drones

Review

Review of Biomimetic Approaches for Drones

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Abstract: The utilization of small unmanned aerial vehicles (SUAVs), commonly known as drones, has increased drastically in various industries in the past decade. Commercial drones face challenges in terms of safety, durability, flight performance, and environmental effects such as the risk of collision and damage. Biomimetics, which is inspired by the sophisticated flying mechanisms in aerial animals, characterized by robustness and intelligence in aerodynamic performance, flight stability, and low environmental impact, may provide feasible solutions and innovativeness to drone design. In this paper, we review the recent advances in biomimetic approaches for drone development. The studies were extracted from several databases and we categorized the challenges by their purposes—namely, flight stability, flight efficiency, collision avoidance, damage mitigation, and grasping during flight. Furthermore, for each category, we summarized the achievements of current biomimetic systems and then identified their limitations. We also discuss future tasks on the research and development associated with biomimetic drones in terms of innovative design, flight control technologies, and biodiversity conservation. This paper can be used to explore new possibilities for developing biomimetic drones in industry and as a reference for necessary policy making.

Keywords: small unmanned aerial vehicles (SUAV); drone; biomimetics; biodiversity

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1. Introduction

The history of small unmanned aerial vehicles (SUAVs), commonly known as drones, can be traced back to human curiosity regarding how flying animals navigate the sky. In 1503, a sketch by Leonardo da Vinci in Italy depicted the novel idea of creating a rotor wing based on the mechanism of bird flapping in nature [1]. In Japan, around 1825, Ikkansai Kunitomo, a blacksmith and inventor, created a drawing of a flapping-wing aircraft design [2]. He measured the shape and weight of a brown-eared nightjar's wings, tail, and body and derived the corresponding lengths for a flying machine based on the ratio of the weight to that of the human body. These are considered the pioneering efforts in "biomimetics".

The term "biomimetics" was originally coined by Otto Schmitt, an American neurophysiologist, in 1957. He invented the "Schmitt trigger," which is an electrical circuit that mimics signal processing in the nervous system and converts an input signal into a square wave, from which noise is removed [3]. "Biomimetics" was first defined in Webster's dictionary in 1974 [4]. Its current definition is "the study of the formation, structure, or function of biologically produced substances and materials (such as enzymes or silk) and biological mechanisms and processes (such as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones" [4,5]. In 2015, ISO defined biomimetics as "interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution" [6]. In recent years, researchers in various fields have studied biomimetics, mainly because the approach is expected to bring sustainable technological innovation by learning from the survival strategies of living creatures.

The term "drone" was first used in the 1940s when the U.S. Navy named the Radioplane's flying machine the Target Drone. Subsequently, the development of power sources such as lithium-ion batteries, computers, and sensors led to smaller and electrically powered SUAVs. Rotor-wing UAVs became popular, particularly in Japan, starting with Yamaha Motor's unmanned helicopter for agricultural chemical spraying in 1983 [7].

However, despite the trend toward miniaturization, industrial technology needs further development. It has been noted that biological systems are very different from human technological systems in terms of materials, energy, methods, and sustainability. While living creatures effectively use information, space, and hierarchical structures, industrial technology relies on energy and materials, as revealed in Vincent et al.'s analysis using TRIZ, a theory for solving inventive problems [8].

As for the environmental effect, we must be aware that some species of birds and insects are threatened with extinction. According to the report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in 2019 [9], the best estimates of the proportion of species threatened with extinction are 13% for birds and 14% for dragonflies and damselflies. IPBES researchers have alerted the science community that the costs of the declining capacity of nature to provide crucial benefits are distributed unequally, as are the benefits of an expanding global economy [10]. Airspace is borderless to flying animals, and they interact with land and sea areas inhabited by other creatures. To follow a direction such as that provided by the "Air Mobility Revolution", for which a roadmap was developed by the Japanese government in 2018 to explore airspace for industrial use [11], we must use the airspace in such a way that SUAVs can coexist with other living creatures. In other words, biomimetic drones can learn from insects and birds but should not replace them or threaten other species. Biomimetics, which involves learning from living creatures that have already achieved sustainable systems, is a straightforward approach to achieving coexistence.

The industry sectors are now directed to reduce environmental impacts and develop sustainable technologies. As a starting point, researchers in the field of biomimetics for SUAVs are aiming to overcome the challenges faced by current commercial drones using the abilities and characteristics of flying animals. In this paper, the existing biomimetic systems were categorized based on the challenges faced by current drones as follows:

- Flight stability: flying in inclement weather, complex confined environments such as underground tunnels and buildings, urban areas, and non-GPS environments;
- Flight efficiency: working for long hours over a wide space;
- Collision avoidance: avoiding other flying objects, buildings, trees, and animals in the airspace;
- Damage mitigation: mitigating the significant damage to aircraft, people, animals, and property that occurs in the event of a collision;
- Grasping during flight: grasping and carrying irregularly shaped heavy objects.

