ENGR 90: Senior Design

Design and Feasibility Study of Personal Ornithopters

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Abstract

While personal jet packs may not be practical, an electromechanically-assisted set of wings may be. No modern heavier-than-air craft flaps its wings; conversely, no bird, bat or insects relies upon fixed wings. Bio-mimicry would suggest that if artificial wings were sized and powered proportional to human weight, it should be possible for a person to fly. This project explores the feasibility of personal ornithopters for short distance commutes.

Contents

1 Introduction

Nature—especially animals—have been the foremost inspiration of the design of many of the objects we use in our daily lives. From items as simple as forks to sophisticated airplanes, humans have continually looked to nature for clues. While some of the efforts to mimic nature have led to great successes, others have failed to materialize into practical outcomes. One such futile effort is the ability to fly like other volant animals in nature. This ability has always intrigued humans for a very long while until the invention of airplanes which although are excellent and reliable in many respects, do not quite satisfy that desire to reach for the skies and soar like birds, bats and insects. The insatiable quest to fly like birds has recently led to the design of various micro-aerial vehicles (MAV) modelled after smaller insects and birds as well as medium sized *ornithopters*—a general term for flapping-wing propelled aircrafts.

As successful as ornithopter designs have been, no success has been achieved in trying to design human-sized[1] ornithopters. While several attempts have been made, only very few have been functional albeit very impractical and with very short flight times. The goal of this project is to conduct a feasibility study on personal ornithopters. Specifically, we set out to analyze the possibility of having human-sized ornithopters by examining past futile attempts and why they failed; more importantly, we make certain bat-inspired design-specifications for a possible practical prototype while discussing aerodynamic and material limitations as well as energetics.

[1]By human-sized, we imply an aircraft capable of carrying a human payload and not necessarily one of the size of a typical human

2 Why Study Ornithopters?

Some of the currently available methods of personal airborne transport like jetpacks, wingsuits, hang-gliders and ultralight aircrafts are impractical for everyday use for somewhat the same reasons. Wingsuits and hang-gliders require a sufficiently high altitude for take-off and are both considered extreme sports in their own rights. Jet packs on the other hand are basically small rocket packs, requiring fuel, hydrogen and on-board oxidizers for highly exothermic chemical reactions that release enormous heat energy and produce lift for only short durations[2]. Ultralights require a significantly long runway for take-off, a problem that will be non-existent with flapping wing flight. In addition, all these methods require professional expertise involving very steep learning curves. We believe personal ornithopters like cars will require very little expertise and will be able to operate at much lower altitudes making them less extreme, relatively safer and more accessible for everyday use.

In comparison with other modes of land transportation, personal ornithopters – depending on how they are powered which we discuss later in this report–will leave lesser or no carbon footprints. If powered electrically, personal ornithopters will consume less power than present electric vehicles for short distance commutes. In addition, personal ornithopters will be not require additional infrastructure like road networks and will be less vulnerable to congestion like cars. All these benefits come in addition to the thrill and joy of being able to fly in a manner similar to other

[2] Why Dont We Have Personal Jetpacks; *http://www.popularmechanics.com*

animals and insects in nature.

3 Past Ornithopter Designs

Several attempts have been made in the past to design human-sized flapping wing propelled aircrafts to no avail. Designed prototypes have either been too large and impractical for day-to-day use or just did not work. A few primitive examples include Leonardo da Vincis ornithopter sketch (Figure 1) for which there is no evidence he actually built or tested even though it was obvious from his design that he understood human muscles weren't sufficient to power a pair of wings.

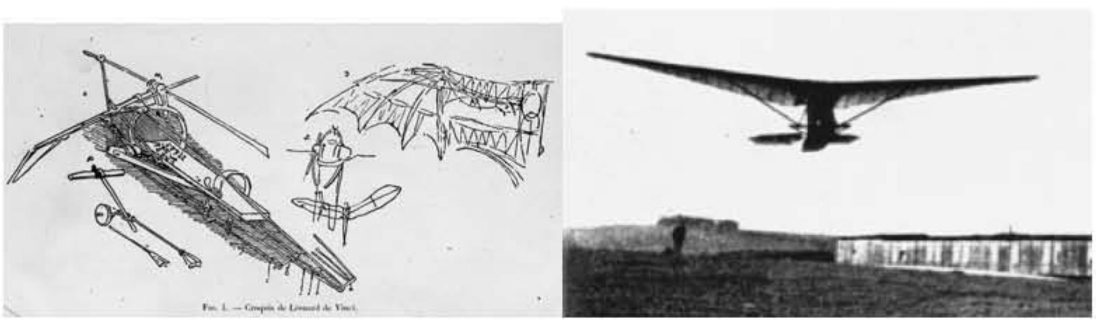

Figure 1: Left: Leonardo da Vinci's complex ornithopter.[3]
Right: Lippisch human-powered ornithopter[4]

