Sizing process and manufacturing of optimal flapping wing micro air vehicle

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Currently the development of functional flapping wing drones is on an uprise. Their ability to be highly maneuverable and discrete makes them desirable for surveillance purposes, from search and rescue to intelligence. Although there are several different competitive flapping wing drones available, they are both expensize and larger in size then typically desired. In this study, the process to design and manufacture micro air vehicles (MAVs) is discussed. To optimize the development of the drone, a sizing process based on theoretical and statistical analyses is used to build a functioning MAV flapping wing drone. The completed product weighs 120g with a wingspan of 48cm, powered by a brushless motor and Lipo-Battery. Given the weight and wing design of the drone, a flapping frequencty of 20Hz to 30Hz must be produced to achieve forward and hovering flights. A wing profile modeled after that of a bumblebee is utilized for each of the four wings. Using 3D prints and carbon spars a wing skeleton was created and overlaid with a Mylar film simulating a wing membrane. The design process used and the fabricated flapping wing are presented in this study.

I. Introduction

Throughout the last several decades, there has been an increased demand for intricate flapping wing drones with similar capabilities to that of larger drones. One of the many applications of this specific variation of drone is search/rescue and surveillance [1,2]. Typically for these applications, it is desired to maintain an inconspicuous profile. There have been several successful developments of flapping wing drones but many are substantially larger than what the average customer would desire. To achieve customer demand, many developments have focused on producing smaller drone sizes including micro, nano, and pico Air Vehicles (MAV, NAV, and PAV) [2]. One of the biggest challenges is ensuring that these miniaturized drones have similar capabilities as a standard unmanned air vehicle (UAV). Although size reduction is a constraint, it is important not to sacrifice efficiency when perfoming size reduction. Luxuries like power, operational longevity, and manuveability are all fundamental constraints. Many of the missions these drones perform are in confined spaces and urban enviroments making it crucial to develop an optimized product [2, 3]. Needs, such as agile maneuverability and long operational capabilities must to be satisfied when the final product is delivered [4].

Typically with flapping wing micro air vehicles (FWMAV), it is challenging to achieve all of the desirable functions of a standard UAV drone. The design process developed to ensure drone optimization utilized a similar statistical analysis used in [5]. Based on the analytical process, a general weight estimation was established in the initial design phase of the drone. After attempting several different system builds, it

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was determined that several of the components would need to be reduced and repurposed to accomplish the initial intent of the development process.

The inspiration behind the layout of this particular drone is drawn from that of a dragonfly. With the dragonfly's general configuration of four wings it is optimized to easily conduct forward and hovering flight [7]. By understanding the general aerodynamics of flying insects and birds, fully functioning flapping wing drones can be designed and manufactured. Using the studies of Hassanalian et al. [5, 6], several different insect wings and their aerodynamic characteristics were studied. It was determined that for the purposes of this study, the bumblebee wing shape would be the optimal wing shape for the drone. Using the body configuration of a dragon fly and the wings of a bumblebee, a standard FWMAV is designed and manufactured

Throughout this work, the design, manufacturing, optimization, and experimentation of a FWMAV is discussed. The goal of this project is to successfully complete a flight mission that properly demonstrates the drones maneuverability, ability to produce forward and hovering flight, and maintain a flight endurance of 10-15 minutes. Using these parameters and weight constraints, a system is designed and tested. Figure 1 is a visual representation of the mission profile that the final drone is being designed to complete.

