Jumping Takeoff of a Flapping Flying Robot

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Abstract—Robots mimicking the flight of insects and birds (i.e., "flapping flying robots") have considerably attracted attention owing to their numerous advantages such as energysaving, reduced noise levels, and safety during a crash. However, the takeoff method leveraged by existing flapping flying robots is limited, as ground-level takeoff may damage the robot. This study aims to develop a remotely controlled flapping flying robot that can fly independently. The developed robot consists of a flapping flying robot that can obtain a thrust of approximately its own weight by flapping its wings and a Snap Motor as a lightweight jumping mechanism. The findings demonstrate that a jumping takeoff effectively avoids wing–ground collision while contributing to stable posture during takeoff.

Index Terms—Flapping Robot, Self-takeoff, Micro aerial vehicle, Ornithoper Robot, Bio-Inspired Robot, Jump Robot

I. INTRODUCTION

A. Motivation and Purpose

With the recent development of batteries, motors, and control technologies, drones have been used in applications such as environmental surveys, disaster relief, and bridge inspections [1], and other applications. However, drones with high-speed propellers face challenges such as noise, cruising range, and safety when a crash occurs. Consequently, robots that mimic insects and birds (hereafter referred to as "flapping flying robots") have considerable attention in recent years [2] owing to the following advantages:

- They can save energy by gliding.
- They reduce noise levels by obviating high-speed propellers.
- They exhibit enhanced safety during crash events
- They are agile owing to the use of morphing wings [3].

B. Related Works

1) Flapping flying robots: Currently, the takeoff of flapping flying robots can be divided into two categories according to their takeoff mechanisms:

• Those that require human assistance, such as Robird [4], Bat Bot [5], USTBird [6], and SmartBird [7].

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Fig. 1. Overview of the flapping flying robot with Snap Motor

• Those wherein the thrust exceeds their weight, such as Nano Hummingbird [8], Robobee [9][10], DelFly Nimble [11], DelFly Explorer [12], KUBeetle-S [13][14], and Ornibot [15].

Both robot categories have limitations not addressed in the existing literature. The flapping flying robots cannot fly without human assistance. The Nano Hummingbird and Robobee can only take off vertically, which is energy-intensive, and the wings of the Ornibot may hit the ground during takeoff. J. Zhang et al. proposed a conceptual design for a jumping mechanism for self-takeoff with a jumping mechanism, but only the concept was provided, as they did not perform any experiments [16].

These challenges limit the applications of flapping flying robots in unassisted takeoff scenarios, as they cannot be controlled remotely as drones. Therefore, this study aims to develop a remotely controlled flapping flying robot that can fly independently.

2) Jump robots: This section describes recent trends in robot jumping mechanisms, such as a jumping mechanism is mounted in a flapping flight robot. Typical jumping mechanisms can be broadly classified as follows:

- An internal combustion mechanism, used in the Sand-Flea [17].
- Pneumatic cylinders, used to facilitate jumping in a Legin-Rotor Robot [18].
- An elastic body, used by the EPFL Jump Robot [19] or JumpRoACH [20].

Internal combustion mechanisms, such as the one used in the SandFlea, require fuel for jumping. Although this mechanism enables robots to jump high, these robots cannot be miniaturized. The Leg-in-Rotor leverages air pressure to jump high, which enables the robot to jump high. However, this mechanism is also unsuitable for miniaturization. Although the EPFL Jump Robot is lightweight, its small impulse may be insufficient for takeoff in a flapping flying robot. The JumpRoACH uses an active clutch with a gear connection and disconnection. This system is unsuitable for continuous jumping, limiting its application as a mobile jumping mechanism. Conversely, the Snap Motor is superior as the weight and size of the mechanism can be moderately reduced, enabling It allows a robot to jumping even with a certain payload and also facilitates continuous jumping in robots. Therefore, we used the Snap Motor as the jumping mechanism.

