# ATA Ornithopter Wings and Flapping Mechanism


MAE 156B Senior Project by:

Tyler Hartwell Kyle Candee Alonso Martinez Cindy Feng

Mechanical and Aerospace Engineering Department
University of California, San Diego

Sponsored by:
ATA Engineering
San Diego, California

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**University of California, San Diego**
Department of Mechanical and Aerospace Engineering
Jacobs School of Engineering
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*Project Sponsored by:*
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Dr. Gordon Hoople
Dave Gillett
Young Woo Seo
Steve Roberts

## ABSTRACT

Humans have sought to mimic bird flight through the bioinspired design of ornithopters, flying machines with flapping wings. ATA Engineering funded a UCSD Mechanical Engineering senior project to develop an ornithopter flapping wing machine with test data that demonstrated positive lift. The flapping mechanism was mounted to a single degree of freedom load cell and calibrated for data acquisition through an Arduino. Post-processing the signal at 70Hz and averaging of the output signal revealed the net vertical force on the upstroke compared to the downstroke for various wing designs. Though the data showed a flexible foamcore wing design produced the most vertical force with an average mean force of 0.105 pounds, the test set up must be revised to measure additional degrees of freedom to verify positive lift.

# CHAPTER 1: PROJECT DESCRIPTION

## Background of Project

One of the oldest dreams of humankind is to fly like a bird and see the world from a bird's-eye view. Birds achieve lift and thrust through the muscle power of their wings. Nature has achieved the functional integration of lift and propulsion through bird flight control, which humans have tried to mimic through bio-inspired ornithopter design.

Both ATA Engineering and Professor Thomas Bewley (Coordinated Robotics Lab) had a desire to pursue research in unmanned air vehicles, specifically bio-inspired UAVs with wings that flap. To facilitate research and design of a flapping wing machine, ATA sponsored the development and fabrication of a mechanical wing mechanism for a UCSD Mechanical Engineering senior project. Any required electronics such as motors, microcontrollers, sensors, etc. were paid for or supplied by ATA and UCSD.

The primary goal of the ATA Flapping Machine project is to design, fabricate, and deliver a flapping wing machine that can demonstrate positive lift. This project required application of mechanical design, structure dynamics, fluid dynamics, finite element analysis, machining, and bio-inspired research and design.

## Statement of Requirements

Design and fabricate wings and a flapping mechanism that mimics the motion of bird flight. This system will be incorporated into an ornithopter that will develop positive lift when powered.

Specific project objectives:

- ❏ Research bird flight physics and existing ornithopter wing designs
- ❏ Develop at least 2 validated wing designs with test data
- ❏ Design a linkage mechanism to achieve a wing flapping motion profile
- ❏ Fabricate the wing mechanism (2 wings) and a body structure that the wings will attach to. This body must be able to self-react all internal forces, meaning the motors and wings will not be connected to any external objects outside the body.
- ❏ Incorporate motors and electronics provided by ATA/UCSD
- ❏ Develop a systems-level design summary for future project phases
- ❏ Demonstrate that the flapping wing machine can produce positive lift

NOTE: Positive lift implies the net upward force is greater than zero, not necessarily greater than the static weight of the ornithopter.

## Final Deliverables

1. Research on bird flight and existing ornithopter mechanisms
2. Wing linkage mechanism that provides positive lift through flapping motion

3. Two validated wing designs that fit on the test frame
4. Raw and filtered test data that demonstrate wing designs produce positive lift

## Bird Flight Research

Given that the problem definition was to develop a linkage mechanism that mimicked the motion of a bird, the first step taken was to conduct research on the mechanics and dynamics behind flapping flight. This initial stage of the project was no small task, and had several weeks dedicated to this effort, providing the foundation of our final design. Research can be divided into various subsections: flapping mechanics in nature, existing flapping machines,comparison of different birds, and wing designs.

*Flapping Mechanics in Nature*

As can be imagined, there are a variety of variables that allow avians and similar creatures to achieve flight. One of the most straightforward and common mechanisms utilized is the manipulation of surface area. Lift can be increased if the effective surface area is maximized on the downstroke. Similarly, drag can be reduced if surface area is minimized on the upstroke.  While this can be achieved by tactful moving of the wing, feather orientation and rotation of the wings also allow birds to achieve the lift necessary for taking off, gliding, and perching.

*Bird Comparisons:*.

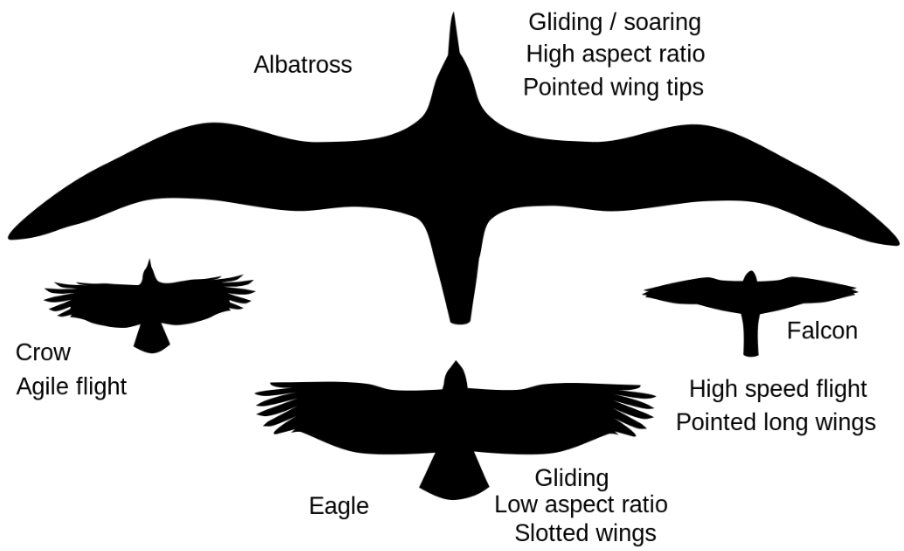



*Figure 18: Bird Size Comparison*

To give the project a focus, it became imperative to select a bird that fit the considerations mentioned in the above section. There are a number of factors that contribute to the variety of flying styles observable in nature. Such parameters involve aspect ratios, wing span, and wing shape. Aspect ratio of a wing is essentially a ratio of wingspan to wing area.Through outside studies, it can be heavily inferred that high aspect ratios, while effective for soaring at low angles of attack, are susceptible to stalling with higher angles of attack. Low aspect ratios, while allowing for quick flight, can be unstable and difficult to control. While intermediate aspect ratios have are not advantageous for quick or powerful flight, this mid-range has proven to be efficient at hovering, and handling different angles of attack. See Table 1 for a comparison of wingbeat frequencies for different bird species. Additionally, drag forces for possible shapes were examined and compared. Thus, the seagull, species *larus dominicanus*, was selected for its 3.6-foot wingspan, mobility through aspect ratio, and 3.5 Hz wingbeat frequency.

*Wing Research:*

Though a seagull was selected for its stability, efficiency, and applicability of controls, the features of the wing did not necessarily have to be tied to this bird. The vast amount of resources and potential for creative wings that can efficiently achieve high levels of lift did not allow for such a restriction. In a similar vein, these factors could potentially lead to years of research. Given the time constraints of this project, it was decided that a lift determining test frame and a flapping mechanism with interchangeable wing designs would allow for the best wing research.

### Review of Existing Solution

Understanding the Festo SmartBird was a natural starting point for existing ornithopter UAV research. The Festo SmartBird is a bird drone that can start, fly, and land autonomously. The flapping motion of its wings is actuated by a single rotary motor. Its wings not only flap up and down, but also twist at specific angles through a servo motor at the end of each wing for torsional control. The wing twists in such a way that its leading edge is directed upwards during the upstroke to create a positive angle of attack.

The torso of the Festo SmartBird houses the battery, crank mechanism, and control and regulation electronics including the microcontroller and three Hall sensors. In total, the entire SmartBird weighs only 450 grams with a wingspan of 2 meters, and requires only 23 Watts of power to operate.

## CHAPTER 2: DESCRIPTION OF FINAL SOLUTION

### Overview of Components

The final design solution consists of a wing flapping mechanism with attached system for data acquisition, as well as four different wing designs that demonstrate positive lift.

