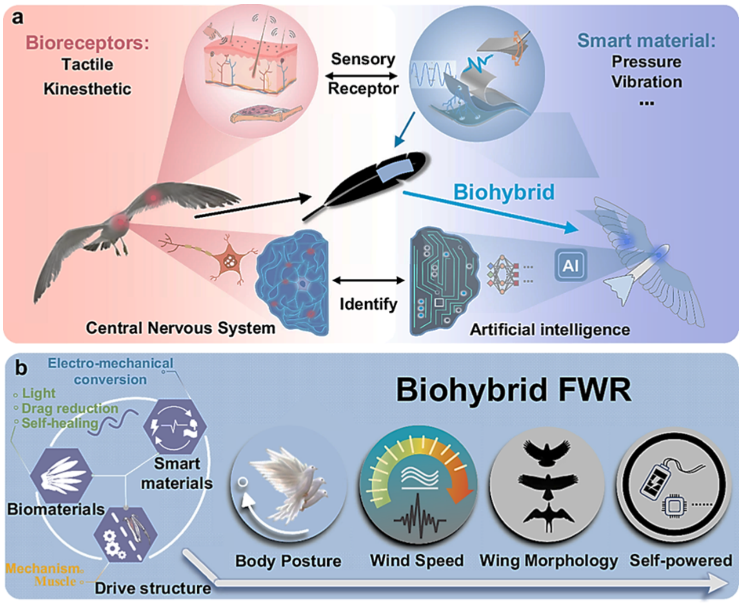


Figure 2. Design schematic of a biohybrid FWR

(a) Flexible, sensor-integrated wings mimic avian tactile and kinesthetic systems using smart materials, (b) A full system that integrates bio-inspired actuators, embedded perception, and adaptive control for environmental responsiveness and shape morphing [19]

3 Attitude Control Mechanisms in FWRs

3.1 Types of Attitude Control Systems

3.1.1 Open-loop control systems

For FWRs, stable flight does require a system of open-loop control. In contrast with closed-loop systems, open-loop systems are instructed in advance of operation so that performance can be evaluated in controlled environments [6]. The programmed motions dictate their flight paths in these robots, which reduces the associated complexity with sensor integration and real-time processing. Costs are reduced, reliability is increased, and fewer components are involved [17]. An example of such a material used by a bionic insect robot comprises piezoelectric materials in the wing movement. Researchers have increased the aerodynamic efficiency of the system compared to conventional configurations by using an open-loop actuator system. This is an example of when open loops are effective in certain performance metrics.

Open-loop FWMAVs commonly use piezoelectric actuators because of their high response frequencies, low weight and compact size. Their aerodynamic efficiency, however, should be backed with the quantitative measures. An applicable performance parameter is the lift-to-power ratio (N/W), the amount of vertical lift obtained per amount of electrical power input.

•The tethered FWMAV, the Harvard RoboBee, has piezoelectric bimorph actuators that work at $\sim$ 120 Hz and produce 1.5 mN lift at $\sim$ 19 mW per actuator. Therefore, its lift-to-power ratio is $\sim$ 79 mN/W [12]. Such is one of the best-documented FWRs in the sub-gram region under open-loop operation.

•By comparison, the KUBeetle-S using open-loop modulation of tracing stroke amplitude and twist hovers at 30 Hz, and lifts a 24 g frame on $\sim$ 1.8 W power lifts with a lift-to-power ratio of $\sim$ 130 mN/W. This is a considerably effective outcome because of the incorporation of the passive wing rotation correlating with the flapping stroke.

•In comparison, closed-loop ones like the adaptive neuro-fuzzy control system displayed by Mou et al. [20] demonstrated a better tracking accuracy in the turbulent airflow. Nevertheless, the lift-to-power ratio decreased to 95 mN/W because of sensing, computation, and correction actuation overhead.

Overall, open-loop piezoelectric systems can be highly efficient in predetermined conditions (with high resonant actuation and the simplest of hardware). Nevertheless, they do not perform so well in the real environment due to lack of flexibility. The drawback is an increased energy demand on the system and latency of the control system; however, it comes with the benefit of the robustness and stability that is noticeable during the wind disturbances.

Simulation studies demonstrate that in conditions of full flapping, adaptive closed-loop control systems can control orientational stability within 2° pitch error during gusty airflow conditions. However, open-loop systems exceed 10o pitch error with the same disturbances using 10-20% less energy in still air. Under different conditions, some FWRs have successfully stably flown using open-loop strategies. In mimicking hummingbird flapping mechanics, these machines change yaw pitch and roll without imminent environmental feedback. Pre-determined stroke amplitude or wing position can be adjusted such that they can execute controlled maneuver [21]. However, appropriate challenges remain in terms of adaptability and responsiveness. If disturbances like wind gusts are seen, then the stability may be limited by following predetermined commands. For this reason, researchers began to explore the hybrid approaches that combine the open- and closed-loop methodologies to enhance dynamic responses, keeping the benefits of modest systems [17].

For the improvement of open-loop control strategies, simulation techniques are important to test hypothetical scenarios, which cannot be physically tested. The first achieves a predictive capability and provides designers with the ability to fine-tune initial conditions for actual flight operations [22]. Furthermore, these alternative actuation methods have the support for flapping motion without an immediate feedback loop and the development of innovative, biological principle-based, yet functionally integral designs for a variety of environments [23]. All in all, open-loop control systems are used to improve stability and efficiency of FWRs by using pre-defined motion sequences based on predictive models of expected dynamics, as opposed to depending merely on reactive control with feedback [23].

In FWRs, the open-loop control systems are known to be a common strategy used in this case because they are simple and less dependent on sensors. These devices are flapping with sequences pre-programmed without feedback. One of the characteristic parameters in such a system is that the flapping frequency (f) is usually between 20 and 40 Hz and the stroke amplitude (0) is often 70-120, depending on the size of the wing and the scale of the robot. As an example, AeroVironment designed the Nano Hummingbird capable of stable forward and hovering flight with open-loop control at a 30 Hz flapping stroke amplitude of about 80. Flight results show efficient control of the yaw and the pitch through the adaptation of the wing asymmetry without the use of active feedback. It has an open-loop performance that enables it to have hover times of between 20 and 30 seconds. However, it is sensitive to ambient air perturbations.

Phan et al. [12] conducted a simulative review of the approach to comparing the low-level control of a pitch based on the KUBeetle-S platform that involved the modulation of stroke plane. The simulations revealed that pitch angle can be altered 15o with the angle of the stroke plane varied between -10o and +10o at steady-state flight at 30 Hz flapping frequency. Such outcomes were confirmed during physical experimental work through the means of high-speed video recording and onboard inertial measurements, exhibiting less than 5% deviations of the predictions in a laboratory environment. In addition, open access Harvard RoboBee studies with a high flapping frequency of 120 Hz have been performed, which made use of structural resonance to conserve energy. Fixed flapping patterns were shown by experimental trials to generate repeatable vertical lift forces with thrust deviations less than 10% even though there were no corrective forces employed. The open-loop systems, however, have poor performance in the presence of disturbances despite their simplicity. According to the wind tunnel experiment done by Teoh [13], flapping robots with linearized wing trajectories did experience a 28% increase in the trajectory drift when subjected to zero-mean white noise perturbation of 0.5 m/s, indicating the necessity of making the closed-loop compensation in the actual world.

