Fluidic Muscle Ornithopter

MAJOR QUALIFYING PROJECT REPORT
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DEGREE OF BACHELOR OF SCIENCE

Report Submitted To:

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Abstract

The scope of the project was to create an ornithopter, a bio-inspired flapping wing mechanism to produce lift. The developed system utilizes pneumatics as the pressure source to power fluidic muscles actuating an ornithopter. Powered by compressed air these muscles take the place of the pectoral muscles of a bird creating a powerful flapping motion in order to counter gravitational forces. This seagull inspired design incorporates airfoil profiled wings with passive angle of attack change and custom motion limiting joints with shock dampening developed for the specifications and scale of the project which produced measurable lift forces.

1. Introduction

1.1 Motivation

The idea of human flight has been present throughout history. Recreating flight has proven successful to varying levels incorporating the use of artificial flapping wings. These attempts have lead research towards the idea of an Ornithopter, a bio-inspired robot utilizing a flapping mechanism to achieve flight. While the development of the airplane and the jet engine have changed history and have led to the evolution of air travel, the ability to achieve flight with flapping wings like a bird has still remained elusive. A large-scale ornithopter can become more efficient than a normal airplane by gliding and flapping, and could become a new mode of transportation if its feasibility was developed further.

This project pushes research forward to creating a new type of flapping wing using fluidic muscles. Beginning with the technology formerly referred to as hydraulic actuated muscles (Effraimidis, 2014), this project researched the application of pneumatic actuated muscles, therefore advancing the technology to an all-encompassing "fluidic muscles".

1.2 Project Goals

The goal of this MQP is to construct a functioning ornithopter to generate and measure lift. The ornithopter will be actuated utilizing fluidic muscles powered by air. In order to achieve this goal extensive research was conducted on compressors and fluidic muscles. The ornithopter will be constructed with articulating wings in order to maximize lift and to more accurately mimic motions seen in nature. If these objective are achieved researchers will determine requirements for future ornithopter adaptations. Figure 1 breaks down the project goal into two main branches.
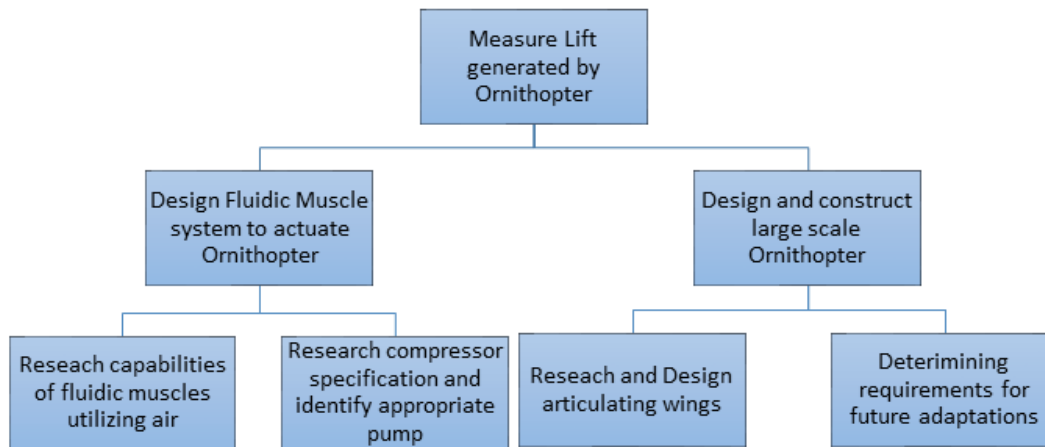
Figure 1: Objectives Tree for Project

1.3 Project Approach

This project began with initial research on ornithopters to develop designs for a system and performed calculations to determine its lift capability. The decision was made to use a tethered ornithopter to evaluate lift in a controlled and measureable environment. The team also researched fluidic muscles to be utilized with compressed air that could be incorporated into the design. Tests were conducted to evaluate different diameters of muscles to choose the appropriate option. Additional calculations were done to determine frequency of flapping required and the pressure the muscles would need for operation. Tests were done by tethering the fully assembled ornithopter and utilizing a high speed camera to quantify lift generated by the wings. The results were used to determine change in position, velocity, and acceleration of the center of gravity. Further research was done to determine an initial velocity the ornithopter would require to achieve sustained flight.

