Re-STOL Micro Ornithopters-

with Four Strategies for Improvement

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***Abstract*—Regarding to the 20-cm wingspan flapping micro-air-vehicles (MAVs) or ornithopters, how to prolong the operation time and improve the flight control is very critical to their roadmap of development. Based on using the available technology and commercial transducer devices, this work presents four new features of ornithopters and proves them feasible. The 1st feature is repeatable short take-off and landing (re-STOL) so that the ornithopter can stop flapping in the air and automatically falls on the ground with resetting to the good gesture of take-off. The 2nd feature is to recharge the onboard Lithium battery by flexible photo-voltaic (PV) thin film on the tail. Recharging can be done either during flight or on the ground if the background light intensity is enough for PV devices to work. The 3rd feature is toward the semi- or fully autonomous flight control of ornithopters. It is realized by integrating gram-weighted microelectronic devices including Arduino-based micro-processors, MEMS inertial measurement units (IMUs) and mini servo actuators. Longitudinal pitching control and altitude control are proposed herein. The 4th feature is to develop new flapping mechanisms with large flap angle and no phase lag between two flapping wings. The above four newly developed features of ornithopters can preliminarily solve their current four shortcomings, i.e., vulnerable to gust wind, short flight endurance, hard to autonomously control and small payload, to great extent.**

Keywords—ornithopter; repeatable STOL; PV-charging; Arduino-based; flapping mechanism

I. INTRODUCTION

Even the research of flapping micro-air-vehicles (MAVs) or ornithopters attract people's attentions, there are four current technical barriers retarding the marching of their development. They are vulnerable to gust wind [1], short flight endurance [2], hard to autonomously control [3] and small payload [4]. In this work, the authors herein proposed four solutions to solve these problems respectively.

<u>The 1st feature is repeatable short take-off and landing (re-STOL) so that the ornithopter can stop flapping in the air and automatically falls on the ground with resetting to the good gesture of take-off again.</u> According to the prediction of eq. (1), the body mass scaling law of flapping birds [5], a 20-cm wingspan (b=0.2 m) ornithopter is supposed to have body mass no more than 11 g (m=0.011 Kg).

$$b = (1.17)\, m^{0.39}\ ;\text{(birds)} \tag{1}$$

which b is the wingspan (unit of meter) and the m is the body mass (unit of kg). Therefore an ornithopter is very easy to be flown away, out of control and fall to the ground even by a small gust wind of 5 m/s in outdoors [6]. The better way for ornithopter to deal with the gust wind is no more flight in such a situation, but rather stays on the ground and waits for gust wind stopping. Afterwards the ornithopter takes off by itself again. This way is intrinsically full of biomimetic interest and like birds. Consequently the capability of re-short take-off and landing (Re-STOL) is necessary to ornithopters and matches the scenario way mentioned above. The Re-STOL capability of new ornithopters also avoids the traditional, unreliable take-off way by hand-throwing but takes off naturally like birds or fixed-wing aircrafts.

Ornithopters are hard to stall and can have high lift due to a high angle of attack (AOA) up to 60-70° [7-8]. So adding a landing gear or supporting truss to ornithopters to make sure its high AOA as well as high lift during take-off and landing is the simplest way to have the capability of Re-STOL. In the following Section II the authors would depict their supporting truss design and the center of gravity (c. g.) position proper for ornithopters.