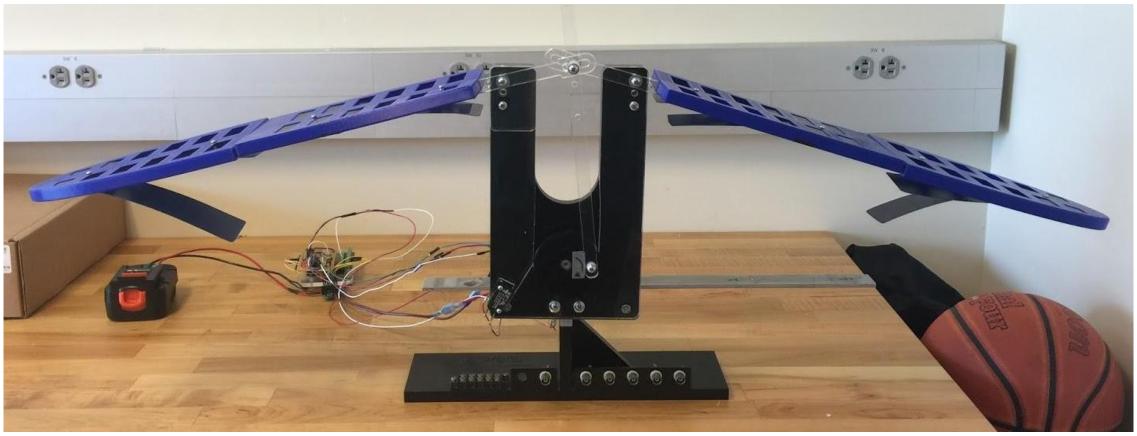


*Figure 2: Vented Flap Wings Mounted on Test Setup*

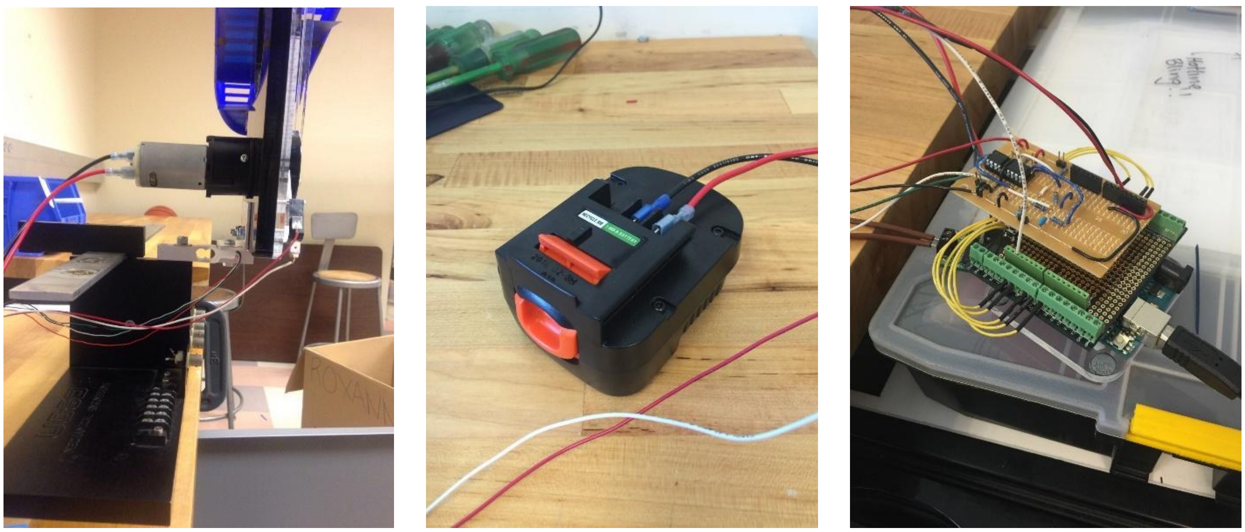


*Figure 3a, 3b, 3c: Side View of Test Set Up, Battery from Cordless Drill, and Arduino with Motor Driver*

The lift data acquisition system was also an integral component of our final design, shown above in Figure 3. This system, whose components are shown in Figure 3, allowed users to interchange different wings to test against our developed wings for any potential improvements. The test bed utilizes a load cell onto which the flapping mechanism is mounted to. Positive and negative forces are interpreted as the lift generated from the flapping motion, with post-processing and filtering to get rid of noise. Finally, a limit switch was used and overlaid on the data in order to differentiate upstroke and downstroke data.

Figures 4-7 shows the four finalized wing designs that were delivered to ATA. The materials used to construct these wings include PLA, Orcon film, woven Nylon tape, and rubber bands.

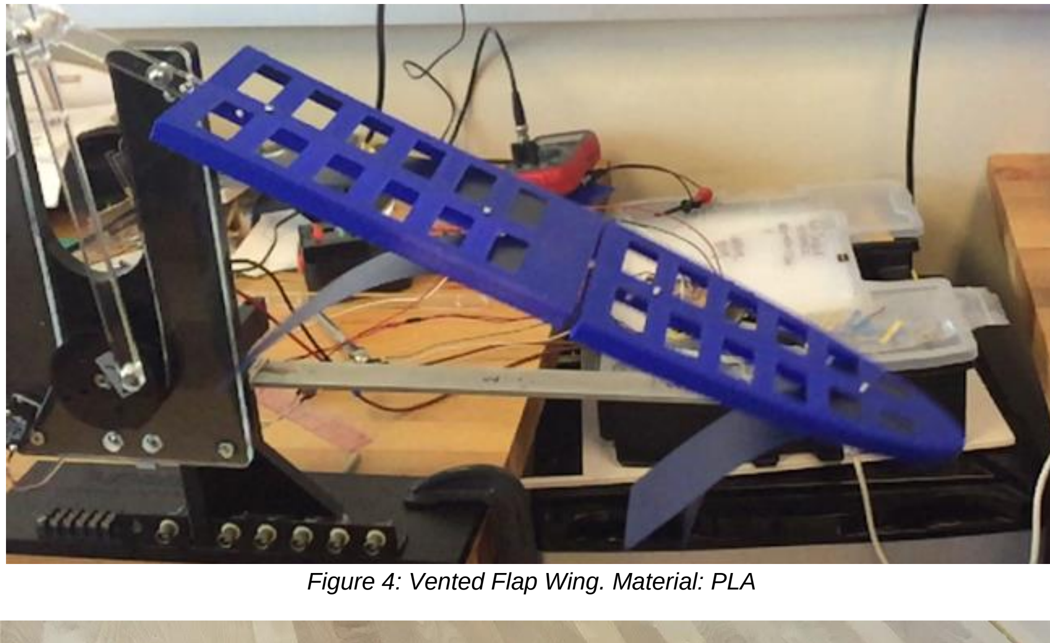


*Figure 4: Vented Flap Wing. Material: PLA*

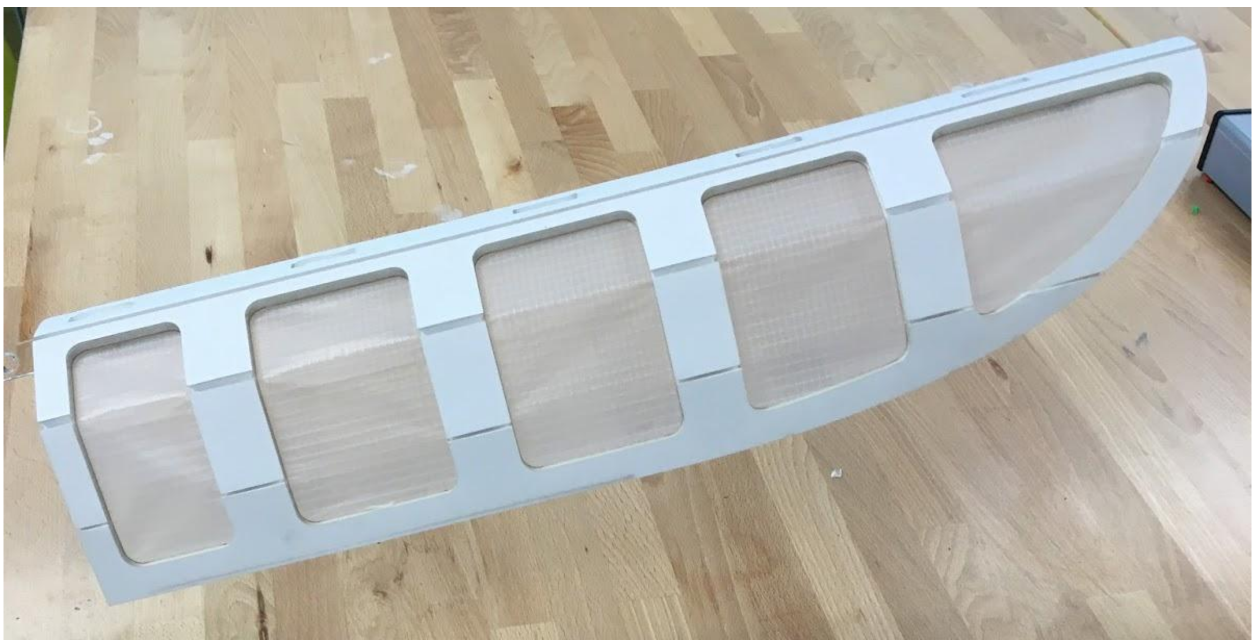


*Figure 5: Flexed Wing: Materials: Foam Core and Orcon Film*

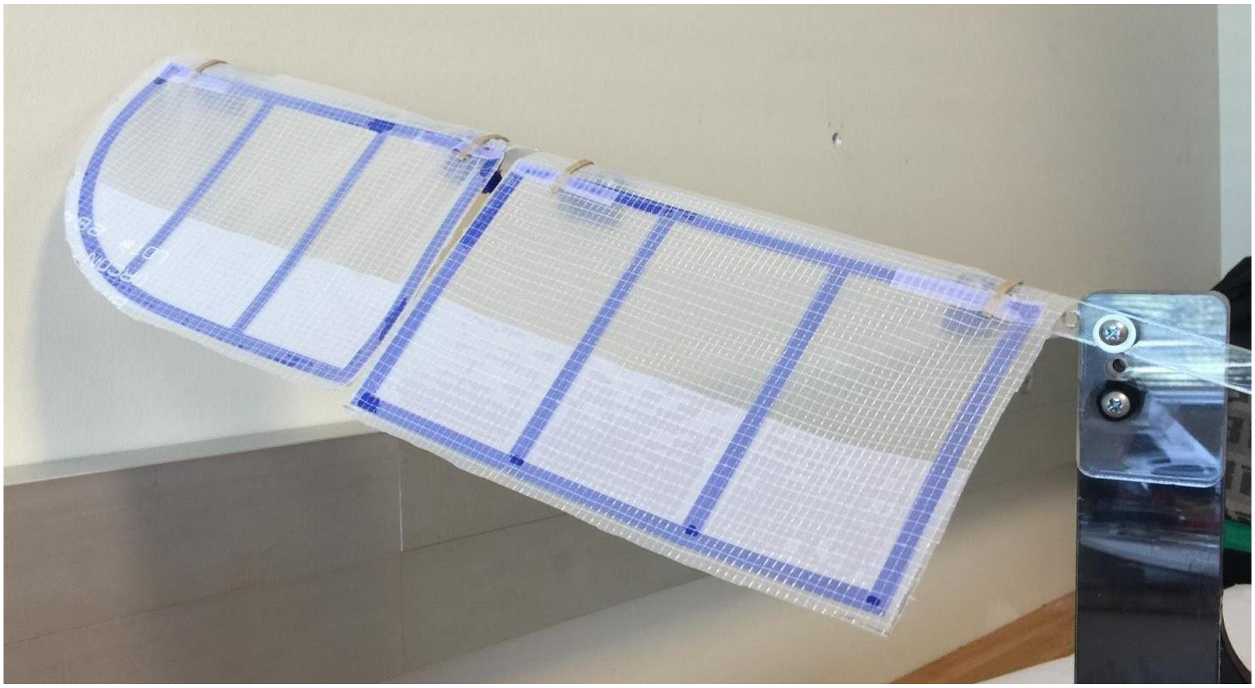


*Figure 6: Flat Torsion Wing: Materials: PLA, Orcon Film, Nylon Tape, and Rubber Bands*