2. Literature Review

2.1 History

An ornithopter is a heavier-than-air aircraft that achieves flight with flapping wings. The name of "ornithopter" is derived from Greek, "ornitho" meaning "relating to a bird" and "pteron" meaning "wing" (Random House, Inc., 2015). Humans have built flying machines which were inspired by birds in order to achieve their dreams of flying, making ornithopters one of the oldest ideas for flight. There have been many attempts of human flight with little success. The first recorded attempt at human flight occurred in 60 AD by Eilmer, a Benedictine monk. Eilmer created a 'tower jumper', wings affixed to human arms that would allow a man to jump from a high place and 'fly'. Unfortunately Eilmer's experiment ended in failure as he glided 200 meters before falling and breaking his legs (Goodheart, 2011). Later Franciscan monk, Roger Bacon, began to investigate human flight. He suggested a model utilizing 'artificial wings that beat the air' (Wegener, 1997), formally discussing ornithopters in an educational setting for the first time in history. While Bacon never successfully built a flying machine, the development of a bio mimicked flight progressed as an area of interest for many scientists and scholars, such as Leonardo Da Vinci, who is believed to be the first designer of a complete ornithopter in 1485 (Gray, 2003). The hot air balloon was the first invention to lead to a successful human flight in 1783 (Goodheart, 2011). For many centuries hot air balloons were the only form of human flight until the invention of Zeppelins in 1898 (Grossman, 2014) and the first successful fixed wing flight of Wright brothers just a few years later (EyeWitness, 2003).

Ornithopters became interest of scientists in 1920s when German scientist Alexander Lippisch made a successful ornithopter design that was able to fly. His 1929 design was able to

achieve 'powered glides with the help of catapult launches' (Rashid, 1995). While many consider this attempt unsuccessful due to the use to catapults, it was a major step forward for the ornithopter.

2.2 Inspiration

Initial client statement included a "biologically inspired design" term. Research was conducted to find acceptable models to base our project on. Team's findings indicate that the wing of a seagull is an appropriate starting point to base the design from. A large amount of research has previously been conducted and published on flight of seagulls, which makes it an optimal starting point to find useable data and information. Scientists concentrated their works on seagull wings and they created a similar airfoil shape. The specific wing design was closest to that of a seagull the S1223 airfoil (Liu, 2015). This airfoil was modified and adapted to our project and serves as a basis for our wing design. Seagulls take advantage of both gliding flight and flapping, which does not limit the project to one type of flight pattern and allows variable flapping frequencies to be tested. This makes it a suitable model for our project which may rely heavily on gliding ability to support time between flaps.

2.3 Current Ornithopters

There have been many attempts to build a flying prototype. In 1999, "Project Ornithopter" was a successful ornithopter. It was designed as a self-accelerated engine powered aircraft with flapping wings and neared a liftoff speed (Project Ornithopter History , 2008). At MIT, a project 'Design and Construction of an Autonomous Ornithopter' by Zachary John Jackowski, succeeded flying in 2009 (Jackowski, 2009). However, arguably, the most successful ornithopter built is the Festo Bird. It has a wingspan of 1.96 meters, weight of 450 grams, a self-contained power source,

and is radio controlled. It was a successfully flown and controlled robotic bird, inspired by seagulls (Project Ornithopter History, 2008).

2.4 Types of Flights

There are two main ways to create lift. The first way to create lift is by using fixed wings as airplanes do. Although helicopters have rotating wings, they are achieving lift in a similar way as fixed wing aircraft do. The second way to produce lift is by flapping. In this way, both lift and thrust is produced. This way of flight is used by insects and birds.

2.4.1 Fixed Wing Flight

The main difference between a fixed wing aircraft and an ornithopter is how they achieve flight. A fixed wing creates lift by utilizing the airflow around the wing. Air flowing over the upper surface of the wing travels a greater distance due to its shape, than the air traveling below the wing. This increases the velocity of the air flowing above the wing relative to the airflow below the wing. This creates a pressure difference between upper and lower sections of wing with higher pressure on the lower side. This pressure difference creates the lift force over the wing.

