Untethered Hovering Flapping Flight of a 3D-Printed Mechanical Insect

Charles Richter, Hod Lipson

Computational Synthesis Laboratory
Mechanical & Aerospace Engineering
Cornell University, Ithaca NY 14853, USA
+1 (607) 255 1686
hod.lipson@cornell.edu

Abstract

This project focuses on developing a flapping-wing hovering insect using 3D printed wings and mechanical parts. The use of 3D printing technology has greatly expanded the possibilities for wing design, allowing wing shapes to replicate those of real insects or virtually any other shape. It has also reduced the time of a wing design cycle to a matter of minutes. An ornithopter with a mass of 3.89g has been constructed using the 3D printing technique and has demonstrated an 85-second passively stable untethered hovering flight. This flight exhibits the functional utility of printed materials for flapping wing experimentation and ornithopter construction and for understanding the mechanical principles underlying insect flight and control.

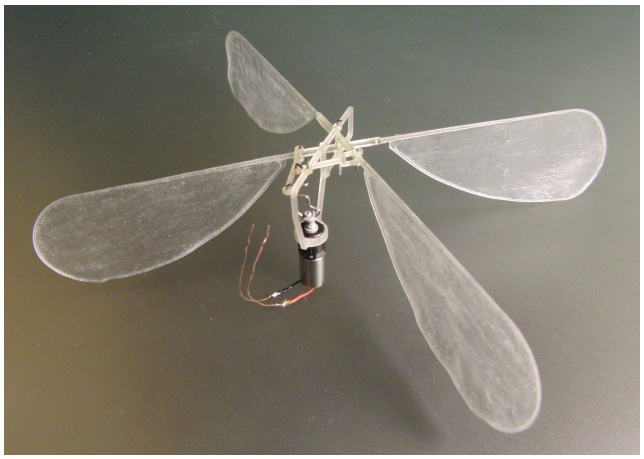


Figure 1: 3D-Printed elements of flapping-hovering insect.

Introduction

Hovering flapping flight of insects and birds has long fascinated scientists and engineers, but only in the last decade has it been successfully demonstrated by man-made flying machines. Unlike forward flight, hovering flapping flight poses several special challenges. First, there has yet to emerge an established body of theoretical and experimental work on the unsteady aerodynamics of flapping wing flight for the purposes of wing design. Second, flapping hovering flight of insects and birds is generally unstable and requires a sophisticated solution to maintain an upright flying position (Taylor and Thomas, 2003; Sun and Xiong, 2005). Third, the energy density of batteries was insufficient for the power demands of hovering flight until small lithium-based batteries became widely available. However with the improvement of electrical power solutions, a number of successful hovering ornithopters have been developed with a variety of wing designs. This project utilizes existing solutions to the power and stability problems and uses 3D printing as a novel approach to designing and manufacturing the key aerodynamic component: the wings.

Thus far, producing effective flapping wings for research and ornithopter construction has been a time consuming and delicate process taking days or longer to complete. The 3D printing technique allows wings to be produced in a matter of minutes, dramatically reducing the time of each design cycle. Overcoming this barrier to experimentation will allow a comprehensive study of lift production for a wide variety of wing shapes including those replicating real insect wings.

A comprehensive understanding of flapping wing aerodynamics and hovering flight will become increasingly important as ornithopters shrink to the scale of real insects where some advantages of flapping wing flight are realized (Ellington, 1999). These advantages include efficiency and maneuverability improvements over fixed and rotary wing aircraft at low Reynolds numbers as well as the suitability of micro-scale actuators to producing vibrating motion for flapping rather than rotary motion for traditional propellers (Pesavento and Wang, 2009; Woods et al., 2001). Maneuverable, low-power micro air vehicles have a wide range of applications including mapping, surveillance and search-and-rescue operations where these properties of small size and ability to maneuver in tight spaces are vital, or in thin extraterrestrial atmospheres where low Reynolds numbers occur (Michelson and Naqvi, 2003). Micro air vehicles also present a challenging synthesis of many areas of engineering, including materials, actuators, electronics, control, vision, guidance, and others (Floreano et al., 2010; Karpel-

