Design and development of UGS flapping wing MAVs

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ABSTRACT

This paper describes the design, build and fly University of Glasgow Singapore (UGS) flapping wing MAVs using fabrication method such as laser cutting and Rapid Prototyping. The first prototype was made from acrylic using a laser cutting machine. The material was strong however it was brittle. The wings were made up of carbon rods and kite material Ripstop. First test showed that the wings were too heavy for the mechanism to work. The second and final prototype was a smaller single gear crank design which was fabricated using a 3D printer. Initial test proved that the prototype 2 could withstand the high frequency flapping required for lift. The second test performed was to tether it on a string. At high frequency the prototype 2 was able to move in a circular motion.

1. INTRODUCTION

In recent years the development and research done on flapping wing MAV is on the rise. This is due to the technological advancement of micro components such as an electric motor. The military in particular is very interested in its development. They seek to one day provide each squad with an MAV to provide real-time intelligence during missions. Although the research is relatively new, there has been some success in the trying to mimic the flight of a bird and insect.

The development of flapping wing MAV has been lagging. This is due to the complexity of the design and the unsteady aerodynamic forces of flapping wing. Only in recent years, flapping wing MAV has been gradually being picked up and researched further. The flapping wing MAV has multiple advantages compared to the other types of MAV. Flapping wing MAV is able to hover and can do so without making much noise. Its lift is more efficient compared to the other 2 MAV. However the most notable advantage is that it resembles either a bird or an insect. Be it on the battlefield or for wildlife research where blending in into the surrounding and not getting noticed is key to the success of the mission. Flapping wing MAV can be categories into: Ornithopters (bird-like flapping) and Entomopters (insect-like flapping). The ornithopter is capable of only flying forward whereas the entomopters is able to fly forward and hover as well.

2. PROTOTYPE 1

The flapping wing MAV would be based on an ornithopter design. The final design would be inspired by all the previous MAV that was researched. The design criteria is, it has to be lightweight, simple and yet strong enough to withstand the stress of the flapping motion and the crash landings during test flight. Simplicity is the key here as most of the components that would be used would be from hobby shops.

2.1 Flapping Wing Mechanism

The flapping wing mechanism function is to convert the motor's rotary motion into flapping motion. It is the most important component of the MAV thus much research was done to assess the many different designs available. Generally the mechanism design is about the same to each other with only slight modifications.

Staggered Crank Design

The staggered crank design in Figure 1 is the most basic of the flapping wing design. The connector rods are staggered in a measured distance and angle to ensure that the left and right wing are flapping symmetrically. This design is favoured by hobbyist who wants to attempt to make their own Ornithopter using household items. Modifications has to be made so that the motor can be used instead of a rubber band as its power source.

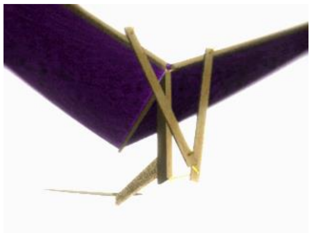

Fig. 1 (left): Staggered Crank
Fig. 2 (right): Single Gear Crank

Single Gear Crank Design

The single gear crank design in Figure 2 taken from University of California Biomimetic Millisystems Lab [13], looks simple however it is more complicated than it seems.

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Figure 1 shows the wings at the same level. The centre point where the connector rod and the wing hinges are connected to each other has to expand and contract as the mechanism flaps. Contracting and expanding at a very high frequency could result in component failure.

Dual Gear Crank Design

Figure 3, taken from a published paper, shows the dual gear crank design from similarly used in the Festo's SmartBird [10]. It features 2 gears that controls each wing hinges separately. There are different variation to the drivetrain design. The one shown in Figure 3, uses the pinion wheel to drive both the secondary gears. The secondary gears will rotate in the same direction with each other. The other design, has the pinion gear rotate the secondary gear and this secondary gear to another secondary gear. The secondary gears would rotate counter clockwise to each other. This design is much simpler to implement and reduce the wing symmetry misalignment.