C. Our Proposal

This study, proposes a flapping flight robot equipped with a jumping mechanism that enables it to jump and take off. We used the Ornibot[15], which takes off by generating a thrust that is higher than its weight. We used the Snap Motor, which is lightweight and can handle a certain amount of payload, to enable jumping takeoff maneuvers in the flapping flying robot (Fig. 2). The contributions of this study are as follows:

- We demonstrate the jumping takeoff and prevention of wing–ground collisions using the proposed flapping flying robot and jumping mechanism.
- We demonstrate that the jumping takeoff contributes to the maintenance of posture during takeoff.

The remainder of this paper is organized as follows: Section II describe the specifications of the flapping flying robot. Section III details the the takeoff trajectory derivation using thrust and mechanical models from static measurement experiments and its effect on the robot equipped with a jumping mechanism. Section IV describes the improvements made to the flapping flying robot, including the jumping mechanism. Section V evaluates jump takeoff and movement using an actual aircraft. Finally, Section VI concludes the study.



Fig. 2. Study concept. We developed the flapping flying robot with a jumping mechanism and evaluated the performance of the jumping takeoff experiment.

II. DESIGN OF THE FLAPPING FLYING ROBOT

Flying robots must be lightweight. Small drones typically use brushless DC (BLDC) motors to achieve a lightweight design. Thus, we used a BLDC motor with the specifications listed in Table I to develop the robot. An electronic speed controller (ESC) was used to control the speed of the BLDC motor. The specifications of the ESC are listed in Table II. A lever-crank mechanism was used to convert the rotational motion into flapping wings. This mechanism is commonly used in flapping flying robots design and in robots that control flapping directly using servo motors.

TABLE I SPECIFICATIONS OF THE BLDC MOTOR

Model No.	T-Motor
	Micro M1104
KV Value	7500[RPM/V]
Weight	2 [g]

TABLE II SPECIFICATIONS OF ESC

Model No.	Turnigy Multistar BLheli 32 ARM
Weight	5.6 [g]

III. DERIVATION OF THE TAKEOFF TRAJECTORY

This section describes the derivation of the takeoff trajectory is discussed. We measured the thrust using a flapping flying robot and a force sensor. The mass and impulse of the jumping mechanism were added to this takeoff trajectory to obtain the setting index for the jumping mechanism.

A. Experimental Setup

To derive the takeoff trajectory, a force sensor was used to measure the thrust (Fig. 3). The specifications of the robot and force sensors used in the experiment are listed in Tables III and IV, respectively.



Fig. 3. Setting to evaluate thrust and lift forces and the definition of the lift and thrust forces of the flapping flying robot.

TABLE III

SPECIFICATIONS OF THE FLAPPING ROBOT

Mass	82.2 [g]
Wing Mass	$13.5 \times 2 [g]$
Wing Length	340 [mm]
Wing Area	$0.03889 \times 2 \text{ [m^2]}$

TABLE IV Specifications of the Force Sensor

Model No.	Leptrino
Rated Capacity	$\frac{FFS080F500M5K0A6}{F_x, F_y, F_z: \pm 50 [N]}$
Output Frequency	$\frac{M_{x}, M_{y}, M_{z} : \pm 5 \text{ [Nm]}}{1.2 \text{ [kHz]}}$

B. Experimental Results

Fig. 3 defines the directions of the lift and thrust forces of the flapping flying robot. Fig. 4 illustrates the time lapse of the forces measured by the force sensor. The results show that the instantaneous lift force is approximately ± 6 N. However, its average is approximately 0 N. Meanwhile, the instantaneous thrust force is approximately 4 N. The average flapping frequency and forces are listed in Table 4.



Fig. 4. Lift and thrust forces from the experiment

 TABLE V

 Average flapping frequency and forces from Fig. 4

Average flapping frequency	5.645 [Hz]
Average lift force	0.04927 [N]
Average thrust force	1.325 [N]

C. Experiment Discussion

The average lift force of approximately 0 N is reasonable as the lift forces generated by the flapping motion during upand-down flapping cancel each other within a single period, that is, the time to complete one up-and-down flapping motion. The relative velocity between the wing camber and airflow generates the lift in an actual flight.