Design	Year	Mass (g)	Span (cm)	Wings	Hover Time (s)	Features
Mentor (Zdunich, 2007)	2002	580	36	4	> 60	Nitromethane Fuel
DelFly II (DelFly, 2010)	2006	16.07	28	4	480	Camera, R/C
van Breugel (van Breugel et al., 2008)	2007	24.2	45	8	33	Passively Stable
Chronister (Chronister, 2010)	2007	3.3	15	4	Unknown	R/C
Wood (Wood, 2008)	2007	0.060	3	2	N/A	Piezoelectric Power
DelFly Micro (DelFly, 2010)	2008	3.07	10	4	N/A	Camera, R/C
NAV (AeroVironment, 2009)	2009	10 (est.)	7.5 (est.)	2	20	Active Wing Pitching
Richter (this paper)	2010	3.89	14.3	4	85	3D Printed Parts/Wings

Table 1: Characteristics of existing ornithopter designs.

son et al., 2008). This project has demonstrated the viability of 3D printed aerodynamic components for experimentation and for use in a real ornithopter on the size scale of the smallest current designs.

Review of Existing Work

The existing work that has influenced this project includes a variety of successful ornithopter designs and some research on the dynamics and control of insect flight. This project is effectively a continuation of an earlier ornithopter design project by Floris van Breugel of the Cornell Computational Synthesis Laboratory. Van Breugel's design used four motors to drive eight wings and featured passively stable flight dynamics using a set of damping sails above and below the body of the aircraft. This model had a mass of 24g and demonstrated stable hovering flight of over 30 seconds in 2007. Broad goals for the current project were to achieve a comparable flight time using this system of passive stability in a vehicle under 10g.

Several other successful designs currently exist, including the series of DelFly ornithopters, which are radio controlled using tail configurations resembling fixed-wing aircraft and the AeroVironment Nano Air Vehicle, which achieves control using active wing control. The Harvard Microrobotics Laboratory has also produced ornithopters weighing 60 mg using piezoelectric actuators and insect-like passive wing pitching, but require a tether for power and stability.

There have also been recent developments in the understanding of insect flight (Dickinson et al., 1999; Wang, 2005; Bergou et al., 2007; Ristoph et al., 2009). These studies have explored one mechanism of passive wing deflection in insect flight that is essential to the simplicity of some ornithopter designs. They have shown that some insect wings deflect to an angle of incidence of 45 degrees, which is thought to be optimal for lift production of a flat plate wing. These findings have also given rise to hypotheses explaining forward thrust, flight maneuvers and disturbance rejection, and experiments have been designed to examine these hypotheses using the ornithopter as a test bed.

Methods

One primary goal of this project was to produce a hovering ornithopter with as many 3D printed components as possible. An Objet EDEN260V printer and the Objet FullCure 720 material were used to produce all printed components. This material costs roughly 0.22 USD per gram and the EDEN 260V prints with a resolution of 42 μm on the x- and y-axes and 16 μm on the z-axis. At first, only the fuselage, hinges and pushrods were printed, however a method of printing entire one-piece wings was soon developed.

First attempts at wing construction were aimed at recre-

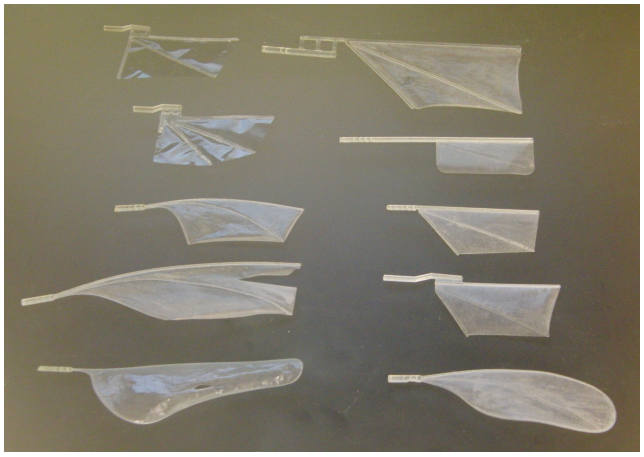


Figure 2: A variety of wing shapes for experimentation.



Figure 3: The most successful wing design during testing.

ating the wings of the van Breugel design, using a carbon fiber rod as the main strut, polyethylene terephthalate (PET) stiffening ribs and a Mylar film wing surface. Two examples of this early printed type can be seen in the upper left corner of Fig. 2. The carbon fiber rod was to extend out of a 3D printed hinge, but after several design iterations, the hinge, strut and stiffening ribs were combined into a single printed piece. When further experimentation revealed that a durable thin film could be printed using only two layers of printed material, this film was used instead of Mylar as the wing surface and the first one-piece printed wings were made. Fig. 2 shows many conventional and biologically inspired printed wings.