2.4.2 Flapping Wing Flight

A flapping wing creates lift by pushing down on the surrounding air. A drag force created by the wing's motion creates upward lift. Main difference between the fixed wing and a flapping wing is that a flapping wing can create thrust by pushing the air backward. In nature, flight has evolved into two main forms, insect flight and bird flight. Birds and insects both utilize flapping wings to achieve lift, although their methods have significant differences.

2.4.3 Insect Flight

Many insects provide excellent examples of hovering flight. Insects flap their wings in a nearly horizontal plane, accompanied by large changes in pitch angle and angle of attack to produce lift. This lift can be achieved in the absence of any forward velocity. Among insects, some of them are capable of taking off backwards, flying sideward, and landing upside down. This proves that an insects' method of flight can be very maneuverable and allow for a highly flexible flight path.
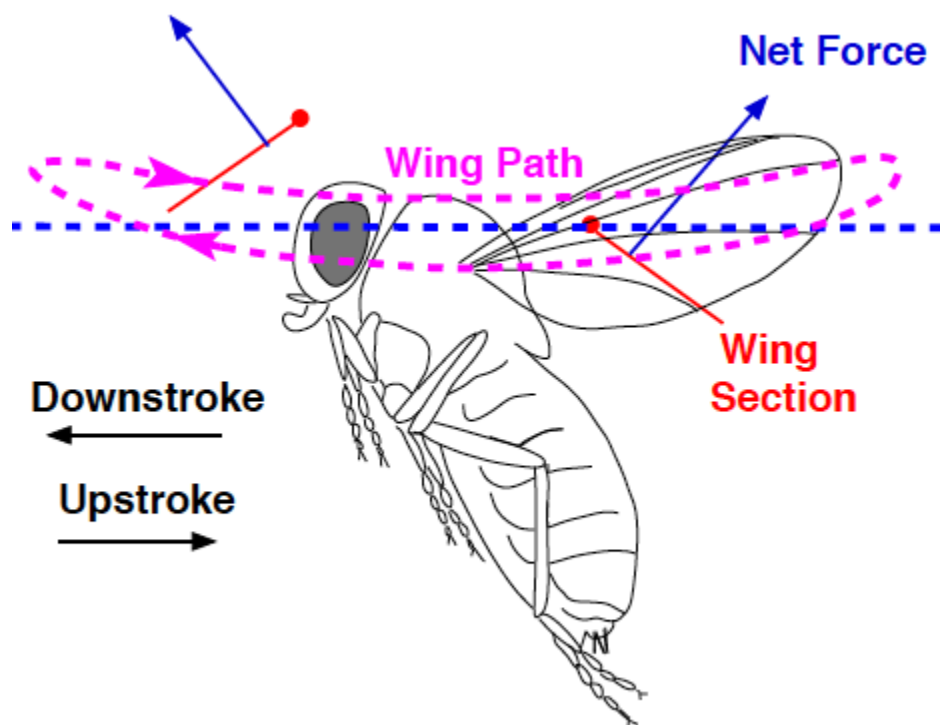
Figure 2: Depicts the typical horizontal flapping motion of an insect (Beerinder, 2006)

2.4.4 Bird Flight

Birds are much larger and heavier than insects leading to the development of a different flapping style. In contrast to flapping motion of the insect, birds flap their wings along a vertical plane with fewer changes in the pitch of the wings as well as reduced change in angle of attack (Beerinder, 2006).
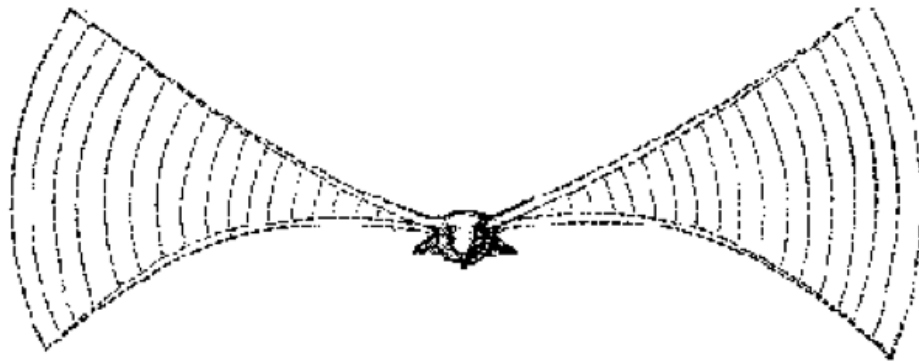
Figure 3: showing vertical wing motion of a seagull (Lilienthal, 1911)