<u>The 2nd feature is to recharge the onboard Lithium battery by flexible photo-voltaic (PV) thin film on the tail. Recharging can be done either during flight or on the ground if the background light intensity is enough for PV devices to work.</u> By the flight power equation for flapping flyers, eq. (2), the power consumption P for a 10 g-weighted ornithopter cruising at V=3 m/s should be around 4 W [5].

$$P = D \cdot V = 2K(Mg^2)/(\rho V \pi b^2) + (\tfrac{1}{2}\rho V^3)(SC_{D,pro} + A_e) \tag{2}$$

where

D= induced drag+ profile drag+ parasitic drag

$$= (\tfrac{1}{2}\rho V^2)SC_D = (\tfrac{1}{2}\rho V^2)(SC_{D,ind} + SC_{D,pro} + S_B C_{D,par}) \tag{2a}$$

Induced drag coefficient:

$$C_{D,ind} = \frac{KC_L{}^2}{\pi \cdot AR}\ ;\ K\text{=1 for elliptic wing} \tag{2b}$$

Profile drag coefficient (neglecting separation):

$$C_{D,pro} = (1.33)/\sqrt{\text{Re}}\ ;\ \text{Re=Reynolds no.} \tag{2c}$$

Parasitic drag: $D_{par} = (\frac{1}{2}\rho V^2)S_B C_{D,par} = \frac{1}{2}\rho V^2 A_e$;

A_e=equivalent flat plate area (2d)

If the driving voltage and current provided by a 18 mAH Lithium battery are 3.3 V and 1,200 mA respectively, the total time duration for running out electricity is about 18 mAH/1,200 mA=54 s. This is almost the flight endurance barrier for one-time charging of Lithium battery of STOL micro ornithopters right now. Even in the future we might animate the formation flight of natural birds [9] to our ornithopter swarm and make the most of the power saving factor up to 30%. Or we may wait for the new high-performance, long-duration Lithium battery. But it is still impossible to extend the flight endurance to one hour except adding extra energy source into the flight system.

One of the candidates as extra energy might come from solar cells or photo-voltaic (PV) devices. Among the available PV devices, the flexible PV thin film is more suitable for ornithopters to equip. Take the commercial product of G-Watt Co., Ltd. [10] as an example, the charging voltage and current of 2-in-parallel cell are 4.2 V, 44 mA, respectively under the good solar exposure condition. The device has the dimension of 8 cm×3 cm and weight only 2×0.8=1.6 g. (This size is good to be placed on the tail.) Comparing the PV charging current of 44 mA to the discharging current of 1,200 mA of Lithium battery, apparently PV devices cannot afford the continuous power requirement of ornithopters during flight. In other words, after 54 s of STOL/cruising flight it needs 1,420 s to do the recharging on the ground by PV devices.

Fortunately augmented by the Re-STOL capability mentioned before, the new ornithopter equipped with PV devices can take off by itself after completing the solar recharging. Therefore with the flight mission of "takeoff→cruising→landing for recharging→takeoff again…", the ornithopter can be left alone without manual recharging and its operation time can be hoped to prolong to several hours or longer.

<u>The 3rd feature is toward the semi- or fully autonomous flight control of ornithopters. It is realized by integrating gram-weighted microelectronic devices including Arduino-based micro-processors, MEMS inertial measurement units (IMUs) and mini servo actuators. Longitudinal pitching control and altitude control are feasible</u>. As we mentioned in the previous discussion of mass scaling law of eq. (1), the total body mass of a 20 cm-wingspan flyer is only 11 g. It is the reason why the conventional flapping MAV is hard to equip with onboard microelectronics for autonomous flight control. Except AeroVironment's "Nano Hummingbird" [11] using some onboard microelectronic sensors and actuators, one successful example for semi-autonomously controlling the flight height of a flapping MAV is Hsiao's work [3] using stereo vision feedback control technique.

Advancing with the rapid commercialization of "quadrotor" [12] or "hexarotor" UAV products, many microelectronic components are getting cheaper and smaller. These components with only gram-weight include Arduino-based micro-processors, MEMS inertial measurement units (IMUs) with 9-axis outputs, MEMS barometers and mini servo actuators. It is feasible to integrate all the above micro sensors and actuators on the same flexible print-circuit-board (PCB) and weights below 5 g in total. So the onboard autonomous control modules for height control or hovering control are possibly realized on a micro ornithopter or a flapping MAV.