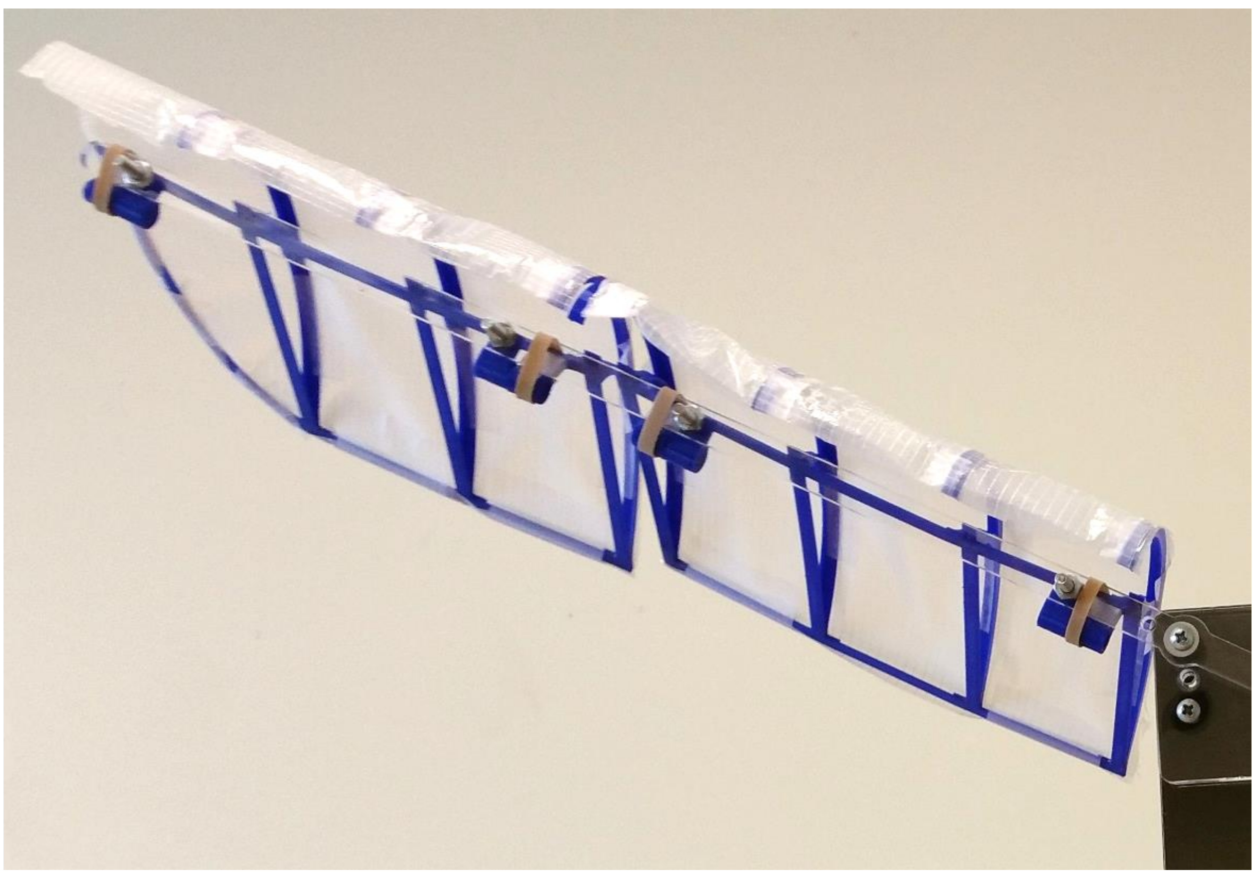


*Figure 7: Ribbed Torsion Wing Design. Materials: PLA, Orcon Film, Nylon Tape, and Rubber Bands*

## CHAPTER 3: Design of Key Components

The initial plan for designing the key components involved extensive use of the Lasercamm and 3D printers within the MAE Design Studio for rapid prototyping. These efforts immediately posed a challenge, as the Design Studio had limited open hours and there was typically a queue for the machines. With research on 3D printers and recommendation from Professor Bewley, we decided there was room in our budget to buy a Robo 3D R1 Plus for our workspace, with approval from ATA Engineering.

The 3D printer proved extremely useful for this project, as many different wing designs and iterations could be rapidly prototyped and tested. Additionally, the PLA material was lighter than acrylic. For example, the first iteration of the acrylic wing box (individual pieces shown in Figure 2 and assembly shown in Figure 5) weighed 674 grams. The 3D printed iteration weighed <insert a weight here once we measure it>. All in all, the purchase of the Robo 3D marked a key introduction of rapid printing technology for ATA Engineering by UCSD students, who also provided a 3D Printing tutorial to the ATA Design Engineers, as the printer will be an available resource at ATA Engineering at the conclusion of this project.

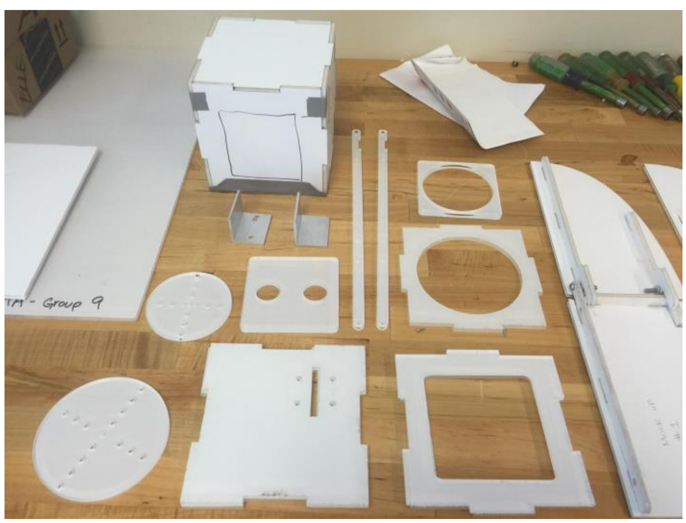


*Figure 8: Laser Cut Acrylic Parts for the Wing Box*

### Flapping Mechanism and Test Frame

Though the main focus of this project was wing design, a mechanism to flap the wings was necessary to compare the forces generated by different wings. The mechanism would need to be housed in a wing box, which could also act as a hinge point for the flapping linkages. For a detailed analysis on the selection of the single bar linkage design connected to the actuator, see Appendix 4-2. This analysis was then transformed to a physical model (Figure 9), using foamcore and a motor provided by the Bewley Coordinated Robotics Lab. The foam core wing box was a proof of concept that worked despite a slow motor, which then led to the second iteration using an acrylic wing box, seen in Figure 10.

*Figure 9: First Iteration of the Wing Box Flapping Mechanism*

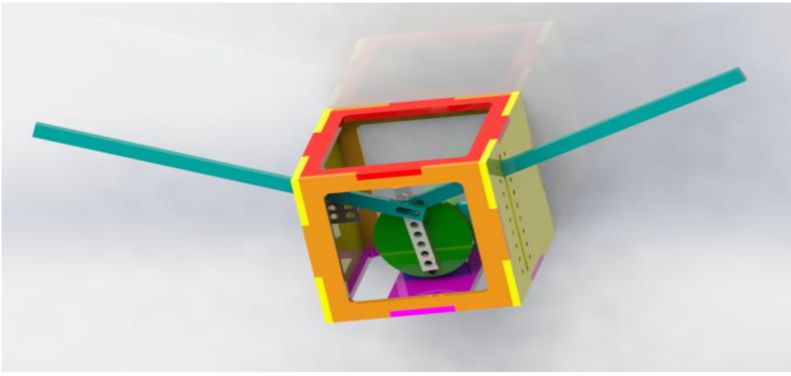


*Figure 10: CAD Model of Wing Box*

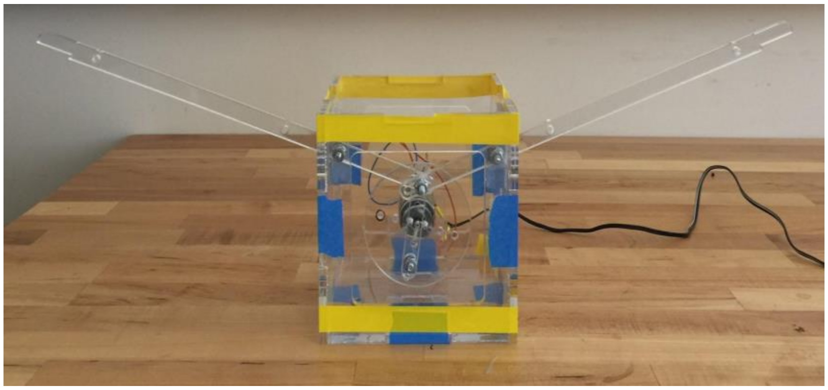


*Figure 11: Flapping Mechanism in Acrylic Wing Box*

## Motor Selection

The first few motors in the proof of concept models were extra motors from the Robotics Lab with unknown specifications. It was found that these motors were not strong enough to move the linkages with the weight of the wings attached. However, without the weight of the wings, it was observed that the linkage mechanism was operable. It was then decided to select a motor with known specifications in order to properly gear down the motor and achieve the desired wing beat frequency.

The ultimate decision was to purchase and disassemble a cordless drill to extract the motor for use in the final flapping mechanism. Based on pricing, the Black & Decker 3/8 inch 12-Volt Cordless Drill was bought and taken apart. Figure 3 shows the extracted motor attached to the test frame and the battery to power it, and Figure 11 shows the product image of the Cordless Drill. See Appendix 6 for the spec sheet of the drill.

## Data Acquisition System

The amplifier included with the load cell contained internal electronics that severely limited the rate at which we could take measurements from it. Because we needed to sample at a much higher rate, we were forced to abandon this amplifier and construct our own from scratch using op-amps, resistors, capacitors, and other standard electronic components.

A two stage amplifier with an analog signal conditioning circuit was created using an AD623 instrumentation amp with a gain of approximately 45, an MCP6271 operational amp with a gain of 10, for a combined amplification of approximately 450. A first order anti-aliasing filter was constructed using a simple RC circuit with a cutoff frequency of approximately 400 Hz. This set up was first assembled on a standard breadboard in order to test and verify operation. To ensure reliable connections, the components were permanently soldered to a copper prototype board, and fabricated to fit directly into the arduino input sockets.