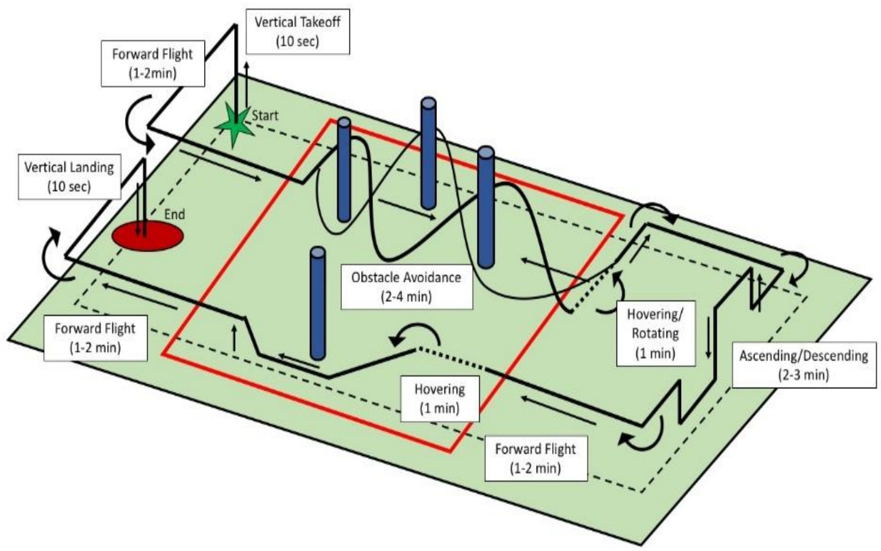

Figure 1. Predefined flapping wing mission.

II. Drone Size and Wing Selection

One of the primary constraints in drone design is the size and the overall weight of the intended product. Understanding that the overall product should fall within the category of a MAV drone, it is easily determined that the drone's weight should be approximately 100 grams. Under these assumptions, the process of selecting the structural components of the drone, such as hardware and wing configuration can begin. A drongonfly's body configuration, consisting of 4 wings, is utilized for the study, due to the dragonfly's ability to achieve both forward and hovering flight capabilities [8]. Having such capabilitiesmake FWMAV competitive in the market of surveillance and reconnaissance missions. Due to the intended size and weight of the drone, it is easy to deduce the overall wing dimensions, such as wing span and wing area for a FWMAV drone. Figure 2 is a simple illustration of the general sizing of drones based on their weight and wingspan.

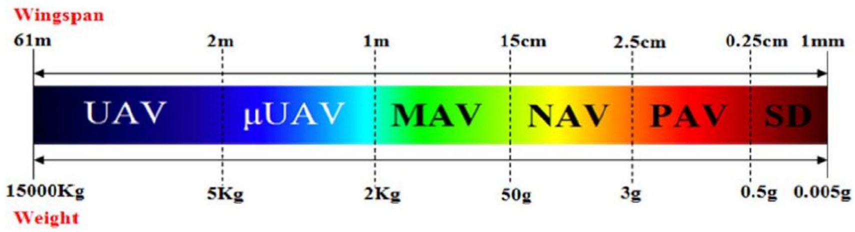

Figure 2. Catogorization of drones based on weight and size [1].

In the studies conducted by Hassanalian et al. [6, 8], seven different insect wings were studied to compare their aerodynamic properties. Two primary theoretical methods were used throughout these studies to determine the characteristics of each of the wing profiles. A quasi-steady analysis was conducted for the seven different wing shapes when considering the wings to have an equal wingspan and another analysis was carried out for the wings having an equal wing surface [6]. In addition, a strip theory method was used to investigate the seven wing shapes in a forward flight. The same studies, an equal wingspan and and equal wing surface were considered using the strip theory analysis [8]. From these studies, it was determined that the bumblebee wing shape is an ideal choice for a FWMAV as it showed strong flight performance characteristics in both hovering and forward flight. The flight performance characteristics that are considered in this choice are lift, thrust, average input power, and average propulsive efficiency.

Considering the general size and 100 grams weight of the drone, the necessary wingspan and wing area can be deduced using the a flapping frequency of 20 Hz. Using the statistical weight analysis proposed by Hassanalian et al. [5], the overall weight of the drone can be broken down and divided into several different components. The statistical breakdown is 23%, 2%, 24%, 13%, and 38% of the weight being devoted to the power plant (motor, speed controller), the payload (loads, sensors, camera, etc.), the battery, the avionic system (servo motors, receivers, navigation systems), and the structure respectively. After constructing the first iteration of the FWMAV drone, it is determined that the overall weight dispersal is unrealistic based on commericially available components. Through development and manufacturing, the weight distribution is adjusted to provide the most optimal design.

III. Structural Design and Manufacturing

When designing the structure of a flapping wing drone, it is important to consider all components of the functioning system. It is crucial that the housing of the drone has the capability to adequately store the electronics, hardware, and gears that mount to the actuation mechanism. The system must maintain its compact composition, meaning that all space and weight must be used to the fullest of its capability. The crucial structural components of every FWMAV are the housing/actuation mechanism and the wing structure. How each component is constructed and integrated with each other is crucial to the successful flight of the resulting product. Within this study, two different FWMAV systems are manufactured and tested. Each system used different housings and actuation mechanisms to provide the flapping motion for the system.

