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Development of a 2g butterfly-style flapping-wing micro aerial vehicle

Abstract

A flapping-wing micro aerial vehicle (FMAV) modeled after a butterfly was developed to realize a palm-sized micro aerial vehicle capable of autonomous flight. It has a wingspan of about 220 mm, a weight of 1.8 g with the drive motor and battery installed, and flaps at a frequency of 7 Hz. The results of flight motion analysis using a high-speed camera showed that this butterfly-style FMAV, which does not rely on an external power source and does not have a tail wing, can fly in a straight line while maintaining a constant altitude with an initial speed given. We were also able to observe the flight trajectory of it, which moved up and down with a flapping motion similar to that of a real butterfly. The development of an FMAV that can fly like an insect is important for the viewpoint of robotics to elucidate the posture control mechanism of insects, which still needs to be clarified. The autonomous flight of this butterfly-style FMAV is significant in this regard.

Keywords: flapping-wing micro aerial vehicle, butterfly, motion analysis

Volume 10 Issue 1 - 2024

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Received: February 02, 2024 | **Published:** February 13, 2024

Abbreviations: MAV, micro aerial vehicle; FMAV, flapping-wing micro aerial vehicle; CFD, computational fluid dynamics

Introduction

Flapping flight is a flying mode found in birds and insects, capable of various flight maneuvers such as gliding and hovering, as well as high turning and acceleration performance. The flapping has drawn attention to flapping as a flight mode, and research to incorporate this mechanism in the investigation of micro aerial vehicle (MAV) development has been active.[1–3] Some flapping-wing MAVs (FMAVs) are modeled on bees,[4] which are smaller in size, but their payload makes it difficult for them to carry a battery, and they must rely on an external power supply. In addition, a typical FMAV must have a tail wing for attitude stabilization and control left-right flapping motion for attitude control.[5] However, these increase the degrees of freedom and the number of actuators, leading to increased complexity of the mechanism and an increase in the mass of the machine body. Therefore, we have developed FMAVs modeled after a swallowtail butterfly.[6,7] The butterfly has a flapping frequency of about 10 Hz, which is lower than that of other insects, and its front and rear wings flap in the same phase, so its wings' freedom is also considered low. It is also larger than other insects, with a wingspan of about 100 mm and a mass of about 0.5 g. It is thought that existing motors and batteries can be mounted on it.

In these viewpoints, using a butterfly as a model is more feasible for developing a small FMAV. Although some research has focused on clarifying the flapping flight mechanism of insects, most of this research has been conducted by analyzing the flight motion of the insects themselves[8,9] or by computational fluid dynamics (CFD) analysis.[10,11] If an FMAV that can reproduce insect flight is developed, it will be possible for researchers to reproduce various flight conditions and analyze the motion to clarify the flight mechanism of the target insects.

Therefore, this study aims to develop an FMAV modeled after a butterfly and reproduce its flight mechanism. We will develop an FMAV equipped with a motor and battery that enables autonomous flight and evaluate its flight performance by analyzing its motion.

Development of a butterfly-style FMAV

Figure 1 shows a developed butterfly-style FMAV. This FMAV is constructed of a motor (MK04S-10, DIDEL), 3.8V rechargeable Li-ion battery (EC382204P-C, NGK), gears, links to flap wings, and motor bracket (Figure 2). Carbon fiber reinforced plastics (CFRP) is used as the main material for the wing frames and links of this FMAV, UV resin is used for the gears and brackets (molded by a 3D printer), and 3 μm thick PET (polyethylene terephthalate) film is used for the wing membrane. Butterflies have two forewings and two hindwings on each side, but since they overlap and flap in flight, they are made as a single wing with both wings combined. The single wingspan of a swallowtail butterfly is about 50 mm, and its total mass is about 0.5 g. However, we considered the wing loading based on the mass of the motor and battery and developed an FMAV with a single wingspan of 110 mm and a total mass of 1.8 g.

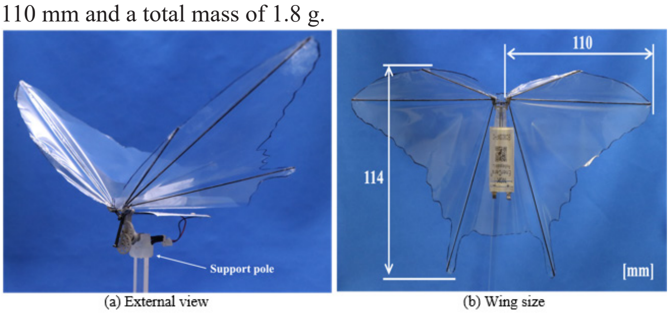

Figure 1 External view of a developed butterfly-style FMAV.

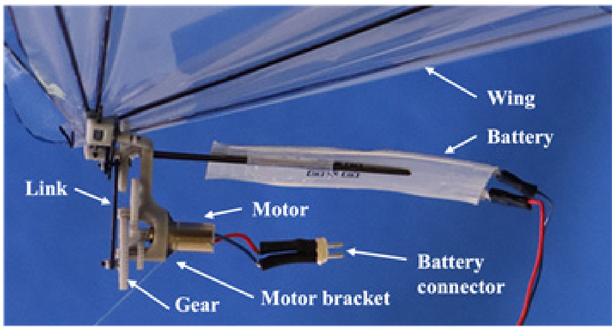

Figure 2 Composition of developed butterfly-style FMAV.

The flapping mechanism is shown in Figure 3. The rotation of the motor is passed through the pinion gear, gear 1, and gear 2, and the flapping motion of the wings is generated by the linkage connected to gear 2. The flapping angle defined in Figure 2 ranges from 60 to -30 deg for free-flying swallowtail butterflies, while the developed FMAV was designed to be from 50 to -30 deg. The flapping frequency was set to about 7 Hz, considering the scale with swallowtail butterflies (about 10 Hz for swallowtail butterflies).