Summing up, open-loop control structures can work well in structured or low interference settings, and they can be refined by the use of resonant actuation, parameter selection, and computational modeling. They can be considered valid use cases of FWRs due to their cost, ease of use, and predictability in tightly controlled indoor environments or during early prototyping phases.

3.1.2 Closed-loop control systems

For FWRs that operate in the complex dynamics with nonlinear and time-varying behaviors, closed-loop control systems are necessary to navigate. Feedback from sensors is used to make real-time corrections of the robot's actions to achieve stability and precision in the flight operations. Among all the approaches used, adaptive control strategies have proved to be one of the most effective methods to solve the issues in the uncertain systems and dynamic environment [3]. The parameters of an adaptive control algorithm may be adapted in feedback to the system itself. This flexibility is critical for FWMAVs which operate in many diversified loads and environmental conditions removed from predicted design models. A classical example of this is multiaxial adaptive controllers whose reference generators enable precise tracking, if the conditions of disturbances or uncertainties in modeling are unknown. These controllers maintain stability even in the presence of external factors (e.g., gusty winds) or internal ones (e.g., manufacturing inconsistencies) [3].

A promising hybrid approach for improving resilient uncertainty response is hybridizing sliding mode control (SMC) with adaptive methods to counteract uncertainties synonymous with flapping wing characteristics. SMC is robust against disturbances but exhibits switching behavior. Therefore, its variations can be jitter. The adaptive control methods have been proposed to achieve system response stabilization along with their stability with respect to rapid changes in flight conditions. This combination facilitates smoother transitions and improved maneuverability overall [20]. Recent technology advances have also advanced and surpassed into incorporating AI-based neural networks to live within closed-loop systems. Furthermore, the use of adaptive neural network controllers has proved to be quite adept at learning the system behavior over time and adapting control outputs better in reaction to changes compared to conventional Proportional-Integral-Derivative (PID) controllers. Finally, these complex nonlinearities can be successfully dealt with in order to open new paths for attitude control in robotic applications [22].

However, such challenges present difficulties in practical automated control design of closed-loop systems for these robots caused by actuator coupling and noise arising from the flapping motion itself. Direct management of such a multitude of actuators is complicated by the intricate interactions between the respective actuators, as their adjustments inevitably affect other actuators as a result of aerodynamic connections, requiring the elaboration of sophisticated coordination strategies designed to achieve desired force distribution per axis with minimal loss of stability [22]. Moreover, these systems require the level of precision that these sensors often demand, that is, advanced sensor technology, which is able to accurately monitor position, orientation, and velocity in different environments. Real-time data fed back to sensors is essential for effective closed-loop feedback mechanisms and sensors should be high fidelity to provide real-time data. Augmented disturbance observers integrated within controllers are able to estimate external perturbations on flight dynamics and simultaneously improve tracking accuracy through tailored compensation strategies that vary according to a disturbance. Closed-loop attitude control systems are the state of the art in the field of FWRs, aimed at emulating the biological flight capabilities with high fidelity and reliability over a wide range of operational conditions [20].

Adaptive neural controllers (ANCs) are one of the advanced closed-loop models that have been found to be an ideal alternative to manage the nonlinearities of the system and the effects of external disturbances in FWRs. Mou et al. [17] proposed an adaptive control framework based on neural networks, which could be applied to underactuated aerial vehicles, such as flapping wing vehicles. Simulation and experimental validation showed the ability of successful multi-axis trajectory tracking under different loads. To be specific, the neural controller reached Root Mean Square (RMS) tracking errors of less than 3.2° in pitch and roll even in the case of model parameter uncertainty of +/- 15%. In contrast, a conventional PID controller, when operating within identical testing circumstances, had more than 7.5 tracking error. Besides, the adaptive neural structure enhanced the robustness margins through dynamic tuning of the control gains by the learning-based reference model. Attitude stabilization was also achieved under gust-disturbance simulation conditions (up to 0.8 m/s perturbations of the wind). An envelope of 4o was maintained under the simulation of a gust disturbance situation, whereas non-adaptive controllers were forced into an oscillatory divergence and failed to recover.

The hover performance of an insect-scale FWMAV that exceeded contraction capabilities was further validated using embedded inertial measurement unit (IMU) data. The data confirmed real-time convergence of angular velocity to the reference inputs, with a settling time of 0.35 seconds. The results confirm the argument that the adaptive neural networks have several advantages in scenarios where dynamic coupling and unmodeled disturbances take center stage in flight dynamics. Nonetheless, these systems are highly demanding in terms of computational resources and bandwidth, and they rely on real-time sensory feedback, which is not feasible for ultralight or energy-constrained FWRs without externally mounted processing modules. Hybrid models that mix some feedback and online learning are currently countering these constraints.

3.2 Sensor Technologies for Attitude Control

Sensor technologies are important in order for FWRs to have precise attitude control to increase maneuverability and stability. These robots are able to adjust their flight based on environmental changes using a number of sensors, including gyroscopes, accelerometers and magnetometers [2]. Angular velocity—gyroscopes with which the orientation is maintained during maneuvers—is measured. Nevertheless, gyroscopes drift with time without outside references. Therefore, additional sensors are needed for more accurate results. Gyroscopes complement accelerometers and provide data of linear acceleration (in spite of the grain of salt that general application of such data can implicate), which provides a gravity-based reference when coupled with sensor fusion techniques [6]. Magnetic field is detected by magnetometers for adding further accuracy to establish heading direction. Magnetometers are best in stable environments but close metallic objects and electric fields can affect them. Hence, they are usually a part of an IMU along with two other sensors and utilize filtering techniques such as Kalman filters to efficiently control their attitude [23].

Recent advancements are the inclusion of tactile sensing elements in the wing structures, enablers for measuring airflow changes and providing feedback of deformation or vibrations in the wing. This information is crucial for the real-time aerodynamic conditions needed for the reflexive control mechanism. In addition, ML algorithms such as convolutional neural networks (CNNs) have been used to improve the analysis and decision-making with respect to FWRs' sensor data. They help the interpreter of complex sensory inputs derive an improved state estimation accuracy to navigate challenging flight scenarios [6]. Adaptive controllers that are coupled to airflow and onboard CPU to make agile flight adjustments in varying gust conditions are also being studied by researchers. This work enables system stability while concurrently optimizing performance by changing operational parameters as a function of changing environmental factors in a dynamical manner. Continuing to integrate bio-inspired sensory approaches into the design of FWRs, improved performance in how these robotic systems interact with their surroundings and conduct autonomous operations is expected [24]. Kalman filters, which are used for the integration of inertial sensors, form the foundation of an accurate sensor fusion architecture essential for real-time attitude estimation in FWRs. Figure 3 is a proposed multi-sensor fusion based on Extended Kalman Filter (EKF) and has been derived to be optimized in the non-linear dynamics of FWR flight.