Gear Train/Actuation Mechanism

Each of of the primary components of the FWMAV drone are comprised of 3D printed materials. This provides ease of manufacturing and reduces the overall cost and weight of each system. All components of the sysem will be incorporated within the housing. The housing must be capable of storing all electronic components, and housing the gear train and actuation mechanism that will produce flapping from each of the four wings. In order to design the optimal housing structure, it is important to consider the actuation mechanisms used for the system. There are five primary actuation mechanism designs. Each have their advantages and disadvantages. For the purpose of FWMAVs, it is important to consider which will provide harmonic flapping motion while maintaining a light structure. Table 1 discusses the advantages and disadvantages of each of the five mechanisms. While each of the five actuation mechanisms can be used to build a flapping wing drone, given some of the disadvantages, it is unrealistic to consider the use of some for FWMAVs.

Table 1. Actuation mechanisms utilized in flapping wing drones.

Actuation Mechanisms		
Mechanism Type	**Advantages**	**Disadvantages**
Single crank	Lightweight and ease of manufacturing	Unsymmetrical flapping can cause the system to be unstable during flight.
Single crank mechanism with offset	Lightweight, harmonic flapping motion, ease of manufacturing	Challenging to design reliable mechanism, risk of joints locking during motion, causing flight failure
Slider crank	Harmonic flapping motion	Challenging to manufacture, high weight, and loss of efficiency due to friction
Dual crank mechanism	Harmonic flapping motion, ease of manufacturing	High weight and challenging design
Alternate configuration	Symmetric flapping motion	Complex configuration, cannot be utilized in biplane flapping configurations

A different mechanism is used for each of the two drones that are built. For the first FWMAV, a hybrid actuation mechanism is constructed using an slider crank and the alternating crank mechanism. The combination of these two mechanisms provides a light weight system while maintaining harmonic flapping frequencies between the four wings. This mechanism is shown in Figure 3. For ease of manufacturing and to conserve weight, the mechanism is 3D printed. To integrate into the system, the crank is secured to the designed gear train and is mounted to two hard points on the housing mechanism. This provided the pivotal motion necessary for flapping. However, after the system is completely integrated and tested, it is clear that the stress produced from the flapping of the wings causes the 3D prints to deform and fail over time. Although this is a capable design, it became clear from physical experimentation that this particular design would require materials that are more capable of handling the induced stress. Given the weight limitation of this particular drone, this is not a feasible alternative.

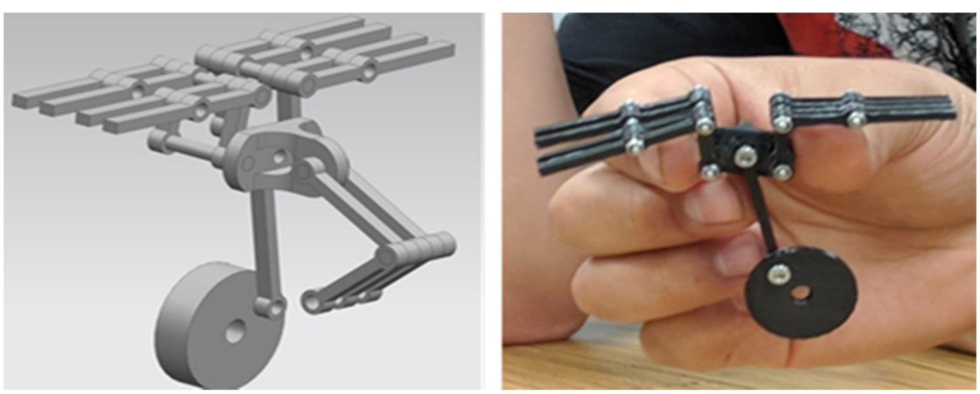

Figure 3. Hybrid actuation mechanism FWMAV 1.

For the second system, a double crank mechanism is considered for actuation and producing flight. Given the nature of the mechanism, the gear train is directy integrated into the actuation of the system. This not only saves weight but also reduced the necessary manufacturing time to build a fully integrated system. With fewer moving components needed to produce flapping, the system is optimized and the overall risk of system failure is substantially reduced. The actuation mechanism/gear train of the second system is shown in Figure 4.