Printed Wing Construction

The printed wings of the ornithopter are comprised of three functional elements: the central beam, the surrounding frame, and the thin film wing surface. Fig. 4 shows the parts of the dual-wing used in the full ornithopter design.

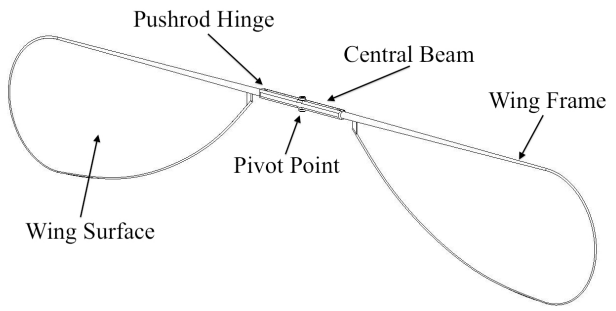


Figure 4: Parts of the one-piece printed wing.

The central beam is the most rigid portion of the wing and contains the pivot point as well as the attachment holes for the connecting rods. Whereas some designs require a bushing or dedicated hinge, 3D printing allows the hinge to be incorporated into the main beam design. Furthermore, the FullCure 720 material features relatively low friction against the stainless steel 0.5 mm piano wire hinge pins when lubricated with a drop of medium-viscosity oil. The holes for the pivot points were designed with a 0.6 mm diameter to provide an adequate gap for low-friction operation. This technique eliminates the need for a heavy bushing or complex assembly.

The outer frames of the wings are attached to the ends of the beam. The outer frames determine the flexibility of the wings and the deflection properties during flapping. The outer frames were defined in the CAD model as lofted curves connecting circular cross sections. By varying the radius of the circular cross sections at various points along the frame, the overall stiffness and flexibility patterns of the wing could be tuned.

The thin wing surface is a flexible film that extends through the area inside the outer frame. The surface has a thickness of 40μm, which is achieved by depositing two layers of material. The ability of the printer to print such a thin flexible film is the development that made a one-piece printed wing possible. While it is possible to print a thinner film using a single layer, wings constructed with a single layer surface are extremely delicate and tend to tear upon vigorous flapping. Chamfers were used to counter the tendency of the wing film to tear at points of discontinuous geometry, such as the edge where the film joins the frame.

One practical element of 3D printing technology is the use of a gelatinous material to support the structure during printing. Therefore, removing the support material is an important step in the manufacturing process, especially with delicate features such as the thin wing surface. Common methods used to remove support material include dissolving it in sodium hydroxide and spraying it off with pressurized water. However, both of these methods have limitations due to the delicacy of the thin film. When a printed wing is soaked in liquid for any period of time, it tends to curl up or become warped, which can be partially corrected by pressing it flat and allowing it to dry. However, the moisture tends to leave some permanent warping of the wing shape. The method of spraying pressurized water is also difficult because extreme care must be taken to avoid tearing the wing film. Again, the moisture tends to warp the wing shape. The best method thus far has been to place the wing on a clean surface with some elasticity such as a dense rubber mat and scrape the support material away using a dull blade. Any residual material can be removed by wiping with a cloth moistened with water or rubbing alcohol. This is the fastest and most successful method for removing support material from the thin wing film.

Wing Design

At the beginning of the project, the wing design process focused on narrowing the vast design space to a size scale that was appropriate for the motors available and desired weight of the vehicle. During initial testing, key wing design features were identified that helped produce the ideal shapes and deflections when flapping. Testing of a wide variety of wing shapes, sizes and structures was carried out by powering them with a small DC gear-motor using a DC power source. The lift of each wing was measured using a custom attachment for a digital lab scale and flapping behavior was analyzed using a high-speed camera capturing 1000 frames per second. Fig. 5 shows the experimental apparatus.