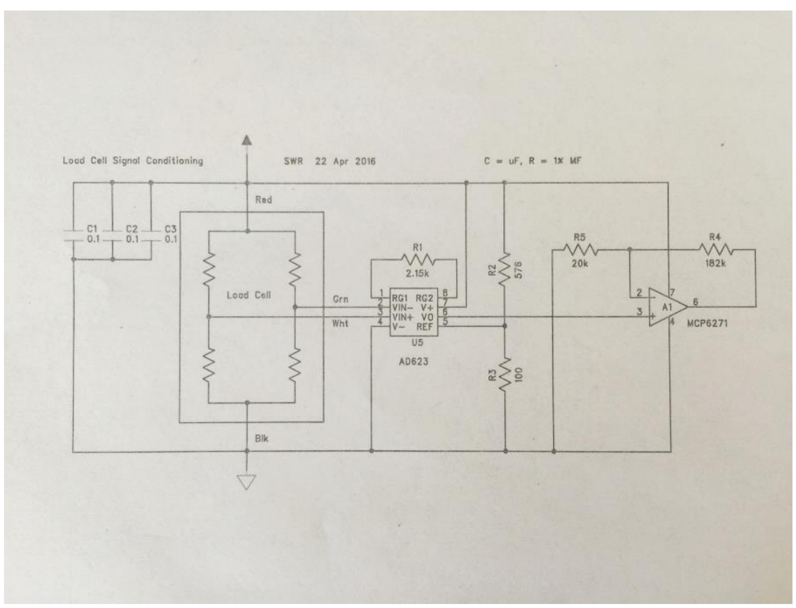



*Figure 12: Data Acquisition from Load Cell Schematic (Provided by Steve Roberts)*

## Motor Controller Relay

The Arduino motor controller proved to be too small to power the motor in our test bed so we had to opt for a larger one. A Pololu VNH2SP30 motor driver was provided to us by Professor Bewley's lab, which was rated for up to 30A peak current. This was wired to control power from the battery to the motor, and received its control signal via a digital PWM pin on the Arduino.

## Test Frame Limit Switch

In order to differentiate the upstroke from the downstroke, the flywheel was recut with a cammed profile and a limit switch was attached to the test frame and wired to provide feedback to the Arduino. Since the signal from the limit switch was connected to a digital pin on the Arduino, a pull-down resistor of 100k ohms was used to ensure there were no false readings due to stray voltage.

## Wing Designs

*Brainstorming:*

During the initial brainstorming session (Figure A5-1), several wing types were conceived in addition to some possible mechanical linkages to operate them. One design was a telescoping wing that retracted via a cable and a winding wheel with a slip gear. A design with more passively actuated wings was ultimately selected. One design that did make it past the first round was the hinged flap/feather design. This design was more bioinspired and actuated passively which were both highly desirable by the sponsor.

*Initial Design Considerations:*

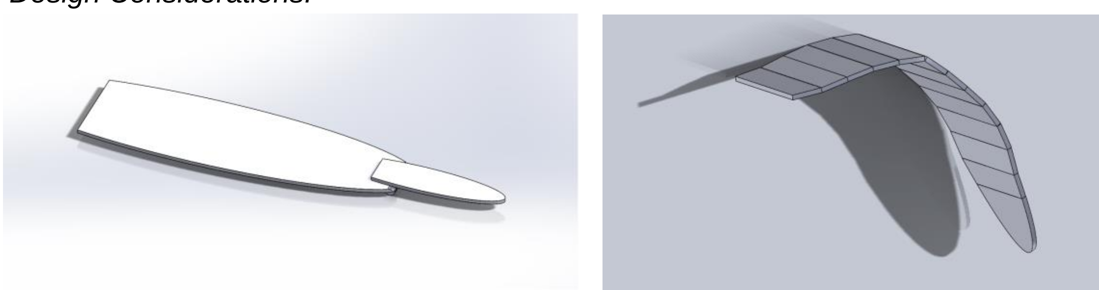


*Figure 13: (a) Hinged Wing; (b) Flexible Wing*

In addition to the telescoping and feathered wing designs, a couple other passively actuated designs were developed. One design was a two piece wing with a hinge in the middle, and the other was a flexible wing with multiple joints allowing the wing to only bend in one direction. Both these wing types collapse during the upstroke, and extend flat and rigid during the downstroke, taking advantage of the changes in effective surface area to decrease/increase drag force.

*Refocused Wing Design:*

After further research and discussion with the sponsors, it was decided that continued development of the wing designs should attempt to better replicate the form and function of a bird as opposed to any arbitrary flapping mechanism. Since the average size and flight capabilities of a seagull matched the desirements of the sponsors, future wing design was to focus on being inspired by the seagull. As a result, the wingspan was modeled to be between 2-3 feet and wing designs that would noticeably deviate from the appearance of a seagull were mostly abandoned.

## Test Bed

The testing set up was integral to the final wing selection process. Furthermore, such a setup will allow for future improvements to project if new and improved wings are desired. As was the case with the design of wings, a variety of approaches could have been taken for determining the lift being produced. Options included strain gauges, accelerometers, pressure transducers, and wind tunnels. In the end, a load cell was determined to being the best option for our purposes, with the strain gauge coming in at a close second. The principle for our setup involves the comparison of the forces produced by the downstroke and upstroke, in an attempt to demonstrate that more upward force is produced overall.

## Fabrication Methods

For most of the wing designs, prototypes were created through 3D printing in PLA on a Robo 3D R1 Plus. Matter Control, the software used for preparing CAD files for printing, chooses to print a material using certain paths, infill patterns, support structures, and layering. Some of these unique aspects of 3D printing were manipulated during wing fabrication in order to create features that would be more difficult, expensive, or time-consuming to make with other manufacturing methods. In particular, for designs that called for feather-like structures, the dimensions of the parts were chosen to match the minimum layer thickness that the 3D printer was capable of producing in order to make the thinnest parts possible. For one of the hinge designs, two interlocking parts were positioned in such a way that when printed, would be able to break the support material connecting the two parts and then function as a hinge despite being inseparable components. Furthermore, many of the wing designs took advantage of the fact that the first layer of PLA that is laid on the glass bed of the printer is flat and smooth. The wings were oriented in such a way that the top surface of the wings would be the surface in contact with the glass. This made it so that the smooth texture of the top of the wings would cause the wings to experience less drag on the upstroke of the wings and help contribute to the goal of achieving positive lift.

# CHAPTER 4: Prototype Performance

Comparison of wings was an integral component of the design process, and thus required a test setup that was both accurate and precise. Figure 6 demonstrates the setup used. A load cell is mounted to the beam, opposite to the wing box, which is bolted to the beam. The flapping mechanism is allowed to run while the data is collected through an arduino. The schematic of the circuit used to gather amplified data is shown below in Figure 9.

### Test Frame Calibration

The test frame and load cell were calibrated by applying known masses in several directions and measuring the resulting signal. A 6.4lb force was applied vertically and averaged an 86 bit response, resulting in a sensitivity of 0.074 lbs/bit. A 2.2lb force was applied in the horizontal direction to measure any effects that forward thrust may have on the signal, which was measured to be 0.0067 lbs/lb of horizontal force.

*Figure 14: Vertical Force Calibration*

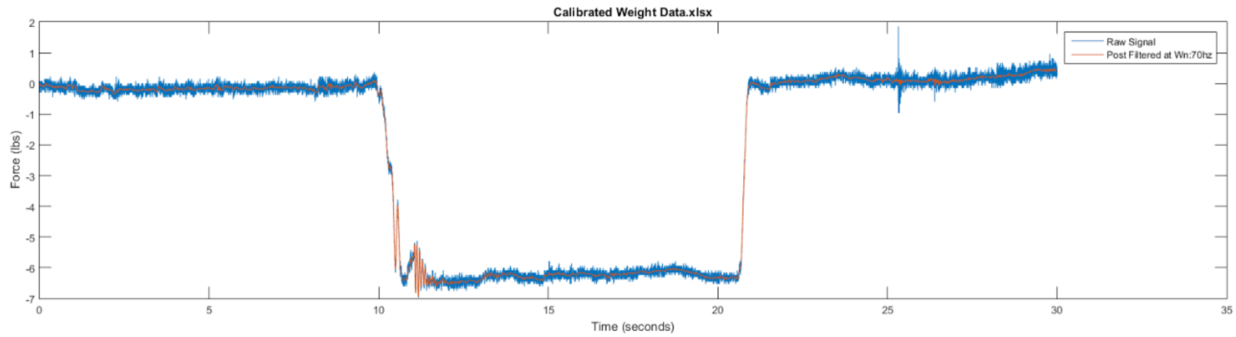



*Figure 15: No Wing Motion Profile*

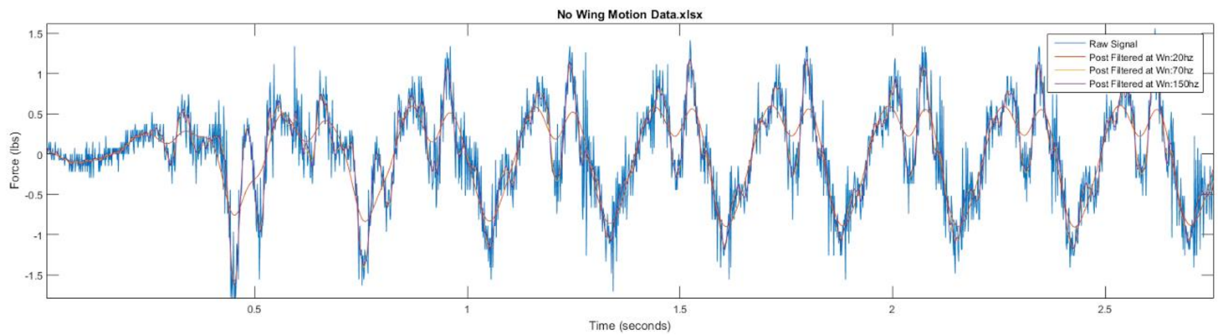
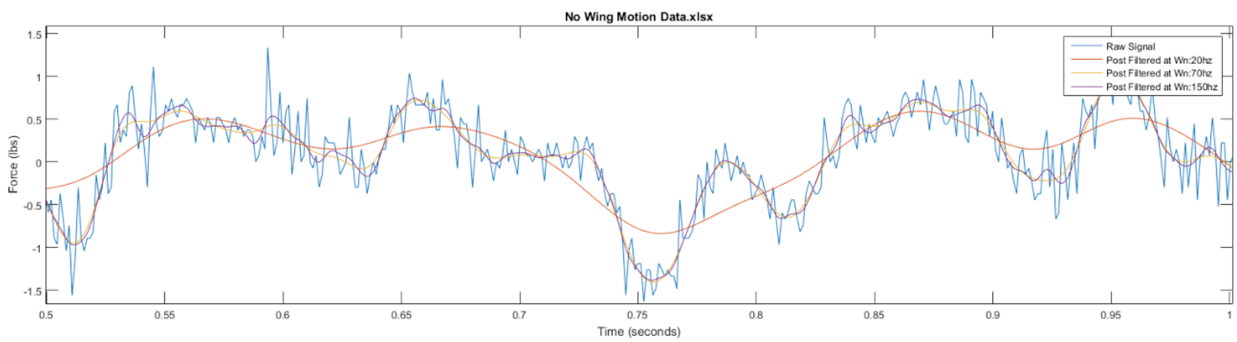



*Figure 16: Filtering of No Wing Motion Data*




## Data Processing and Results

Raw signals were collected via the Arduino and loaded into Matlab for post processing and analyzing. The baseline signal for operation with no wings was filtered at various frequencies, and decided that 70 Hz eliminated the most noise while still maintaining signal integrity, so all subsequent data was filtered at 70 Hz. A 3rd order Butterworth filter was used, passing forward and backward to maintain phase information, and compared against the raw signal.