Another engineer, Alexander Lippisch—who would later design the world's first rocket-powered fighter plane—worked extensively on manned flapping wing flights. One of his designs was flown by an athlete and covered a distance of 250-300 meters from launch. The ornithopter was launched with an elastic cord and amidst doubts,

[3] Top 10 Bungled Attempts at One-person Flight, *http://science.howstuffworks.com*
[4] Manned Ornithopter Flights, *http://www.ornithopter.org/history.manned.shtml*

Lippisch declared his design successful even though critics still question the ability of the ornithopter to fly on its own. While modern researchers and engineers have turned a blind eye to the subject of manned ornithopters, a modern aircraft called "Snowbird" (Figure 2) was designed by a team at the University of Toronto Institute for Aerospace Studies led by graduate student Todd Reichert. Snowbird has a wingspan of 32 meters and is powered by energy generated by a pedalling pilot. During the test flight, it was towed by a car until it attained some altitude and was released, after which it was able to sustain flight for about 19.3 seconds. While this was termed a "success", we believe an ornithopter like Snowbird is not practical for daily use due to its enormous size and the energy required by the pilot to pedal hard enough to keep the wings flapping.

Figure 2: Snowbird by Todd Reichart

While some of these attempts have sustained flight for fractions of a minute, we believe they are all very far from what can become a regular means of transportation.

We believe a practical design would rely on an external source of power and will more importantly be modelled after bats, not birds. This is because most birds have sophisticated morphological features that support flight and do not solely rely on flapping wings. These features includes hollow bones that account for a lower body density and wing-loading, highly specialized feathers, and tails for steering and balancing.

4 Bats as better models

Bats are better models than birds for personal flapping wing flight for a couple reasons. First is the fact that bats have similar body densities as humans and can therefore serve as proof of concept for flapping wing flight provided wings can be scaled proportionally for humans. Studies show that bats and humans have very similar body densities—approximately 1.0 g/cm^3 for bats and 1.1 g/cm^3 for humans as compared with the relatively lower 0.7 g/cm^3 for birds[5]. This similarity in body densities stem from the fact that bats like humans are mammals with dense bone marrows. Due the higher body density relative to other volant animals, bats must possess some flight characteristics that enable them overcome this disadvantage. We believe these characteristics can be emulated in the design of a pair of wings for a human payload.

A second reason why bats are better models for personal ornithopters is because

[5]Human Body Density of an Adult Male Populationas Measured by Water Displacement *http://www.dtic.mil/dtic/tr/fulltext/u2/639241.pdf*

bats have their wings as the sole flight feature. Bats generate lift and thrust, control roll, pitch and yaw and steer with their admittedly complex and sophisticated wings alone. Birds on the other hand have specialized tails for steering and pitch control. If we are to design just a pair of wings for personal ornithopters, then we must take a cue from bats on how to flap these wings efficiently to generate all the aerodynamic forces needed to control and maneuver the ornithopter to keep the pilot in the flight.

4.1 Aerodynamics of Flapping Flight

Flapping wing flight like fixed wing flight works based on the principle of action and reaction as described by Newton's third law of motion. A flying body generates lift by displacing a mass of air downwards and thrust by displacing a sufficient mass of air in an opposite direction to the desired direction of flight. How this mass displacement is achieved is the key difference between fixed and flapping wing flight. The image below shows an airfoil (a wing cross-section) and the generated aerodynamic forces caused by a stream of air flowing directly at the wing.

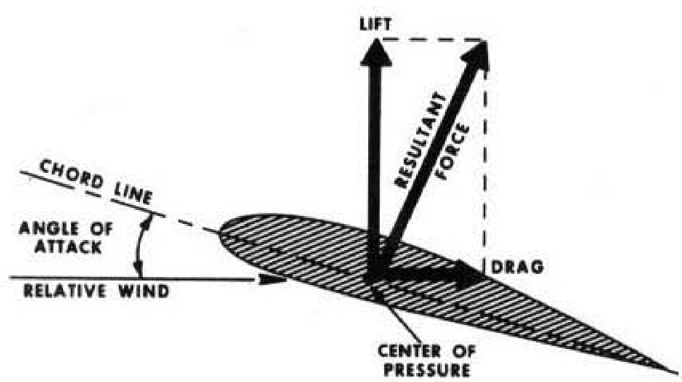

Figure 3: Aerodynamic forces on an airfoil.