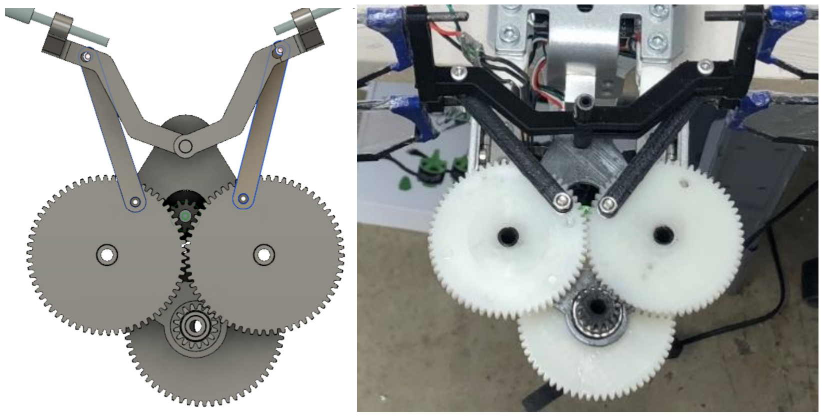

Figure 4. Double crank mechanism FWMAV 2.

Wing Structure

After determining that the bumblebee wing profile would be utilized for these systems, it is important to consider how the wings would be built. Several different approaches are considered to establish a wing skeleton that would provide ample surface area for Mylar film, the wing membrane, to bond to and take the shape of the wing. The design of each iteration strongly considers the weight of each componenet and how it might impact the overall functionality of the system. For example, the number of supports/ribs used in the wing structure is considered. By reducing the number of ribs, each of the wings could be anywhere from 1-2 grams lighter. However, without an adequate number of ribs to support the Mylar, the dexterity of the wings would fail after several flapping cycles, which would rule them out of the finalized wing design.

The final wing design used a combination of carbon fiber and 3D printed material to build the wing skeleton. This is shown in Figure 5a, where each of the blue components represent 3D printed parts and the black pieces represent carbon sheets/spars. Once each wing structure is built, the Mylar film can be adheared to it to make the wing membrane. In order to accurately obtain the wing profile, a thin line of MonoKote tape is applied to the trailing edge of each wing before trimming the Mylar to fit the shape of the wing. The manufactured product is show in Figure 5b. Each completed wing weighs roughly 4.5 grams giving the wing components an overall weight of 18 grams.

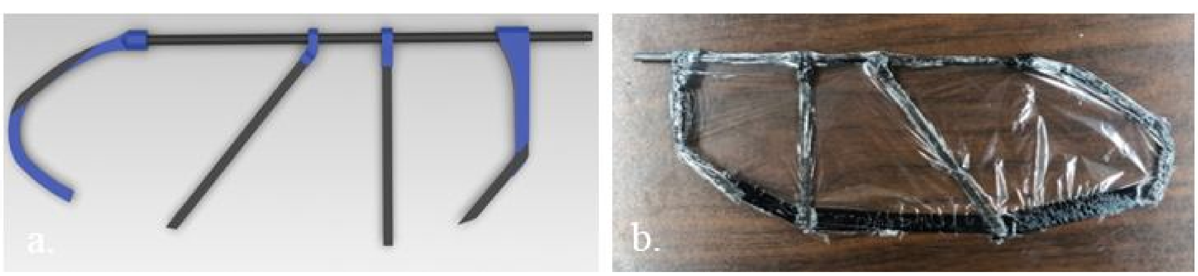

Figure 6. a) wing skeleton model and b)fabricated wing.

After each wing is built, it is integrated into the system by mounting it to a 3D printed component that mounts to the central spar of the system. The desired angle of attack for each of the wings is established before being fixing it in place with epoxy. Accurately mounting the wings at specified angles of attack is critical to the successful operation and flight of the system. It is important to consider and test the most optimized angles of attack that will produce both forward flight hovering flight for the system.

IV. Conclusions

Two different FWMAV drones designs are manufactured and tested. A process has been accurately developed to design, manufacture and test different variations of these drones using this method. Although each system has been successful in functioning, several of the constraining factors were not met; such as weight and structural rigidity. This has restricted some of the desired capabilities. Future variations of the drone will consider different hardware to achieve the intended weight constraint of 100 grams.

To further optimize the efficiency of the drone, the angles of attack of the mounted wings should be considered. The results of this experiment will provide valuable data to be used moving forward in this project. The results from these thrust tests will guide the decision of the final angle of attack of the system. The next optimized FWMAV drone that will be developed will undergo aerodynamic testing in the wind tunnel and complete a free flight mission as a proof of concept.

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