During each test, prior to running the motor, sensor output was measured to calculate a specific tare weight for each wing test. This was then used to normalize the measured data so forces in the up and down directions were reflected as positive and negative numbers respectively, centered about zero. Mean values for each test were calculated, excluding the first

1000 data points to allow for startup. The mean values of each wing test have been tabulated below, and the wing test data plots are shown in the appendix.

| | Average mean force |
|---|---|
| Vented Wing | 0.0613 lbs |
| Torsional Flex Wing | 0.075 lbs |
| Air Foil Wing | 0.035 lbs |
| Modified Foamcore Flex Wing | 0.105 lbs |

# CHAPTER 5: Design Recommendations and Conclusions

In order to help assure the safety of operators and nearby pedestrians, several design decisions were influenced by possible safety concerns.

## Applicable Standards

The flapping wing machine is the initial development for a possible UAV system that will be led by ATA Engineering. As this drone is still in its early stages and it is not currently known whether it will be used for government or commercial operations, it must first and foremost comply with Model Aircraft Operations Standards set forth by the Federal Aviation Administration.

The statutory parameters of a model aircraft operation are outlined in Section 336 of Public Law 112-95 (the FAA Modernization and Reform Act of 2012). Below are some excerpts that apply to a bird UAV system:

- ➔ Sec. 336. Special Rule for Model Aircraft, a3: the aircraft is limited to not more than 55 pounds…
  - ◆ One of the main criteria for the flying machine project is to maximize lift to payload ratio, so the bird drone will definitely weigh less than 55 pounds. The inspiration for this project, the Festo SmartBird, weighs 1 pound in total.
- ➔ Sec. 336. Special Rule for Model Aircraft, a3: the aircraft is operated in a manner that does not interfere with and gives way to any manned aircraft.
  - ◆ Since the bird-drone seeks to simulate seagull flight, it will not gain enough elevation to soar as high as manned aircraft, provided it is not operated near airports.

Since the complete ATA bird drone will be less than 55 pounds (25 kilograms), it must comply with FAA Small UAS standards, some of which are outlined below:

- ➔ Maximum airspeed of 100 mph (87 knots)
- ➔ Maximum altitude of 500 feet above the ground
- ➔ Minimum weather visibility of 3 miles from control station
- ➔ Visual line-of-sight (VLOS) only; the unmanned aircraft must remain within VLOS of the operator or visual observer

## Impact on Society

The increasing numbers of unmanned aerial vehicles (UAV), as well as the emergence of a growing UAV industry has been met with positive and negative responses. Drones have enormous positive impact in many industries such as agriculture, where UAVs have been used to visualize the growth or depletion of crops from a bird's eye view. The public response to the presence and development of UAV systems has been largely divided, with drone makers and hobbyists swearing to abide by government restrictions placed on drone manufacturing and obeying public airspace laws.  However, still UAVs have been reported flying where they do not belong, including over airports and up close to high rise apartment buildings, for possible surveillance purposes.  The government has had to step in and impose limitations on flying drones in recent years, so the drone industry has invoked political participation.  UAV's have the potential to change the way wars are fought, along with the possibility used with malicious intent by terrorist groups for mass destruction.

Drones are categorized in terms of range and altitude--for example, the HALE classification means high-altitude, long endurance--but what the ATA Flapping Wing project is concerned with is low speed flight and bio-inspired design.  After the wings have been designed, ATA Engineering may further develop the wings and overall UAV system so that it can achieve dynamic flight control and perching to achieved the original goal of developing a bio-inspired bird drone.

While effects of this project on the economy may be low reaching, the development of a drone that looks and acts like a bird can affect the defense industry, as well as the growing drone industry.  The technologies developed in this project have the potential to make these industries more profitable, and therefore lead to an influence on the economy.

## Lessons Learned

Naturally, there were many lessons involved with a project involving complex flying mechanisms. Rapid prototyping is integral to projects that involve a fair amount of research and development. Tools such as 3D printers and laser cutters allowed for numerous iterations of both wing designs, and flapping mechanisms. Additionally, the use of proper amount of sensors is a very important factor that could have improved upon final wing designs. Ultimately, the importance of research to determining an effective solution to problems posed is something that is demonstrated throughout the process of the project.

## Conclusions

Though the team initially sought to develop a flying mechanism, the project scope grew and developed with the research conducted. The flapping mechanism has become a lift data acquisition system, capable of testing a variety of wings through its flexible design. Such a system has allowed for the determination of effective wings, and will facilitate the creation of even more efficient wings in future uses. Though the test bed has proven to be useful, there are the aforementioned issues caused by non-vertical forces on the load cell. Future improvements will utilize more sensors in order to factor these variables out of the final results. The intended simple, passive design of this machine will allow for changes and improvements to be easily implemented. Similarly, applications of controls should not be too difficult to achieve, giving large potential of effective, controlled flight.

## Acknowledgements

The UCSD Design team would like to acknowledge the following people for all of their time, thoughtful advice, and generous feedback:

David Gregg
Dr. Thomas Bewley
Michael Pogue
Dr. Gordon Hoople
David Gillett

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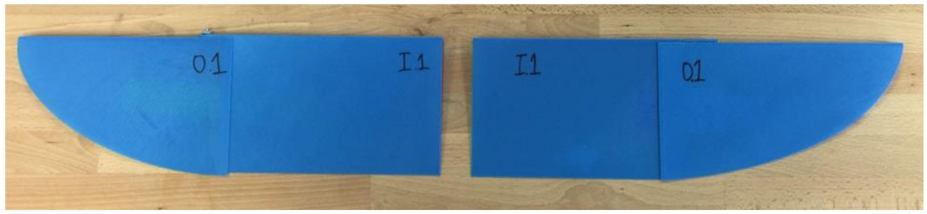
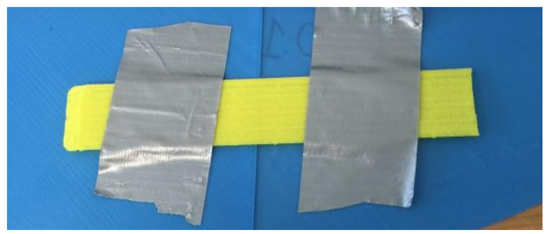
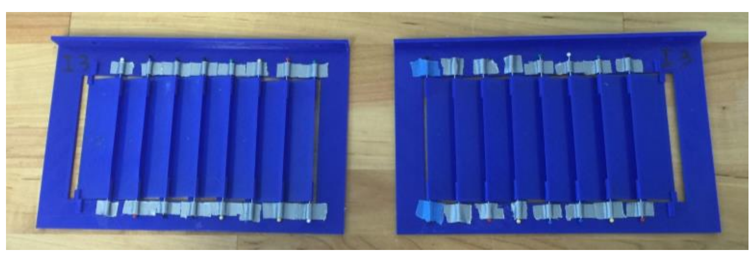
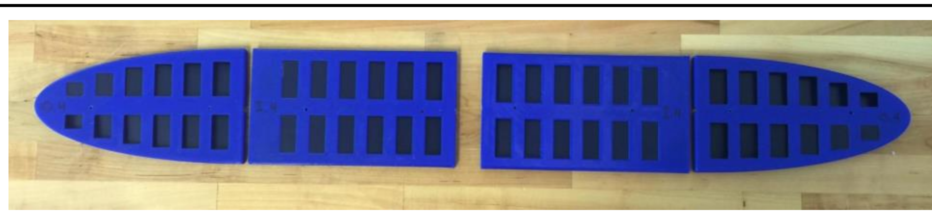
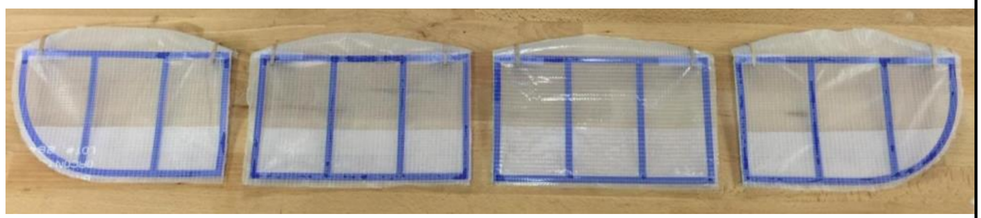
Federal Aviation Administration. Small UAS Notice of Proposed Rulemaking (NPRM), 2015. Web, Accessed Apr. 2016. <https://www.faa.gov/regulations_policies/rulemaking/recently_published/media/2120-AJ60_NPRM_2-15-2015_joint_signature.pdf>

## Appendices

**APPENDIX 2: Wing Iterations List**

| **Key**<br>*I: Inner*<br>*O: Outer*<br>*H: Hinge* | **Description** | **Image** |
|---|---|---|
| I.1 | Flat PLA |  |
| O.1 | Flat PLA | |
| H.1 | Duct tape and support material |  |
| I.2 | Flat PLA, different hole orientation for linkage attachment |  |
| I.3 | Check valve; shutter design |  |
| I.4 | Inner vented flap |  |
| O.4 | Outer vented flap | |

<table>
<tr><td>O.5</td><td>PLA Ridges on underside</td><td></td></tr>
<tr><td>I.6</td><td>Inner Flat Torsion Wing made of PLA, Orcon Film, Rubber Bands, and Nylon tape</td><td rowspan="2"></td></tr>
<tr><td>O.6</td><td>Outer Flat Torsion Wing</td></tr>
</table>

**APPENDIX 4-1:**

**Individual Component Analysis: Determining Positive Lift**

A myriad of potential wing designs exist for flapping machines. Information on these flying techniques vary greatly and have not proven conclusive when it comes to flying efficiency It is therefore necessary to develop a method that can effectively test one design over the other. For such a test, the team has decided to focus on the positive lift generated by different prototypes of wings. This important component in bird design can similarly be handled in numerous ways. The report at hand therefore seeks to analyze different methods and compare them on price, complexity, and effectiveness.

