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REVIEW ARTICLE

A Review of Research on the Mechanical Design of Hoverable Flapping Wing Micro-Air Vehicles

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Abstract
Most insects and hummingbirds can generate lift during both upstroke and downstroke with a nearly horizontal flapping stroke plane, and perform precise hovering flight. Further, most birds can utilize tails and muscles in wings to actively control the flight performance, while insects control their flight with muscles based on wing root along with wing's passive deformation. Based on the above flight principles of birds and insects, Flapping Wing Micro Air Vehicles (FWMAVs) are classified as either bird-inspired or insect-inspired FWMAVs. In this review, the research achievements on mechanisms of insect-inspired, hoverable FWMAVs over the last ten years (2011–2020) are provided. We also provide the definition, function, research status and development prospect of hoverable FWMAVs. Then discuss it from three aspects: bio-inspiration, motor-driving mechanisms and intelligent actuator-driving mechanisms. Following this, research groups involved in insect-inspired, hoverable FWMAV research and their major achievements are summarized and classified in tables. Problems, trends and challenges about the mechanism are compiled and presented. Finally, this paper presents conclusions about research on mechanical structure, and the future is discussed to enable further research interests.

Keywords Hoverable · Flapping wing · Insect-inspired · Mechanical design · Motor drive · Intelligent actuator

1 Introduction

The definition of insect-inspired Flapping Wing Micro Air Vehicles (FWMAVs) is derived from the definition of the Micro Air Vehicle (MAV) [1]. The MAV was first mentioned in a research report on future military technology submitted by Rand Corporation to the Defense Advanced Research Projects Agency (DARPA) [2] in 1992. The MAV is generally defined as an aircraft whose dimensions are less than 15 cm and whose design objectives are as follows: mass: 50 – 100 g; flight range: 10 km; cruise speed: 30 – 60 km/h; endurance time: 20 – 60 min. To improve the concealment of MAVs, FWMAVs were first developed by Michael Mitchell of DARPA in 1997. According to the principle that insects and small birds [3] utilize their wings to realize flapping flight, he conceived a kind of aircraft with the same scale as insects or hummingbirds, which utilizes flapping flight to generate aerodynamic force and realize low-speed flight, hovering, rapid turning, and inverted flight.

In addition to all features of MAVs, the most prominent feature of insect-inspired, hoverable FWMAVs is mimicking the flight of insects and hummingbirds. Hovering flight ability is the most significant difference between it and bird-inspired FWMAVs. Insect-inspired, hoverable FWMAVs have a low cost, low noise, and strong concealment and are flexible. In particular, its bionic shape and flight mode greatly enhance its battlefield concealment and operational efficiency. It can be seen from the above that insect-inspired, hoverable FWMAVs can perform military reconnaissance, target tracking, weapon delivery, electronic jamming, ground attack and relay communication tasks in the military field. The application prospect of hoverable FWMAVs in civil field is now broadening. In terms of transportation, it can patrol a certain area day and night to find various traffic hazards or accidents in time; in terms of monitoring, environmental monitoring, and forest fire prevention, crop pest monitoring can be carried out; in terms of disaster rescue, it can enter narrow, complex, and dangerous areas for personnel search and rescue [4].

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The design of hoverable FWMAVs includes a mechanical structure, bionic wings, a flight dynamics model, airborne electronic equipment, a flight control system, and micro energy. As the only source of aerodynamic force, to realize a high-flapping frequency and attitude change, the mechanical structure design is the most important [5]. Different from fixed-wing and rotor aircraft, due to the need to transform or amplify the driving motion, it is necessary to design a transmission mechanism that withstands high-speed impact and friction, so the mechanical structure of hoverable FWMAVs requires a higher strength and reliability [6]. In particular, the flapping mechanism needs to operate under dozens or even higher frequencies to generate enough aerodynamic force and ensure the reliability and efficiency of aircraft. On the other hand, to simulate the influence of the biological musculoskeletal system on the angle of attack (AoA) and the flapping plane of the wings, researchers designed control mechanisms to control these actively to achieve better flight stability. Therefore, the mechanical design and the performance of the materials utilized directly determine the service life and performance of insect-inspired FWMAVs, which is also a research hotspot.

The United States [2, 7], South Korea [8], Singapore [9], Belgium [10], the Netherlands [11, 12], and other countries have allocated special research funds to accelerate the research and development of various insect-inspired, hoverable FWMAVs, which are applied to military and civil fields, and have made great progress. One of the most representative research projects is the research projects of FWMAVs funded by DARPA. Typical projects include “MFI” [13], developed by the UC Berkeley, “Microbat” [14], developed by Caltech and UCLA, “Mentor” [15], jointly developed by Stanford Research Center and University of Toronto, “Entomopter” [16], jointly developed by Georgia Institute of technology and ETS Laboratory of Cambridge University, “Robobee” [7], jointly developed by Harvard University, “Nano hummingbird” [2], jointly developed by AeroVironment company *et al.* However, due to the imperfect of hardware circuit and the processing and application of new materials, the FWMAV research before 2010 was still in a relatively slow development state, and the aircraft before this cannot achieve controllable hovering flight.

Due to the immature human technology, the design goals regarding the performance parameters of hoverable FWMAVs are difficult to achieve. Therefore, this review mainly discusses the mechanical structure of the hoverable FWMAVs with a wingspan of less than 30 cm and a weight of less than 30 g.

According to the keywords of micro-flapping wing, FWMAV, micro-aircraft and robot, we searched the research results of insect-inspired, hoverable FWMAVs published in the past ten years (2011–2020) on the Web of Science (in order to ensure that the research literature is aimed at the prototype itself, we excluded the literature from the field of physics, zoology, biotechnology, and other biological fields). The data obtained are shown in Fig. 1 below showing that, in recent years, research literature on hoverable FWMAVs is on the rise (as 2020 may be affected by special circumstances, such as epidemic situation), so more attention is being paid to insect-inspired, hoverable FWMAV research.

Based on survey results of literature published in the last ten years, we analyzed and summarized the representative research institutions and the main journals that published the related literature. As shown in Fig. 2, *Bioinspiration & Biomimetics* and *International Journal of Micro Air Vehicle* published the most research papers. These journals mainly focus on the fields of bionics and aeronautic. Figure 3 shows the 11 research institutions that have published the most research results in the past decade. Delft University of Technology [11], University of California system and Harvard University [7] published nearly half of their research results. Asian research institutions, such as Beihang University, Konkuk University [8, 17, 18], National University of Singapore [9], and Shanghai Jiaotong University [19], also occupy a large part. It can be seen that insect-inspired, hoverable FWMAVs have attracted the research attention all over the world.

It can be seen that the current research direction is focused on the aerodynamics, mechanical structure design, and flight control of the prototype, as shown in Fig. 4. According to our analysis and summary of search results on Web of Science, the mechanical structure design mainly focuses on theoretical design and physical verification, the literature on control is mainly based on theory and simulation, and the literature on aerodynamics includes theoretical calculation, simulation, and physical verification.

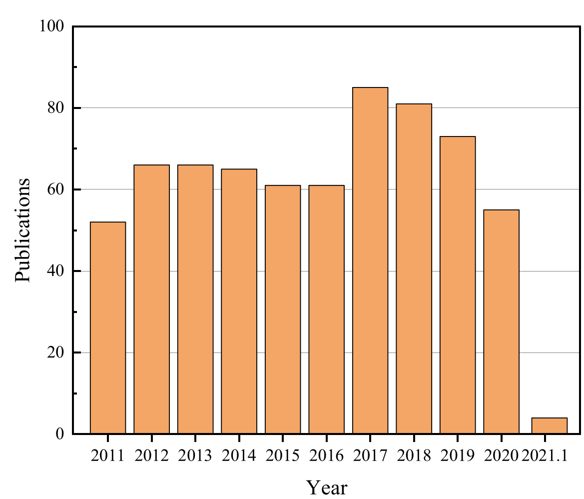


Fig. 1 Publication search results in the Web of Science Core Collection

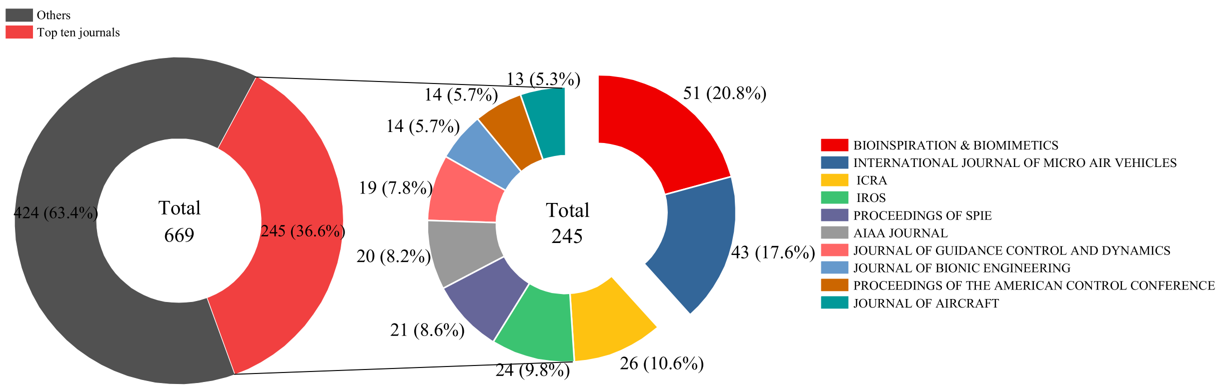


Fig. 2 Main journals that published the related literature about insect-inspired, hoverable FWMAVs