The wing size partially determines several important variables, including mass and surface area, which in turn determine how fast the wings can flap for a given power input. For the motor chosen for this project (GM 15 gear motor available from Solarbotics.com with 25:1 gear reduction) and the power expected from a pair of Lithium- Polymer bat-

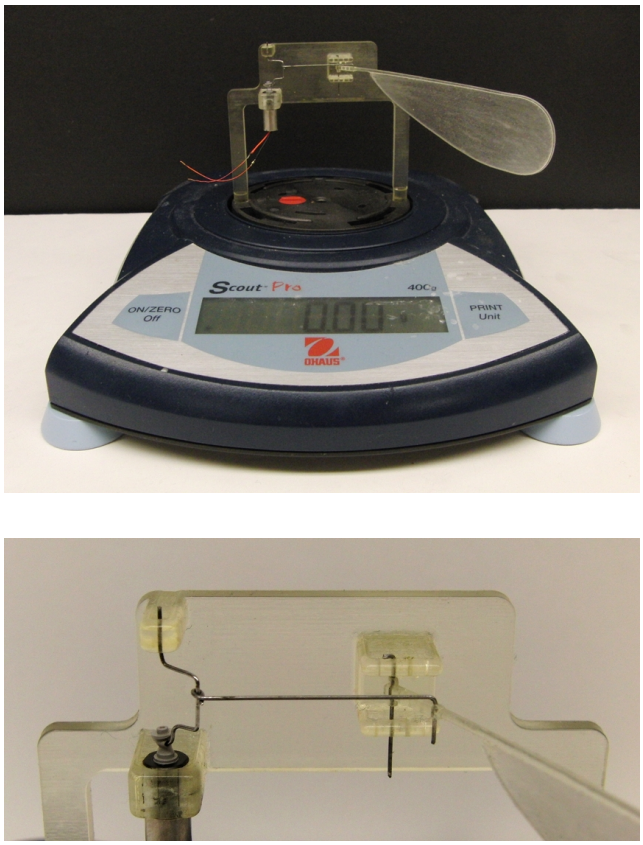


Figure 5: Experimental test setup on the lab scale (above); Close-up of mechanism (below).

teries (7.4V , 200mA), the best performing single wing of all wing designs tested had a length of 80 mm and a maximum chord of 30 mm. The overall weight of the wing was approximately 0.3g and the thickness of the wing film was 40 μm. This wing flapped at approximately 30 Hz through an angle of 110 degrees and produced a maximum lift force of 2.92g. This wing design is shown in Fig. 3.

The wing structure is important to proper deflection and wing shape during flapping. For maximum lift, the wing should deflect to an angle of attack of roughly 45 degrees at the middle of the stroke. This angle of attack can be tuned by adjusting the flexibility of the main wing strut and the ribs that stiffen the interior of the wing. Thus far, successful wing designs have been created with and without wing ribs.

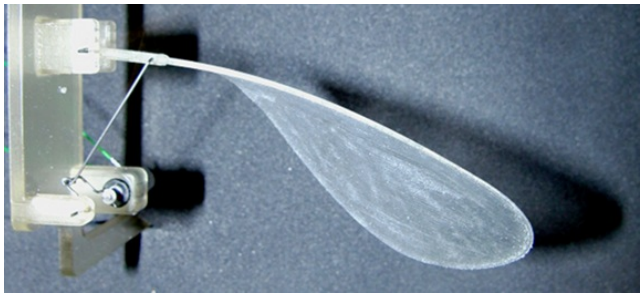
One major problem associated with simple deflecting wings is that they do not deflect as flat plates. Instead, the leading edge tends to remain vertical rather than flexing torsionally, while the wing surface bends away underneath it. This behavior creates an inverted camber shape that is undesirable. Several methods were explored to overcome this problem. The most effective solution was to extend the wing frame all the way around the tip of the wing. This design forced the leading edge to twist when the wing deflected, thus maintaining a roughly continuous slope across the chord of the wing near the tip. In other words, the tip of the wing behaved more like a flat plate with the entire wing deflecting to the proper angle, rather than just the lower half.

Wing ribs have also been used to control the deflection patterns and add stiffness in certain directions. Various rib designs were tested, featuring rectilinear patterns as well as curved patterns inspired by the wings of dragonflies and other insects. However, the current design does not feature stiffening ribs. Fig. 6 shows a top-down view of a wing deflecting during flapping tests on the experimental setup.

This general wing design, while not optimal, was deemed satisfactory for use in the challenge of building a full ornithopter using 3D printed wings. A new double-ended version of this wing shape was produced for use in the full ornithopter.