## Functional Requirements:

Determine positive lift generated by wing prototypes

- Must be able to measure the drag and lift generated by wings to attain net lift.
- Must be able to compare one side of the wing versus the other side of the wing.
- Incorporate sensors and simulate flapping for reliable information

## Possible Implementations:

Use of wind tunnel located in UCSD MAE 171A Lab will most likely be implemented in most considerations.

Experiment that uses pressure ports connected to pressure transducer to determine pressure at different points of wing. May be unnecessary to determine various points of lift along wing, when general drag and lift can give a decent enough idea. Constructing points for pressure manipulation may be time consuming.

Strain gauges at base, middle and tip can give general drag and lift data with easy implementation. Would need to run test twice with wing orientation reversed to get complete information.

Load cell implementation can give more information than strain guages, depending on the type of load cell used. One DoF load cell is cheap but gives information, while 6 DoF load cell gives force and moments on 3 axes but cost around $4000.

## Summary of Implementations:

| | Strain Gauges on Wing | Pressure Ports | Complex Load Cells |
|---|---|---|---|
| Complexity | | | |
| Effectiveness | | | |

| | | | |
|---|---|---|---|
| Cost | | | |

## References:

MAE 171A Wind tunnel Experiment:
https://docs.google.com/viewer?a=v&pid=sites&srcid=ZW5nLnVjc2QuZWR1fG1hZS0xNzFhLTE3NWEtMTI2YXxneDozNjk0YmNmOWU5Yjc3YTlk

NASA Experiments: https://www.grc.nasa.gov/www/k-12/airplane/dragdat.html

NASA Model Mounts: https://www.grc.nasa.gov/www/k-12/airplane/tunbalmnt.html

Nasa Strain Gage: https://www.grc.nasa.gov/www/k-12/airplane/tunstraingage.html

Papers:

Contacts:
Steve Roberts
Chris Cassidy
Thomas Bewley

## APPENDIX 4-2:

**Analysis of Testing Frame and Actuation for Two-Dimensional Flapping Motion**

**INTRODUCTION:** Assembling an ornithopter test bed to simulate flapping motion is the first step to testing various wing designs. This test frame will create 2-D flapping of a leading edge, since birds and existing ornithopters control flight by mainly flapping and rotating the leading edge of their wings, with the rest of the wing trailing behind as a membrane. This analysis will focus on selecting a basic 2-D model for a test frame that will minimize mechanical components and allow for interchangeable gear ratios to control flapping speed.

The functional requirements, as desired by ATA, are:

1. The flapping motion will be actuated by a single rotary motor contained in the wing box.
2. This test frame must be able to self-react all internal forces, meaning that the motors and wings will not be connected to any external objects outside of the body (ATA).

Some secondary considerations to support dynamic wing designs are:

1. The components of the test bed must be accessible so that the motor and gears can be interchangeable for different wings. This is important for testing different wing designs.
2. The baseline sweep angle for the wings will be +/- 45 degrees and the range of motion can be adjusted by widening or narrowing the walls of the wing box.

**EXISTING DESIGN:** The Festo SmartBird wing actuation within the wing box features a four-bar linkage mechanism similar to Fig. 2. The yellow gear represents the motor, which uses 23 Watts of power to flap both wings simultaneously. Since ATA desires passive hinging during flight of a 2-piece wing, the 4-bar linkage is too complicated for the test frame, but it is still useful to examine the mechanism used by Festo.

Fig. 1: Baseline Wing Sweep Profile

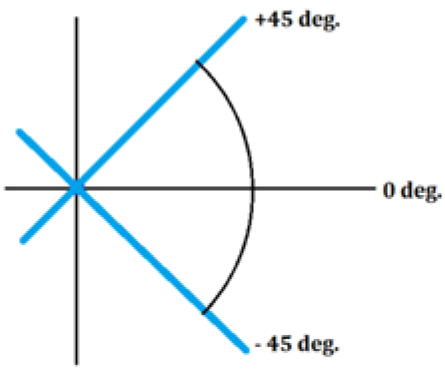
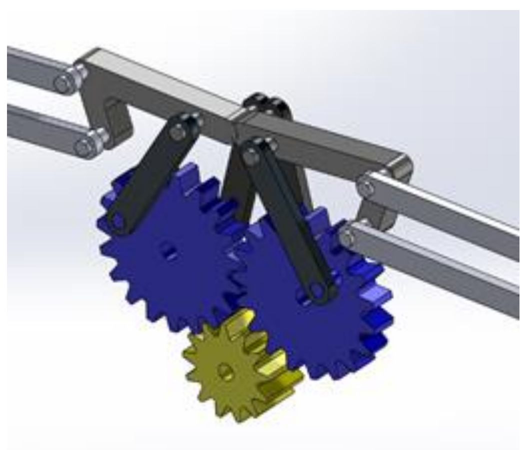



Fig. 2: Festo SmartBird 4-bar Linkage Mechanism



**DESIGN CONSIDERATIONS:** (Note that figures are not drawn to scale.)

ATA provided a wooden kit to build a toy ornithopter, whose flapping motion is actuated by the unwinding of a rubber band. A 2-D diagram of the mechanism is shown in Fig. 3. In the diagram, the crank path represents the unwinding of the rubber band or the rotation of a geared motor. The black box represents the walls of the wing box, so the different wing designs will attach to the linkage outside of the wing box. This is the most simple design, since it does not require any additional gears and minimizes components. However, this design does not create much friction for controlled flapping motion and would need to use a low-speed geared motor. Fig. 4 shows a design that features the gears of the Festo design and the single linkage of the toy ornithopter design.  This design allows for friction control between the motor and the gears to control flapping speed.

Fig. 3: Wooden Toy Ornithopter Design

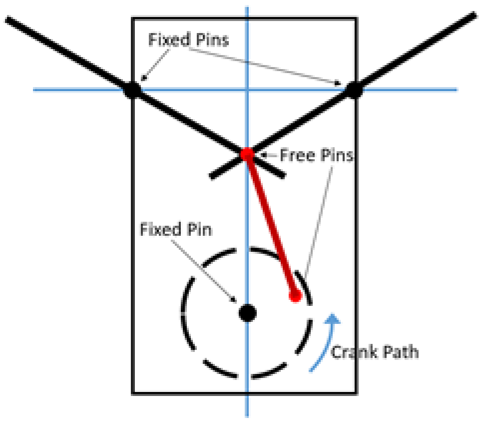
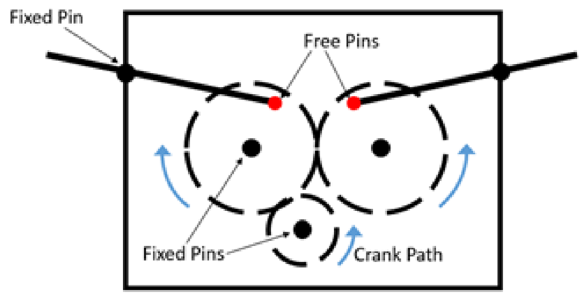



Fig. 4: Hybrid Design for More Friction Control




**SUMMARY TABLE:**

| | Festo 4-Bar Linkage | Toy Ornithopter | Hybrid |
|---|---|---|---|
| Pros | Active wing hinging during flapping. Works for the SmartBird. | No additional gears necessary.  Minimal components. | Can interchange parts. |
| Cons | Complicated design. 4-bar linkage unnecessary for passive hinging. | No friction control. Single speed. | Complicated mechanism for initial needs. |

Thomas Bewley, robotics expert and UCSD professor, said that his robotics lab could provide a motor for any combination of stall torque and no load speed.  Therefore, a single low-speed geared motor is desirable so that all the wing designs will be tested for lift and drag forces at the same flapping speed.

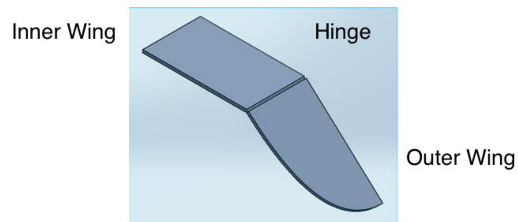
**CONCLUSION:** Keep the testing frame simple at one flapping speed to compare initial prototypes.  Once a wing design is selected, a future iteration of the testing jig can incorporate different flapping speeds.
**Keywords –** Festo SmartBird, Ornithopter, Flapping Wing, Test Bed
**Meetings –** Thomas Bewley, ATA Engineering

## APPENDIX 4-3:

### Two Part Hinged Wing

### Functional Requirements

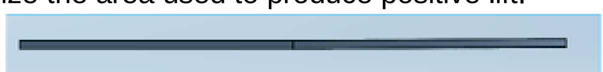
An ornithopter can mainly produce lift from either torsion of the wing or bending of the wing. This analysis aims to focus on how a bending wing alone should be configured to produce positive net lift as opposed to a non-bending flapping wing. The introduction of a hinge on the wing is intended to increase the amount of positive net lift generated and decrease the amount of energy expended during the flapping motion. This is to be achieved by separating the wing into two parts comprised of the inner wing, which is actuated by the motor, and the outer wing, which rotates on a spring loaded hinge that only allows rotation at angles at and below the plane of the inner wing and that tends to rotate the outer wing into the same plane as the inner wing.




By changing the angle of the outer wing, the projected area while flapping changes so as to effect the bluff body drag, and therefore lift, of the machine based on the coefficient of drag equation.

$$Cd = D / (.5 * r * V^2 * A)$$

During the downstroke, the outer wing should be in line with the inner wing in order to maintain full wingspan and maximize the area used to produce positive lift.



During the upstroke, the outer wing should rotate below the plane of the inner wing in order to decrease the projected area being rotated upwards. This is so that negative lift is minimized and so that the torque required to lift the wing is decreased because of the smaller moment arm.

The location of the hinge along the wing should be optimized in order to maximize net lift, decrease energy required to flap the wings, and allow the machine to appear similar to a bird in flight.

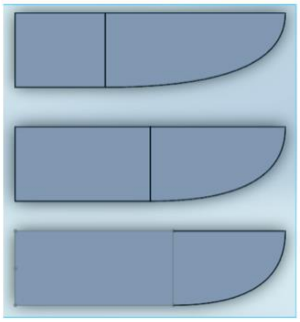
### Component Options

Since the seagull best represents the desired size and mobility of the flying machine, a wing design with a hinge located at a location similar to where a seagull's wing bends is one option. Based on photos and videos of seagulls in flight, it is determined that the ratio of the inner wing length to the outer wing length is about 1:1. Due to the differences inherent in the design of a flying machine compared to seagull, other hinge locations will also be analyzed in order to determine the optimal design for the actual project. Each option will be assumed to have the same total length and surface area, differing only in the location of the hinge.