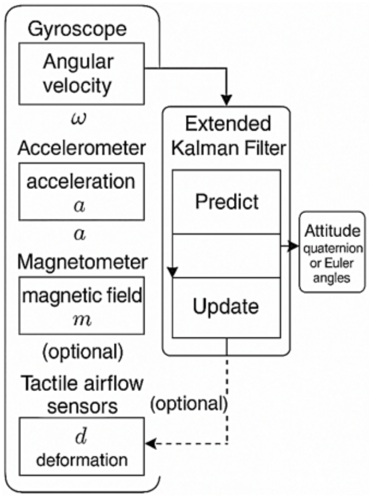


Figure 3. Sensor fusion architecture for attitude estimation in the FWR diagram

Data is fed to the system by:
•Gyroscope: Angular speed (more but shifts after some time)
•Accelerometer: Used in linear acceleration and gravity vector (zones to vibration noise)
•Magnetometer: Absolute heading reference (prone to magnetic interference)
•Tactile airflow sensors (optional): Those sensors are used to obtain the required measurements of deformation due to airflow that is used to estimate the aerodynamic state.

This is a predict-update loop to fuse these signals using EKF. In the prediction step, the angular velocity is combined to make the prediction of orientation (quaternion or Euler angles). In the update step, accelerometer and magnetometer measurements are used for correction to minimize drift. Tactile correction (optional) corrects the wing flexion effects during conditions of gusts.

Analysis of latency:
•Sampling rates of sensors: 500-1000 Hz (IMU), 200-500 Hz (airflow)
•EKF cycle latency: 1-3 ms (on embedded ARM Cortex-M4 or up)
•Total attitude update rate: $\sim$ 250-400 Hz, which, due to control loops running at about 100-200 Hz, is adequate to run small FWRs

3.3 Actuation Methods in FWRs

In the field of FWRs, suitable actuation methods are necessary to achieve coordinated dynamics for the control of the maneuver such as aerial navigation. Replicating the complex behavior of birds and insects, in which they flap, depends on complex interactions of wing movements and aerodynamic forces; this has been a great challenge. Several advantages and limitations in actuation have emerged. Ambient motor-driven systems are one commonly employed technique. The reciprocating wing motion is achieved using small motors or servos through mechanical linkages. This is the case, for example, for the DC motors with gear reductions built into the Nano Hummingbird, which, instead of a large motor, work with very fast flapping frequencies. Indeed, other bird-inspired models employ mechanisms such as crank rocker systems to convert the desired flapping to the output from the rotational motor. Although the mechanisms provide good control over wing dynamics, they might not be scalable due to their weight [8].

In addition, there is an increasing application of piezoelectric actuators in FWRs as they are lightweight and can give fast movements. When electric fields are applied, these devices change shape, and in doing so, can be precisely controlled to stroke their wings in either amplitude or frequency. As this type of actuation can be made very small, this allows the engineers to create smaller, more agile flying robots capable of performing complex maneuvers like other real birds or insects. In addition, smart materials, like SMAs, are being studied for shape changes with respect to temperature variations, and others. Therefore, these wings can change their shape during flight without external mechanical linkages. Although SMAs have been advanced for lightweight and flexible applications, they are subject to slowness and energy inefficiency [12].

One more interesting thing is to take inspiration from nature and integrate compliant transmission mechanisms to promote motion like natural systems. The focus of this design philosophy is on structural flexibility in the wings, including the facility for aerodynamic forces to naturally contribute to lift and thrust production without the need for high motor power. Finally, the performance of these actuation methods is further improved by use of sensors to provide real-time data on environments and flight dynamics. For instance, sensors networks can be integrated with various forms of wing structures to both provide aerodynamic loads and structural deformation information that can be used to derive control performance, and participate in such closed-loop control systems that dynamically adjust actuation parameters while in flight [18].

Although there have been substantial developments on various actuation strategies in FWRs, little progress has been made on ensuring robust performance under changing environmental conditions and optimized efficiency of energy. With researchers now trying to imitate nature through new materials and new designs through nature, we might be seeing bold innovations that give micro aerial vehicles some new attributes [24].

4 Trends in Research and Technological Advancements

4.1 Recent Innovations in Materials and Structures

Since the field of soft robotics has seen significant developments in materials and structures for the bio-inspired flapping robot, it has recently transformed the field. It draws inspiration from the rich plethora of organisms that nature has to offer and innovative materials have been created, aiming to increase some aspect of structural strength and functional versatility. Soft actuator technologies of materials like hydrogels, elastomers, and polymers have become a key area for investigation and have been cleverly engineered to mimic biological systems' responsive and dynamic movements. They give this wide range of motions that are important for effective flight dynamics, allowing agile maneuvers similar to those of birds and insects [17]. Another interesting detour and progress has been taking advantage of such smart materials that change their properties in response to the environment. For instance, polymer nanocomposites have recently gained attention because they can change stiffness in response to chemical triggers nearly as fast as that of animal life such as sea cucumbers, for example. This adaptability enables robots to not only exploit the complexity with which environments are experienced but also renders them to be more resilient against the mechanical stresses that they will endure [17].

Along with this, the development of 3D printing technology has also fundamentally changed the manufacturing process of soft robotics. The advantage of this method is that it makes the formation of intricate structures considerably simpler and gives us fine control over the distribution of material in robotic designs. Not only does it streamline production but also it inverts the design of lightweight actuators that use energy from their soft material framework instead of rigid batteries and generally enhances efficiency [17]. In addition, biohybrid designs are also recent innovations that mathematically incorporate synthetic components with biological components like muscle cells and sensory receptors. Such robots combine movements using natural mechanisms to improve performance in the presence of diverse conditions. Just as an example, robotic systems mimicking jellyfish utilize soft actuators similar to the kind of propulsion engineering as found in nature with high thrust/weight ratios that are lightweight.

Researchers have been exploring new actuation methods driven by unconventional energy sources, e.g., thermal gradients or the magnetic field. In addition, these approaches address actuation techniques within wider variations than what has been considered in the previous approaches while providing energy-efficient designs that force little power input and strong interactions with the environment. As part of ongoing research, composite materials that are flexible and durable are being refined to balance the tradeoffs of where joints are used for gain in flexibility with the loss to durability in the presence of challenging operational conditions. These advanced composites are developed towards durable composites without the lost compliance or responsiveness for stable flight [24].

Additional insight into natural geometries leads to the move towards bio-inspired structures that have been optimized using nature's own designs, as the roboticists pursue avian flight mechanics to adapt wing structure and learn how to improve lift and thrust during aerial maneuvers. But their introduction as enemies in robotics research undoubtedly serves as an ever-growing reminder to engineers and material scientists that as research continues to deepen these biological principles, they will eventually impact the choices of materials and the structural designs for the applications in robotics and beyond [24]. These advancements show how the coordination of engineers and biologists with material scientists can increase robotic capabilities and lead to new uses in such areas as search and rescue missions or environmental monitoring, where mobility is required to be changeable [25].