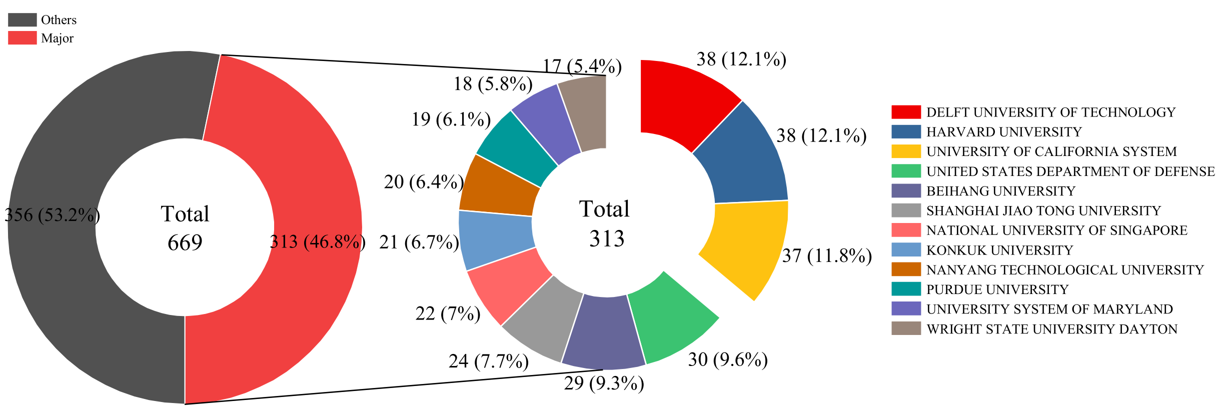


Fig. 3 Representative research institutions

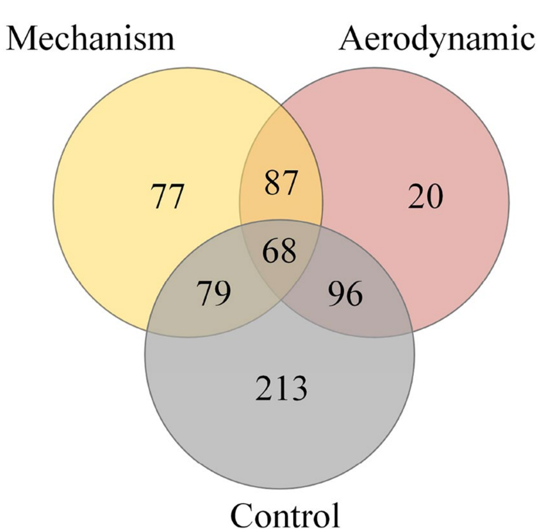


Fig. 4 Current research direction of hoverable FWMAVs

As mentioned above, some research institutions have carried out research in the field of hoverable FWMAVs for more than ten years, including Delft University of Technology [20] and Korea's Konkuk University [21]. Delft University of Technology in the Netherlands has also been committed to research on insect flight mechanisms and prototype development. At present, it has developed several FWMAVs, including Delfly II [22] and Delfly Nimble [11]; Korea's Konkuk University developed KU-Beetle [23] aircraft and passive folding wings by studying the flight mode and flight mechanism of rhinoceros beetles; in addition, National University of Singapore [9], University of Maryland [24, 25], Belgium's Brussels Free University [10, 26], Purdue University [27, 28], Beihang University [29, 30], and the Harbin Institute of technology have also developed different hoverable FWMAVs prototypes and have made research progress, as shown in Fig. 5.

The objective of this paper is to present the current state-of-the-art mechanical structure of hoverable FWMAVs based on the past decade. This review is composed of six sections, and its structure of this paper is as follows. In Sect. 1, insect-inspired, hoverable FWMAVs and their broad application prospect are briefly described. Section 2 mainly introduces the bio-inspiration of aircraft and includes the flight mechanism and basic characteristics of some insects

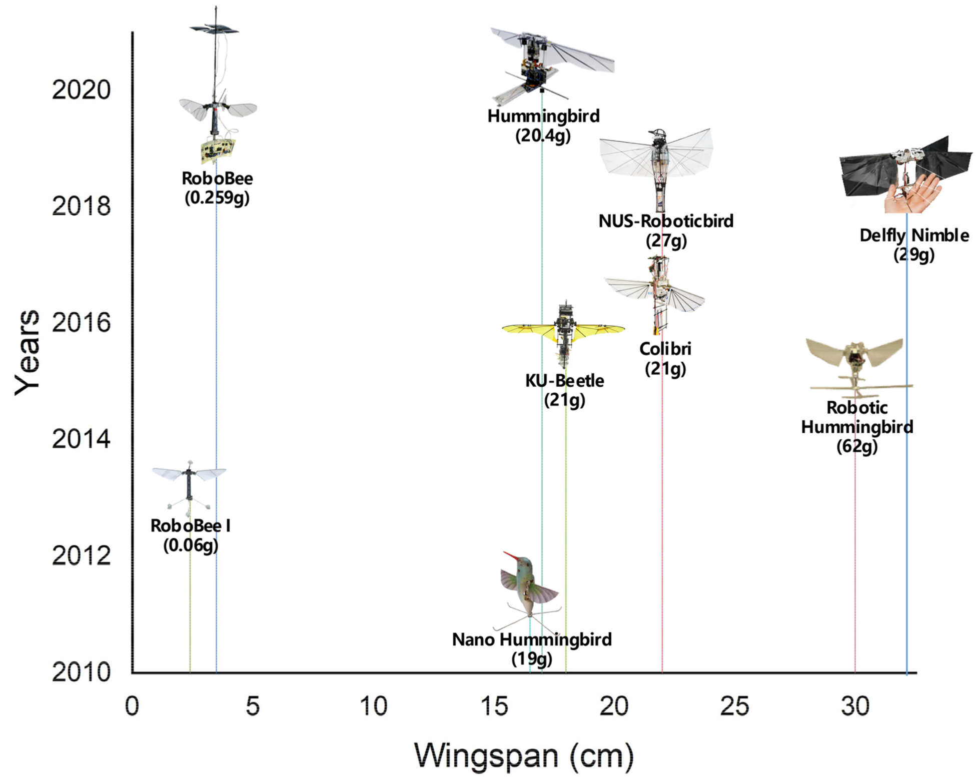


Fig. 5 Research achievements of hoverable FWMAVs

and birds. Section 3 introduces the mechanical structure of hoverable FWMAVs based on motor driving in the last ten years, compares the parameters and performance of different structures, and introduces the related materials utilized in aircraft. In Sect. 4, the insect-inspired FWMAVs driven by intelligent actuators are introduced, and described in terms of driving materials and transmission mechanisms. Finally, trends and research challenges facing researchers are summarized in Sect. 5, and Sect. 6 provides conclusions and thoughts regarding the future mechanical structure of FWMAVs.

2 Biological Characteristics and Motion Mechanisms

In recent years, researchers have basically taken hummingbirds or insects as bionic objects and carried out aircraft mechanical designs by referring to their body structure and motion mode [31]. Moreover, they studied the flapping trajectory, frequency, wing scale, and flow field around the wings and the energy consumption of the wings, revealed the hovering flight mechanism and flight mode, and applied them to the research on hoverable FWMAVs. At present, human beings have not fully grasped the principle of insect aerodynamics, but have preliminarily explored four mechanisms of insect lift, namely, the clap-fling mechanism [32], the delayed stall mechanism, the rotational effect mechanism and the wake capture mechanism. Meanwhile, the researchers observed and summarized the movement track of the wing tip of insects or birds, and found that when they hovered, the movement track of their wing tip was close to an “8” shape or a “0” shape [33]. The flapping plane of their wings was close to the horizontal state, which also revealed the movement mechanism of hovering flight.

2.1 Motion Characteristics of Hummingbirds

Because of the unsteady flow, the Reynolds number of insects is very small [34], about $10^2 - 10^4$, and the flapping frequency ranges from dozens to hundreds of Hz. The body structure and motion mode of bios also play an important role in the research on insect-inspired FWMAVs. Take the hummingbird as an example shown in Fig. 6a. The body of the hummingbird mainly includes the chest and abdomen, and the muscles and bones inside the chest are closely connected to the wings, which is the driving force for the flight. The skeleton features of the hummingbird enable a high-flapping frequency and a high-flapping amplitude at the same time [35]. The skeleton joint is similar to the simulation of two spherical pairs and a rotation pair, so the movement trajectory of the wing tip of the hummingbird in hovering flight is an “8” shape and a “0” shape, and the flapping plane is horizontal [36, 37], as shown in Fig. 6b.