In this paper, we review the recent advances in biomimetic approaches for drone development with a specific focus on how researchers can explore biomimetic approaches to tackle the above challenges. Several representative biomimetic designs associated with drones are highlighted. We further present an extensive discussion and identify the limitations of the current biomimetic systems. Finally, we discuss the future tasks on drone development in terms of innovative design, flight control technologies, and biodiversity conservation.

There are several comprehensive reviews in this field, i.e., those on avian-inspired morphing [12], biomimetic flow control techniques [13], beetle hindwings [14], grasping functions [15], dragonfly-inspired micro air vehicles [16], and flapping-wing micro air vehicles (FWMAV) [17]. We appreciate those reviews and introduce more recent works aiming to solve the problems of existing drones with solutions inspired by diverse model animals.

As a study methodology, we used keywords such as "biomimetics", "bioinspired", and "drones" to extract articles from the Web of Science, Google Scholar, and worldwide media reports, mainly between 2017–2022. We then categorized the articles by purpose and included those considered to have a high societal impact in the review. We also referred to some government and UN documents on biodiversity as background information.

2. Representative Biomimetic Designs in SUAVs

The five challenges listed in Section 1—namely, (1) flight stability, (2) flight efficiency, (3) collision avoidance, (4) damage mitigation, and (5) grasping during flight—are typical issues that existing commercial drones face, and researchers are providing new ways of solving these issues in terms of biomimetics. We believe these five challenges are essential to provide a whole picture of the current biomimetic design. In this section, we introduce some representative biomimetic designs to tackle the five challenges. In particular, as shown in Figure 1, which depicts the classification of biomimetic drones by weight, (1) flight stability is a major issue, and the number of studies on it is more than that of other challenges. Therefore, we describe flight stability based on three approaches: morphing-wing-based gliding, wing-flapping-based agility, and attitude control in flight.