To sustain a body in flight, the generated lift force must counterbalance the effect of gravity and enogh thrust must be generated to overcome drag. Most commercial airplanes generate lift with a pair of wings and thrust from powered propellers; however, flapping-wing animals generate both lift and thrust from their wings. These forces are also non-constant but cyclic in nature, making the aerodynamics of flapping-wing flight complicated as the shape and angle of attack of the airfoils of the wings change continuously during one wingbeat cycle.

4.2 Biomechanics of Bat Flight

A few flight mechanisms distinguish the flapping wing flight of bats from that of other volant animals. One of these features is the very prominent wing-folding during upstroke. While some species of birds slightly fold their wings during upstroke, wing-folding is more prominent in bats and studies have shown that this significantly increases the efficiency of flapping wing flight in bats. During downstroke, the wings of a bat are fully extended to increase the surface area which consequently results in an increase in the volume of air displaced downwards to generate lift. During upstroke however, bats fold their wings to reduce the effective surface area thus decreasing the amount of negative lift generated. As a result of lift generation in the upwards and downwards direction during downstroke and upstroke respectively, the body of a bat oscillates during a wingbeat cycle. Because of wing-folding, the downward displacement during upstroke is smaller than the upward displacement during downstroke which accounts for a positive net lift. While there are energetic costs associated with wing-folding, Riskin et. al showed in [4] that the total energetic costs during upstroke with wing-folding is only 65% of the energetic cost without wing-folding.

Another key morphological feature for flight in bats is the highly compliant wing membrane. The high compliance of bat wings allows them to passively deform in airflow, increasing camber and aerodynamic force production [1]. Recent studies also reveal that bats possess a network of hair-thin muscles in their wing membranes with which they control the stiffness and shape of their wings during flight. In addition, the bones (humerus, forearm and digits) supporting the wing-membrane can deform and have flexural stiffness decreasing from the proximal to the distal end. These bones are connected by several joints that can be independently controlled allowing for a wide range of motion [1]. Wing-folding and the possession of highly deformable wing bones and membrane are the two key flight features in bats.

4.3 Challenges of Mimicking Bats and Potential Workarounds

While the flight mechanisms of bats are very impressive, they are difficult if not impossible to replicate at a human scale. The first limitation in mimicking bat flight at such a scale would be in designing an appropriately compliant membrane. It is difficult to synthesize materials with J-shaped stress-strain curves like bio-materials and synthesizing one with the exact same properties as a bat's wing membrane is literally impossible. Secondly, designing wing supports that simultaneously possess high flexibility and strength as the upper arm bones in bats will be quite challenging. Nevertheless, we believe personal ornithopters can be modelled after bats by making a compromise in design where necessary. This idea is corroborated by work done by a group of researchers at Brown University who designed a robotic bat wing so as to independently measure the effects of various flight mechanisms in bats [1, 2]. A robotic model—an excellent one at that—was built as it is difficult to isolate the contributions of each flight mechanism in actual bats. The importance of this experiment to the study of personal otnithopters is that it serves as a proof of concept that a man-made bat model can be created to capture some of the flight kinematics of bats.