Full Ornithopter Design

Once a satisfactory wing design was obtained, it was implemented in the four-wing vehicle. The wing chosen for this purpose was the rib-less design that produced the greatest lift. A fuselage was designed to hold the motor, crank, and wing hinge. Care was taken to place the motor as close as possible to the wing pivot point to center the mass.



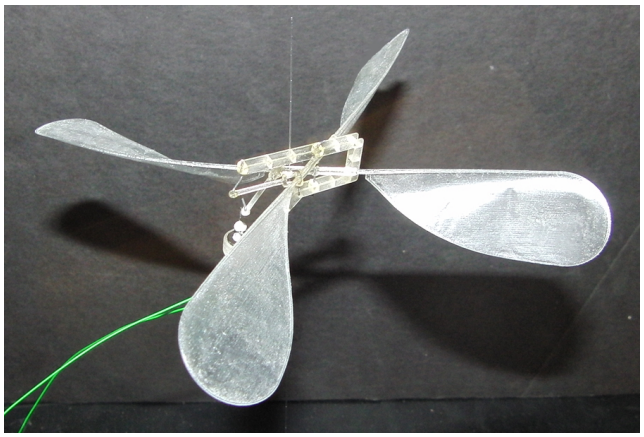


Figure 6: Flash photos showing deflection while flapping (above); wing deflection in a tethered flight test (below).

The wings are driven by a crankshaft connected to the motors gearbox. In order to drive the wings in a roughly symmetrical motion, the crankshaft includes two attachment points for the connecting rods powering the left and right wing. These two attachment points are roughly 30 degrees out of phase from each other to compensate for the asymmetry of the crank position at any given point in the stroke. Fig. 7 shows a top view of this offset-crank mechanism, which is similar to the DelFly I design (de Croon et al., 2009) and many toy ornithopters.

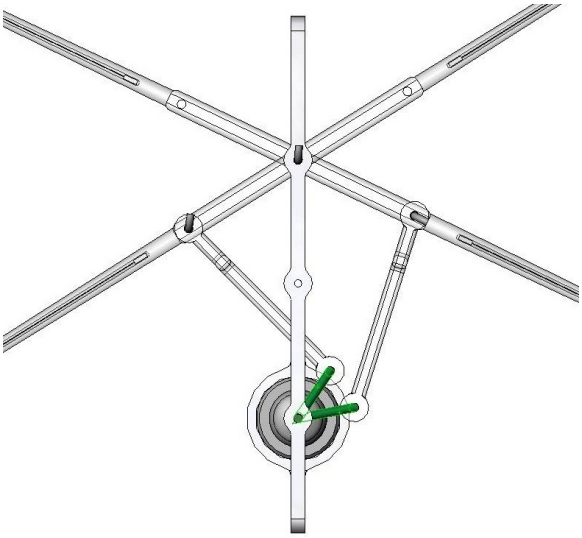


Figure 7: Top view of ornithopter with offset-crank in green.

The ornithopter was tested first using a DC power source and a fishing line tether to verify proper operation of the crank mechanism and proper flapping behavior of the wings. The crank is designed to flap each of the four wings through roughly 80 degrees, and when the flexibility of the wings is included, this angle is enough to allow the wings to clap and fling at the end of each stroke. The clap and fling phenomenon may aid in lift production (Lehmann et al., 2005). Fig. 6 shows a photo of a tethered flight test showing ideal wing deflection of roughly 45 degrees. In this test configuration, the ornithopter was able to lift up to 1.5g of payload, which is roughly equivalent to the mass of batteries required for flight.

Once the ornithopter was able to support a payload while flying on the tether, it was outfitted with batteries and untethered flight tests began. Two 10mAh Lithium Polymer batteries were used to power the motor and were attached on the opposite side to the motor to balance the mass. The other feature required for untethered flight is a set of thin foam damping sails attached to a thin carbon fiber rod above and below the fuselage to maintain an upright flying position. This method of achieving passive stability was developed by van Breugel and is replicated here (van Breugel et al., 2008).