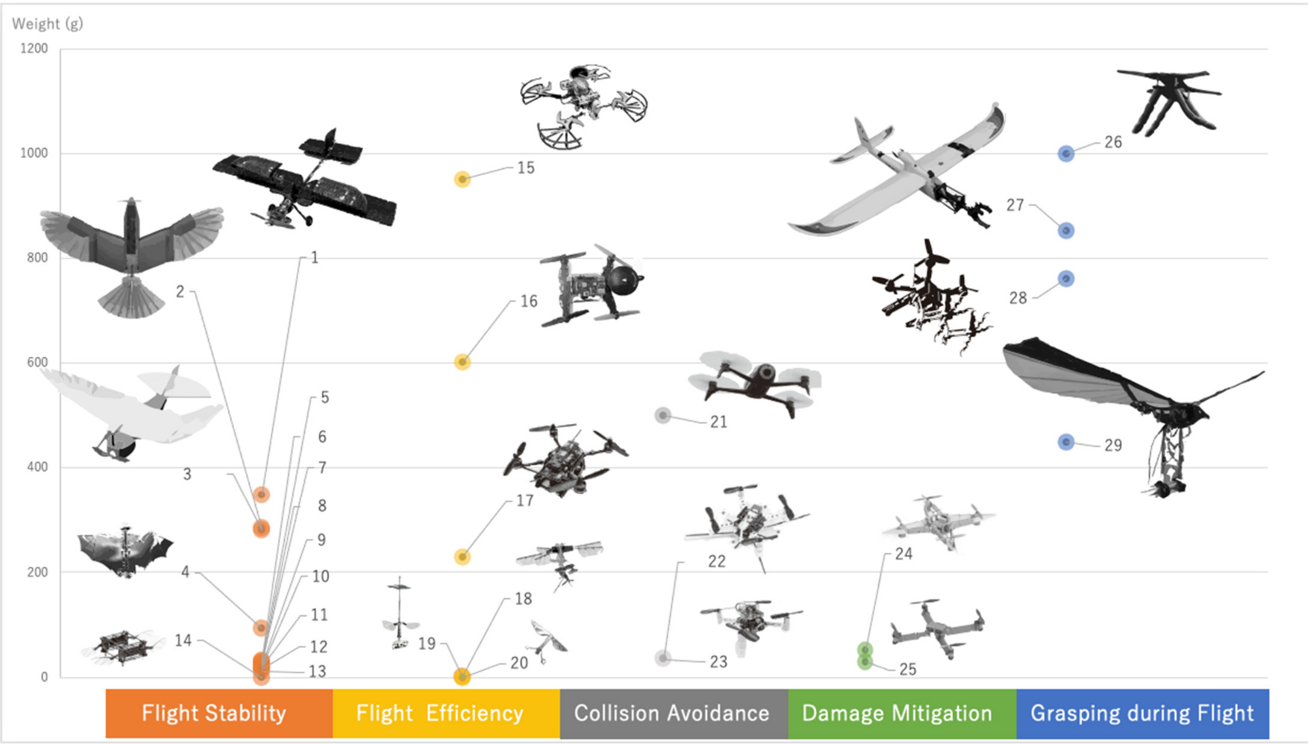

Figure 1. Classification of biomimetic drones according to weight. Each colored box at the bottom displays the challenge that various research teams have attempted to address. Most biomimetic drones are less than 600 g, except in the grasping challenge, where the weight varies from 400 to 1000 g. The names of the vehicles depicted in the figure are as follows: 1. Ely [34], 2. LisHawk [18], 3. PigeonBot [19], 4. Bat Bot B2 [22], 5. NUS-Roboticbird [30], 6. Wifly [32], 7. Delfly [20], 8. X-wing ornithopter [23], 9. COLIBRI [26], 10. Flapping Drone [28], 11. Nano Hummingbird NAV [24], 12. KUBeetle-S [29], 13. Hummingbird Robot [27], 14. Soft-Actuator Flapping Robot [33], 15. Aerial-aquatic Robot [43], 16. NLE-UAV-001 [38], 17. KMel Nano+ [41], 18. flapping-wing micro air vehicle [39], 19. RobeBee X-wing [40], 20. Biologically-inspired robotic insect [42], 21. Parrot Bebop 2 [44], 22. Crazyflie 2.0 with mosquito-inspired sensory system [45], 23. Crazyflie 2.0 with flow and multi-ranger expansion decks [48], 24. Collision-tolerance Quadcopter [50], 25. Origami quadcopter [51], 26. Soft drone [54], 27. Aircraft with perching claw [56], 28. SNAG [55], and 29. Ornithopter with bioinspired claws [57].

2.1. Flight Stability

SUAVs normally fly in the airspace under a certain altitude and are prone to flight instability due to air turbulence caused by the natural environment and urban structures. Therefore, researchers are trying to understand and apply bioinspired flight systems that allow birds/insects to dynamically change their posture during flight without stalling and crashing in turbulent or bad weather. As shown in Table 1, various animal models have inspired researchers to realize stable flight. We review those representative biomimetic design for flight stability by three different approaches in order.

Table 1. Biomimetic approaches for flight stability.

Approach	Model Animal	Targeted Function	Mechanical Components
Morphing-wing-based gliding	1. Northern goshawk	Responsive body	A front propeller, adjustable tail, wings
	2. Pigeon	Seamless feathers	Wing ex-intensions linked to wrists
Wing-flapping-based agility	3. Fruit Fly	High acceleration	Flapping wings
	4. Bat	Acrobat flight	High DoF * of wings
	5. Swallow	Multimodal flight	Anti-whirl transmission, flexible wing membrane
	6. Hummingbird	Hovering	Wing twist modulation
Attitude control in flight	7. Birds	Seamless hovering and horizontal flight	Mechanism of shifting the center of gravity
	8. Insects	High-speed flapping	Soft actuators
	9. Beetle	Recovering from flipping over	Elytra-like wings

* DoF: degrees of freedom. The name of each vehicle and the associated study are as follows. 1. LisHawk [18]; 2. PigeonBot [19]; 3. Delfly [20]; 4. Bat Bot B2 [22]; 5. X-wing ornithopter [23]; 6. COLIBRI [26]; 7. Wifly [32]; 8. Soft-actuator flapping robot [33]; 9. Ely [34].

2.1.1. Morphing-Wing-Based Gliding

Conventional drones have inflexible elements; however, they can greatly benefit from controlled or adaptive shape variations. Birds such as the northern goshawk adapt their wing and tail areas to realize aggressive flight in dense forests and fast cruising. Researchers at the Swiss Federal Institute of Technology in Lausanne (EPFL) developed LisHawk [18], a raptor-type drone inspired by the northern goshawk, which can change the area of its wings and tail in response to the flying environment (Figure 2a). The propeller attached to the front of the fuselage generates a forward thrust. The synergistic effect of the front propeller and adjustable tail and wings increases the airborne distance, flight stability, and agility.