The reality of avian flight is intricate and complex. Different species of birds implement different types of flight. Flapping frequency of a smaller bird is higher than a bigger bird and larger birds are observed to be gliding more often than smaller birds. Size changes the way birds fly. Pigeons are examples of smaller birds. They flap their wings at a greater frequency than a larger bird and have a more of a bounding flight. Hawks have a large wingspan and rely on their aerodynamic wings to glide through the air and can sustain flight without the need to regularly flap to conserve energy.

In order to develop the control of flight, birds have evolved to control the shape and the span of their wings by flexing their wings inwards. However, without large changes in wing pitch and angle of attack, this type of motion does not create enough vertical force to support the weight. This means that in absence of any forward speed, most birds cannot hover (Beerinder, 2006).The

cruising speed of the bird flight is determined by different factors such as wind speed. During migration birds fly at a higher altitudes and slower speeds than normal in order to maximize energy efficiency for the long distance traveled. Depending on whether the bird is a predator or a prey, birds have adapted to fly at specific speeds (Hedenstrom & Alerstam, 1995).

2.4.5 Flight Characteristics of Seagulls

Seagulls are classified as larger birds due to their mass and size. Their flapping frequency of a seagull is about 3 Hz which is much lower than a small bird such as pigeon that has a flapping frequency of 5 Hz (Journal of Engineering & Technology, 2013). The flight behavior of seagulls reflects partially on their physical anatomy and partially on their needs to be successful in their environment. Seagulls have been recorded with air speeds of 10 to 40 MPH in various flight situations (Ehrligh, Dobkin, & Wheye, 1998). While in flight, maintaining a constant and optimal air speed requires the least amount of energy to be expended for continued flight and increases the efficiency. An ornithopter that can maintain level flight rather than climbing and falling will be more efficient to fly. For a gull that has an optimal level flight airspeed of 22 mph could fly between 15 and 28 mph with less than a 15 percent increase in metabolic rate (Ehrligh, Dobkin, & Wheye, 1998). When building an ornithopter of similar shape, it is important to find its own optimal flight speed and range for maximum efficiency and performance.

Aside from the takeoff, level flight, and landing expected, gulls are frequently circling in level patterns for searching for food and protecting themselves from predators. Circling also is done to take advantage of updrafts which make the gulls use less of their own energy.

In order to create an optimal design for the ornithopter, the geometries and motions that make a gull wing function must be understood. The wing profile, airfoil shape, joint locations, and

bending angles during sustained flight must be identified and quantified. Once this information is known, a mechanism can be developed to mimic the necessary motions during flapping. Angular changes at each joint as well as along the length of the wing occur. These changes are governed by the bones and muscular system of the gull. Even with these flexing locations, the wing remains a continuous entity.

Below, five different gull wing types are shown. Exact shapes and dimensions vary from species to species, however they all perform the same general motions. Each wing comes from a gull of roughly the same shape and weight, but of different species. The similarities in function allow us to select the most applicable shape to model of the gull wings.

Figure 4: From top to bottom, adult Herring, Thayer's, California, Ring-billed, and Mew, all from Washington (Descritption of the Herring Gull, n.d.)

The wing shape of the adult herring gull was selected for use because of the consistency in structure over the wing length that will allows for both ease of modeling as well as physical construction.