1:2

1:1

2:1



**Summary**

| Hinge Location (ratio of inner wing length to outer wing length) | Pros | Cons |
|---|---|---|
| 1:2 | Possibly minimum negative lift due to greatest reduction in projected area | Large outer wing inertia and moment may hinder ability to reach full wingspan on downstroke |
| 1:1 | Most comparable to anatomy of seagull and intermediate negative lift minimization and angle control | Sub-optimal minimization of negative lift and angle control |
| 2:1 | Easy to achieve desired angle of outer wing due to small inertia and moment | Smallest possible minimization of negative lift compared to the other options |

Since the primary objective of the ATA Flying Machine project is to maintain positive lift at low speeds, a design that leads towards maximum net lift seems to be the best choice. This would appear to be the wing with the hinge location ratio of 1:2. However, since it is desired to mimic a bird as much as possible and maintain a certain degree of control, it may be better to focus on a design closer to the 1:1 configuration. Testing needs to be done with these configurations in order to experimentally compare the functionality of the hinged wings but it is expected that the optimal design will have a ratio in between 1:2 and 1:1.

**References**

Image Source (Datei:Seagull flying)
NASA Space Flight Systems
LMNO Engineering
Google Scholar, Keywords: Bluff body, wing flapping, rectangle drag, projected area

## APPENDIX 4-4:

**Wing Prototype Structure and Function**

Each wing prototype will need to be able to mount to a test cell and withstand the back and forth motion provided by the motor and drive linkage mechanism. Each prototype will undergo this motion so that enough measurable data can be recorded and compared against other prototypes. All prototypes need to be durably constructed to withstand testing and provide accurate measurements.

**Wing Design Features**

Vented Wing Frame -

- Overall length to be 18”
- Single piece wing frame
- Aluminum frame to provide rigid support for acrylic surface
- Wing surface to be laser cut from ⅛” acrylic
- Torsional springs will maintain vents in the closed position by default.
    - Various springs may need to be tested in order to determine the correct stiffness to maintain closure, but also allow opening during upstroke.

Cupped Wing Frame -

- Make use of pre-manufactured dirtbike fender for fast proof of concept.
- Reinforce with aluminum tubing for mounting to test cell.

**Wing Design Comparison**

| | Pros | Cons |
|---|---|---|
| Vented Wing Frame | - Reduction in drag force is directly related to the reduction of surface area when the vents are open.<br>- Can be prototyped from relatively inexpensive, common materials. | - Lots of moving parts.<br>- Actual reduction of surface area may be limited depending on support structure needed.<br>- Requires moderate assembly |
| Cupped Wing Frame | - Coefficient of drag is reduced to almost 50%, just by reversing the direction of the wing.<br>- No moving parts<br>- Very easy and cheap to assemble | - May prove difficult in achieving forward flight, and/or agile control during flight. |

**References**

Federal Aviation Administration. Public Law 112-95 (the FAA Modernization and Reform Act of 2012). "Subtitle B--Unmanned Aircraft Systems." Model Aircraft Operations, Sec. 331. Web, Accessed Apr. 2016. <https://www.faa.gov/uas/media/Sec_331_336_UAS.pdf>

Federal Aviation Administration. Small UAS Notice of Proposed Rulemaking (NPRM), 2015. Web, Accessed Apr. 2016. <https://www.faa.gov/regulations_policies/rulemaking/recently_published/media/2120-AJ60_NPRM_2-15-2015_joint_signature.pdf>

Picture on cover page: http://wallpoper.com/wallpaper/seagulls-in-flight-441541

## APPENDIX 5: IMAGES & TABLES

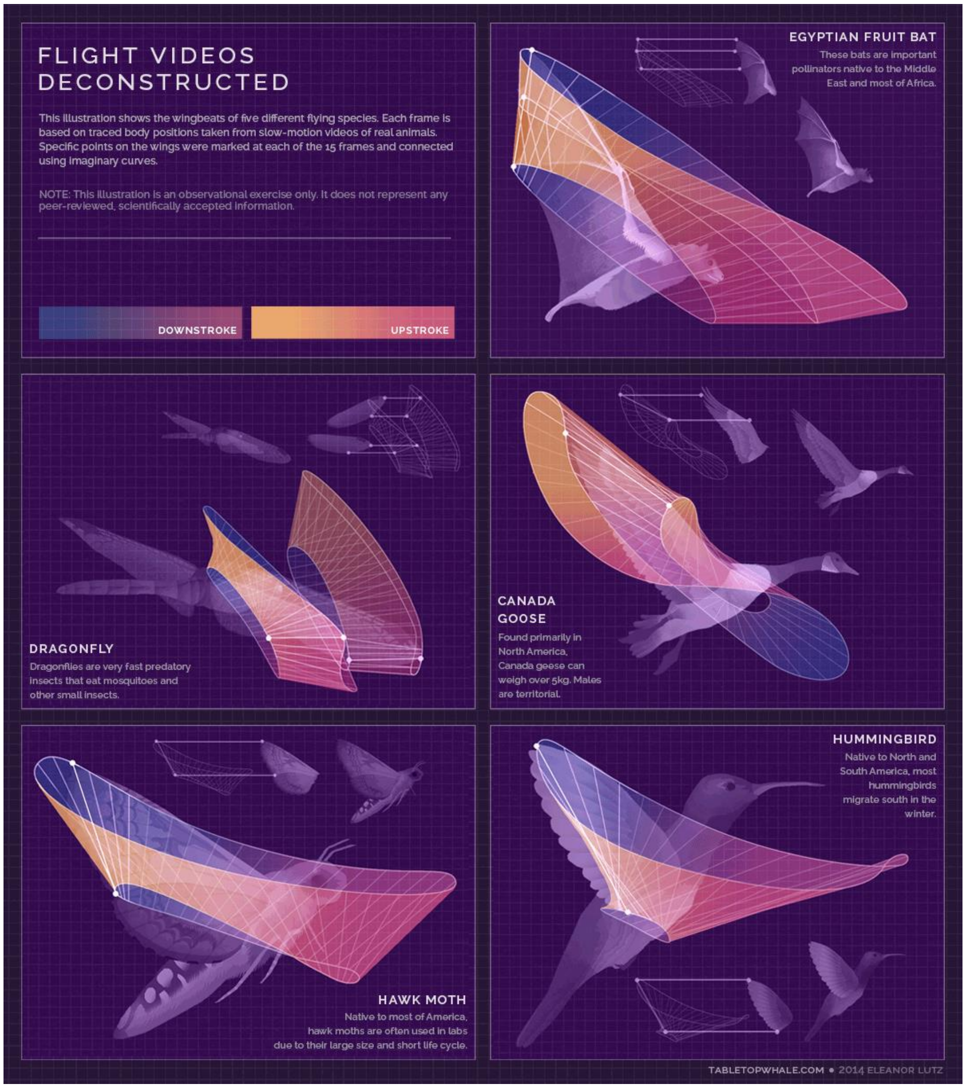



*Figure 17: Wing Profiles of Various Flapping Organisms*

*Table 1: Wingbeat Frequencies for Different Bird Species*

| Taxonomic name | English name | Mass (kg) | Span (m) | Area ($m^2$) | Frequency ± S.D. (Hz) | $V$ ($m\,s^{-1}$) | $\lambda$ (m) | $H$ |
|---|---|---|---|---|---|---|---|---|
| *Diomedea exulans* | Wandering albatross | 8.55 | 3.01 | 0.583 | 2.49±0.11 | 15.0 | 6.02 | 2.00 |
| *Diomedea melanophris* | Black-browed albatross | 3.08 | 2.19 | 0.354 | 2.97±0.15 | 13.3 | 4.48 | 2.04 |
| *Macronectes giganteus/M. halli* | Giant petrel | 3.24 | 1.98 | 0.326 | 3.14±0.19 | 15.2 | 4.84 | 2.44 |
| *Procellaria aequinoctialis* | White-chinned petrel | 1.23 | 1.41 | 0.167 | 3.93±0.10 | – | – | – |
| *Daption capensis* | Cape pigeon | 0.418 | 0.875 | 0.0773 | 5.61±0.55 | 12.3 | 2.19 | 2.51 |
| *Pachyptila desolata* | Dove prion | 0.155 | 0.635 | 0.0469 | 5.42±0.36 | 11.1 | 2.05 | 3.23 |
| *Oceanites oceanicus* | Wilson's storm-petrel | 0.035 | 0.396 | 0.0215 | 7.65±0.60 | 10.4 | 1.36 | 3.43 |
| *Pelecanoides georgicus* | South Georgia diving petrel | 0.122 | 0.388 | 0.0197 | 12.3±0.64 | – | – | – |
| *Pelecanoides urinatrix* | Common diving petrel | 0.133 | 0.408 | 0.0221 | 12.3±0.64 | – | – | – |
| *Phalacrocorax atriceps* | Blue-eyed shag | 2.23 | 1.13 | 0.183 | 5.85±0.25 | – | – | – |
| *Catharacta skua* | Southern skua | 1.69 | 1.43 | 0.241 | 3.95±0.21 | – | – | – |
| *Larus dominicanus* | Kelp gull | 0.890 | 1.41 | 0.228 | 3.46±0.16 | – | – | – |
| *Chionis alba* | Sheathbill | 0.610 | 0.822 | 0.105 | 6.35±0.29 | – | – | – |
| *Anas georgica* | South Georgia pintail | 0.437 | 0.682 | 0.0646 | 7.62±0.23 | – | – | – |
| *Cygnus cygnus* | Whooper swan | 8.50 | 2.26 | 0.589 | 3.56±0.11 | – | – | – |

The last three columns are included for comparison with Pennycuick (1990).
$V$, observed mean air speed from Pennycuick (1982); $\lambda$, wavelength; $H$, advance ratio assuming a stroke angle of 1 rad.
Frequencies based on 63–1118 wingbeats per species (mean 310).