The mechanism of wing flexion and extension in birds has also been elucidated. Researchers at Stanford University [19] measured the skeletal and kinematic properties of a typical pigeon wing and found that wing flexion and extension are linked via a nearly linear transfer function that uses the angle of the wrist as an input. They also developed PigeonBot, a flying robot incorporating real pigeon wings (Figure 2b). They found that in birds other than owls that fly quietly, a hook-like microstructure similar to Velcro holds the wings in place, preventing gaps during extension and automatically unfastening them during flexion. Using a flying robot as a bird model to elucidate the biological mechanism of flight is expected to be a new approach for developing next-generation SUAVs.

(**a**) (**b**)

Figure 2. (**a**) LisHawk drone (**top**) inspired by a bird of prey called Northern Goshawk (**bottom**), with morphing wings and tail to switch between aggressive flight and cruising. The picture shows the aggressive flight mode. (**b**) PigeonBot (**top**) inspired by morphing wings of pigeons (**bottom**), with overlapping microstructures in the form of feather Velcro for flexible flight.

2.1.2. Wing-Flapping-Based Agility

Some researchers have examined the high agility of small flying animals with flapping wings to develop small agile autonomous flying robots. For example, researchers at the Delft University of Technology (TU Delft) [20] examined the agility of fruit flies and created a flying robot called Delfly, which weighs approximately 28 g and can accelerate up to 25 km/h by flapping its four wings and quickly return to its original position, even after it hits an obstacle. However, the flight time is only approximately 6–9 min. Guido de Croon mentioned the difficulty in making a flapping drone fly entirely on its own, with minimal sensors, computing power, and memory, as a challenge in developing a viable alternative to existing drones [21].

Researchers at California Institute of Technology and the University of Illinois [22] were inspired by the morphology and flight mechanism of the flexible wings of bats. They developed Bat Bot B2, which implements the key degrees of freedom (DoFs) in the bat's flight mechanism using a 93 g body containing a 56 µm silicon thin film and a control unit. The thin film can deform as the bot flaps its wings, enabling autonomous flight with high energy efficiency.

Swallows demonstrate aerobatic flights. Researchers at National Chiao Tung University [23] developed an X-wing ornithopter with a fuselage length of 200 mm and weight of 26 g, which is capable of multimodal flight. Raising the tail to obtain a large thrust allows it to hover, fly forward at a high speed, make aerobatic turns, and dive.

The agility and hovering capability of hummingbirds have also inspired researchers. AeroVironment's Nano Hummingbird [24] is the first flapping-wing micro air vehicle (FWMAV) capable of stable hovering and is controlled by a human-operated remote control. A vehicle ordered by the Defense Advanced Research Projects Agency (DARPA) in 2011 can continuously hover for 8 min without an external power source [25]. The authors at Université Libre de Bruxelles (ULB) developed COLIBRI [26] using a mechanism known as wing twist modulation, which was initially used by Nano Hummingbird to stabilize the wings' pitch and roll for hovering. COLIBRI can hover autonomously for 15–20 s using an onboard battery. Researchers at Purdue University [27] developed a hummingbird robot. This tethered FWMAV demonstrates autonomous and fast evasive maneuvers with a hybrid control policy that combines model-based nonlinear control with model-free reinforcement learning. Other hovering FWMAVs include the Flapping Drone, which employs a control method for its gravity center position, developed by researchers at Nagasaki University [28]; KUBeetle-S, which can simultaneously modulate the stroke plane and wing twist, developed at Konkuk University [29]; and NUS-Roboticbird, which has a wing stroke plane modulation mechanism, developed at the National University of Singapore [30].

An extensive review of FWMAVs and flying animals as of 2016 by the researchers at Chiba University suggests that insects choose agility for survival in the trade-off relationship between flight stability and maneuverability, and that agility could be supported by a multiple sensing system to achieve a quick and precise response and to allow adjustments of their controls constantly to stabilize the flight [17]. This mechanism is expected to inspire insect-inspired multisensing and real-time control technologies, which also help drones to avoid crashing into birds and insects.

2.1.3. Attitude Control in Flight

The standard structure of the current drone has four rotary-wings, and it has high agility with advanced control methods. Still, from an aerodynamic standpoint, the angle of attack (AoA) of the rotary wing is smaller than that of the flapping wing. This makes the rotary wing inferior to a flapping wing in terms of stability and maneuverability. Because flapping wings can perform large movements while dynamically varying AoAs in a wing stroke over a broad range of AoAs, they can avoid or greatly delay stalling, substantially enhancing flight stability [1,17], and further create a larger lift surface, thus augmenting the robustness in lift and torque production during maneuvering [31]. By combining a unique mechanism with flapping wings or fixed wings, some researchers have controlled the attitude of SUAVs, even under sudden flight instability.