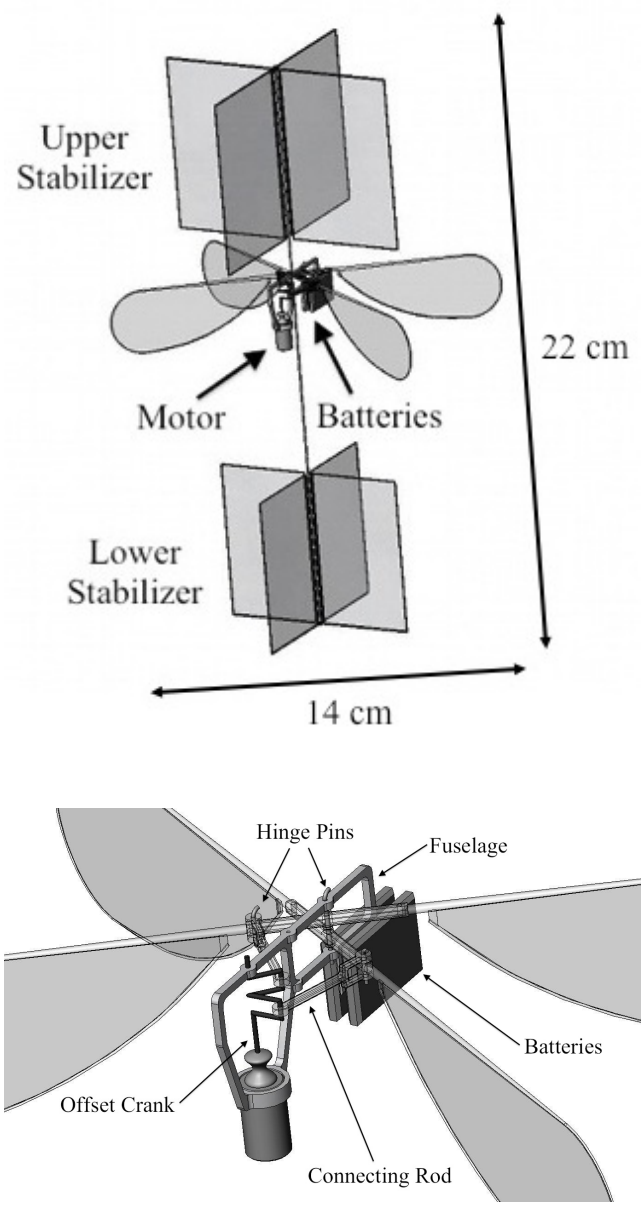


Figure 8: Final configuration and large view of mechanism.

Passive Stability

The sails employed to maintain stability help keep the ornithopter upright. Without sails, the ornithopter tends to tip over, causing a loss of upward lift. However, when the sails are attached, the larger top sail acts as a damper on the tendency to tip over, which allows the bottom sail to swing back under the fuselage, righting the ornithopter. The bottom sail is just large enough to dampen any oscillation when it swings. If launched upside down, the ornithopter will right itself, demonstrating the robustness of the design.

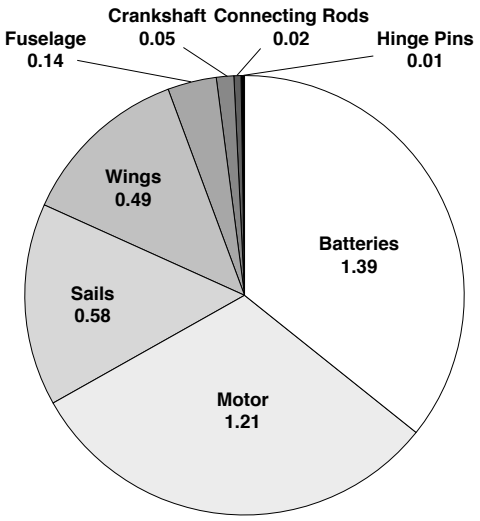


Figure 9: Breakdown of total mass (3.89g).