BTW, the onboard camera module with the wireless transmission function right now only weights 4 g [13]. If we could develop a stabilized gimbal [14] to hold and modulate the camera gesture in a real-time manner, a flapping MAV for optical surveillance can be fully realized. In other words, the video captured from the onboard camera could have no bad quality problem caused by the vigorous shaking of ornithopters during flight right now.

<u>The 4th feature is to develop new flapping mechanisms with large flap angle and no phase lag between two flapping wings.</u> Increasing more lift and thrust for ornithopters are important to improve the payload performance and to realize the fore mentioned onboard electronics for autonomous control. The substantial goal is to develop new flapping mechanisms for generating lift larger than the prediction of scaling law in eq. (1).

Two kinds of flapping wings are available, including mono-flapper [1, 15] and bi-flapper [16]. For the mono-flapper like natural flyers, the basic requirements are large flap angle and almost zero phase lag between right and left wings. The flap angle should be close to 120° like natural birds [5] as possible as it could be. Combining the multiple linkage system with linear constraints like Stephenson or Evans mechanisms is one approach to meet these two requirements [8]. Moreover the corresponding flapping frequency for mono-flapper should be larger as well. The scaling law for flapping frequency of natural flyers is shown as below [5].

$$f_w = (3.98)\, m^{-0.27} \ ; \text{(birds)} \quad (3)$$

where f_w is the flapping frequency (unit of Hz.) A 20-cm span MAV should have f_w of 15Hz. For matching a good flapping frequency near to the predicted value in eq. (3), properly selecting the motor specification and the gear-reduction ratio are the keys. Of course the appropriate control of the whole mass of the flapping mechanism is also very crucial. A classical weight design for a 20-cm span MAV is 1.4 gf but its generated lift or thrust is 13 gf [8].

The authors summarized the above 4 technical strategies for improving ornithopter performance in Fig. 1. The technical details of Fig. 1 will be depicted in the following Section II.

II. Methodology and Testing

Early attempts of the authors in the year 2007 led to the development of a kinematic model with a four-bar-linkage (FBL) mechanism in Fig. 2(a) for a 20 cm wingspan flapping MAV called 'Golden Snitch' [1,3,7-8] in Fig. 2(b). It was driven by a 6 mm-diameter motor with a gear reduction of 26.67 and test flights with an endurance of 480 s were realized.

A. Re-STOL

One proper material assigned as the re-STOL landing truss for micro ornithopters is Y-shaped carbon fiber spars in Fig. 3.

The installed high AOA (or inclined angle) is setup as 50-60°. The demo videos of re-STOL for "Golden Snitch" are shown at the following two websites:

https://www.youtube.com/watch?v=3k0tP_IgrgI

https://www.youtube.com/watch?v=AnS7yroZG4U

This video shows that the AOA during flight is also kept about 50-70°. This can be done by shifting the c. g. (center of gravity) position of the ornithopter as backward as possible. Carbon fiber has the merits of light weight and low cost. However one problem of the carbon-fiber Y-shaped spar in Fig. 3 is its finite mechanical strength vulnerable to many times of the violent landing crash. How to increase the lifetime of the landing truss subject to crash landing is still under developing.

B. PV-Charging

The development of PV cells is not the main mission of this work. The authors just bought the flexible PV cells shown in Fig. 4(a) available on shelves [10]. The specification of one PV cell has the output of 22 mA and 4.2 V subject to full exposure to sunlight. The horizontal tail of the MAVs or ornithopters in this work is suitable for installing a pair of PV cells. The MAV with PV tails is shown in Fig. 4(b). The real test in the sunny day needs about 50 min to complete the recharging for the 18 mAH Lithium battery used in the MAV.