Researchers at the Waseda University [32] developed WiFly, a flapping robot weighing approximately 30 g and equipped with a center-of-gravity shifting mechanism. With two types of feedback control—proportional-integral-derivative (PID) control and reinforcement learning (shallow Q-learning) system—in addition to control of the pitch angle, the WiFly can seamlessly switch its flight attitude between hovering and horizontal flight.

An insect-inspired flapping-wing microrobot developed by the researchers at Harvard University [33] has thin rubber cylinders coated with carbon nanotubes as soft actuators that flap 500 times per second. This 600 mg drone with four flapping wings can recover its attitude from in-flight collisions by exploiting material robustness and passive vehicle stability.

As a recovery feature from tipping over, the researchers at EPFL [34] developed a drone that could return to its original position after it was flipped over. The drone is equipped with an additional fixed wing, such as the structural wing called elytra in the beetle.

Limitation: as we have seen, most of the biomimetic drones mentioned above have flapping wings. The more DoFs in the flapping wings, the more complex control system is required to maintain long-distance flight. We expect a standardized design and a sophisticated control system to overcome this issue. We will disscuss this point in Section 3.

2.2. Flight Efficiency

To achieve long-duration and long-distance flights with limited energy sources, the energy used for flight needs to be conserved; improving the power efficiency of UAVs is effective and straightforward, but efficiency can also be improved by using biomimetic flight strategies. To realize efficient flight over long distances and durations, we can study the collective behavior of migratory birds. The researchers at New Mexico State University [35] took advantage of the aerodynamics of the V-formation of birds during flight. They proposed a conceptual design of a multi-flapping-wing drone with multiple pairs of wings arranged in a V-shape, which was inspired by the aerodynamic advantage of the high propulsive efficiency of collective bird flight. They tested several wing shapes and airfoils, and the proposed bioinspired design achieved a propulsive efficiency of 73.8% during forward flight. Inspired by the small correlations between the flapping wings and body in insects' flight, researchers at Chiba University found the optimal rotor configuration in four rotor wings and confirmed its increase rate of 7.0% in lift force compared to the basic rotor configuration [36].

The Bionic Swift by a German pneumatic equipment manufacturer, Festo, has multiple plates constituting the wings. When the wings are moved up, the plates open between them to reduce power consumption, and when they are moved down, the plates close to create a large lift force. By using a radio module compatible with ultrawideband wireless (UWB) communications, the aircraft can also fly in formation with multiple aircraft [37].

A straightforward solution to realizing efficient flight is to reduce the aircraft weight. Researchers at the Netherlands Organization for Applied Scientific Research [38] proposed a nature-inspired algorithm for operating SUAV swarms using swarm intelligence to acquire real-time video footage data for inspections. This decentralized approach can significantly reduce communication infrastructure requirements and computational costs.

Externalizing the batteries by employing wireless energy transfer is another strategy for reducing the weight of an insect-scale aircraft (<10 cm and <5 g). Researchers at Toyota Central R&D Labs [39] developed an electromagnetic wave-transmitting flying robot with a total weight of 1.8 g. This FWMAV succeeded in performing untethered flight using a subgram high-frequency power receiver with a power-to-weight density of 4900 W kg^{-1}, which was five times that of commercially available lithium polymer batteries. The lift-to-power efficiency, with the inclusion of the electronics, was 3.6–3.7 gf W^{-1} during hovering flight, which was higher than those of previous insect-scale FWMAVs—for example, 2.4–3.0 gf W^{-1} of the RoboBee X-Wing developed at Harvard University [40], which is known for stable hovering and maneuvering.

Stop-of-flight and perching are alternative solutions for saving energy. Researchers at the University of Pennsylvania [41] developed a vision-based system that can perch on arbitrarily oriented lines in space. At a small scale, magnetic forces dominate the gravitational forces. Researchers at City University of Hong Kong and Harvard University [42] exploited this phenomenon and attached small steel discs on the robotic insect, which weighed only 80 mg. They used iterative learning control and the proposed adaptive tracking controller to make it perch on a vertical surface. A new type of perching biomimetic drones is the aerial-aquatic "hitchhiking" robot proposed by the researchers at Beihang University [43]. This remora-inspired robot with an adhesive disk can perform rapid attachment to and detachment from various surfaces, both in air and under water.

Limitation: the smaller the drone size, the more limited its functionality. For example, an insect-scale aircraft cannot carry objects, and even drones utilized for surveillance or reconnaissance need to be equipped with at least a camera or sensor. Therefore, it is essential to achieve a balance between efficiency and the minimum weight possible, considering the intended use of the drone.

2.3. Collision Avoidance

SUAVs are operated under an altitude of approximately 1 km and they share the airspace with birds and insects. Avoiding flying animals/objects as well as indoor walls and other obstacles requires a highly intellectual function to calculate the exact distance from the obstacle.