The thrust force measurements demonstrated that the wing-flapping thrust was proportional to the flapping frequency, consistent with the results of a previous study [21]; thus, they were reasonable.

From the force measurement experimental results during wing flapping, we concluded that while the lift force oscillates, peaks during the upstroke and downstroke indicated thrust force generation. Furthermore, the data listed in Table V indicate that the proposed flapping flying robot can selftakeoff because it generates a thrust greater than its weight.

D. Trajectory Without a Jump Mechanism

From Fig. 5, the equations of motion are given by (1) and (2).

$$m\ddot{x} = T\cos\theta - \frac{1}{2}\rho V^2 SC_D\cos\theta - \frac{1}{2}\rho V^2 SC_L\sin\theta \qquad (1)$$

$$m\ddot{y} = T\sin\theta + \frac{1}{2}\rho V^2 SC_L \cos\theta - \frac{1}{2}\rho V^2 SC_D \sin\theta - mg$$
(2)

Where, m is mass, T is the thrust force, θ is the pitch angle, ρ is the air density, S is the wing area, V is the airspeed, C_L is the lift coefficient, C_D is the drag coefficient, and gis the gravitational acceleration. In Fig. 5, L represents the lift, T represents the thrust, and D represents the drag as in (3).

$$L = \frac{1}{2}\rho V^2 S C_L \qquad D = \frac{1}{2}\rho V^2 S C_D \qquad (3)$$

$$C_L = 0.6$$
 $C_D = 0.04$ (4)

We used experimentally known values of C_L and C_D in (4) [22]. The generation of the lift force in the same camber as that observed in the developed flapping flying robot was previously reported in the study [22]. We used the values listed in Table V for T. The lift force included only those forces generated by the velocity and lift constants, ignoring those generated by wing flapping. This was because the flapping at launch only produced a small lift force.



Fig. 5. Illustration of forces

Fig. 6 illustrates the trajectory without the jumping mechanism obtained by using x(t) and y(t) from (1) and (2), respectively, is illustrated in . Fig. 6a, viewed in the x-y plane, represents the takeoff trajectory. When y = 0, the robot is on the ground. Fig. 6b shows the takeoff trajectory for each pitch angle, suggesting that when the flapping flying robot has a pitch angle of

 $\theta > 50^{\circ}$,

takeoff is possible owing to thrust. Furthermore, even at a pitch angle $\theta \leq 50^{\circ}$, takeoff by thrust is possible for

$$y \ge 1.5$$
m



(a) Overview of takeoff trajectory



(b) Trajectory for various pitch angles

Fig. 6. Trajectories with various pitch angles without the jump mechanism

E. Trajectory with a Jump Mechanism

Fig. 14 shows the calculated takeoff trajectory, as described section III-D, considering the effect of the initial velocity generated by the jumping mechanism; legends show the mass of the jumping mechanism and the impulse produced by the jumping mechanism. The comparison in Fig. 14 indicates that the effect of the mass of a jumping mechanism is more significant than the effect of the impulse produced by a jumping mechanism.

The mass and force products of the jumping mechanism for the ground takeoff are plotted in Fig. 7. Regarding the mass and force products of the jumping mechanism, the EPFL Jump Robot [19] and Snap Motor [23] are illustrated in Fig. 7. Furthermore, Fig. 8 shows the takeoff trajectory when the Snap Motor. According to the figure, the flapping flying robot cannot take off appropriately when equipped with the Snap Motor.

IV. IMPROVEMENT FOR JUMPING TAKEOFF

This section describes the jumping takeoff improvement in the flapping flying robot, considering two areas: the flapping flying robot and the jumping mechanism(the Snap Motor) specifications.