C. Arduino-Based Electronics

(1) Arduino microprocessor

As constrained by the very limited payload for flapping MAVs, only several grams are available for the processor, sensor suite, actuators and battery pack. It is of paramount importance to choose a powerful processor that is ultra-lightweight, accommodate several input channels as data would be flowing in from the IMU, radio receiver and output channels that would be controlling the actuators. With the wealth of information available in both hardware and software sides, Arduino compatible microprocessor family was chosen for the purpose of on-board computing. Initial coding was done on Arduino Uno in Fig. 5(a) as the preliminary way to test the functionality and subsequently moved to smaller versions of the same processor.

As the code to test the basic data acquisition was completed, the Arduino Uno was replaced by TinyLily in Fig. 5(b) from tinycircuits.com, consisting of 7 digital pins and 4 analog pins. This gave the project the much needed push in terms of weight reduction, as the processor only took up 0.39 grams. The number of pins available was over the required amount and there was no need to add extra circuits to compensate for the absence. To connect the chip to the computer for the purpose of uploading program, a FTDI to USB connector was used. The FTDI computer connector is a separate chip that mounts on the microprocessor, and can be removed once the program has been uploaded to it.

The hardware was also kept minimal so that there was no need to carry the connecting apparatus in the payload. One of the two disadvantages of stepping down from Arduino Uno to TinyLily is that the latter has a reduced clock speed of 8MHz compared to the 16MHz of the former. In the later stages of testing with data acquisition from IMU and actuation of servo, it was determined that 8MHz was good enough for the purpose. Furthermore, to keep the size of the chip to a minimum, a voltage regulator was not added. This prevents usage of voltages excessive of 5.5V, beyond which permanent damage to the chip could be done.

(2) IMU and micro actuators

The IMU is one of the most critical components of the MAV as all its pose estimation data arises from within this sensor. The primary aim of the project is to develop a system that can help the MAV hold its position with respect to its surroundings. It was evident that a MEMS gyroscope would be the best sensor as the sensor would be able to give the rate of rotation about each of the X, Y and Z axis to which corrective commands can be generated based on the intensity and sent to actuators. But the use of only gyros warrants another problem of drift over the long run. From prior experience relating to 3-axis gyroscopes, the data was known to be drift and this needed another standard sensor for the purpose of calibration of the gyros.

With the choice of altitude sensor, the weight was a great concern and it was intended to limit the gross weight of the sensor under 1.5 grams. Bosch Sensortec BMX-055 9-axis IMU and Freescale MPL3115A2 barometric pressure sensor was determined to be a good fit with their compact size, ready layer mounting and Arduino I2C compatibility. The barometric pressure sensor measures pressure and calculates the altitude with respect to sea level. The effect of flapping of the wings on the data from pressure sensor remains to be investigated. Although the additional temperature sensor aboard the pressure sensor is of less relevance to the scope of the project, it could be used in the future to gather data about MAV's environment.

Flapping wing MAVs in the past have been controlled by a control surface-based actuator. Tamkang's "Golden Snitch" has used hinge-magnetic actuators that have either a fully positive or fully negative actuation that can be considered digital in nature. There is no intermediate value to their actuation and if the rudder is driven left, it goes fully left and vice versa. For the development of the envisioned MAV, proportional actuation is important and a micro servo was considered as the actuator. The actuation and control procedure of the MAV primarily differs from the control-surface based implementation and it aims to control the MAV by way of modifying the position of root chord with respect to the body axis of the MAV. Hinge-magnetic actuators used in the past lack the proportional control and do not have a torque more than a couple of grams. The micro servos of chosen herein are low-weight (1.7 g), fast response and high torque motors (available at hobbyking.com).

(3) Control code

The upcoming activities for the implementation of autopilot programs are expected to move at a faster pace. So far, choosing the right set of components, carrying out proof-of-concept studies and demonstrations, testing the capabilities of the acquired components has consumed extended amounts of time. They include demonstrating proportional control with the chosen processor board, DAQ methods, filtering techniques and micro servo motors. This has already provided the basic framework for the implementation of PID control and the only major steps in the future are integrating the setup with the airframe and swapping the proportional algorithm inside the microprocessor with a PID algorithm.