As shown in Figure 4, nature inspires ideas for the design of aerial robots that act as platforms to develop smart materials for aerospace applications. In general, birds make dynamic maneuvers and react to disturbances. Their ability is reflected in three functions: flight (an image credited to World Wildlife), perching (an image credited to Bernard Spragg) and grasping (an image credited to Alexas Fotos). These functions have inspired roboticists to develop aerial robots that mimic the ability to perform using biohybrid, biomimetic and bioinspired structures. A set of three such systems ("robots") employs soft robotic underactuated morphing wings made with real bird feathers for flight, stores, converts energy to quickly perch or grasp, catches flying targets, and eventually recovers from those collisions. Together, they make up an integrated framework that supports the realization of intelligent aerospace applications and facilitates the development of robotic materials [24]. While numerous materials have been explored for bio-inspired flapping-wing systems—including elastomers, polymers, and composite biomaterials—a structured comparison of their mechanical and functional properties offers valuable design insight. Table 4 summarizes key material candidates based on their suitability for structural flexibility, energy return, and operational durability.

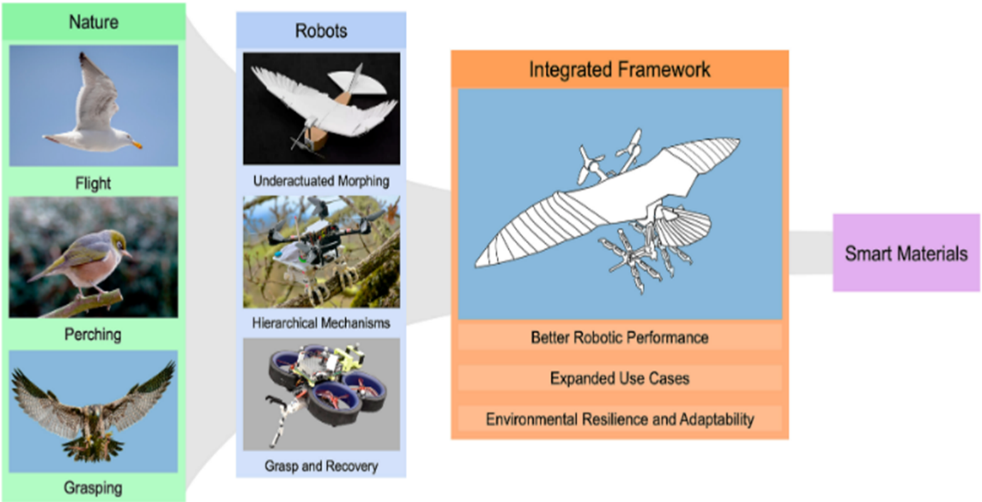


Figure 4. Bio-inspired design of aerial robots as platforms for developing smart aerospace materials

Table 4. Comparative analysis of common materials in FWRs

Material	Density (g/cm^3)	Young's Modulus (MPa)	Fatigue Life (Cycles)	Elastic Recovery	Thermal Stability	Typical Use Case
Silicone elastomer	1.1-1.3	1-3	$\sim 10^5$	Excellent	Low (200°C)	Wing membranes, soft joints
Polyimide (Kapton)	1.4	2500–4000	$> 10^7$	Good	High (400°C)	Flexible sensors, substrates
Hydrogel (PVA-based)	∼1.0	0.01–0.1	$\sim 10^4$	Very high	Poor (100°C)	Soft actuators (wet environments)
SMA (e.g., NiTi)	∼ 6.5	28,000–76,000	$\sim 10^6$	Moderate	Medium (≈ 250°C)	High-power actuation, variable stiffness
Carbon fiber composites	1.6–1.9	70,000–200,000	$>10^7$	Low	Excellent (400°C)	Spars, structural frames
Thermoplastic polyurethane (TPU)	1.1–1.3	10–50	$>10^6$	Excellent	Moderate (250°C)	Flexible wing membranes, impact buffers

4.2 Advances in Autonomous Flight Technologies

The first advance is the rapid state of the art of autonomous flight technologies for FWRs, fueled by recent engineering design and nature-inspired efforts. Integration of vision-based navigation systems enables a further degree of automation in these aerial machines. For example, optical flow algorithms can be used in FWRs so that they are able to detect obstacles and change their flight paths in real time. The CNUX Mini, a compact and 27 cm robot that performs effective evasion midair [6], demonstrates this progress. In addition, including AI and ML, these robots are now relearning how to perceive their surroundings and make decisions. Flying robots have ML capability, where they are able to fly and learn their flight patterns based on the conditions in their environment. It is essential because in missions like environmental monitoring and search-and-rescue operations, navigations through uncertain situations have to be fulfilled [6].

To solve these problems related to nonlinear dynamics, as well as uncertainty and sensory complexity in the environment, AI and ML progressively become part of FWRs. Multiple particular algorithms have great potential:

•CNNs find their main application area in estimating the flight state with the help of visual and inertial data. CNNs can learn to estimate the robot orientation, avoid obstacles, and provide stabilization based on optical flow and the inertial measurements by training on sequences. As an example, the project called RoboBee used CNNs to recognize safe landing spots based on synthetic aerial photographs, and the accuracy of the models generally surpassed 90%.

•Policy training in closed-loop flight has used reinforcement learning (RL), notably deep reinforcement learning (DRL) algorithms, e.g., Proximal Policy Optimization (PPO) and Deep Q-Network (DQN)-based algorithms. FWRs can use such algorithms to determine superior control schemes through feedback as a reward for successful flight maneuvers. An example of particular interest is the hummingbird-like robot brainchild of Tu et al. [26], where a DRL agent was trained to execute fast escape moves and close body rotation. RL-trained control of the robot resulted in comparison with the traditional PID, being more agile and more energy-efficient.

•Controllers based on Artificial Neural Networks (ANNs) have model-free behavior since they learn the system dynamics in real time and apply new control outputs by keeping in mind the previous control outputs. This is particularly applicable in uncertain aerodynamic settings where it is difficult to control through modeling-based controllers. The effectiveness of ANN-based control was demonstrated on the KUBeetle platform where better response to gust disturbances was shown by more than 25% superior to PID.

•Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) architectures have been investigated for predictive trajectory generation, that is, prediction of future by making use of historical motion history. They are especially effective where dynamic stability or disturbance rejection is needed in oscillatory conditions.

Overall, the given AI methods can encompass the autonomy, resilience and adaptive control of FWRs beyond the constraints of traditional linear control. Extensions will involve hybrid AI with improvements in real-time performance due to the combination of DRL with novel choices such as physics-based models or bio-inspired decision layers.

In addition, the materials used to construct these robots are advancing, which greatly affects their autonomous capabilities. With advances in the lightweight materials, flight durations have been extended and have become energy efficient. Soft robotics has made leaps and bounds in terms of supplying flexible, responsive, durable substances, allowing FWRs to successfully operate in a variety of unimproved environments with little or no maintenance [25]. The autonomous flapping wing designs still suffer from a lack of energy autonomy. Various energy storage solutions, including lightweight batteries and energy harvesting systems that convert kinetic energy in flight into usable power, are still under research. These improvements will increase operational capabilities without external power [25]. Improvement of the control mechanisms in autonomous flight is still a matter of bio-inspired design research. To give a more effective actuation technique, engineers emulate the flapping motions of birds and insects. Glide performance can be improved by randomizing cambered wings with adjustable dihedral angles, as innovations such as these may have potential benefit for long distance missions [27].