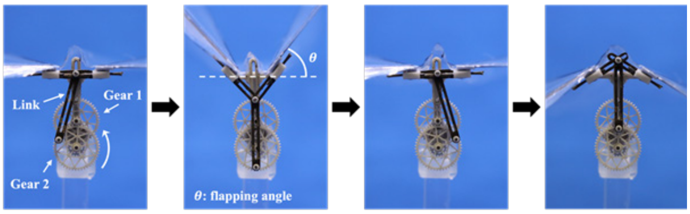

Figure 3 Flapping mechanism and definition of flapping angle.

Performance evaluation experiments by flight motion analysis

To investigate the flying ability of the developed FMAV, a high-speed camera is used to capture images of free flight and analyze the motion. The experimental environment is shown in Figure 4. In this experiment, the FMAV is flown five times from a height of 1.6 m using a catapult machine, and the images are captured by five high-speed cameras (1920 x 1080 pixels, 250 fps, HAS-U2M, DITECT). The flight trajectory is calculated by 3D motion analysis based on the acquired images. Here, the FMAV is given an initial velocity of 0.3 m/s by the catapult machine, which is the value that the FMAV flew in a stable posture when it was hand-held and flown by trial and error.

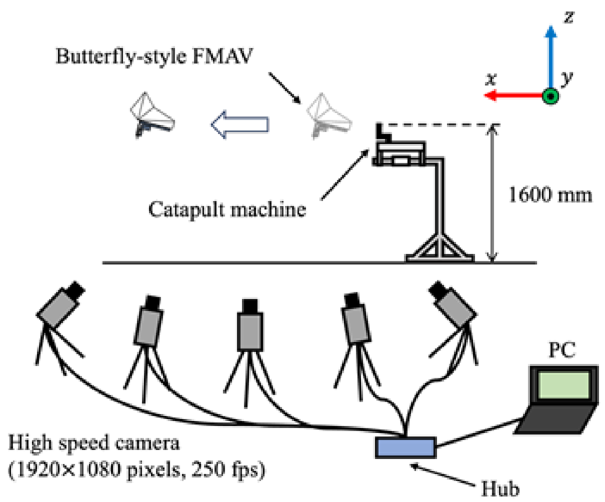

Figure 4 Experimental environment.

Experimental results and discussion

Figure 5 shows an example of a sequence of images of the flight taken by the high-speed cameras. Figure 6 shows the transitions of the flight height (0 mm at the starting point) for five trials. These are the results of about 1.5 seconds of analysis possible from the angle of view of the high-speed cameras (straight-line distance is about 2 m). It can be confirmed that the FMAVs descend slightly immediately after the start of the flight but then fly while maintaining a constant altitude. The butterfly periodically raises and lowers its body during flight, which causes it to sway up and down. Figure 5 and Figure 6 show that our developed FMAV achieves flight similar to that of a butterfly.

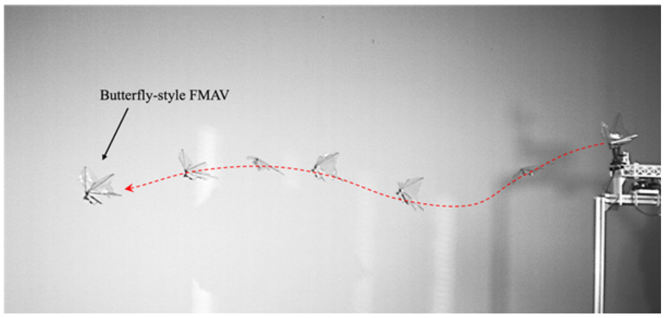

Figure 5 Stroboscopic photographs of a development butterfly-style FMAV captured during flight (dashed line denotes approximate trajectory).

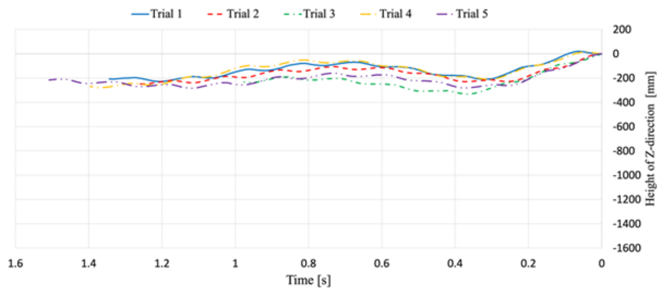

Figure 6 Trajectories of flight altitude for five trials (initial position is 0 mm).

Conclusion

In the field of MAV development that incorporates the flapping flight mechanism of living creatures, we have developed a butterfly-style micro aerial vehicle that weighs only 1.8 g and is modeled after a butterfly, which is smaller in size. Furthermore, flight motion analysis was conducted to evaluate its flight performance. The analysis showed that the palm-sized FMAV achieved free flight while maintaining a constant altitude. Its flight was similar to that of a butterfly in a swaying motion. Although the developed FMAV can fly in a straight line, it has yet to turn to the left or right. Therefore, future work is to devise an attitude control method to realize vertical and horizontal flight.

Acknowledgments

This study was supported by JSPS KAKENHI (Grant Number 21K03969). The authors are deeply grateful for their assistance in this project.

Conflicts of interest

The authors declare no conflicts of interests.

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Citation: Teranishi Y, Fujikawa T. Development of a 2g butterfly-style flapping-wing micro aerial vehicle. *Int Rob Auto J*. 2024;10(1):1–3. DOI: 10.15406/iratj.2024.10.00275

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