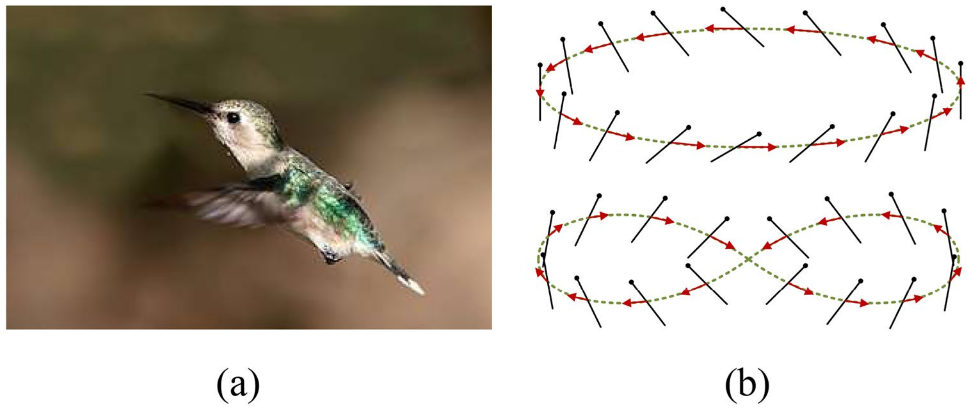


Fig. 6 Hummingbird and its flight characteristics. **a** Hummingbird. **b** Flapping trajectory of its wing tip

2.2 Lift Mechanism

In addition to the musculoskeletal system, researchers have paid more attention to research on the high lift mechanism [38], which is the most important reference for insect-inspired FWMAV design. Weis Fogh's [39] research on wasps shows that at the end of each flapping period (each period consists of an up-stroke movement and a down-stroke movement, and the end of the flapping period refers to the end of the up-stroke), the two wings are completely overlapped on the back; at the beginning of the next period, the wings open quickly, forming a low-pressure area between the two wings, which gives the insects a higher lift at the beginning of the flapping period. Lighthill and Maxworthy [40] also proved the mechanism through theoretical calculation and experimental research. This mechanism, also known as the clap-fling mechanism [41], inspired researchers to study the flight mechanism of insects via unsteady fluid dynamics [42]. The delayed stall mechanism is that the leading edge vortex is formed and attached to the wing surface during the flapping process, which can effectively increase the lift coefficient. In Ellington's research on moths [43], it was found that the leading edge vortex generated by the downward flapping of wings can produce a greater lift. This mechanism is also called the delayed shedding mechanism. Sun Mao *et al.* also proved the effectiveness of this mechanism by computational fluid dynamics [44–46]. Dickinson [47] *et al.* found the mechanism of the rotation effect and wake capture through the experimental study on the equal-scale amplification model of *Drosophila* and its wings [48, 49]. The rotational effect means that the wing will twist in the process of flapping [50]; wake capture refers to the phenomenon where the wing encounters the air flow from the last stroke in the opposite direction during the transformation stage between the down-stroke and up-stroke, which will increase the relative speed between the wing and the air and add additional force to the wing [51, 52]. The average lift produced by these two mechanisms accounts for 35% of the

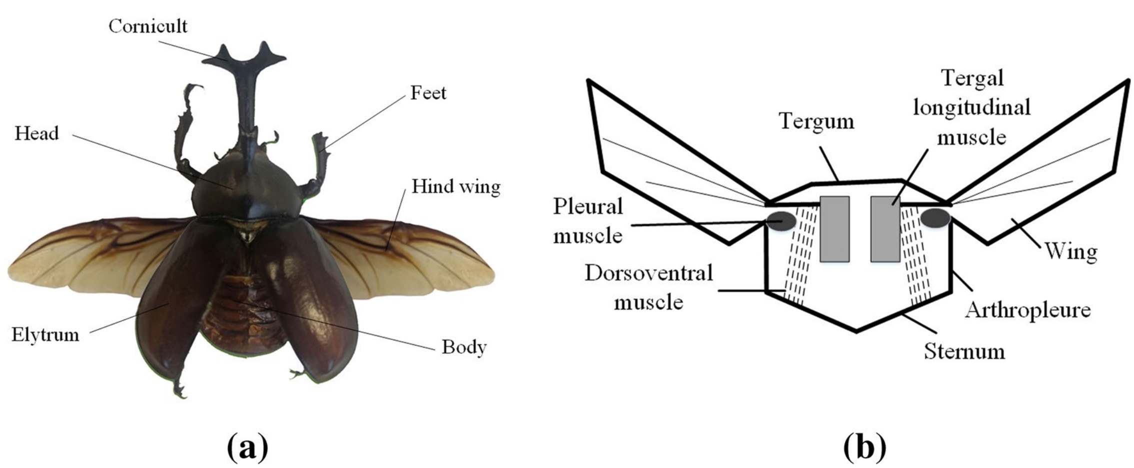


Fig. 7 Insect muscle movement system. **a** *Allomyrina dichotomus*. **b** Structural sketch of indirect wing-

total lift in the whole flapping period, which plays a very important role.

2.3 Motion Characteristics of Insects

Similarly, the movement trajectory of most insects' wing tips in hovering flight also presents an “8” shape and a “0” shape [30]. Different from the body structure of hummingbirds, the musculoskeletal system of insects is more simple and efficient [53]. Taking *Allomyrina dichotomus* as an example, Fig. 7 shows its body structure and musculoskeletal system. Figure 7b is a simulation diagram of the indirect wing-flapping muscle-driving system. In the process of flapping, the dorsal longitudinal muscle and the dorsal abdominal muscle play a major role, and their contraction and relaxation make the wings flap [21]. The pleural muscle at the root of the wing can twist the wing to produce the AoA. The system can achieve high frequency and precise motion, and it is also the most important reference in the design of insect-inspired FWMAVs. It is worth mentioning that its wings tip trajectory are also close to the “8” shape or “0” shape.

The biological scale effect is also an important factor affecting the bionic design. Through the research of different scales of bios, such as seagulls, pigeons and hummingbirds, the researchers found that there is a certain proportional relationship between the wingspan, mass, flapping frequency, wing area, and the aspect ratio of bios. By observing and summarizing the shape characteristics and flapping characteristics of a large number of bios, the researchers came up with a set of scaling formulas for some bios. Designers can obtain the basic parameters of insect-inspired FWMAVs according to this formula, which can be utilized as the design standard [54].

According to the statistics of research results in the last ten years, the mechanical design of insect-inspired, hoverable FWMAVs can be divided into two categories according to the different driving modes. One is the design of a bird-like aircraft driven by motors [55], and the representative achievements include the Nano Hummingbird and the Delfly Nimble. This kind of aircraft is driven by motor and servos and utilizes linkage mechanisms or string-based mechanisms for transmission, and the flapping actions of wings and the change in the AoA of the wings are finally output. The other is the design of insect-like aircraft driven by intelligent actuators, such as the RoboBee series robots from Harvard University. This kind of aircraft is driven by new materials to generate small amplitude, and the amplitude is then amplified by the related linkage mechanism, finally meeting the flight requirements. The third and fourth sections of this paper explore this classification, and the development of the mechanical design of insect-inspired, hoverable FWMAVs in the last ten years is described.

3 Motor-Driving Mechanisms

According to the research achievements in the past decade, the conventional motor-driving mechanisms design forms of the flapping mechanism are mainly divided into two types: one is the flapping mechanism with a single pair of wings represented by Nano Hummingbird of the AeroVironment company (U.S.A) [2], which imitates the flapping mode and form of birds or insects with only one pair of wings flapping on both sides of the body; the other is the flapping mechanism with two pairs of wings represented by Delfly Nimble of the Delft University of Technology [11]. Different from the flapping mechanism with one pair of wings, each side of the body has two wings, which make a reverse symmetrical flapping, and utilize the clap-fling mechanism similar to wasps to achieve a high lift. The mechanism of the above two modes is different, but its mechanical structure design principle is consistent. This section mainly introduces the flapping mechanism and the control mechanism of hoverable FWMAVs driven by a motor and the materials used in these aircraft are briefly introduced.

3.1 A Single Pair of Wings

In 2007, Matthew *et al.* at AeroVironment company, researched FWMAVs with the support of DARPA. In 2011, they successfully devised a hummingbird-like flying robot “Nano Hummingbird” with a mass of 19 g, a wingspan of 16.5 cm, a flapping frequency of 30 Hz and an endurance of 4 min [2]. Researchers designed a flapping wing mechanism based on a string drive. This kind of driving mechanism is made of 7075 aluminum, and a lightweight design was carried out through structural optimization. The flapping mechanism driven by the motor drives the wire wheel on the gear to rotate so as to drive the wire wheels on both sides to move according to the designed trajectory, and thus achieve a flapping effect. This method overcomes the limitation of the motion range of the traditional four-bar mechanism, and makes the flapping angle of the mechanism the same as that of a real hummingbird. The string-based flapping mechanism adopted by the Nano Hummingbird meets the performance requirements of a light weight and a low-impact load as shown in Fig. 8.