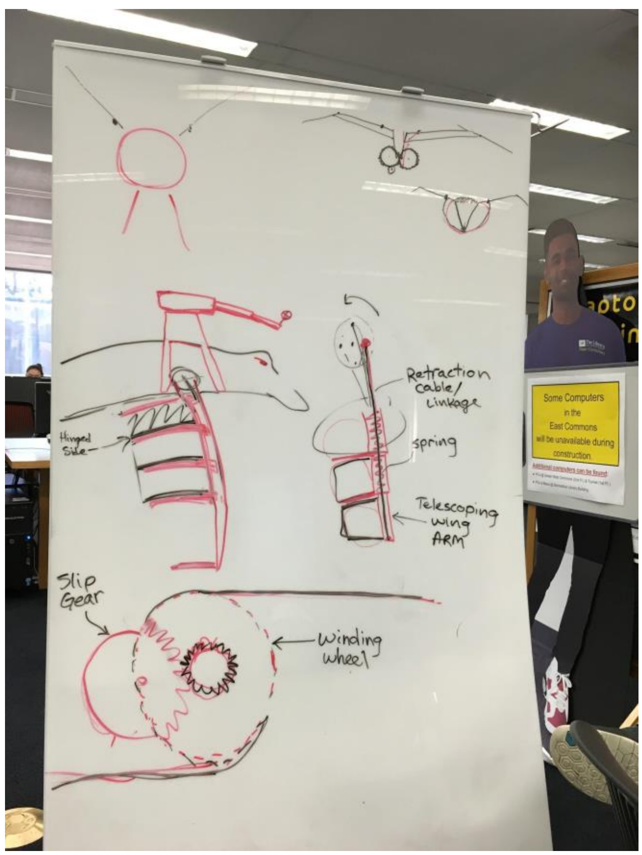



*Figure 19: Brainstorming Board*

*Figure 20: Proof of Concept Test Frame Mounted on Beam for Testing*


*Figure 21: Black & Decker 12-Volt Ni-Cad 3/8 in. Cordless Drill (Image from HomeDepot.com)*

Figure 22: Inner and Outer Wing Design Iterations

| Wing Type | Tare | Averaged Signal | Change |
|---|---|---|---|
| Baseline (No Wing) | 451 | 451.86 | 0.86 |
| Flat Hinged | 451 | 449.39 | -1.61 |
| Inner Flat | 446 | 447.65 | 1.65 |
| Shutter (inward) | 450 | 447.96 | -2.04 |
| Shutter (outward) | 450 | 445.83 | -4.17 |
| Vented Fixed | 484 | 486 | 2 |
| Vented Fixed (Adjusted Swing) | 457 | 461.67 | 4.67 |

Table 2: Output Data from Arduino of Initial Wing Iterations

Figure 23: Vented flap wing data; Average mean force: 0.0613 lb

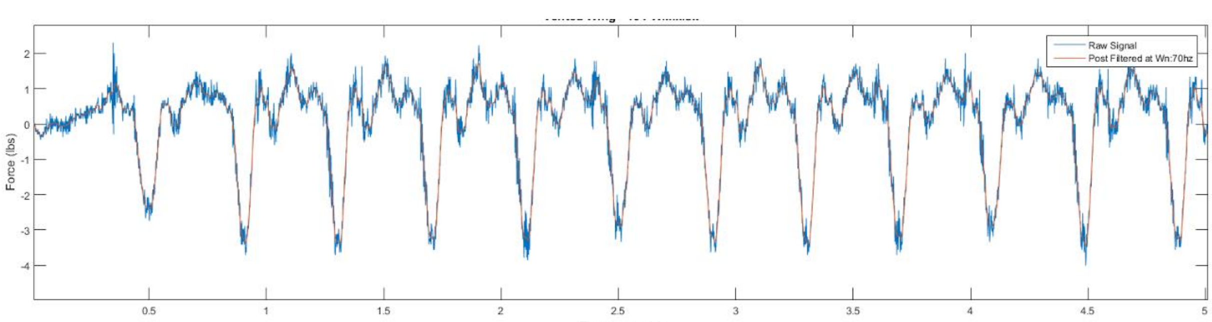


*Figure 24: Flat torsion wing data: Average mean force: 0.075 lb*

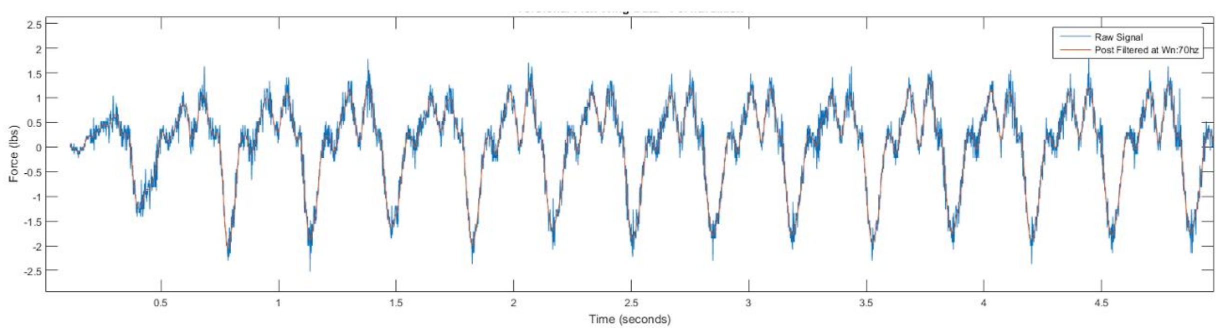



*Figure 25: Ribbed torsion wing data. Average mean force: 0.035 lb*

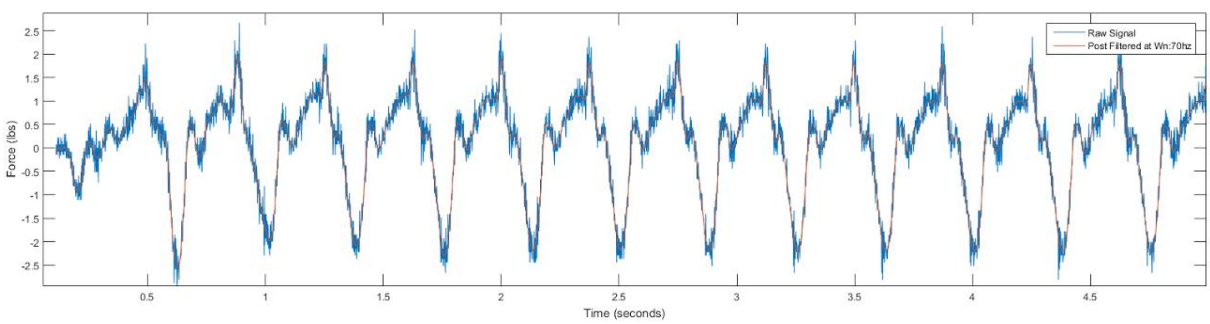
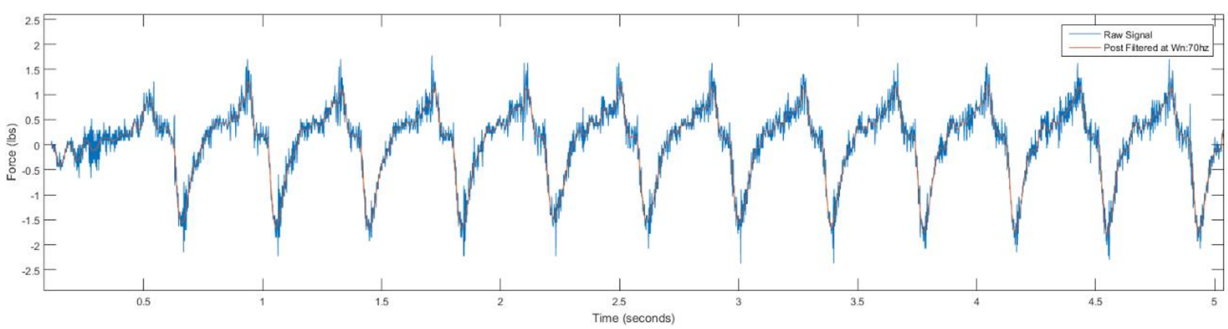



*Figure 26: Flexed wing data; Average mean force: 0.105 lb*



## APPENDIX 6: Spec Sheets for Purchased Items

Item: Black & Decker 12-Volt Ni-Cad 3/8 in. Cordless Drill with Soft Grips
Model #: GCO1200C

| | | | |
|---|---|---|---|
| Batteries Included | Yes | Maximum Speed (rpm) | 750 |
| Battery Amp Hours | 1.5 | Number of Batteries Included | 1 |
| Battery Power Type | Ni-Cad | Power Tool Features | Keyless Chuck,Variable Speed |
| Battery Size | Sub-C | Power Tool Product Type | Cordless |
| Case Included | No | Product Weight (lb.) | 4.75 lb |
| Charger Included | Yes | Reconditioned | No |
| Chuck Size | 3/8 In. | Returnable | 90-Day |
| Chuck Type | Keyless | Tools Product Type | Power Tool |
| Color Family | Orange | Variable Speed | Yes |
| Cordless Tool Type | Combo Kit | Voltage (volts) | 12 |
| Cordless/ Corded | Cordless | | |

*Table 3: Specification Sheet for Black & Decker Cordless Drill*

## APPENDIX 7: Budget

| **Budget Limit =** | **$1,500** | | | **Total Spent =** | **$1,266.25** | **Remaining =** | **$233.75** |
|---|---|---|---|---|---|---|---|
| Date | Description | Vendor | Specified by (team member name) | Order Method: Purchase Request Form or Personal Reimbersment | Amount | | |
| 4/18/2016 | Robo 3D R1 Plus Printer | Amazon | Tyler Hartwell | Purchase Request Form | $908.79 | | |
| 6/6/2016 | Electronics | We-Supply | Kyle Candee | Personal Reimbersment | $44.80 | | |
| 6/6/2016 | Electronics | Fry's Electronics | Kyle Candee | Personal Reimbersment | $23.57 | | |
| 6/6/2016 | Foamboard and Pins | Michael's | Cindy Feng | Personal Reimbersment | $9.57 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6/6/2016 | PLA Filament | Amazon | Tyler Hartwell | Personal Reimbersment | $50.57 | | |
| 6/6/2016 | Cordless Drill | Home Depot | Kyle Candee | Personal Reimbersment | $32.37 | | |
| 6/6/2016 | Bike Fender | Wholesale MX | Kyle Candee | Personal Reimbersment | $40.84 | | |
| 6/6/2016 | Geared Motor | ServoCity | Kyle Candee | Personal Reimbersment | $21.98 | | |
| 6/6/2016 | Load Cell and Amplifier | SparkFun | Kyle Candee | Personal Reimbersment | $72.66 | | |
| 6/6/2016 | Acryllic | Campus Research Machine Shop | Kyle Candee | Personal Reimbersment | $58.40 | | |
| 6/6/2016 | Nylon Bearings | Marshall's | Kyle Candee | Personal Reimbersment | $2.70 | | |