Hybridizing robotic systems too is popular, and these include fusing flying along with other locomotion, or sensing capabilities. This is an approach for FWRs that can navigate airspace, actuating on either terrestrial or aquatic environments in a multi-modal robot that is equipped to perform complex tasks over multiple domains. Overall, the development of autonomous flight technologies in FWRs combining biological inspiration and technological advancement is shifting from simple systems with particular applications to more complex systems with a wider range of applications [28].

5 Challenges in Bio-Inspired Attitude Control

5.1 Limitations of Current Technologies

In recent years, great progress has been made for FWRs inspired by biological systems, but many issues prevent their real performance and realization. The actuation system is also highly inefficient. Any of the current FWMAVs can require a large input of power to execute even a common set of flight operations, and require expensive voltages that may eventually exceed the hard limits of the actuators' maximum duty cycles. In particular, this represents energy inefficiency that limits flight duration and the reached range of maneuvers of these robots [16].

Among the most enduring setbacks of FWMAVs is their inefficiency when it comes to energy, especially regarding rotary- or fixed-wing vehicles. Such constraint is captured in a number of quantitative benchmarks:

•A popular FWMAV prototype is the Nano Hummingbird, which burns $\sim$19 W of power to hover, giving it a power-to-weight ratio of about 80 W/kg, and with an endurance of only 810 minutes using lithium polymer batteries (carrying a payload of 19 g).

•By comparison, the Harvard RoboBee not only lifts at a 120 Hz flapping frequency but also needs higher voltage drive circuits. It is now tethered, with power densities being well above 300 W/kg. Therefore, untethered flight without smaller voltage solutions is out of the question.

•Flight with a flapping frequency of 30 Hz was observed in experimental studies with KUBeetle-S [12] with a total mass of 24 g at an estimated power cost of 1.8 W, corresponding to a specific energy of 75 J/m, several times greater than current rotary-wing MAVs of the same mass.

•Comparatively, typical averagely sized (with available payload capacity) quadrotors (e.g., 25 g) can fly up to 15-20 minutes at hovering power densities of approximately 60-100 W/kg. Hence, they have a better energy-to-endurance ratio.

The main sources of this difference include nonlinear aerodynamic work drag, mechanical inefficiencies in the flapping motion, and the absence of intermittent, regenerative actuation. Although bio-inspired compliant structures can reduce actuator loads, much of the input energy is dissipated as heat or inertial oscillation. Future improvements could derive from harvesting of energy (e.g., piezoelectric recovery), ultralight structural composites and resonant flapping designs, which seek to achieve performance comparable with natural flyers such as hummingbirds (∼1015 W/kg metabolic power) that are well beyond current robotic counterparts in the lift-to-power ratio.

It is difficult to replicate the inherent adaptability of living organisms, making the problem worse. For instance, even the loss or injury to their wings does not influence the ability of hummingbirds to keep flying. Unfortunately, however, robotic prototypes to date have been unable to achieve this level of resilience, leading to instability when the wing is subjected to imperfections. Current control systems used in these robots are mainly based on traditional Proportional-Derivative (PD) or PID methods, for which there is no effective means to accommodate wing morphology changes, resulting in the robots being unrobust and not operationally versatile [17]. Yet, as with almost all things to do with flapping flight, picking the materials for constructing flapping wings is also an obstacle. The bio-inspired designs intend to mimic the natural structures discovered in bird and insect species; however, there has been a tough balance to achieve strength and lightweight properties. High-strength materials with low density are still being sought in this field. The existing techniques are mostly experimental and have no standard manufacturing protocol, leading to different assembly quality and aerodynamic performance [18].

In addition, most of the existing FWRs are tethered or depend on external energy sources for operation, prohibiting their autonomy and restricting deployment in real-world scenarios, such as search and rescue missions or environmental assessments. Under this need, advancements in lightweight energy storage and harvesting technologies are requisite to enable extended untethered functionality [17]. A second limitation concerns the costs involved in dealing with the many degrees of freedom inherent to most soft robotics designs implemented using compliant mechanisms for enhanced maneuverability. These features offer much-needed flexibility for dealing with environments that are highly variable, but at the same time they make control strategies more difficult because of the erratic movement patterns. Some advanced control methodologies described in ML could increase real-time responsivity, but there is not enough research performed to determine its optimal dynamic treatment for flapping wing dynamics [21].

Although progress has been made at integrating bio-inspired elements in robotic systems—the usage of soft actuators that mimic animal locomotor movements—there is still a scope for scaling up functionalization across different operational settings. Before fully autonomous bio-inspired robots can operate reliably under different conditions, issues on actuator diversity and sensing technologies have to be addressed [29]. Finally, while much promising progress with respect to bio-inspired robotics towards flapping wing mechanisms is still to come, numerous technical challenges such as energy efficiency, adaptability in the structural change, material selection, robustness of the control system, independence and power supply out of the box, and sophisticated movement management strategy remain to be resolved [30].

The claim that FWRs are low-energy-efficient than rotary-wing MAVs may be scientifically tested by means of particular energy consumption or specific energy measures like watt-hours per kilometer (Wh/km) or Joules per meter (J/m). Comparison of published performance data is as follows:

•The Nano Hummingbird uses ∼ 19W during the target flight speed of ∼ 2.5 m/s, giving the power of nearly 7.6 Wh/km.

•Also being highly miniaturized, the Harvard RoboBee is tethered because it requires a lot of energy. Simulated projections hold an identical 15-18 Wh/km that assumes a scale-up in the onboard power supply as a result of high-frequency piezoelectric flapping (120 Hz) and low lift margins.

•By contrast, typical small rotary-wing MAVs have higher power consumption: the Parrot Mambo quadrotor (95 g) consumes ∼12 W at 3.5 m/s, which makes 3.4 Wh/km.

•The larger class of MAVs (e.g., DJI Mini 2 at 249 g) may last up to ∼30 minutes at 10-12km, or 1.2-1.5 Wh/km, greatly exceeding the cruising efficiency of FWRs.

This is caused by the loss of inertial lift and energy experienced in the course of flapping that cannot be recovered and inefficiencies during the phases where the wings reverse direction and aerodynamic loading occurs again. In addition, FWRs usually cruise at lower speeds (∼131 m/s) with greater instantaneous electrical demand and this increases their Wh/km expenditure. Although FWRs are more agile, have better destabilized hover, and can perform biomimetic maneuvers, their propulsion efficiency can be between two and five times lower than that of rotary MAVs of similar size. A focus of research to improve the ratio includes resonant wing tuning, low-loss actuators, and energy-regenerative structures, as shown in Table 5.