For the control mechanism of the aircraft, the mechanism of the hummingbird wing twist is imitated, the displacement of the side bar of each wing is controlled in two directions (perpendicular to each other) utilizing servos, and the aerodynamic force/moment of each wing is then changed. When the aerodynamic forces/moments of the wings change, the attitude of the aircraft also changes. Similarly, the mechanism utilizes 7075 aluminum, plastic, and carbon fiber materials, so these mechanisms have compact structure and high

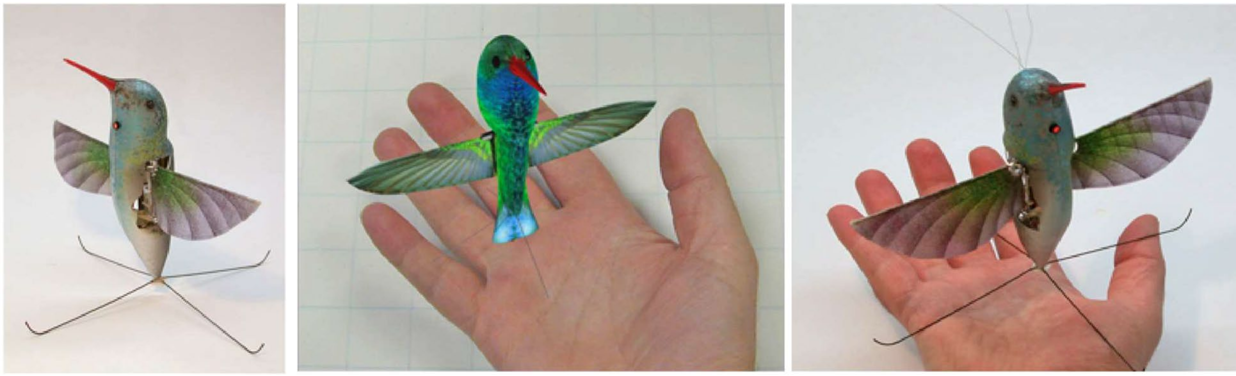


Fig. 8 Nano Hummingbird developed by AeroVironment company [2]

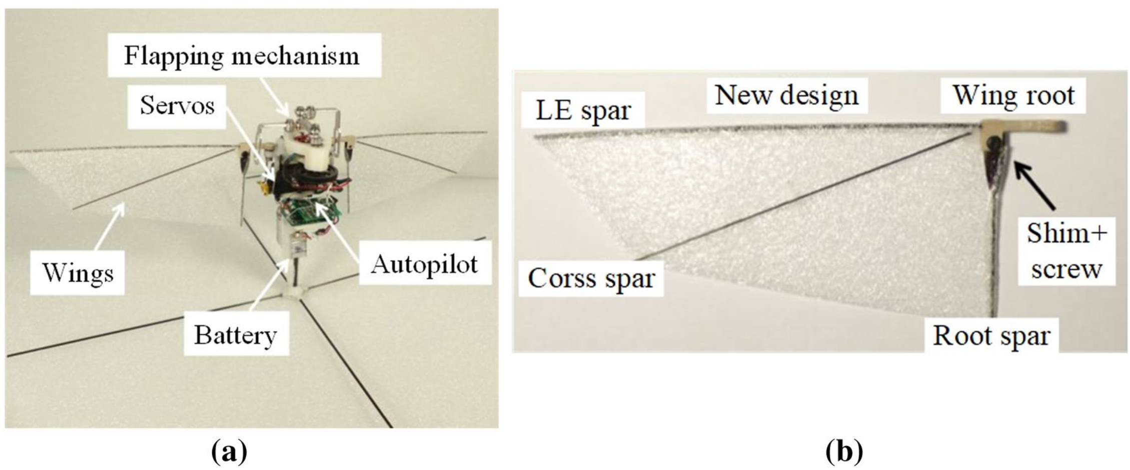


Fig. 9 Robotic Hummingbird developed by Maryland University [25]. **a** Robotic Hummingbird. **b** Bionic wing

mechanical efficiency and ensure the structural strength of the aircraft.

After several years of research, in 2015, David *et al.* from the Department of Aerospace Engineering of the University of Maryland finally devised an FWMAV prototype, called the "Robotic Hummingbird" that can generate ultra-high lift, as shown in Fig. 9 [25]. This prototype can generate a lift of up to 66 g when flapping frequency is 22 Hz. The total mass of the aircraft is 62.1 g, and the wingspan is 30 cm. The body of the aircraft is made of a 3D printing component with material of ABS plastic, the actuator is made of a metal rod, and the wing root is made of PEEK material to increase the strength and wear resistance. A single crank and double-rocker mechanism were adopted, which basically eliminate the output-phase difference of the rocker on both sides after optimization and ensures the compactness of the mechanism. The guide bar mechanism at the end enlarges the output angle, so that it has a flapping angle of 110 – 120 degrees.

Unlike the Nano Hummingbird, the researchers of Robotic Hummingbird combine the flapping mechanism and control mechanism of the aircraft, as shown in Fig. 9b. In the yaw and pitch attitude, the flapping planes of both sides are changed, compared with the Nano Hummingbird. Its design layout increases the variation range of the flapping plane of the wings. In a rolling attitude, the control mode changes the flapping amplitude of both wings so as to change the aerodynamic force of both wings and achieve a rolling attitude. The researchers also utilize a kind of carbon fiber sheet as a structure connecting the wing root and the wing side bar to achieve the passive deformation of the wing so as to obtain a high lift. Now the prototype successfully achieved a 40 s stable hovering flight. In 2016, Phan *et al.* at the Department of Advanced Technology Fusion of South Korea's Konkuk University, a team that has long been committed to the experimental research of bionic FWMAVs and insect flight mechanisms, successfully devised an FWMAV prototype named known as the "KU-Beetle [56]". The flapping mechanism

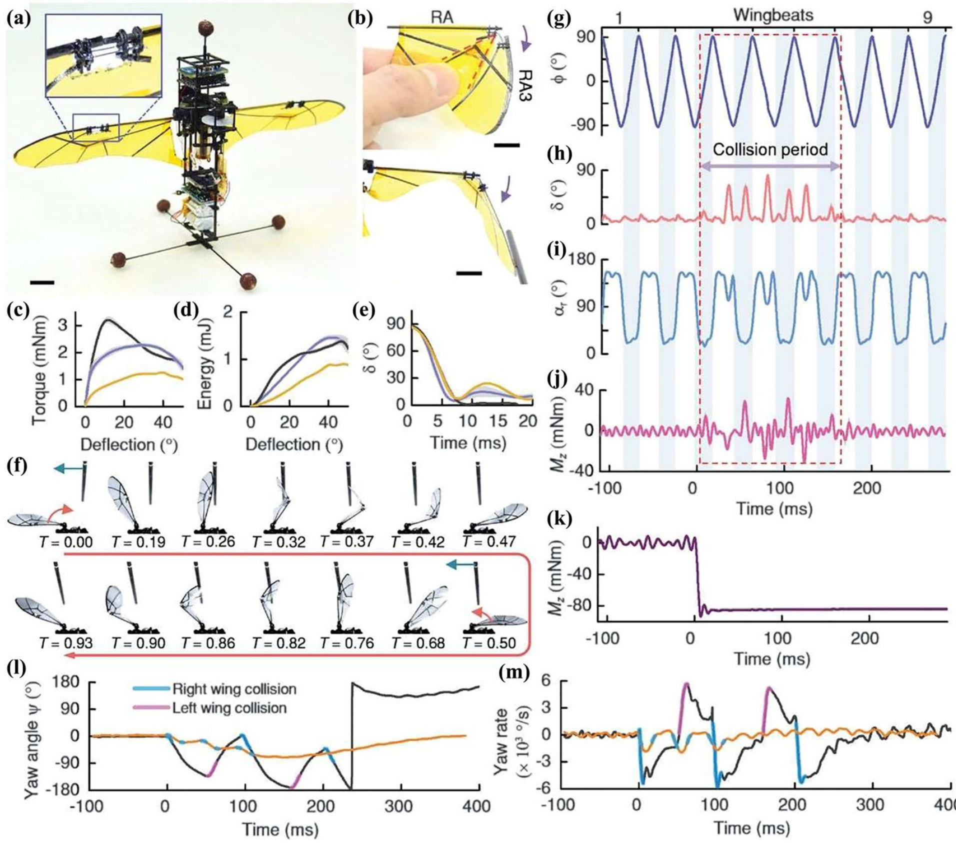


Fig. 10 KU-Beetle with unfolding wings developed by Konkuk University [58]

adopts a combination of a string-driving mechanism and crank-rocker mechanism, which improves transmission efficiency and ensures the reliability of the mechanism, and the flapping amplitude of one wing can reach 190 degrees [23]. This mechanism can make good use of the clap-fling mechanism. The flapping frequency of the prototype is as high as 35 Hz, and the mass of a single wing is only 0.12 g, which reduces the work of overcoming the inertial force when the wing moves. With this prototype, stable hovering flight in the air has been achieved [8].

As shown in Fig. 10, the control principle adopted by the KU-Beetle is also based on the active twist function of the wing side bar [57]. Three rotary servos are utilized to control the displacement of the wing side bar. One of the servos controls both side bars to move in the left and right directions at the same time, and the other two servos control the side bars on both sides to move forward and backward, respectively [23]. The body structure of the aircraft is made of carbon fiber material, which enhances the strength of the whole aircraft and reduces its weight. When the aircraft is equipped with a 7.4v polymer lithium battery, the mass of the entire aircraft is only 21 g [17]. In 2020, Hoang Vu Phan and Hoon Cheol Park published the latest research results [58]. They utilized the folding mechanism of rhinoceros beetle wings in flight and utilized hyperplastic titanium alloy filaments to simulate wing folds, and devised a new generation of aircraft. The newly devised aircraft can automatically return to a flight state when it is impacted by the outside world, which fully reflects the powerful bionic effect of FWMAVs, and this achievement also greatly promotes the research progress of insect-inspired FWMAVs.