Researchers at TU Delft [44] utilized the mechanism employed by honeybees to measure the distance between themselves and surrounding objects during flight, which involves focusing on the optical flow and applying it to avoid collision in air. Optical flow refers to the velocity field of the entire image projected onto the retina in the vision of an organism, caused by its motion and changes in the external world. By combining the optical flow and visual information, the flying robot can avoid obstacles approaching it from the front.

We can also utilize distortions in the flow field around an aerial vehicle to detect obstacles by learning from the insect antennae, which are highly sensitive to airflow. Researchers at the Royal Veterinary College [45] developed a drone inspired by the aerodynamic imaging of mosquitoes and succeeded in detecting floors and walls using an array of differential pressure sensors mounted on the drone.

As one of the commercially available biomimetic drones, Bionic Bird's Metafly is famous for flying indoors at low altitudes while avoiding obstacles. The flight speed can be adjusted by manually changing the angle of the tail. If it hits an obstacle, the resilient material absorbs the impact. Currently, the company has also announced its successor, the Metabird, which can be controlled by a smartphone [46]. Other approaches to realize collision avoidance include the use of event cameras, which are bioinspired sensors with reaction times of microseconds [47]; swarm intelligence to communicate with other flying objects [48]; and neurons of locust-inspired collision detectors [49].

Limitation: these biomimetic drones do not have a set of uniform obstacles to avoid. The obstacle's shape, size, and speed will also change the drone's required functionality, so it is desirable to have a list of the minimum necessary obstacles to avoid, such as animals or other flying vehicles, while complying with the specific regulations of each airspace.

2.4. Damage Mitigation

The rotor blades used for conventional SUAVs are inflexible and sharp for high aerodynamic performance and can damage the aircraft itself as well as people, animals, and indoor and outdoor properties when they crash. For damage mitigation, the materials and structures of the SUAVs must be selected carefully.

Researchers at the EPFL [50] attempted to take advantage of the flexibility and rigidity of insects. They implemented a dual rigid frame that softened and folded in the event of a collision to avoid damage and verified the shock-absorbing effect with a 51 g quadcopter.

Another approach was proposed by the same team [51] to incorporate the flexibility of insect wings into an origami-like structure. They mimicked the elastic protein resilin found in insect wings by sandwiching an elastomeric membrane between rigid tiles to create an origami structure, which they implemented in the frame element of the quadcopter. This allowed the rigid structure to withstand the aerodynamic forces during flight and soften upon impact to avoid catastrophic damage.

Researchers at the Japan Advanced Institute of Science and Technology [52] proposed a new deformable propeller design inspired by the wings of dragonflies. This propeller has flexible nodules that can be bent and twisted to absorb the force of collision and protect the propeller from damage. A propeller deformed in a collision can return to its original shape within 0.4 s and resume regular operation.

Researchers have focused on the superior flight performance of dragonflies, and numerous studies have been conducted on the aerodynamic design and control of dragonfly-inspired micro air vehicles [16,53].

Limitation: The focus of these biomimetic drones is to minimize damage to the aircraft itself. We expect that further experiments will be conducted to develop drones that avoid damaging objects or humans in the environment.

2.5. Grasping during Flight

In logistics, construction, agriculture, and forestry, SUAVs are expected to transport objects of various shapes and sizes and work in high or isolated places that humans cannot access. To meet this requirement, researchers have focused on the avian function for grasping.

A dynamic grasping function that grasps objects of various shapes from a height close to the ground without breaking them and then returns to regular flight is noteworthy.

Researchers at MIT [54] developed a quadrotor, where the traditional rigid landing gear was replaced with a soft tendon-actuated gripper.

Furthermore, researchers at Stanford University [55] proposed a biomimetic robot that could grasp irregular objects and had the ability to perch on complex surfaces such as branches and trees. The SNAG (Stereotyped Nature-inspired Aerial Grasper), inspired by peregrine falcons, can grasp a dynamic prey-like object during flight, carry it along, and hold ten times its weight.

Smooth perching is technically challenging. Excessive reduction of the kinematic energy causes unstable flight, but high kinematic energy at touchdown will damage the vehicle. Researchers at EPFL [56] developed a mechanism that transfers kinematic energy to other energies for opening and closing the claws and realizes high-speed perching at 7.4 m/s. Researchers at University of Seville [57] developed an ornithopter that uses shape memory alloy springs to reduce the weight and has bioinspired claws that can adapt to any shape.

According to a comprehensive review article on perching and grasping robots by Jiawei Meng et al., grasping is one of the approaches for achieving perching, and other approaches include attaching or embedding [15]. As mentioned in Section 2.2, energy saving can be achieved through several approaches, but grasping is the best approach for SUAVs that carry objects.