Once the aforesaid steps are established, the MAV would be able to fly at a predetermined altitude and location. Gaining manual control over the MAV would be by pairing a low-weight radio receiver to the Arduino and mapping the stick controls to the motor throttle and servo positions. This is regarded as a relatively easy goal to achieve as the amount of software resources needed to do this is plenty.

To quantify the effectiveness of the PID tuning parameters, extensive flight testing in both tethered and free flying mode is planned. Depending on the magnitude of deviation from the desired position of the MAV, case based tuning parameters are planned to be employed whereby a large deviation would mean aggressive tuning parameters and smaller deviations would make use of milder ones. The 1st trial of the stabilized platform for MAV is shown in Fig. 6.

By integrating IMU/ micro sensor and microprocessor with gram-sized weight, some simple flight controls like orientation-fixed straight forward flight or constant-altitude level-turning could be programed and done in the very near future.

D. Flapping Mechanism [8]

In the body of research relevant to high-performance flapping MAV, development of light-weight, compact and energy-efficient flapping mechanisms occupies a position of primacy due to its direct impact on the flight performance and mission capability. Realization of a such a versatile flapping mechanism with additional ability of producing thrust levels that fulfill requirements of cruising forward flight and vertical take-off and landing (VTOL) conditions demand extensive design validation and performance evaluation.

Herein presents a concerted approach for developing the mechanism of 20 cm span flapping MAV through an iterative design process and synergistic fabrication options involving electrical-discharge-wire-cutting (EDWC) and plastic injection molding (PIM) in Fig. 7(a). The lightest flapping mechanism made of POM is only 1.4 g. Dynamic characterization of each mechanism is done through high speed photography, power take-off measurement, wind tunnel testing and proof-of-concept test flights. The research outcome represents best-in-class mechanism for a 20 cm span flapping MAV with desirable performance features of extra large flapping stroke up to 100°, minimal transverse vibrations and almost no phase lag between the wings. The gear reduction ratio of 26.67 has achieved the lowest friction dissipation and the maximum lift of 13.8 gf (larger than the total body mass of 9.62 g) and thrust of 2.9 gf. The highest flapping frequency is measured as 18.9 Hz. The VTOL is demonstrated in Fig. 7(b).

III. Conclusions

Four features including re-STOL, PV-recharging, onboard electronics and large flapping stroke for flapping MAVs or ornithopters are proposed herein. The whole research framework is to resist gust wind, to prolong the flight duration time, to control autonomously and to increase payload. Final goal is to enhance the characteristics of stand-alone operation of flapping MAVs.

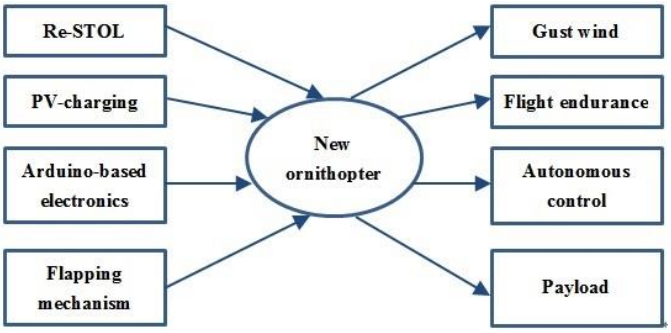
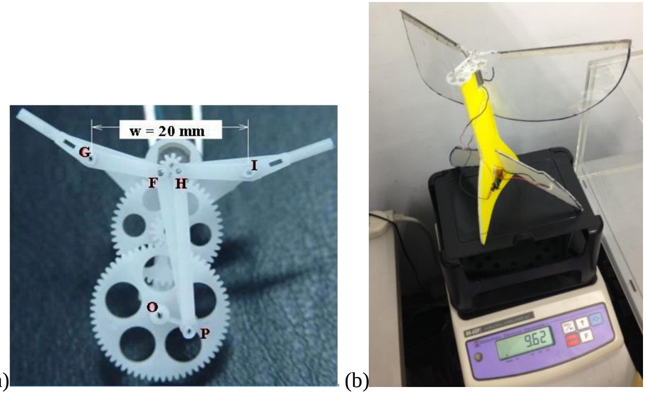


Fig. 1. The 4 strategies for improving ornithopter performance.