Conclusions

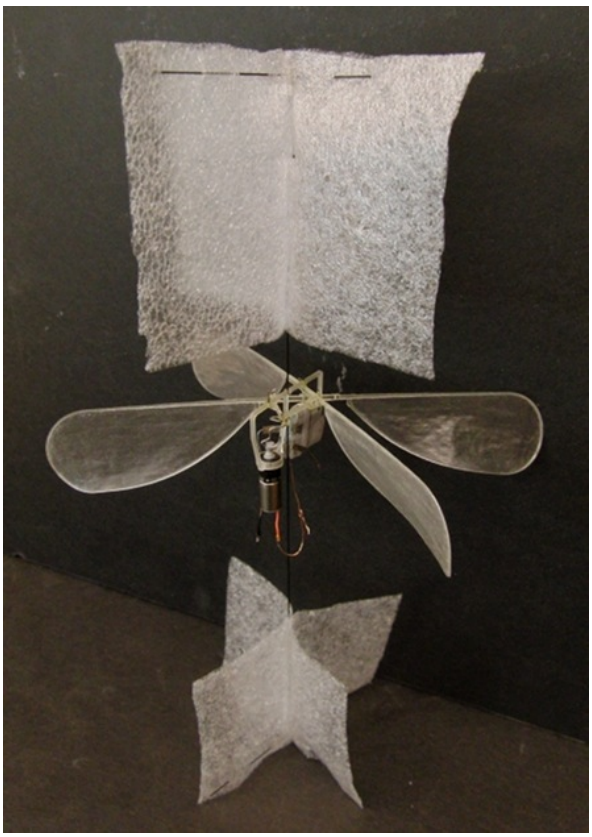
This project has yielded several significant results thus far. First, wing tests and the hovering demonstration have validated the concept of a printed ornithopter. This method of construction has greatly accelerated the design cycle, since a set of wings can be printed in less than 30 minutes and a complete set of ornithopter parts can be printed in 60 minutes. Thus, several design iterations can be tested per day.

The Objet FullCure 720 material has some limitations, particularly in its mechanical properties. It is not as light or as stiff as carbon fiber or balsa wood, which are the main alternative options for wing struts. Therefore, printed wings do not store as much energy when they flex and energy is lost to friction during each wing stroke. Different strut cross sections will be tested to improve stiffness per volume of material.

Other limitations of the 3D printed material include a tendency of thin wings to curl up after a period of days, rendering them useless. This problem can be corrected by storing wings between flat plates or in the pages of a book, which requires disassembly. Thin wings also tend to develop small tears after minutes of vigorous flapping, however this problem can be partially prevented with chamfered edges along the wing frame to avoid discontinuous geometry.

Experimentation with wing designs has begun to uncover some of the features and parameters of successful wings for this size and power scale. The GM15 motor seems to be well matched to wings that are approximately 80-100 mm long from base to tip with a chord length of 30-40 mm when it is running at a power of 1.5W (typical power consumption during flight). If the wing strut is extended further, then the drag of the wing acts along a longer lever arm, slowing down the rate of flapping and reducing lift.

One very successful design feature is the wing frame that extends around the wingtip. This feature helps maintain a continuous wing slope at the tip of the wing and helps approximate the flat-plate airfoil cross section of many hovering insects. The continuous wingtip frame was a design borrowed from the structure of dragonfly wings, which exhibit ideal shape and deflection at the wingtips. Overall, the use of 3D printing to create flexible wings that are aerodynamically functional is the main accomplishment of this project and will be one area for future improvement.



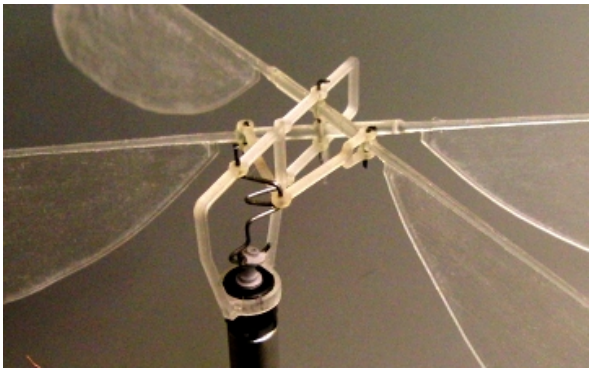


Figure 10: Final design with sails and mechanism close-up.



Figure 11: Ornithopter taking flight and hovering.

Future Work

A long-term project utilizing a hovering ornithopter will be to test hypotheses of insect propulsion and control. This project will be carried out by building wings with a nominal bias of several degrees built into the angle of incidence to produce forward thrust or turning maneuvers. If successful, these principles could form the basis of hovering ornithopter control.

Another project planned for the future is to perform a detailed study using 3D printed wings to develop analytical models predicting wing performance. The lift of many different wing designs will be measured to identify relationships between the major variables involved in lift production such as wing length, chord, surface area, flapping frequency, parameterized shape, etc. This data will then be mined for analytical relationships using the Eureqa software (Schmidt and Lipson, 2009). These laws will then be compared with current designs to evaluate the model and ultimately produce the best possible wings.