Fig. 7. Impulse versus mass of jumping mechanism



Fig. 8. Trajectory with the Snap Motor having a mass of 0.050 kg and an impulse of 0.100 N·s. The gray dotted line shows the trajectory without a jumping mechanism.

A. The Flapping Flying Robot Specifications

The results of the indexes (Fig. 7) suggest that the Snap Motor may not perform a jumping takeoff. However, because the average thrust and lift were used to derive the design index, a jumping takeoff experiment was conducted to validate the derivation.

The weight of the robot is crucial (Fig. 7); therefore, a lightweight and robust flapping flying robot was designed . The effect of the pitch angle was also considered (Fig. 6b), and the pitch angle was set to 50° (Fig. 1). The flapping flying robot specifications are presented in Table VI.

TABLE VI Specifications of Flapping Robot with Snap Motor

Mass (body)	82.2 [g]
Mass (Snap Motor)	59 [g]
Mass (body+Snap Motor)	141.2 [g]
Wing Mass	$13.5 \times 2 [g]$
Wing Length	340 [mm]
Wing Area	$0.03889 \times 2 \ [m^2]$

B. Design of Jumping Mechanism

As explained in Section I-B.2, the Snap Motor [23] was selected as the jumping mechanism of our flapping flying robot owing to its lightweight and high impulse generation capability.

The generated impulse by the Snap Motor is strongly related to the shapes of the elastic rod just before and after snap-through buckling which determine the released strain potential energy of the elastic rod. Therefore, we have to choose an appropriate distance between both ends of the rod for its length.

On the other hand, the generated impulse is also correlated with the bending stiffness of an elastic rod. Therefore, we have to select an appropriate size for the cross-section of the elastic rod (the width and the thickness of the elastic strip with a uniform rectangular cross-section in our case) within the range where the motor exerts sufficient torque for the deformation of the elastic rod.

Table. VII shows our design parameter setting for the Snap Motor. These parameters were selected by trial and error. See the textbook of soft robots [24] for more detail about quasistatic simulation of an elastic rod which can be utilized for the design of the Snap Motor.

TABLE VII Parameters of the Snap Motor

Width	15 [mm]
Thickness	0.10 [mm]
Length	273 [mm]
Distance of Rod Ends	110 [mm]
Micro servo motor	TowerPro SG92R

V. JUMPING TAKEOFF EXPERIMENT

The effectiveness of the jumping takeoff was verified by experimenting on a robot equipped with a Snap Motor.

A. Experimental Setup

The following three experiments were conducted.

- Flap takeoff without the jumping mechanism
- Flap takeoff with the jumping mechanism
- Jumping flap takeoff with the jumping mechanism

We used LEAG-SDK, a high-precision marker image measurement software development kit, to determine the takeoff of the flapping flying robot (Fig. 9).



Fig. 9. Description of Experiment Device

B. Experiment Result

Fig. 10 illustrates the takeoff and takeoff trajectories calculated using the marker system; Fig. 12 illustrates the comparison between the takeoff trajectories and the changes in each trajectory; Fig. 13 presents the comparison between pitch angles during each takeoff; and Fig. 15 shows the photographs for each takeoff.



(a) Without Snap Motor







(c) With jump

Fig. 10. Experimental results. Red crosses indicate the points where the robot contacts the ground.

C. Discussion

The red circles in Figs. 15a and 15b, illustrate the wings hitting the ground during the first flap. In contrast, as shown in Figs. 12 and 15c, installing the jumping mechanism enables the aircraft to maintain its takeoff posture and gain altitude. This prevents wing–ground impact during selftakeoff owing to wing flapping (Fig. 15). As illustrated in Figs. 10c and 15, the pitching moment is also suppressed,



Fig. 11. Schematic of the position, posture, and force during "with Jump" and "Without Jump". Red, blue, and green arrows indicate gravity, thrust, and lift respectively. This schematic was created from images captured to measure the takeoff.