Table 5. Summary of key metrics

Platform	Cruise Speed	Power Draw	Energy Use (Wh/km)	Notes
Nano Hummingbird	2.5m/s	∼ 19W	∼ 7.6Wh/km	Flapping, untethered
Harvard RoboBee (est.)	1.5m/s	∼ 14W	∼ 15–18Wh/km	Tethered; extrapolated
Parrot Mambo (quad)	3.5m/s	∼ 12W	∼ 3.4Wh/km	Typical rotary MAV
DJI Mini 2 (quad)	5–6m/s	∼ 20W	∼ 1.2–1.5Wh/km	Highly optimized consumer-grade MAV

5.2 Environmental Factors Affecting Performance

External factors that affect the stability, maneuverability and energy efficiency of FWRs present great challenges. Big hurdles are the atmospheric conditions that include wind speed and direction, temperature variations, and moisture variation. And when it comes to the wind - wind gusts that cause instability to the flight - attitude control to mitigate these disturbances is required in a precise manner, and current algorithms may not perform well in turbulent environments [7]. These robots have been designed and the materials chosen (lightweight is best for agility and low-energy consumption but lasts poorly in heavy rain or extreme temperatures). It states that the advanced materials with desirable mechanical properties can improve robustness, while retaining a lightweight profile [17]. FWR performance is further complicated by its interaction with the environment, especially during takeoff and landing. Because of unpredictable aerodynamic behaviors, navigation approximately nearby terrain or obstacles must be accomplished with real-time adjustments [17].

Usually, bio-inspired designs reproduce the molecular nature of processes but have to take into account the physical limitations, like induced drag, which increase the energy demand when flying. For improvements in the efficiency and performance, a complete knowledge of the aerodynamic principles behind these interactions is necessary [17]. The fact that amphibious robots must be able to smoothly cross from swimming to flying makes environmental factors such as water presence very different. A strong attitude control algorithm is needed that can work through a period of dynamic changes [20]. Besides environmental influences, sensory feedback is extremely important in order for robotic systems to adapt to changing circumstances. However, thanks to advanced sensor technologies, robots can capture real-time data about their environment so that the necessary adjustments can be made to keep their path of flight as optimized as possible in the wake of different conditions [22].

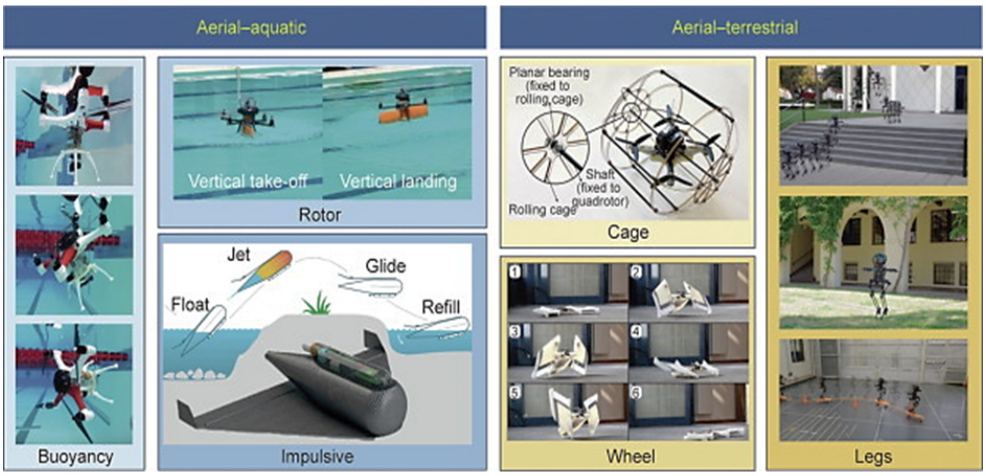


Figure 5. Rotor-wing, fixed-wing, and biomimetic amphibious airborne robots on three platforms [28]

The other challenge lies in the fact that it's not easy to integrate onboard energy storage solutions in a variable environment. Many current designs are tethered power-source designs that limit the range of operations. Thus, there exists a need for lightweight batteries for sustained autonomous flights as a means to improve versatility in applications, ranging from search and rescue to environmental monitoring. Stabilization mechanisms that can work in the extreme environment and the development of more resilient robotic counterparts can be driven by insights from biological organisms that survive in such an environment. Figure 5 shows the rotor-wing, fixed-wing, and biomimetic amphibious airborne robots on three platforms. Aerial-terrestrial amphibious robots accomplish transition by using cages, wheels, and legs, while aerial-aquatic amphibious robots accomplish transition by using buoyancy, rotors, or impulsive methods [28].

5.2.1 Compensation and controlling design of the environment

Rain, wind gusts and airflow impairments caused by the terrain are cited as constraining factors of FWRs but newer systems feature more active methods of environmental compensation. The two possible solutions are as follows:

a) Active morphing wings

•Wings with SMAs or dielectric elastomers (e.g., embedded actuators) can dynamically vary camber, dihedral or stroke amplitudes by using compliant materials.

•As an illustrative example, one morphing-wing FWR tested in the wind tunnel [17] could actively vary the stroke amplitude within the range of 15 degrees (both up and down) in response to the airflow sensors signal. This slowed sideslip below 0.6 m/s tailwind by 32% of the basic models.

•Under low rain or spray, wing hydrophobic coatings with morphing stiffness structures assisted in maintaining the lift, reducing water attachment and restoring equilibrium temporarily, raising the wingbeat rate.

b) Disturbance-resilient control law design

Adaptive as well as robust control laws have also been devised to address stochastic environmental input. As a common approach, it comprises:

•SMC that features an airflow-sensitive switching feature.

$$s(t) = \dot{\theta} + \lambda\left(\theta - \theta_d\right)$$

where, θ_d is the arrangement, guaranteeing that convergence will occur despite the perturbation caused by wind.

•The Augmented Extended State Observer (AESO) has the ability to estimate external disturbances (e.g., turbulent gusts) in real time, and incorporate corrections into torque control outputs.

•Adaptive gain tuning: PID, or neural adaptive control, recalculates the flapping amplitude or stroke timing according to the cumulative sensor output (e.g., IMU + airflow + visual flow) using ML.

The experimental insight is as follows:

•Closed-loop adaptive FWRs with active wing morphing achieved reductions in attitude error of up to 45% and yaw drift of up to 60% compared to the open-loop FWRs in turbulent environments (0.5-1.2 m/s gust range).

•Control loop refresh rates of more than 200 Hz were required to handle gust-initiated instabilities in the hover and slow cruise states.

•Such strategies merge biomechanical inspiration (e.g., birds changing wing dihedral during flight) and feedback provided by real-time sensory information, producing a basis on which versatile autonomous behaviors can be built to operate in uncontrollable outdoor environments.

6 Future Perspectives in FWRs

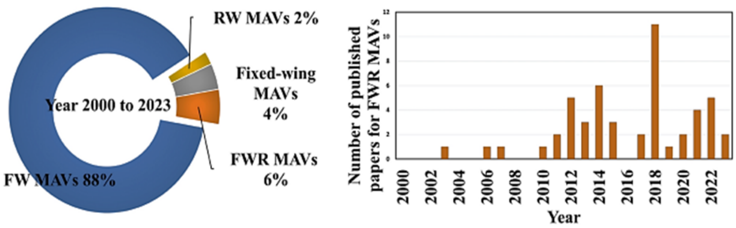
6.1 Potential Developments in Robot Design and Functionality

The future holds a great promise of innovations in FWRs based on the bio-inspired concepts and advanced technologies that would fundamentally change the design and functionality. Morphing wings that allow the wings of these robots to morph fluidly during flight have been investigated as a significant area of research. Higher durability and responsiveness in these materials can be designed, which would result in overall performance under a wider variety of conditions. One such example is that composite elastomers or hydrogels reinforced with composites might be able to create structures that are like the biological case but can endure wear and environmental challenges. Improvement in the actuation methods is also another promising field. Distributed actuation techniques for current mechanical systems involving wing movements could enable more precise control of wing movements. Other new designs may include soft actuators that emulate natural motions exhibited by birds and insects. In addition to improving performance, this approach also reduces weight that is a prerequisite for enhancing flight efficiency [1].