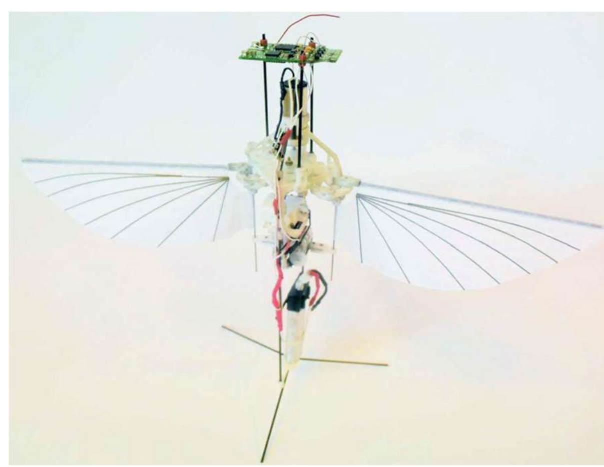


Fig. 11 Colibri with string-based flapping mechanism [60]

Since 2011, Roshanbin *et al.* from the Active Structures Laboratory of Vrije Universiteit Brussel have also carried out research work on Insect-inspired FWMAVs. After a series of explorations and improvements, the team successfully devised a new generation of insect-inspired FWMAVs known as “Colibri” in 2017 [59], as shown in Fig. 11 [60]. The flapping mechanism and frame of the aircraft are made of a 3D printing nylon material with a low cost. The combination of a crank-slider mechanism and a slider-rocker mechanism is utilized in the flapping mechanism, and three sliding pairs are utilized to achieve the compactness of the mechanism, and to increase the friction during the operation of the mechanism. The crank-slider mechanism transforms the rotary motion into a swing motion, and the slider-rocker mechanism amplifies the motion to achieve a flapping angle of 120 degrees. Depending on the inertial force and flexible deformation of the wing, the final flapping amplitude can reach about 180 degrees.

For the design of the control mechanism, this research team has carried out long-term research. In 2013, Karasek *et al.* designed an SMA-driven control mechanism based on the wing twist mechanism of the hummingbird [10]. However, the reaction speed of the mechanism is slow. The researchers then changed the control method and designed a new mechanism. This mechanism integrates the flapping mechanism with the control mechanism and changes the flapping amplitude of each wing by changing the position of the joint in the flapping mechanism [59]. In the follow-up test, the mechanism shows good experimental results, while the assembly is more complex. Finally, in 2017, Roshanbin *et al.* designed a new control mechanism utilizing linear servos and rotary servos as the drive and linkage mechanism as the transmission system [59]. On the basis of this mechanism, they added two universal joints at the wing root to improve the control effect of the aircraft. This aircraft has a wingspan of 21 cm, a mass of 22 g, and a flapping frequency of 22 Hz. It can hover in the air for 15–20 s and achieve multiple attitudes of yaw, roll and pitch.

In 2020, Deng *et al.* of the Beihang Robotics Institute took the *Allomyrina dichotomus* as the bionic object and optimized the flapping mechanism of Insect-inspired FWMAVs [30]. This prototype has a wingspan of 21 cm, a mass of 21.2 g (without battery), and a flapping frequency of 26 Hz. The flapping mechanism of aircraft is composed of crank-rocker mechanism and the double-rocker mechanism. They take the expected output angle as the optimization objective and optimize the rod length and structure layout of the mechanism by establishing the kinematics model of the flapping mechanism so as to obtain the mechanism parameters. The prototype can generate a 28 g lift at a flapping frequency of 26 Hz. They also adopted a control mechanism design similar to the Nano Hummingbird and the Colibri, and simulated the displacement of the wing side bar. The prototype adopts 3D printing technology for parts processing, and nylon material is used to ensure the reliability and structural strength of the mechanism.

In 2020, Zhan *et al.* from Purdue University took the hummingbird as a bionic object, broke the conventional design method, and designed the insect-inspired FWMAV called “Robot.I” based on the idea of motor commutation [61]. This mechanism cancels the transmission mechanism in the traditional design method and utilizes the high-frequency swing of the motor itself to achieve 68 high-speed swings in 1 s, and its flapping frequency is as high as 34 Hz. Due to the cancelation of the reduction gear and transmission rods, the output power of the motors can be directly transmitted to the wings, which greatly improves the operation efficiency of the mechanism and reduces the power consumption. The whole mass of the aircraft devised by them is only 20.4 g, and the maximum lift weight ratio can reach 1.6 (without battery). Because its wings are only 0.1 g, it also greatly reduces the power consumption to overcome the inertial force in the flapping process.

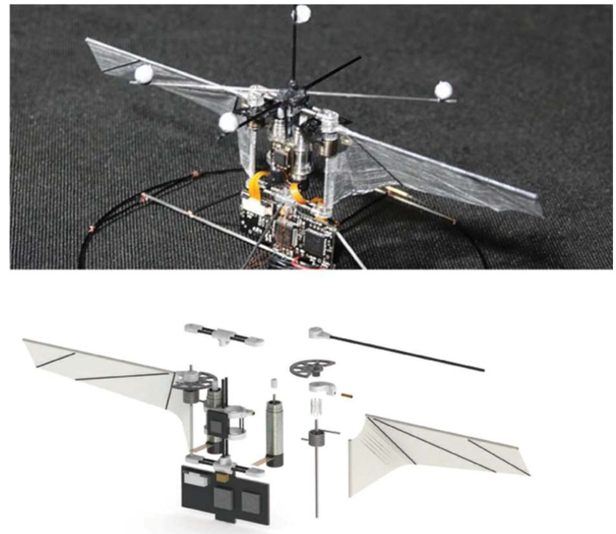


Fig. 12 Robot.I developed by Purdue University and its structural composition [61]

Through the precise control of motors currents and speeds, and with the semi-circular gear of the transmission system, the aircraft can adjust the flapping angle and range, so as to achieve the change in attitude. As shown in Fig. 12, the motor gear and rocker gear mesh with each other. When it is necessary to adjust the flapping range, the motors will adjust the speeds and positions, so as to integrate the design of the flapping mechanism with that of the control mechanism. The innovation of the aircraft is that the deep reinforcement learning method is utilized for control, the motor current and speed are monitored all the time, and the aircraft shows a great flight control ability.

3.2 Double Pairs of Wings

Nguyen *et al.* of Temasek Laboratory of National University of Singapore devised a bird-like FWMAVs called

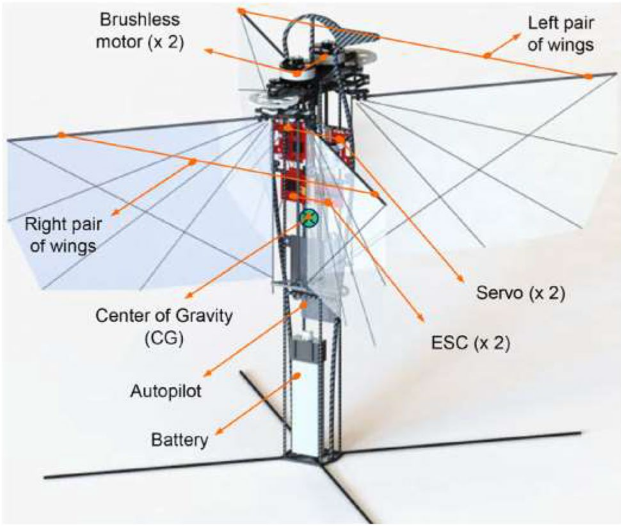


Fig. 13 The NUS-Roboticbird developed by National University of Singapore, and its flapping mechanism [9]

Fig. 14 Delfly Nimble developed by Delft University of Technology, and its mechanism [63]

"NUS-Roboticbird" in 2018 [9] The prototype has a wing span of 22 cm and a mass of 27 g and can carry a micro camera for aerial photography. This aircraft has two pairs of flapping wings; the flapping mechanism was designed based on a crank-slider-rocker mechanism, which is more complex and requires higher assembly accuracy. In each flapping cycle, the wings can use the clap-fling mechanism twice, and the mechanism makes full use of it to generate a high lift at a flapping frequency of 14 Hz.

The researchers designed a control mechanism based on the principle of controlling the flapping plane and the flapping frequency on both sides. As shown in Fig. 13, the left and right flapping mechanisms are connected with the frame to form rotating pairs, and the flapping mechanisms on both sides can rotate around the axis. The linear servos are used to pull the flapping mechanisms on both sides so as to change the flapping plane of the wings on both sides to achieve pitch and yaw motion. Meanwhile, the roll attitude can be achieved by changing the flapping frequency of both wings [62]. The aircraft takes carbon fiber material as the skeleton to make a bird-shaped shape structure. Its carbon fiber structure and parts fully ensure the lightweight and miniaturization of the structure and reduce the friction power consumption of the mechanism.