Fig. 12. Trajectory comparison between the three experiments . The red crosses indicate the points where the robot contacts the ground.

and the robot takeoff is more stable than the takeoff without jumping.

The suppression of the pitching moment due to the jumping takeoff is illustrated in Fig. 13, which shows the change in pitch angle. The other two takeoffs, without jumping and without the jump mechanism, show that although the pitch angle decreases quickly, installing the jump mechanism reduces the pitch angle deterioration.

We also discuss the occurrence of pitching moment and its suppression by jumping takeoff. As shown in Fig. 11, a counterclockwise moment is expected to be generated since the center of gravity is displaced from the point of action of the thrust and lift forces, a counterclockwise moment is expected to be generated. This expectation is reasonable based on the results shown in Fig. 13. However, while the above discussion explains the reason for the occurrence of the counterclockwise moment, this discussion alone does not explain why the jumping takeoff suppresses the pitching moment.

One possibility is that the Snap Motor suppresses the counterclockwise moment by shifting the center of gravity slightly backward. A similar discussion was made in a



Fig. 13. Pitchi-angle comparison between the three experiments . A larger pitch angle causes the flapping flying robot to fall forward.

paper study [25]. Conversely, the effect of the backward shift of the center of gravity may not significantly affect the suppression of the counterclockwise moment, depending on the comparison shown in Fig. 13 between "Without Snap Motor" and "Without Jump" which shows a smaller difference compared with the difference between "Without Jump" and "With Jump". If the backward shift of the center of gravity alone significantly affects the suppression of the counterclockwise moment, the difference between "Without Snap Motor" and "Without Jump" is larger. Since some studies have successfully controlled the altitude by shifting the center of gravity, thus generally contributes to controlling the altitude of flying robots such as Wi-Fly [26].

A possible explanation for this is that the pitching moment is suppressed by the impulsive force generated by the Snap Motor, generating a clockwise moment and that suppresses the counterclockwise pitching moment during takeoff.

The initial takeoff trajectory relying on the thrust suggested that takeoff is impossible, as shown in Figs. 7 and 8. However, the experimental results (Figs. 10c and 15c) show that the robot takes off. This discrepancy, between the takeoff trajectory and actual experimental results may arise owing to the derivation of the takeoff trajectory (Section III) using the average thrust and lift. Therefore, the takeoff trajectory should be obtained using the actual results to determine the design index for the jumping mechanism. However, the following must be addressed for flapping flight after jumping and evaluation:

- The occurrence of crashes owing to the pitching moment.
- The unelucidated effect on the altitude of the jumping for a stable takeoff.
- The establishment of a stable landing technique for a flapping flying robot by actively controlling the posture.
- An evaluation of the effective of jumping takeoff mechanism in suppressing the pitching moment by a specified number.

VI. CONCLUSIONS

We proposed a jumping takeoff mechanism for a flapping flying robot. The effectiveness of the proposed method was verified through jumping takeoff experiments using a marker image measurement software. The findings demonstrated that a jumping takeoff effectively avoided wing–ground collision while contributing to stable posture during takeoff.

Nevertheless, the proposed flapping flying robot and the analysis approach still have some limitations. Future studies will consider two point to address these problems. First, the robot can handle the flapping wings more independently, similar to the flight method of living organisms. Research on such flight methods will lead to the development of more agile and efficient robots, with applications in rescuing disaster sites and inspecting infrastructure facilities. Moreover, these robots could collaborate better with humans more than ever before. Second, we must provide a more detailed analysis of the flapping flying robot trajectory. The model proposed in this paper, shown in Fig.5, is considerably simplified. For instance, we also have to consider the transition of the forces made by wing flapping.

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Fig. 14. Results of the jumping takeoff simulation for different impulses. Legends show the mass of the jumping mechanism and impulse.



Snap Without (b) Without Jump Motor

(c) With Jump

Fig. 15. Experimental results. The red circle represents the contact between the wing and the ground during takeoff. The red crosses indicate where the robot contacts with the ground.