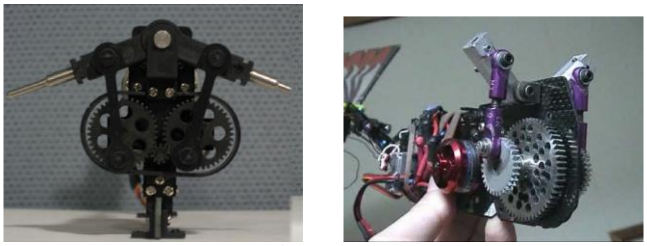


Fig. 3 (left): Dual Gear Crank
Fig. 4 (right): Transverse Shaft

Transverse Shaft

The transverse shaft design shown in Figure 4 is the other variation of flapping mechanism from Cybird 2 [6] which allows for the most symmetrical flap, however, it is the heaviest and the most complicated design. The rotating gears and the flapping wings are not in the same plane thus the connector rod has to be able to rotate. The connector rod has a ball bearing inside and this adds weight to jus the component itself. The number of gears used in this design is more than any other design. The transverse shaft design is usually used for a bigger MAV design where weight could be overcome by large wings.

2.2 Tail

The tail design varies with its intended use. Some of the design uses it only for stability but in most cases they are used for control as well. For stability, the tail is tilted upwards so that it the downward force of the tail would force the nose to pitch up. The angle is typically around 15 degrees or less. For control the more common designs implemented are the swinging tail and the tilting tail due to their simplicity. The swinging tail works by causing a rolling moment to when it swings to either side. The tilting tail works like a rudder, when it tilts to the right it causes the MAV to yaw to the right. A horizontal stabilizer tail design unlike the other 2 design could provide additional control. It can act as an elevon. Providing pitch and roll control. However this design requires 2 servos to be used and a more complicated design.

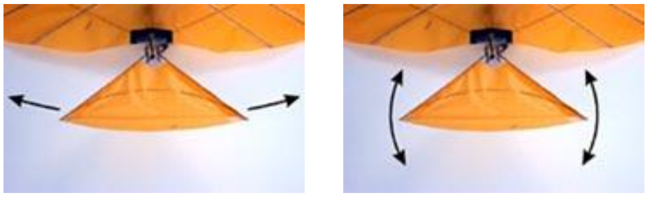


Fig. 5 (left): Swinging Tail
Fig. 6 (right): Tilting Tail

2.3 Body

The body is the part where the components like the electronic speed controller, the receiver and the battery is located. The body also has to hold all the components from moving around too much. This is to prevent the shifting of the centre of gravity of the MAV. The components would each be taped separately and then hooked to the body by Velcro tape. As the design would not require much space the body design could be hollowed. Figure 7 shows the body design with holes in them. This significantly reduces the total weight of the body. The body design had to be glued to the flapping mechanism at 90 degrees angle. Small triangles were added in between them as a support structure to prevent the body and the flapping wing mechanism from snapping off.

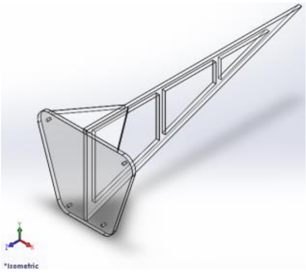


Fig. 7: Body Design

2.4 Gear and Motor Selection

Sourcing out for custom gears was a big issue. The gears that were out in the market were either too small or too big. Therefore it had to be custom design and fabricated. The gear design was dependent on the motor that is going to be used. The motor rating affects the gear ratio which then affects the flapping frequency. The formula for flapping frequency is,

$$FlappingFrequency = \frac{MotorLoadSpeed}{GearRatio} \cdot \frac{1}{60} \quad (1)$$

The motor that is used is a brushless outrunner motor. Outrunner motors have lower KV ratings meaning they have more torque but less speed. More torque is needed than speed for this project as the motors have to turn the gears to flap. The motor also needed a front mount so that it could be mounted easily to the flapping mechanism frame instead of a separate mount just for the motor. This narrows down to 2 motors as shown on the table below

Specification/Motor	Motor 1	Motor 2
Motor Rating (KV)	1200	2800
Load Speed (rpm)	5800	8350
Voltage (V)	11.1	7.4
Weight (g)	38	25

Table 1. Motor Specification Comparison

Motor 2 was chosen as it was lighter and requires lesser voltage. Voltage is linked to the number of cells that the Lithium-Polymer (Li-Po) batteries has and the rating of Electronic Speed Controller (ESC). Each cell on a battery is 3.7V so the higher the voltage the heavier the battery. It is the same for ESCs, higher ratings means bigger and heavier ESCs.

2.5 Fabrication and Material

There were 3 materials being considered: carbon fibre, balsa wood and acrylic. The first material of choice was to use carbon fibre due to it being strong and light. As it turns out, laser cutting a carbon fibre sheet would burn the material.. Balsa wood is very light and easy to cut however due to complex design of the MAV it was decided that it was not a suitable material. Acrylic was the only choice left. Acrylic is not as light and strong as carbon fibre however it can use laser cutting machine to do precision cutting.