In addition, sensor integration is a critical factor in the development of any FWR. Future models should feature sophisticated sensing technologies that are beyond the standard drone sensors which include modes such as tactile or environmental sensing. By integrating these sensors directly into robotic systems, the load they impose on robotic systems can be diminished and they can enable improved navigation and maneuvering, as found in biological organisms. The studies presented in this thesis explore hybrid systems that combine synthetic components with biological elements, for which there is considerable opportunity in developing FWRs. Living tissues or cells could be used as bases of enhanced aspects of biohybrid designs, with desired regenerative abilities, longevity, and adaptability to different operational demands. For example, this methodology may perhaps uncover autonomous behaviors previously unheard of in a completely mechanical method so that robots can instinctively respond to environmental stimuli [10].

In addition, modular design frameworks offer good potential for the formalization of faster iterations in the prototyping and testing phases of FWRs. By adopting techniques such as injection molding for scalable manufacturing, the costly and advanced robotic technologies can be more accessible, which would simplify the production itself and reduce the cost at scale. This would speed up the testing cycles and would be conducive for innovation by exposure to iterative design improvements without untoward expense. The other important advancement in increasing capabilities across numerous applications involves the integration of multifunctional structures into robotic frameworks. Verifying that these robotic systems are applicable inside and outside of the lab to address various problems will be necessary to establish their usefulness. Increases in maneuverability and flight dynamics are likely to continue to be the topics of intense, bio-inspired research in the future as researchers pore over a broad spectrum of organisms beyond conventional avian models, including insect-derived adaptations, aquatically derived adaptations, and a myriad of other biological adaptations in the ocean [17].

Ultimately, progress in this field will require collaboration among interdisciplinary teams of mixtures of those in materials science, robotics engineering, biology, and environmental science to drive innovation in FWRs. The integration of knowledge from different disciplines enables the development of comprehensive solutions that expand the possibilities with FWRs [24].



(a) (b)

Figure 6. Publications on MAVs from 2000 to 2023

(a) Search terms used to extract data from the Scopus database, (b) Annual number of publications on FWMAVs [1]

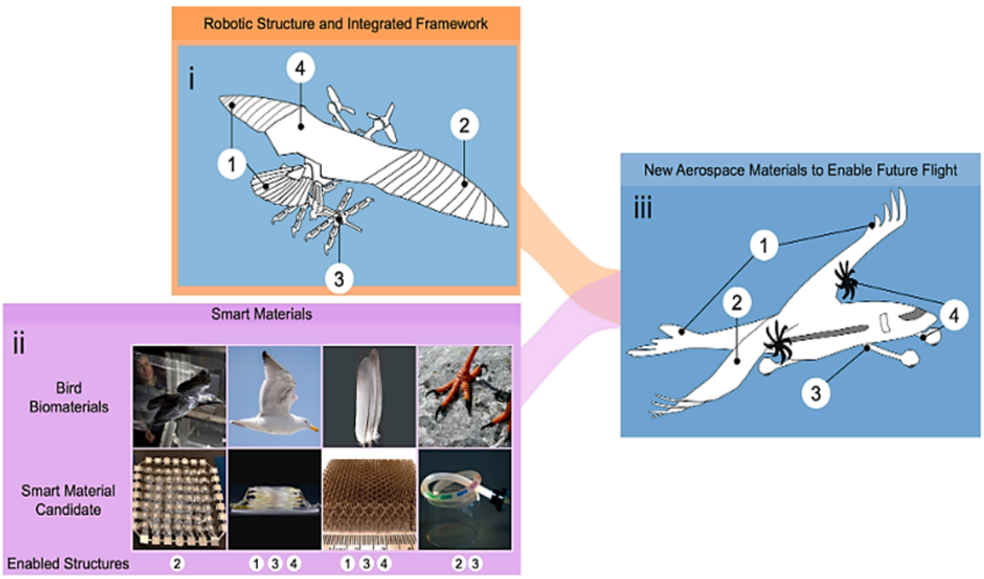


Figure 7. Conceptual framework for FalconBot and its aerospace equivalent

The design combines elements from biohybrid (PigeonBot), biomimetic (SNAG), and bio-inspired (AGR) systems: (1) Wing morphing for high-agility flight; (2) Embedded proprioceptive sensing; (3) Dynamic aerial grasping; (4) Vertical take-off and landing (VTOL) capabilities with multifunctional grippers [24]

Figure 6 shows the publications on MAVs from 2000 to 2023. The search terms used to extract data from the Scopus database were TITLE (flapping-wing AND robot OR vehicle OR MAV) for FWMAVs, TITLE (fixed-wing MAV) for fixed-wing MAVs, and TITLE (rotary-wing OR rotorcraft AND MAV) for rotary-wing MAVs (RW MAVs). For flapping-rotary-wing MAVs (FWR MAVs), the keywords used were TITLE (flapping-rotary wing) and TITLE (flapping perturbed revolving wing) [1]. Figure 7 shows the conceptual framework for FalconBot and its aerospace equivalent. The framework illustrates the translation of avian biomechanics into smart material systems and robotic control strategies [24].

Although RL has been mentioned among future directions for increasing the autonomy of FWRs, it would be practical to implement DRL within FWRs by developing task-specific learning architectures. The following presents an example of an RL-based methodology tailored to FWR control: the FWR can be trained to perform smooth hovering, maintain attitude control or execute aggressive flight maneuvers (e.g., high-rate turns or evasive actions).

a) State space (SS)

•The agent notes the following input parameters:

-IMU information: angles of the pitch, roll, yaw and angular rates

-Stroke amplitude or angles at the wing joints

-Coordinates of positions (in case of their existence)

-Option: input of airflow sensor or onboard vision (e.g., optical flow)

•Typical vector:

$$s = [\theta, \dot{\theta}, \phi, \dot{\phi}, \psi, \dot{\psi}, \text{stroke angle, flap rate}]$$

b) Action space (AA)

•The robot changes:

-Discrete/continuous wingbeat frequency

-Symmetry and amplitude of stroke

-Pitch plane or angle of attack

•Continuous action vector for PPO or Deep Deterministic Policy Gradient (DDPG):

$$a = [f_L, f_R, \Delta\phi, \alpha]$$

where, f_L and f_R are left and right wing frequencies.

c) Reward function (RR)

A form of reward helps the robot to achieve a stable and efficient flight:

$$R = -w_1 \cdot ||\theta - \theta_{\text{target}}||^2 - w_2 \cdot ||\dot{\theta}||^2 + w_3 \cdot T_{\text{hover}} - w_4 \cdot P_{\text{consumed}}$$

•Penalizes attitude error and high angular velocity

•Rewards the time duration of sustained hovering and thermic economy

d) Training strategy

•Testing environment: PyBullet, Gazebo or user-defined simulators of aerodynamics

•Algorithm: PPO is more recommended (contiguous action and strong)

•Domain randomization: Add random noise and variation with regard to wind, weight and sensor noise to simulate how the model is expected to perform in the real world

•Transfer learning: The policies acquired using sim-to-real frameworks are simplified onboard to adapt to the real world

In terms of literature findings, Tu et al. [26] also used PPO-based RL to train a hummingbird-scale FWR to do evasive maneuvers. Their approach successfully achieved 98% stability maintenance and reduced orientation recovery time by 41% compared to PID controllers. The obtained results show that models of RL-enabled FWR modified gust disturbances in less than 200 ms by adapting the symmetry of the stroke and pitch plane compared to fixed-gain control controllers which do not allow this adaptation. This approach facilitates real-time response and dynamic trajectory planning and allows filling the gap between the pre-programmed and biological-like flight intelligence.