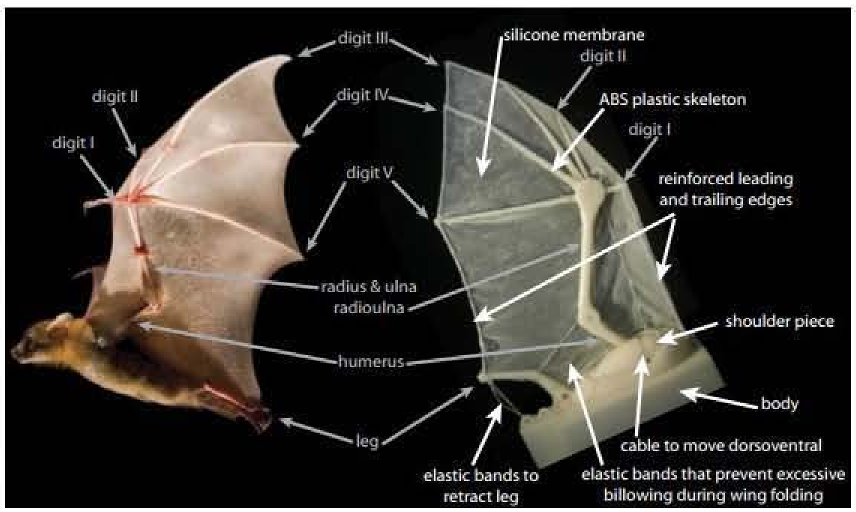

Figure 4: Robotic bat model designed at Brown University

The robotic wing (shown in Figure 4.) was modelled after the wing of a lesser dog-faced fruit bat (*Cynoptherus brachyotis*) using 3D printed materials from ABS plastic. It included shoulder, elbow and wrist joints that were independently controlled to assume various wing orientations and to facilitate wing-folding. The shoulder joint had two degrees of freedom to allow for rotation in the dorsoventral and craniocaudal directions while the elbow and wrist joints each had one degree of freedom for in-plane motion. Cured polydimethylsiloxane (PDMS) was used as wing membrane material. At a wingspan and wing area of 19.6 cm and 195.5 cm^2 respectively, the single wing model was able to generate about 0.62 Newtons of downstroke lift with an incoming stream speed of 5 m/s at a flap rate and amplitude of 7.8 Hz and 75 degrees respectively. The mechanical power also decreased with wing-folding during upstroke since mechanical power is proportional to torque and less torque is required to move the retracted wings. Results from this experiment also showed a 50% increase in the net lift with wing-folding and a 40% decrease in net thrust. While a significant decrease in net thrust with wing-folding might be a counter-argument against adopting this feature in personal ornithopters, we believe the goal for personal ornithopters would not be to run at blinding speeds but at comfortable speeds for short distance commute for an exposed[6] pilot. These results serve as a validation of the idea that we can implement the flight behavior of bats in a man-made model and observe performance improvements when compared with fixed-wing flapping flight models. This further suggests that articulate wings are the way to go for improvements on current personal ornithopters designs and we believe a flapping mechanism similar to that of the robotic wing model can be successfully adopted at a human scale.

5 Choosing Wing Dimensions

Basing our choice of wing dimensions for personal ornithopters on the robotic model, we can propose brute force approximations of the necessary wing dimensions to

[6] since personal ornithopters are open-cockpit aircrafts, pilots will be exposed to the incoming air stream

overcome the effect of gravity on a 150 pound (668 Newtons) human. Because of the almost linear relationship between wing area and lift, we can approximate that if a 310.4 cm^2 wing area (twice the wing area of the single-wing model) produces 1.24 Newtons of lift, the required wing area to generate 668 Newtons of lift would be about 16.7 m^2 provided that we can keep the same pressure differential. If we proceed to keep the an aspect ratio of 7.7 as the robotic bat model, then we end up with a wingspan of about 11 metres[7]. While this approximation ignores the cyclic nature of the forces generated by a bat's wing, we believe it is a good enough ballpark that will be in the region of the wingspan of any practical design. This belief is supported by the fact that a wingspan of 11 meters is about the same as that of the *Quetzalcoatlus northropi*–the largest natural flyer known.