2.6 CAD Design Dimensions

In order to find out the total dimensions and the weight that is allowed for flight, a lift equation was used. Certain assumptions that has to be made before using this equation are as follows:

1. The resulting lift would be higher in reality due to neglecting other flapping wing effects that contribute to lift when flapping.
2. The coefficient of lift is independent of the location on the wing and time.
3. Induced inflow of blade element theory is ignored.

From the assumptions made the equation for a rectangular wing shaped lift could be expanded to

$$L = \varphi_0^2 \cdot \pi^2 \cdot f^2 \cdot C_L \cdot \rho \cdot c_0 \cdot l^3 \cdot \frac{1}{3} \qquad (2)$$

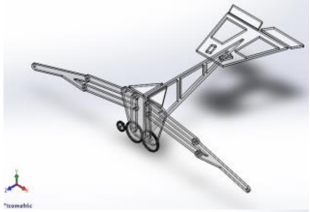
where φ_0 is flapping angle, f is the flapping frequency, c_0 is the chord length and l is the wing span length. The equation is for a rectangular shaped wing however as mentioned above the equation is to be used as a rough estimate so that the dimensions and weight of the MAV could be measured. Table 2 shows the results from using the equation.

Parameters	Values	Unit
Flapping Amplitude	70	deg
Flapping Frequency	6.5	Hz
Lift Coefficient	0.8	
Air Density	1.225	kg/m^3
Chord Length	0.13	m
WingSpan	0.3	m
Lift	**1.684**	**N**

Table 2. Lift Generated

CAD Design

Using the dimensions above and the design criteria, a CAD design using SolidWorks was modelled. It would incorporate a dual gear crank and a horizontal stabilizer tail design. The dual gear crank was the simplest design with not much wing symmetry misalignment. The horizontal stabilizer tail design was chosen as it could provide both pitch and roll control. The initial design showed in Figure 8 featured a articulated wing. This design was not used as there were too many moving parts in the design and may complicate things. Therefore the chosen design is the one shown in Figure 9.



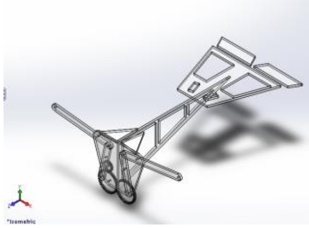


Fig. 8 (left): Articulated Flapping Wing
Fig. 9 (right): Single Flapping Wing

The total weight of the MAV was measured using one of the features in SolidWorks. Now the total weight of the MAV plus the components could be compared to the lift equation result. Table 3 shows the sum of all the component weights. The 2 measurements shows that the weight of the MAV is below the total lift generated. An image of the assembled MAV is shown in Figure 10.

Components	Values	Unit
Brushless Outrunner Motor	25	g
Radio Receiver	11.5	g
Servos	9	g
Li-Po Battery	15	g
Electronic Speed Controller	10	g
MAV Design	80.24	g
Total Weight	**150.74**	**g**

Table 3. Total Weight of MAV

Fig. 10: Assembled Flapping Wing MAV

3. PROTOTYPE 2

Learning from prototype 1, some design considerations were made:

- the flapping mechanism needs to be more simplified
- the number of moving parts need to be reduced
- the overall design has to be much smaller to reduce weight
- changing the tail design to either a tilting or swinging tail would reduce the number of servos used which would reduce weight

3.1 Flapping Wing Mechanism

The flapping wing mechanism for prototype 1 had too many moving parts and was not simplified enough. A simpler design was needed and thus another look at the single gear crank was taken. The design idea was to shift its fixed pivot point from being at the centre of the wing to it being at the end of the 2 wing joints. Figure 11 shows this design. The changes made to its pivot point made the flapping mechanism worked properly. A simulation test was done using the software and it showed that it could hold at high frequency flapping and the flapping movement is synchronized.

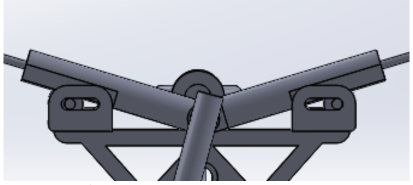


Fig. 11 (left): Prototype 2.2 Flapping Mechanism

3.2 Tail

The previous prototype was using an elevon tail design which could provide pitch and roll control however it requires 2 servos to be used. For weight reduction and simplicity sake, a simple tilting tail would be used instead. The tail frame would be made up of carbon rods which would be fixed to the tail piece and covered with Ripstop. The tail piece has a ball bearing inside it so that the tail could tilt easily. Figure 12 shows the tilting tail design.