Limitation: The existing shape of the grasping device and its control method can vary depending on the payload and size of the SUAV; therefore, we expect that more generic materials and structures, as well as control models for any type of object, will be explored.

3. Future Tasks of Biomimetic Drones

As explained previously, biomimetic drones utilize the characteristics observed in birds and insects in relation to flight stability, flight efficiency, collision avoidance, damage mitigation, and grasping during flight. R&D in biomimetic approaches for drones has resulted in some successful designs capable of achieving better performance than conventional drones by mimicking the materials, mechanisms, and structures observed in flying animals. These R&D projects are expected to expand the utilization of drones in various industries.

Most of the current studies have adopted the approach of extracting some of the morphologies and/or functions of flying birds and insects, reproducing their characteristics, and implementing them in drone mechanisms, but they have not yet achieved the highly integrated, embodied intelligence of flying animals. There are several reasons for this.

3.1. Innovative Design

First, creating such an integrated closed-loop system, which remains entirely unknown, requires an innovative design. Studies on insect flight suggest that it is controlled by a highly integrated, closed-loop system in which an internal working system composed of muscles and a nervous system interacts with an external exoskeletal shell and wing [17]. Over hundreds of millions of years, insects have evolved organic, flexible structures at different levels of the body, wing, wing-hinge, musculoskeleton, sensors, and motor, but these features are not well understood. However, by focusing on the resource efficiency (parsimony) of insect intelligence, studies on insect-inspired artificial intelligence for autonomous robots are underway [58]. The parsimony of insect intelligence, whose main aspects are embodiment, sensory-motor coordination, and swarming, has attracted the attention of biomimetic drone engineers.

An open-science approach using 3D printers is also promising. Researchers at Nagasaki University proposed software to produce 3D printable insect-inspired wings that allows users to reproduce, customize, and share their products [59]. Another new trend is the biohybrid approach to manufacture drones equipped with actual insect body parts for odor source localization. Researchers at the University of Tokyo introduced a small autonomous drone with a portable electroantennogram based on the silk moth antennae [60]. The biohybrid approach is attracting attention because of its low development costs, although we have to avoid negatively affecting the ecosystem by overhunting insects.

Other studies have adopted the approach of creating new forms of robot by combining several functions. Examples include the single-leg hopping robot Salto-1 developed at UC Berkeley [61] and the walking and flying robot LEONARDO developed at Caltech [62]. The evolution of animals has taken various forms to adapt to the environment; therefore, it may be possible to refer to animals that do not exist today for the design of next-generation drones to adjust to a globally warming world.

We expect the integrated system design to include built-in functions such as flight stability, intelligence, and environmental adaptation to accommodate the new trend of the studies mentioned above.

3.2. Flight Control Technologies

Second, biomimetic drones require sophisticated control technology to support their integrated design. The level of control of biomimetic drones has not yet reached that of other robotic technologies, such as precise manipulators and agile mobile robots. Most of these studies have focused only on structural development and dynamic analysis inspired by flying animals. This is because researchers have focused on determining the effects of the body design of birds and insects on flight performance as they dynamically interact with the environment. However, owing to the desire to mimic the motions of flying animals, the structures of biomimetic drones have become more intricate, thereby complicating their control. For example, PigeonBot aimed to replicate wing-morphing in birds. The design resulted in a serious underactuation problem, where a wing had 21 DoFs but was actuated by only two inputs [63]. Consequently, variants of PID control are the most common choice for control, where a model is not required [18,20,26,32,64–68]. However, control without a robust and efficient model has been proven to have limitations in any application. Therefore, most present biomimetic drones cannot mimic the level of performance and sophistication of their model animals.

Model-based and machine learning/deep-learning-based control algorithms can be used to improve the control in biomimetic drones. The creators of the LisHawk drone suggested the implementation of either optimal control or machine-learning control in future studies [69]. However, certain challenges must first be overcome to implement these types of controllers. A model needs to be obtained, and stability analysis must be performed to implement model-based control strategies such as adaptive control, optimal control, and sliding-mode control. In the robotic hummingbird developed at Purdue University, modeling problems were addressed using system identification, and exponential stability was guaranteed using a nonlinear geometric controller [70].

Machine learning/deep-learning-based techniques can circumvent such issues because they are model-free. However, these methods require a large amount of data and computational time for effective learning, which requires a sizable computation ability. The developers of RoboBee X-Wing utilized a learning-based spiking neural network control and achieved rapid target following ability, which allows online implementation [71]. A promising and safe flight test environment was developed in [72] where learning-based approaches could improve the performance under different environmental conditions. Furthermore, a combination of model-based and learning-based control methods has the potential to address more challenging problems. In [27], a model-based nonlinear controller was combined with a reinforcement learning strategy to develop a hybrid controller that can allow the extreme maneuvers observed in hummingbirds.