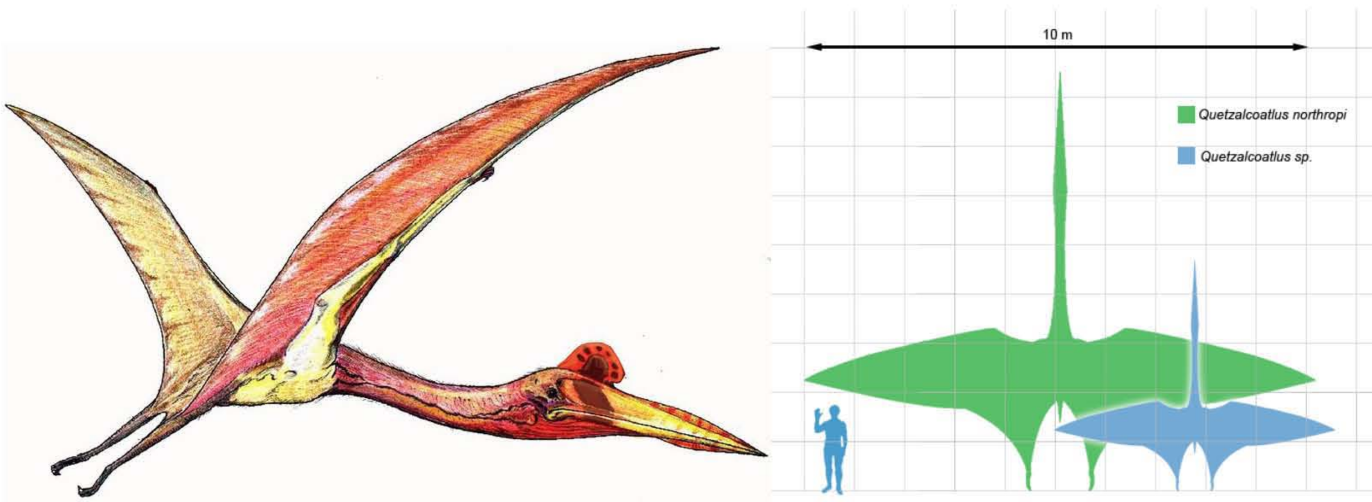

Figure 5: Artist rendition and size scale of a Quetzalcoatlus northropi

Even though this pterodactyl has a larger wing-less body frame than humans, it is able to get away with the relatively smaller wingspan because it is designed by

[7] $AR = b^2/s$. where $AR =$ Aspect Ratio, $b =$ Wingspan, $S =$ Wing Area

nature–the best designer known. Many ultralight aircrafts also have wingspans of about 11 metres.

6 Material Considerations

To successfully implement wing folding in personal ornithopters, the wing membrane chosen must be able to withstand large deformations due to the constantly changing wing shape. As Bahlman et al rightly described in [1] - "A suitable wing membrane should be compliant enough to stretch sufficiently to allow the wing to expand to its full area; be able to recoil so that when the wings fold during upstroke, the surface, and especially the trailing edge, does not billow and slacken to the point where it becomes an unsuitable lifting surface; and must have modulus low enough to provide minimal resistance to expanding the wing". We believe typical polyester clothes used in hang-gliders will suffice in this respect since the expected flap-rate for an 11 meter wingspan aircraft will be reasonably low. For the wing support, the spars–to mimic the humerus and forearm of bats as in the robotic model–and the battens–to mimic the digits–can all be made of carbon fiber composites due to their high tensile strength and lightness with densities of about 1.6 g/cm^3.

We proceed to estimate the mass of materials needed for the wing support and membrane. With an 11 meter wingspan and assuming a similar configuration as the robotic model in Figure 4, a reasonable estimate of the length of composites needed for the spars would be approximately 11 meters (one full wingspan) and an upper limit estimate for the battens–if we assume each one of the 10 digits is half the span of one wing–would be about $10 \times 11/4 \approx 27.5$ meters making a total upper bound of about 40 meters in length of support material. A decent upper-bound approximation of the necessary cross-sectional area based on the cross-sectional area of a 5.2 cm outer and 4.8 cm inner diameter tubing used in hang-gliders will be about 3.14 cm^2. We double this area to accommodate for possible design choices in cross-sectional shapes and area and settle for a 6.5 cm^2 upper bound area. With this and a 1.6 g/cm^3 density for carbon fiber composites, we can approximate an upper bound on the mass of the "skeleton" of a personal ornithopter to be about 42 kg. Since membrane materials are usually very light, the amount of material needed will definitely weigh less than the wing supports and as a result, we can safely put an overall bound on the combined mass of the wing support and membrane at 68 kg which is equivalent to the mass of a 150 lb human.

7 Powering Personal Ornithopters

In addition to the complicated aerodynamics of flapping wing flight, another important consideration in designing a flapping wing propelled aircraft is the problem of power. Bat flight is strictly powered by the energy stored in arm and hair-like wing muscles; however, the same cannot be expected of humans for personal ornithopters judging from the failure of previous attempts to do so. Since we envision personal ornithopters as a pair of wings with a backpack-like power pack and control box, we will eliminate the use of flammable and combustible power sources because the prospects of flying a pair of wings is already by itself daunting and having a gasoline or diesel powered engine onboard with an exposed pilot escalates the potential hazards. If the goal to make personal ornithopters accessible to all and less of an extreme sport is to be achieved, then the power source adopted would be such that a common user is comfortable to have it around them in close proximity without protection at a reasonable altitude. That said, the two sources that come to mind meeting these requirements are solar panels and batteries.