In September 2018, Karásek *et al.* from MAVlab of Delft University of Technology in the Netherlands [11] devised an insect-inspired FWMAV named "Delfly Nimble" shown in Fig. 14. The mass of the aircraft is 28.2 g, the wingspan is 33 cm, and the flapping frequency is 17 Hz. Due to the double flapping-wing flight mode, the aircraft is driven by brushless motors on both sides, adopts a crank-rocker mechanism to make the output rocker move symmetrically, and makes full use of the clap-fling mechanism to generate a high lift. It has the best flight maneuverability among FWMAVs at present, and its roll acceleration can reach $5000°/s^2$. The researchers designed the control mechanism by changing the flapping range and frequency. The flapping mechanisms on both sides are meshed by gears. Rotary servos on the top can drive the flapping mechanism on both sides to rotate and achieve pitch. Rolling is achieved by changing the speed of the motors on both sides. The aircraft can also combine pitch and roll to adjust the yaw attitude. This kind of mechanism has a simple structure, advanced processing technology, and new materials, which afford the mechanism with a high reliability and mechanical efficiency (Table 1).

In addition to the above introduction of the mechanism design of insect-inspired FWMAVs, according to the definition and research objectives of insect-inspired FWMAVs, the miniaturization and lightweight of the aircraft is a major research direction. At present, it is difficult for existing FWMAV prototypes to achieve the same scale and mass as birds or insects. Researchers have used a variety of new materials and molding processes to produce aircraft parts [64]. 3D printing technology and carbon fiber processing technology are increasingly applied to insect-inspired FWMAV processing, which can ensure the structural strength and meet the needs of a lightweight and miniaturization of the machine [4].

4 Intelligent Actuator-Driving Mechanism

The traditional motor-drive mechanism mainly relies on motors, reduction gears, and bars to form a flapping mechanism. Although the technology of this type of mechanism is mature, it has the disadvantages of high-energy consumption and low efficiency. At present, human beings have not yet developed millimeter-level or milligram-level motors, and it

Table 1 Comparison of insect-inspired, hoverable FWMAVs with motor-driving mechanisms

FWMAVs	Year	Research group	Flapping mechanism	Wing span (cm)	Flapping amplitude (degree)	Hover frequency (Hz)	Mass (g)	Flight endurance	Wings
Nano hummingbird [2]	2011	AeroVironment Inc	String-based[a]	16.5	180	30	19	4 min	2
Robotic hummingbird [25]	2015	University of Maryland	Single-crank and double-rocker[b]	30	110	25	62	5 s	2
KU-Beetle [58]	2016	Konkuk University	String drive and 4-bar[b]	18	190	35	21	40 s	2
Colibri [59]	2017	Universite' Libre de Bruxelles	Crank-slider and 4-bar[a]	22	120	22	21	20 s	2
NUSRoboticbird [9]	2018	National University of Singapore	Crank-slider and linkage[c]	22	90	13.3	27	3.5 min	4
Insect-like FW-MAV [64]	2018	Seoul National University	String-based	15	140	22.6	10.8	–	2
DelFly Nimble [11]	2018	Delft University of Technology	Crank-rocker[c]	33	44	17	28.2	5 min	4
Humming-bird [61]	2020	Purdue University	Motor direct drive[c]	17	150	34	20.4	20 s	2

[a]Wing lateral margin twisting

[b]Wing root twisting

[c]Wing root twisting and differential motion

is difficult to miniaturize motor-driving mechanisms. At present, the scale of insect-inspired FWMAVs driven by motors is generally more than 15 cm, which is not satisfactory miniaturization. If millimeter-level or even micron-level Insect-inspired FWMAVs are to be devised, new design methods and drivers need to be adopted.

MEMS refers to the use of nanotechnology to manufacture millimeter or micro-scale devices [65, 66]. Human beings have achieved a major breakthrough in research on MEMS technology and intelligent actuators, which encouraging researchers to develop millimeter-level insect-inspired FWMAVs. The intelligent actuator-driving mechanisms can greatly improve the flapping wing efficiency and reduce the scale of the aircraft. Therefore, an intelligent actuator-driving mechanism has become a research direction regarding to the flapping mechanism. At present, intelligent actuator-driving mechanisms mainly include piezoelectric actuators [7, 67–70], electromagnetic actuators [71–75], dielectric elastomer actuators [76, 77], and electrostatic actuators [78, 79]. Research results have also focused on piezoelectric actuators and electromagnetic actuators.

4.1 Piezoelectric Actuators

In 2007, Steltz *et al.* from the Department of EECS of the University of California, Berkeley, devised a Micromechanical Flying Insect (MFI) with a flapping frequency of 275 Hz based on bionics [67, 80–82]. They utilized two piezoelectric bending actuators whose displacement is amplified through a double four-bar mechanism and a differential to create a flapping and rotational degree of freedom. The wingspan of the whole prototype is only 25 mm, which is basically the same as the size of insects. While its flapping angle is 43 degrees, it can produce a 506uN lift at a 160 Hz flapping frequency and a 1400uN lift at 275 Hz. Because piezoelectric actuators need an alternating voltage of 200 V, the aircraft can only fly freely for a short time under the condition of an external power supply of a thin wire.

In 2013, Teoh *et al.* from the Microrobotics Laboratory of Harvard University devised a micro-robot insect called "RoboBee" [7, 83–85]. It is also driven by a piezoelectric actuator, with a height of 2.4 cm, a wingspan of 3 cm, a total mass of 60 mg, a flapping frequency of 110 Hz, and a maximum flight speed of 6 m/s, and the Reynolds number is 1200. Based on research on the musculoskeletal system of insect thorax, a bending bimorph cantilever actuator has been developed, and two planar four-bar mechanisms are utilized to amplify the vibration displacement generated by the actuator and output the flapping angle to meet the flight requirements. To change the AoA of wings, researchers have also designed a hinge mechanism, established a kinematic model of the mechanism, and realized the active control of the attitude. This micro-robot insect represents a miniaturized FWMAV that can attach itself to most surfaces.

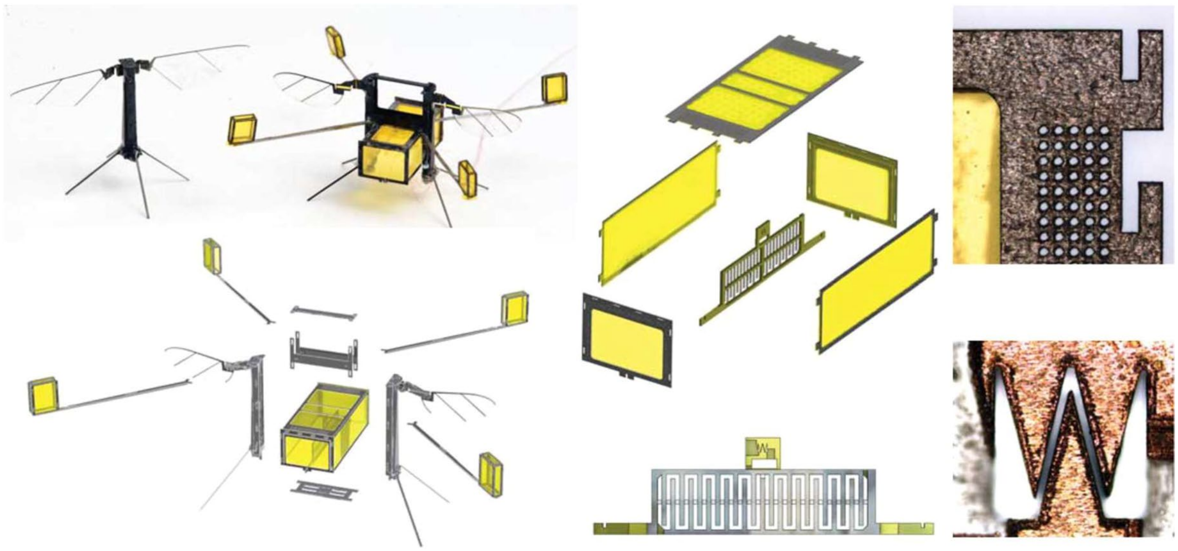


Fig. 15 RoboBee series FWMAVs prototypes [87]

However, the power of the micro-robot insect needs an external power supply, so it cannot fly for long distances.

In 2017, this research team made significant progress. The new generation of "RoboBee II" can not only complete basic flight and landing actions, but also dive and swim, as shown in Fig. 15a [86, 87]. The mass is about 175 mg. The research team proved that the impact of sharp edges, hydrophilic coating and surfactant can greatly reduce the surface tension of water, thus enabling the robot to dive into water. The research team also utilized the principle of electrolyzing water to generate gas and improve the buoyancy of the robot, so that the robot can stably float on the liquid surface. When separated from the water surface, the robot ignites the combustible gas produced by the electrolytic water, so that the robot can be pushed out of the water surface instantaneously so as to realize cross-medium flight.

In 2019, Jafferis *et al.* of this laboratory devised a four-wing-flapping wing aircraft called "RoboBee X-Wing" with controllable flight based on a flexible circuit and a photovoltaic array, as shown in Fig. 15b [88]. It utilizes two bending bimorph cantilever actuators as the drive, and the vibration displacements are amplified by the four-bar mechanisms. The weight of the aircraft is only 259 mg, with a wingspan of 3.5 cm and a height of 6.5 cm. The maximum lift-to-weight ratio is 4.1, and the average power is only 110 – 120mW. This is also the smallest aircraft that can fly independently.

4.2 Electromagnetic Actuator

Bontemps *et al.* from University of Valenciennes presented an innovative power modeling of a flapping-wing nano air vehicle actuation-transmission system in 2014 [89, 90]. The total mass of the prototype is only 22 mg, and its wingspan is 3 cm, which can produce 1.75 times its own gravity lift. A central electromagnetic actuator is utilized to generate vibration, and the movement is then transmitted to the wings through the connecting rod. The vibration model of the system was established and verified by simulation.