Finally, another ornithopter will be designed using 3D printed wings and other parts that is still smaller and lighter and is composed of an even greater proportion of printed components.

Acknowledgements

This work was supported in part by the U.S. National Science Foundation (NSF) Grant ECCS 0941561 on Cyber-enabled Discovery and Innovation (CDI). We thank Leif Ristroph and Itai Cohen for useful discussions.

References

AeroVironment (2009). Darpa awards aerovironment phase ii contract extension for nano air vehicle development program [online]. Accessed 4/9/10. http://www.avinc.com/downloads/NAVPRLongDARPAV4.doc.pdf.

Bergou, A. J., Xu, S., and Wang, Z. J. (2007). Passive wing pitch reversal in insect flight. *J. Fluid Mech.*, 591:321–337.

Chronister, N. (2010). Micro air vehicle ornithopters [online]. Accessed 4/9/10. http://www.ornithopter.org/history.mav.shtml.

de Croon, G. C. H. E., de Clerg, K. M. E., Ruijsink, R., Remes, B., and de Wagter, C. (2009). Design, aerodynamics, and vision-based control of the delfly. *Int. J. of Micro Air Vehicles*, 1(2):71–97.

DelFly (2010). Accessed 4/9/10. http://www.delfly.nl/.

Dickinson, M. H., Lehmann, F., and Sanjay, P. (1999). Wing rotation and the aerodynamic basis of insect flight. *Science*, 284:1954–1960.

Ellington, C. P. (1999). The novel aerodynamics of insect flight: Applications to micro-air vehicles. *J. Exp. Biol.*, 202(23):3439–3448.

Floreano, D., Zufferey, J. C., Srinivasan, M., and Ellington, C., editors (2010). *Flying Insects and Robots*. Springer.

Karpelson, M., Wei, G. Y., and Wood, R. J. (2008). A review of actuation and power electronics options for flapping-wing robotic insects. In *IEEE International Conference on Robotics and Automation*.

Lehmann, F., Sane, S. P., and Dickinson, M. (2005). The aerodynamic effects of wing-wing interaction in flapping insect wings. *J. Exp. Biol.*, 208:3075–3092.

Michelson, R. and Naqvi, M. (2003). Extraterrestrial flight. In *Proc. von Karman Institute for Fluid Dynamics RTO/AVT Lecture Series on Low ReynoldsNumber Aerodynamics*, Brussels, Belgium.

Pesavento, U. and Wang, Z. J. (2009). Flapping wing flight can save aerodynamic power compared to steady flight. *Phys. Rev. Lett.*, 103(11):118102.

Ristoph, L., Berman, G. J., Bergou, A. J., Wang, Z. J., and Cohen, I. (2009). Automated hull reconstruction motion tracking (hrmt) applied to sideways maneuvers of free-flying insects. *J. Exp. Biol.*, 212:1324–1335.

Schmidt, M. and Lipson, H. (2009). Distilling free-form natural laws from experimental data. *Science*, 324(5923):81–85.

Sun, M. and Xiong, Y. (2005). Dynamic flight stability of a hovering bumblebee. *J. Exp. Biol.*, 208:447–459.

Taylor, G. K. and Thomas, A. L. R. (2003). Dynamic flight stability in the desert locust schistocerca gregaria. *J. Exp. Biol.*, 206:2803–2829.

van Breugel, F., Regan, W., and Lipson, H. (2008). From insects to machines: A passively stable, untethered flapping-hovering micro air vehicle. *IEEE Robotics and Automation Magazine*, 15:68–74.

Wang, Z. J. (2005). Dissecting insect flight. *Annu. Rev. Fluid Mech.*, 37:183–210.

Wood, R. J. (2008). The first takeoff of a biologically-inspired at-scale robotic insect. *IEEE Trans. on Robotics*, 24:341–347.

Woods, M. I., Henderson, J. F., and Lock, G. D. (2001). Energy requirements for the flight of micro air vehiles. *Aeronautical Journal*, 105(1045):135–149.

Zdunich, P. e. a. (2007). Development and testing of the mentor flapping-wing micro air vehicle. *Journal of Aircraft*, 44:1701–1711.