Researchers are expected to consolidate the ideas and designs of existing biomimetic drones and develop an ideal control technology. A consolidated design, which has advantages over previous designs, can serve as a benchmark for future development. Furthermore, it can serve as the basis for a generalized model for model-based control techniques.

3.3. Biodiversity Conservation

Third, biodiversity conservation must be considered as a primary criterion of the design principle. Biodiversity is key to ensuring the sustainability of the entire planet. Humans are merely one of the species of living creatures and have occupied the earth for only a short period in the entire history of the planet. When drones are used near habitats and activity zones of living creatures, we must carefully ensure that noise, lights, and electromagnetic radiation do not interfere with the maintenance of the ecosystem.

Regarding noise, there is an urgent need to improve the functionality of propellers and other devices, given their convenience in the human sphere of life; however, ensuring that drones do not threaten the ecosystem is also crucial. In Japan, the "Guidelines for the Delivery of Packages Using Drones," released by the government in June 2021 [73], mentions the possibility that in areas inhabited by rare wildlife, the approach and sound of drones may cause excessive stress in the animals and falling drones may cause injury. It states, "you should consider not to affect wildlife ecology adversely".

For example, swallows that visit Japan in summer are also associated with the ecosystems of other Asian countries, as they mainly overwinter in the Philippines, Indonesia, Malaysia, and southern Vietnam [74]. A study shows that in the developing countries and countries in transition, the ecosystems are the most complex and richest in the number of species, whereas research capacities are the highest in the "North", i.e., the industrialized countries [75]. We need to study the specific drones that may have a negative impact on the wildlife ecology as well as establish a service allowing business drone owners to confirm the habitat areas of rare wildlife and migratory birds. There are the Federal Aviation Regulations (FAR) in the U.S. and the European Union Aviation Safety Agency (EASA) regulations, so the functions with low environmental impact should be developed and accommodated with each local rule.

Another related example is the consideration of biodegradable materials in the research on wireless sensors that mimic plant seeds [76]. In the case of drones, achieving both robustness and natural degradability is technically challenging. However, if the drone is to fly near marine areas or forests inhabited by endangered species, it will be important to select materials that minimize the environmental impact in the case of a crash. Considering recycling or reuse of materials is also crucial for minimizing drone waste. Biomimetic drones are also expected to have significance in development as an academic research tool for monitoring living creatures and the environment; thus, they are not intended solely for industrial use. For example, demonstrating the effect of global warming on living creatures based on data captured by drones has social significance. Researchers at Stanford University showed that SNAG [55] can be used to study ecosystems by measuring the ambient temperature and humidity onboard while in a perched position.

Including such scientific proposals in political manifestos and creating a system to accumulate successful case studies in each academic institution are crucial for expanding the field of drones in both science and industry while preserving biodiversity.

4. Conclusions

In this paper, we highlighted the recent advances in biomimetic approaches for drone/SUAV development. Each study was reviewed based on the challenges faced by current drones—namely, flight stability, flight efficiency, collision avoidance, damage mitigation, and grasping during flight. These approaches have provided various promising designs and additional functions to achieve better performance than conventional drones and have further accelerated the trend toward miniaturization. These R&D projects are expected to expand the utilization of drones in various industries.

We also addressed the challenges and future perspectives on the R&D of biomimetic drones. Most current studies have adopted the approach of extracting some of the morphologies and/or functions of flying birds and insects, reproducing their characteristics, and implementing them in drone mechanisms. However, their models, i.e., the flying animals, have highly integrated, embodied intelligence interacting with the natural environment, which has evolved over hundreds of millions of years. To realize such an integrated mechanical system, innovative designs with new fields of study, including insect-inspired artificial intelligence, open science, and bio-hybrids, and development of drones based on ideal model animals, are necessary. These designs should incorporate advanced control techniques, with the preservation of biodiversity as a primary criterion of the design principle.

Biodiversity conservation is essential for drone development because the flight airspace of a drone is under an altitude of approximately 1 km, which overlaps with the range of birds and insects, and noise, light, and electromagnetic waves may interfere with the entire ecosystem, which is also crucial for human beings to maintain their life and culture. In particular, researchers in the field of biomimetics should create a roadmap for technological development with biodiversity conservation as the first requirement by recognizing the habitats of rare wildlife and migratory birds, considering biodegradable materials, and developing technologies for monitoring organisms and the environment.

We expect that this paper will inspire researchers and practitioners to explore new possibilities for developing biomimetic drones and be a useful reference for necessary policy making.

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