Roll *et al.* from Purdue University proposed an insect-inspired FWMAV with a weight of 2.6 g and a flapping frequency of over 70 Hz [73, 91–93]. This driving system of the aircraft consists of a single electromagnetic coil, a permanent magnet rotor and a "virtual spring" magnet pair. A

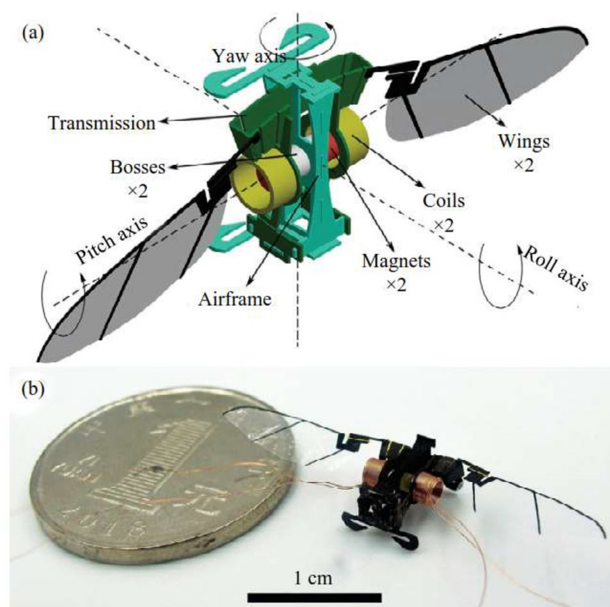


Fig. 16 FWMAV prototypes based on an electromagnetic actuator [19]

flapping action is generated by applying periodic excitation voltage on the coil. Through the construction of a simulation model and a wing experiment, the researchers verified the lift effect of the aircraft, showing a lift-to-weight ratio much higher than 1 under 24 V.

In 2011, Meng *et al.* of Shanghai Jiaotong University devised an insect-inspired FWMAV prototype with a wingspan of 3.5 cm and a weight of 144 mg, and completed a flapping wing test of the prototype [69]. The resonance frequency range of the prototype is 120 – 150 Hz. A new LIGA process based on SU-8 photoresist technology was used to fabricate the chest, gingiva and vein. Zou *et al.* devised a self-lifting FWMAV driven by electromagnetism in 2016 [94]. This prototype weighs 80 mg and has a wingspan of 3.5 cm, and double planar four-bar systems are used to transform small actuator motions into large wing displacements. The flapping angle is about ± 70° when the flapping frequency is 80 Hz.

In 2020, Wang *et al*. of this team [19, 95] devised an insect-inspired FWMAV with a weight of 96 mg and a wingspan of 3.5 cm using an electromagnetic actuator, as shown in Fig. 16. There are two symmetrically distributed actuators on the back of the aircraft, which drive the wings on both sides, respectively, and can control the moment of pitch, roll, and yaw. The alternating current power supply makes the actuator produce a reciprocating motion, which imitates the contraction and relaxation of back muscles of insects. Then, the sphere four-bar mechanism is utilized to amplify the amplitude of the reciprocating motion to make the wings flap; meanwhile, the wings generate a thrust through passive rotation. The body and parts are composed of an 80-micron carbon fiber board processed by UV laser engraving technology. There is a flexible deformation layer composed of a 7.5-micron polyimide film between the carbon fiber interlayer to simulate the movement joints of insects; the wings are made of polyester film and carbon fiber. Through experiments, the researchers have proved that the aircraft can generate a lift of 0.94mN more than its own weight at a flapping frequency of 80 Hz, which can meet the lift demand, and the moment of the attitude change of the aircraft under different voltage excitation was measured.

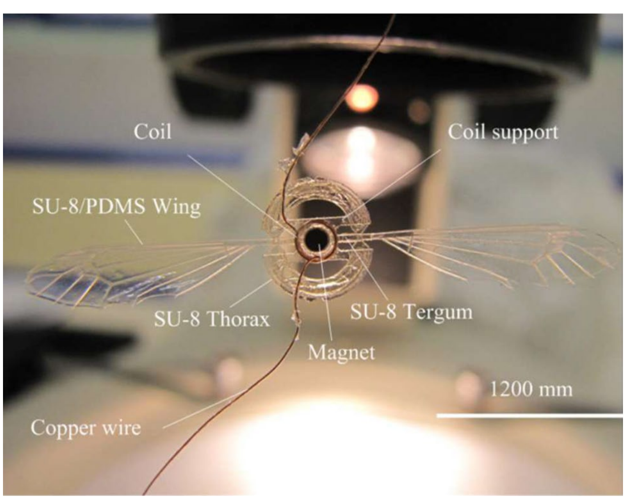


Fig.17 FWMAVs prototypes based other intelligent actuators [97]

4.3 Others Actuators

Bao *et al*. designed an electromagnetically driven flapping wing mechanism in 2011, as shown in Fig. 17. It utilizes a tergum–wing–thorax structure to amplify the flapping angle, with an active bending mode coupled with the passive torsion of the wings [96, 97]. Resin SU-8 was utilized as vein material and PDMS was used as a wing membrane. The mass of the prototype is about 41 mg, the wingspan is 3.6 cm, and the flapping angle can reach 31° at a driving frequency of 51 Hz.

Lau *et al* of Nanyang Technological University successfully applied Dielectric Elastomer Actuators (DEAs) to the design of insect-inspired FWMAV [98]. They devised a lightweight shell using a cross-ply laminate of Carbon-Fiber-Reinforced Polymer (CFRP) to pre-strain a rolled DEA in 2014 [99]. This CFRP shell can amplify an axial DEA stroke into a larger transverse shell deformation. Therefore, they combined this kind of CFRP shell with a rolled DEA to simulate the musculoskeletal system of the insect thorax, formed a set of insect wing mechanisms, and verified the feasibility of the mechanism.

In 2015, Yan *et al*. of Beihang University designed self-lifting artificial insect wings by means of electrostatic actuation. The driver is powered by a DC power supply and drives the parallel metal beams by electrostatic force. The crossbeam and two extracts from drone honey bees were glued together to achieve the reciprocating motion of the two wings [100]. The weight of the prototype is 3.1 mg, and its typical resonant frequency is 50–70 Hz. When the frequency is 66.7 Hz, the amplitude is 38.49 degrees. It can successfully take off at 2.2 mm/s when the input voltage is 5 kV and the flapping frequency is 70 Hz (Table 2).

5 Trends and Challenges About Mechanical Design for Hoverable FWMAVs

With the development of the mechanical design and other related fields, many types of problems appear when the design, experiments, and simulations are performed. To solve these problems, researchers globally present new and exciting ideas. With the ongoing development of research, numerous trends have been formed. However, there remain many challenges on mechanical design and other fields for

Table 2 Comparison of insect-inspired, hoverable FWMAVs with Intelligent actuator-driving mechanisms

FWMAVs	Year	Actuators	Research group	Mechanism	Wingspan (mm)	Flapping amplitude (degree)	Frequency (Hz)	Mass (g)
MFI [67]	2007	Piezoelectric	UC Berkeley	Slider-crank	25	80–120	100–275	0.1
RoboBeeI/II [7]	2017	Piezoelectric	Harvard University	Slider-crank	25–30	110	110–120	0.06–0.175
RoboBee X-Wing [88]	2019	Piezoelectric	Harvard University	Slider-crank	35	68.8–88	165–173	0.259
FWMAV [91]	2016	Electromagnetic	Purdue University	Direct-driven	86	120	90	4.0
Insect-inspired flapping-wing robot [94]	2016	Electromagnetic	Shanghai Jiao Tong University	4-bar	35	140	80	0.08
FWMAV [89]	2014	Electromagnetic	University of Valenciennes	Direct-driven	30	70	30	0.022
FWMAV [75]	2017	Electromagnetic	Beihang University	Slider-crank	≈ 30	20	101.4	0.093
FWMAV [100]	2018	Electrostatic	Beihang University	Pivot-spar	56	20	50–70	0.0031
Bio-inspired flapper [99]	2014	DEA	Nanyang Technological University	Thoracic mechanism	130	5–10(1 Hz)	/	10.47
FWMAV [77]	2019	DEA	University of Brisol	Slider-crank	40	63	18	/

insect-inspired, hoverable FWMAVs. In this review, the key issues, research trends and challenges in related fields regarding the mechanical design of FWMAVs are analyzed.