6.2 Integration with Other Robotic Systems for Enhanced Capabilities

FWRs can assist in boosting the capabilities and expanding the use of other robotic systems. Such hybrid models that combine the benefits of agility and endurance are achievable with collaborating FWRs and traditional fixed-wing or rotary drones. The strength of each type is harnessed with its weakness in a more flexible fleet approach [1]. Thanks to multi-vehicle collaborations, especially utilizing swarm intelligence, groups of FWRs can accomplish complex objectives through swarm intelligence mimicking the bird flock behaviors. This method facilitates cooperative sensing to share information and provide a more improved situational awareness during operations and improves mission success rates [1].

Collaboration between aerial FWRs and ground-based units showcases another innovative integration path. In particular, aerial vehicles are suitable for providing scouting capabilities for tasks that must be coordinated with ground robots for mobility, such as in agriculture, where the aerial information informs the ground machinery for crop management or pest control [3]. Furthermore, when integrated into a robotic platform, the bio-inspired technology can further improve the adaptability and resilience of the platform in different environments. Using principles of soft robotics and advanced natural materials, FWRs can become flexible and durable to allow freedom to simply roam their terrain and adapt dynamically to environmental changes [3]. Aerial systems, with coupled sensor networks, are used to gain real-time data acquisition. Advanced sensors enable FWRs to return vital information to command units, where resource allocation can be improved in crucial situations like disaster response [17].

An exciting development in improving the effectiveness of an operator on bio-inspired aerial platforms is its partnership with the human operator through intuitive control interfaces. Combined with human input, ML algorithms help decrease the time taken for drones interacting with users to break into smoother interactions, and among them, drones are able to independently learn to adapt to user commands and stay safe [17]. One subject of research is modular designs aimed at easy integration of new functionalities into an already existing framework, resulting in quick upgrades without complete redesigns which promotes faster innovation in this area. Overall, merging FWRs into a broader robotic ecosystem further enhances the performance and potential of such applications across many different sectors [28].

Multimodal FWRs, capable of switching between aerial, terrestrial, and aquatic environments, can be a huge asset in various areas of work. In particular, such examples are:

•Air-ground disaster response: Aerial FWRs that contain collapsible legs or rolling support (e.g., wheel-leg hybrids) are able to fly in collapsed structures, and then roll out on the ground to reach confined areas to detect victims or map hazards.

•Agricultural monitoring (air-ground): Multimodal robots can fly over the fields to monitor stress in plants through spectral or thermal imaging, and land and crawl between plants to make more direct observations or apply pesticides, thereby reducing human exposure to harmful substances.

•Surveillance and marine biology (air-water): Air-water amphibious FWRs can splash down on water, use sealed bio-inspired wings or buoyancy control, search the surface of the water, track sea creatures or conduct surveillance of aquaculture planting. One such outstanding concept is a watertight flapping MAV capable of making it stable by having wing-locking mechanisms when floating.

•Military reconnaissance (air-ground): FWRs can fly stealthily over an area of interest with a guarding party, land out of the wind behind cover, and then use stealthy ground locomotion to move off the radar screen, continue surveillance, or drop micro-sensors.

•Environmental sensing in wetlands (air-water-ground): In order to monitor the climatic conditions or to study an ecology, it is valuable to have flying robots that land on wet ground or float over the surface of a marsh to acquire data on pH, humidity, or chemical compositions of the water and soil.

The incorporation of multimodal capability in FWRs requires a delicate tradeoff between actuation complexity, weight and environmental robustness. The works have progressed to modules of wings and legs, hydrophobic coating of the wings and an autonomous set of algorithms that make the operations reliable in any domain.

7 Conclusion

An outstanding development of bio-inspired attitude systems in FWRs is illustrated by the satisfaction of natural complexity and technological breakthrough. Whereas many concepts experiment in improving the design and functionality of MAVs, a serious wealth of advances has been attained from watching actual flying creatures, e.g., birds and insects, to seeing MAVs incorporate lessons learned from them. As the investigations dive deeper into aerodynamic principles and flight control tactics performed by these biological beings, the search may lead to more sophisticated autonomous systems for performing complicated maneuvering. RL techniques have proved to be effective for AI to achieve remarkable performance improvements of FWRs. Recent research shows how these methods allow robots to do acrobatic feats that once were thought to be unattainable for mechanical designs. The adaptive nature of natural flight is exemplified by this adaptability, especially when it comes to swiftly reacting to constantly changing environmental conditions [3]. Moreover, continuous improvements of the sensor technology are necessary to refine the attitude control systems. Developers will ensure that more agile systems are created that combine real-time data of position and orientation, given state of the art sensors. Such improvements are necessary to guarantee reliable operation under different situations, which is a widespread problem in conventional aircraft [10].

The work continues to focus on developing lightweight materials with unaltered structural integrity and energy efficiency improvements. New soft robotics innovations have paved the way for the creation of flapping wings modeled after the supple but forceful nature motions seen in the wild. In addition to optimizing aerodynamics, these materials are even more resilient, as they are bio-inspired to resist external disturbances during operation [10]. Finally, the bio-inspired designs can be integrated with other robotic frameworks and a new avenue of exploration appears. Accelerated capabilities could result from collaborative ventures between diverse End Airborne Robot (EAR) technology fields, e.g., autonomous navigation and ML. This includes drawing inspiration from insect communication and behavior to help create coordination between so many FWRs doing joint tasks that would be insurmountable by individual units ever [20].

Although some opportunities are promising, they must be addressed so as to realize their full potential. Actuator technologies available today place limits as to how far they can move while still staying close to what their biological counterparts can execute. Moreover, the effects of environmental variables, such as wind turbulence and obstacles on flight paths, further complicate the control problem that requires the investigation of robust control algorithms capable of adapting to such fluctuations. The overall process of developing bio-inspired attitude control mechanisms at the advanced level is summed up as a device within this broader development toward engineering practice of natural proven solutions. Continuous teaching from biological models has enabled researchers to make a quantum leap in their abilities to harness existing technologies to bring aerial robotics of the future into the development of highly efficient systems capable of complex maneuvers across a range of environments. This interplay between biology and engineering not only clarifies but also establishes the foundation upon which future innovations may reshape the definition of what is possible in terms of how robots can behave [31].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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