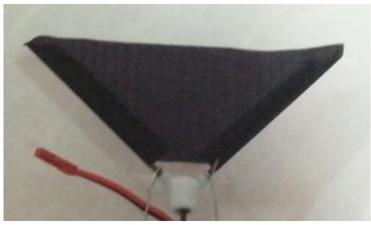


Fig. 12 (right): Prototype 2.2 Tail

3.3 Body

In previous design the body was made out of acrylic and had to be solvent weld together. The design was simpler to implement however it was bearing a lot of weight. In order to reduce more weight, carbon rods would be connected to the front piece and the tail piece to form a rigid triangle frame. The frame would then be covered with Ripstop and Velcro tape to secure the components to the platform. Figure 13 shows the CAD design of the body.

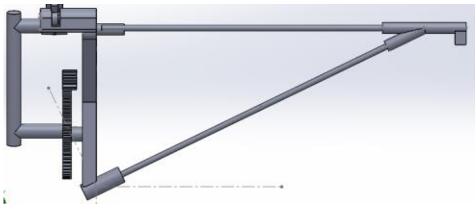


Fig. 13: Prototype 2.2 Body

3.4 Gear and Motor Selection

The new flapping mechanism uses only 2 gears. This allows more fine tuning to the gears which allowed a gear ration of 5.5:1. This was acceptable as the newer motor has a slower load speed but higher torque. The new gear is specially hollowed at the centre for a ball bearing to be inserted so that it can spin freely around the connecting part of the front piece.

Specification/Motor	Motor 1	Motor 2
Motor Rating (KV)	1700	2800
Load Speed (rpm)	7800	8350
Voltage (V)	7	7.4
Weight (g)	20	25

Table 4. Motor Specification Comparison

3.5 Fabrication and Material

In the previous design, a laser cutting machine was used. For the new prototype, a Rapid Prototyping Machine or also known as a 3D printer would be used. A 3D printer allows for more freedom of design. An extruded part could be combined during the design process easily, compared to assembling the parts after it has been fabricated. The chosen material was PLA as the design such as the gears needed the material to be strong and durable.

3.6 CAD Design Dimensions

Fig. 14 (right): CAD design Prototype 2.2

Figure 14 shows the completed CAD design of prototype 2. Once again to find out if the dimensions of the prototype could produce enough lift, the lift equation in chapter 3.6 was used and compared to the total weight of the prototype. Table 5 below shows that the lift is more than the weight thus the prototype fabrication can proceed.

Table 5. Lift & Weight Comparison

3.7 Flight test

Figure 15 shows the assembled prototype. Similarly a dry run test was done for the flapping mechanism. Everything was working normally. Next it was the tethered flight. The MAV was also able to move in a circular motion. Finally the free flight test. The MAV was held until it flapped at high frequency after which it was hand thrown in the forward direction. After it was thrown, the MAV continued to fly forward while slowly pitching upwards. The left and right controls were tested and the MAV showed that it could maneuver left and right. The last test was the pitching control. Increasing the rpm of the motor pitches the MAV upwards and decreasing the rpm pitches the MAV downwards. However decreasing the rpm too much would make the MAV stall. This happened when the MAV tried to land. It stalled and crashed into the ground, breaking the parts that was holding the body. The flapping mechanism however is still intact. Although the MAV crashed during its landing, the test was a success, the MAV showed that it can fly and was able to be controlled remotely. The video clip can be seen at Youtube website:"http://youtu.be/hp-Kpw6sll0".

Fig. 15: Assembled Prototype 2.3

4. CONCLUSION

The objectives which were to design, build and fly a flapping wing MAV, was all met. The design section of prototype 1 and 2 has discussed and evaluated the conceptual designs of the flapping wing MAV. There were 2 fabrication methods that were used, laser cutting and 3D printing. Although it seemed that the 3D printing was a better fabrication method as it allows for more complicated design it does has its limitations in the area of melting point and breaking strength.

References

The references are shown in alphabetical order.

Component	Weight (g)	Parameter	Value
Brushless Outrunner Motor	20	Flapping Amplitude (deg)	50
Radio Receiver	11.5	Flapping Frequency (Hz)	10
Servos	4.5	Lift Coefficient	0.8
Li-Po Battery	4	Air Density (kg/m^3)	1.225
Electronic Speed Controller	10	Chord Length (m)	0.1
MAV Design	14.77	WingSpan (m)	0.15
Total Weight	64.77	Lift (g)	97.77

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