5.1 Bionic Mechanisms

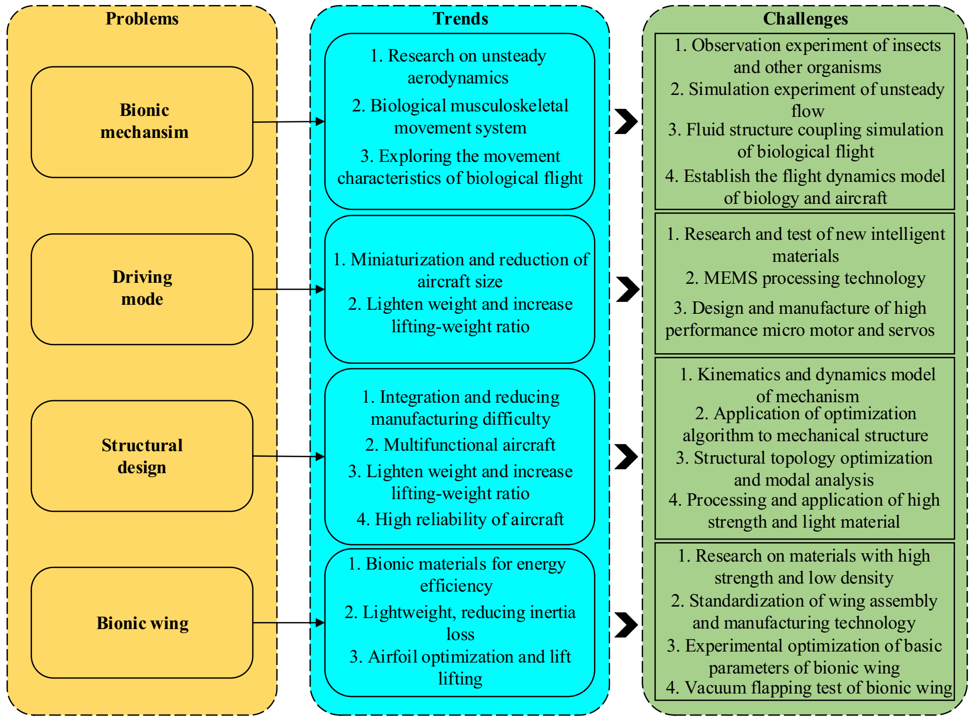
As a kind of bionic robot, the prerequisite for insect-inspired FWMAVs to achieve a major breakthrough is human's mastery of bionic mechanisms. This is also the first key problem in the field of hoverable FWMAV design. Through analysis, we can draw three research trends: (1) The unsteady aerodynamics of insects or small birds [46, 48, 101–103]. Early researchers used an unsteady flow to explain the changes in the air flow field around insects and the mechanism of lift generation [104]. It is still limited to the qualitative analysis of the action mode of the unsteady flow, and the specific role of the unsteady flow in the process of insects wings flapping cannot be quantified [105]. There is also no mathematical model that is more accurate, which will become an important research direction in the field of biology and fluid mechanics [106]. (2) The musculoskeletal system of bios [107, 108]. The musculoskeletal systems of insects are different from that of birds, and the output trajectories of their wings are also different. The kinematic model of the wing can be obtained by observing the movement trajectory of the wing and accurate kinematic modeling can effectively guide the design of mechanical structure. (3) The trajectory of the wings [40, 109, 110]. The motion of the musculoskeletal system is output to the wings as a rigid flexible coupling body, which is also an important reason for its lift. Therefore, it is necessary to research the change of airfoil shape and trajectory in the process of wing movement.

In light of the above three trends, corresponding challenges also need to be faced. (1) Researchers need to carry out different insect observation experiments according to different bionic objects, including flight observation, wing movement observation, and PIV experiments [111, 112]. (2) After obtaining the relevant data of insects, the fluid environment of bios needs to be simulated [113], the Reynolds number must to be calculated, an equal-scale amplification model of wings needs to be established, simulation experiments need to be carried out, and sensors need to be arranged to obtain the force/moment data [114]. (3) According to the relevant motion data, combined with the original parameters of the wing, the fluid structure coupling simulation needs to be carried out to obtain the lift and drag coefficients, and the changes in the surrounding fluid [115]; (4) After the completion of the above work, the obtained motion data, simulation experiment results, and fluid simulation data must be combined to derive a biological flight dynamics model [62, 116], which is most critical in the development process of FWMAVs. The same experimental process can also be applied to the development of aircraft, which plays an important role in improving the performance of aircraft and the development of flight control systems [49, 117].

5.2 Driving Modes

From the above analysis, we can see that human exploration of new drivers can greatly improve the performance of FWMAVs. A motor drive, a piezoelectric drive, an artificial muscle, and other different driving methods can be used in the manufacture. The driving mode is also developing toward the trends of miniaturization and a lightweight. Miniaturization can further reduce the scale of the aircraft,

Fig. 18 Problems, trends, and challenges



improve the portability and concealment; lightweight can further improve the lift-to-weight ratio and improve the mobility and carrying capacity. These require people to complete the following challenges: (1) Research and tests of new intelligent actuators, and these materials can complete high efficiency motion output with minimal power consumption [118, 119]. (2) With further improvement in MEMS processing technology, the precise and complex processing of new materials can be completed; (3) The research and development of high-performance motors and servos [61] is mainly directed at the miniaturization and lightweight of motors and servos, which also enables a mechanism with minimal power consumption, and it is better for directly outputting the desired speed and torque, so as to reduce the power loss of the transmission mechanisms as shown in Fig. 18.

5.3 Mechanical Structure Design

At present, regardless of the driving form, the design of a mechanical system is still a crucial part of FWMAVs. The reliability and efficiency of mechanisms are always being pursued in the robot field. The research and development of hoverable FWMAVs puts forward greater requirements for the design of mechanical structure. (1) The integration of a mechanical structure [120]. For centimeter-level or even millimeter-level aircraft, it is necessary to reduce the difficulty of manufacturing and assembly errors as much as possible and to eliminate the impact of errors on aircraft performance as far as possible [121]. (2) The multiple functions of the aircraft. Hoverable FWMAVs not only need to perform flight missions, but also need to carry a variety of functional agencies to complete multiple missions. These mechanisms include a Pan-tilt Platform stabilization device, grabbing mechanisms, landing mechanisms, and other special mechanisms. (3) The lightweight design of the mechanical structure. This part is also closely related to the performance requirements of the aircraft. Reducing the mass can also improve the operation efficiency of the mechanism and reduce the weight of the whole machine, which will also have an important impact on the maneuverability of the aircraft. (4) The reliability of the mechanical structure. As mentioned above, improving the service life of aircraft and reducing loss and cost will greatly promote future applications of FWMAVs.

Regarding these development trends, the challenge of the mechanical structure is more obvious. This is mainly divided into the following four aspects: (1) Designers need to establish the kinematics and dynamics model of the mechanisms, which is convenient for the optimization of the mechanism and the calculation of the transmission efficiency [122]. (2) Through the use of various optimization algorithms to optimize the parameters of the mechanism, the better operation effect of the mechanism needs to be obtained, and the operation of the mechanism needs to be verified by simulation. (3) For a lightweight design, the structural topology optimization method needs to be adopted to optimize the body structure, and the natural frequency of the body needs to be analyzed to avoid resonance phenomenon [123]; (4) New high-strength and low-density materials need to be utilized for processing and need to be reliable and lightweight.

5.4 Bionic Wing Design

For flapping wing aircraft, wings are very important to improve flight performance [65, 124]. The design of a bionic wing mainly focuses on improving lift and reducing power consumption [125, 126], the two future trends of bionic wing design. The challenges facing bionic wings are mainly divided into the following four points: (1) Just like the mechanical structure design, wing materials also need to be as high-strength and low-density as possible, and it is difficult to develop materials and related processing technologies comparable to the wings of insects or birds [127]. (2) According to the current literature, wing design is still mainly based on experimental methods [128]. There is no unified design guidance theory, and the applicable wings of each kind of aircraft are also different [42]. In the long run, even if the relevant guiding theory is improved, bionic wing tests are still necessary, including aerodynamic/moments tests and wind tunnel tests. (3) To reduce the influence of inertial force and improve energy efficiency, researchers also need to carry out a vacuum flapping experiment to simulate a vacuum environment as much as possible to obtain results on energy consumption caused by inertial force [129]. (4) At present, the assembly and manufacturing of wings are still mainly manual, with a long production cycle and an uneven assembly effect, which affects the aerodynamic performance. Considering the actual application of insect-inspired FWMAVs, researchers need to develop relevant standard processes and design assembly equipment to realize the standardization of wing manufacturing.

6 Conclusion and Future

This paper presents a literature review of the mechanical design for a bionic flapping wing micro-air vehicle. The research state was introduced. Works on hoverable FWMAV mechanisms were presented in three categories. Regarding bionic inspiration, we explored the bionic design in terms of biological movement and flight mechanism. According to the different driving modes, insect-inspired, hoverable FWMAVs are divided into two types: motor-driving and intelligent actuator-driving. The mechanical design of hoverable FWMAVs is introduced in terms of the flapping mechanism, the control mechanism, the wings, and the materials. Related research groups and major achievements were presented in figures and tables for easy access. Problems, trends, and challenges were concluded and presented. Based on the current trends, insect-inspired FWMAVs based on motor-driving are easier to design, manufacture, and put into practical applications. However, aircraft driven by intelligent actuators has a smaller scale and mass, and their application scope is wider. These two types of hoverable FWMAVs have their own characteristics, but they still depend on a continuous breakthrough of new theories in mechanical design and new material technologies to apply them more quickly. In the future, researchers need to make continuous breakthroughs and attempts in mechanical design, and combine the latest mechanical design theories with the biological musculoskeletal system. Significant work needs to be undertaken in the future. This includes the research on biological flight mechanisms, new materials and new driving modes. Furthermore, not many industrial and commercial applications have been made. A significant amount of research on the mechanical design for bionic flapping wing micro-air vehicles still needs to be done.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest to this work.

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