(a) (b)

Fig. 2. (a) Flapping mechanism of 1.2 g; (b) the flapping MAV "Golden Snitch" of 9.62 g [8].

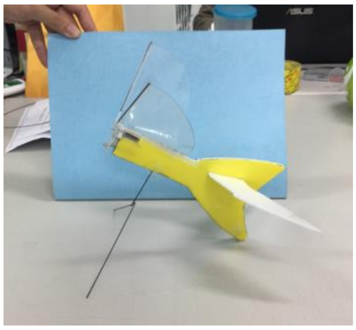
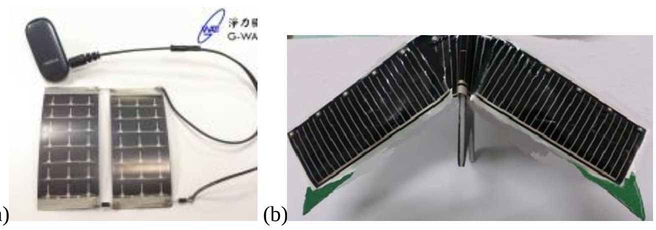


Fig. 3. "Golden Snitch" added with high AOA landing truss.



(a) (b)

Fig. 4. (a)The flexible PV cell [10]; (b) PV pasted on the horizontal tail of a MAV.

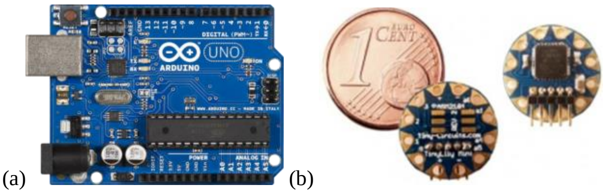


Fig. 5. (a) Arduino Uno with Atmega328 MCU; (b) TinyLily with ATmega 328P MCU.

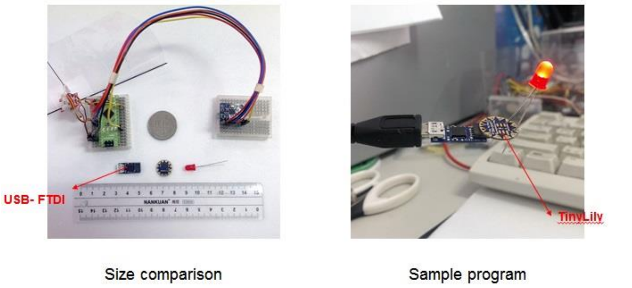


Fig. 6. A stabilized platform (left) and the mini-control module (right).

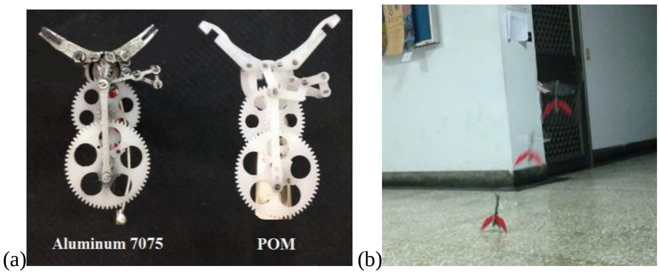


Fig. 7. (a) Evans flapping mechanisms, made of Al-alloy 7075 by EDWC, and POM by PIM; all the gears are made of POM by PIM [8]; (b) The VTOL flight.

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