Nathan Chronister—a popular ornithopter enthusiast—approximated on his website, the "Ornithopter Zone"[8] a power requirement of about 100 Watts per kilogram for man-made membrane-winged ornithopters. While this approximation was made with fixed-wing ornithopters in mind, we can use it as a reasonable ballpark of the upper bound of the power required for an articulate-wing ornithopter since we have established that wing-folding is a more power efficient mechanism. Using the estimate of a 68 kg wing and 68 kg flyer, we get a combined weight of roughly 140 kg suggesting that such an ornithopter model would need about 14 kiloWatts of power supply. The infeasibility of solar panels as a direct power source become quickly apparent as the area of solar cells necessary to provide 14 kW of power would greatly exceed the wing-area of 16.7 m^2 assuming it is even possible to install solar panels on the wing membrane. This is because at the time of writing this report, the most efficient mass produced solar modules have power densities of up to 0.175 kW/m^2 which puts the

[8] http://www.ornithopter.org/

required cell area at about 80 m^2. Nonetheless, we believe solar energy can be used as an indirect power source for charging batteries that can potentially be used to power the actuator system for the pair of wings.

Powering personal ornithopters with batteries becomes the only available reasonable choice. In 1985, Paul MacCready and a group of engineers successfully designed a half-size replica of the (*Quetzalcoatlus northropi*) with flapping wings powered by Nickel-cadmium batteries [3]. However, this model was much smaller and lighter—weighing only 40 lb (about 18 kg). The quest for the right kind of battery puts one in a conflict between additional weight and available power. This is because the energy densities of commonly available batteries are such that the mass of battery cells required to generate 14 kW would be very significant relative to the combined weight of a personal ornithopter and 150-lb pilot. Furthermore, high power-density batteries tend to be low on energy density meaning they run for shorter amounts of time. While energy density might be a reasonable trade off when considering the use of personal ornithopters for short distance commutes, we believe that the prospects of a personal ornithopter running out of power during flight is unacceptable. That said, until there are advances in battery technology that allow high power density batteries to simultaneously be energy dense, powering personal ornithopters with batteries would not be a feasible option. As a result, the only potential limitation we see to having personal ornithopters as described is an adequately safe, non-toxic and non-flammable power source.

8 Takeoff and Landing

With a wingspan of about 11 metres and combined pilot and aircraft weight of about 140 kg, the subject of takeoff and landing becomes less trivial than it is with smaller volant animals. For takeoff, smaller birds can take a leap to generate enough airflow to initiate flight while larger birds typically have to run up a few metres to generate enough airflow. As a workaround to this constraint, some large birds typically perch on trees so as to just drop off to initiate flight; this is the behavior in most bat species. We believe personal ornithopters can take off in a similar manner as bats and larger birds except that in place of trees, we envision the need for some elevated takeoff platform. We believe a decently high elevation of about 20 meters should be sufficient. The choice of 20 meters is such that the takeoff elevation is high enough for the pilot and ornithopter to generate enough airflow during freefall to initiate flight but low enough that no additional infrastructure is required to house the take-off platform as most rooftops are already beyond 20 meters in height. In addition, since in the upper limit, a full downstroke covers a vertical distance of half the wingspan (about 5.5 metres), there will be enough ground clearance for flapping during freefall.

Landing on the other hand would be a relatively easier problem to tackle. One possible solution would be to have a pilot tuck in the wings and aim for a landing spot towards which they slowly glide. A better but potentially more difficult solution will be to include a landing control system that articulates the wings in such a way to generate just enough lift to balance the weight of the pilot and the system such that they descend at a slow and comfortable speed.

9 Summary and Conclusion

While it is easy to think of applications for small scale unmanned ornithopters, we believe there are potentially beneficial applications for personal manned ornithopters. We argue that bats represent better flight models for manned ornithopters than birds as bat flight is more power and aerodynamically efficient. We also explore possible design materials and the necessary energetic requirement and conclude that there is a need for safe power sources with high energy and power densities for personal ornithopters to be feasible and accessible to all.

It is worthy of note however that this study focused only the aerodynamics and energetics of personal ornithopters but does not consider potential control systems. Control systems are difficult to implement. The control systems for fixed wing aircrafts are complicated enough that the problem of designing controls for a more chaotic flapping wing aircraft seems very daunting. Nonetheless, with some dedicated years of advanced research, we believe a suitable control system can be designed.

10 Acknowledgements

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