2.5 Wing Structure and Muscular System of Seagulls

Birds have evolved for efficiency in flight through the development of their skeletal and muscular systems. A light skeleton and powerful muscles both contribute to a birds' ability to fly. Bird skeletal systems are very different from many other animals; their bones are hollow and many individual bones have fused together to create a rigid structure. The skeletal system of birds pneumatized, or became hollow though evolution (Dumont, 2010), decreasing their body mass and decreasing the required energy needed to fly. Additionally many bones, such as the lower vertebra, have fused together to create a more rigid skeleton that can withstand the forces created by flight (Tumlison).

In addition to their modified skeletal system, bird's muscles are similarly suited for flight. Strong muscles are needed in the wing to overcome the forces of flight. Muscles make up a majority of a bird's weight, large flight muscles such as the pectorals make up most of a bids muscular mass. In a seagull, the ratio of pectoral mass to body weight is 10:1 (Damian, 2011). These pectoral muscles are very important in pulling the wing through the down stroke. As seen in figure 5 many of the other muscles in the wing are much smaller than the pectorals and are used mainly for stabilization and the upstroke.
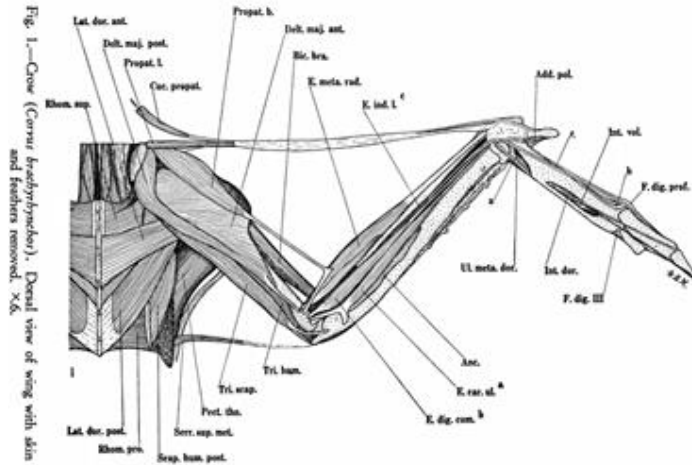
Figure 5: Muscular system of a bird's wing (Dumont, 2010)

2.6 Advantages of Flapping Flight

Ornithopters can be designed and built in a way to mimic bird flight. Making use of winds, gliding, and the able to hover at almost zero forward velocity can greatly increase efficiency. Ornithopters have the potential to be more maneuverable and able to fly to places that are currently unreachable (Van Breugel & Lipson, 2005) (Mueller & DeLaurier, 2001). An aircraft with flapping wings would require a shorter runway than a fixed wing aircraft. The ability to create large amounts of lift over a short distance allows for nearly vertical takeoff. These characteristics make ornithopters an excellent option as possible future transportation aircrafts (Ebrahimi & Mazaheri, Aerodynamic Performance of the Flapping Wing, Applied Aerodynamics, 2012).

Ornithopters have many advantages to fixed-wing aircraft, especially in surveillance and guarding. They have the potential to produce quieter aeroacoustics (Goodheart, 2011) and hover more efficiently than helicopters. For example, a Dutch company is developing "Robirds", radio-controlled ornithopters for use in various environments such as airports and waste facilities. (Whitney Hipolite, 2014). The robot birds look like a predator and scares the birds at airports to

avoid any collisions with aircrafts and increase flight safety. At waste facilities, they are designed to keep the birds away from the waste, which will decrease the spread of the waste materials in the surrounding areas. Slow flights and high maneuverability of ornithopters make them important Micro Aerial Vehicles (Burns, 2014). The development of larger load carrying ornithopters may be beneficial to transporting supplies with stealth too hard to reach places.

3. Project Strategy

3.1 Initial Client Statement

A project topic and a client statement were drafted at the start of the project. This statement was used to ensure that the client's objectives would be fulfilled throughout the course of the project. After the team's initial meetings with the client, Professor Marko Popovic, the following initial client statement was established:

"The goal of this project is to design, build, and test a bio-inspired ornithopter actuated with hydraulic muscles. The ornithopter must be self-contained and powered, and able to fly 50 meters. The ornithopter must be able to maneuver in order to maintain a stable flight path".

One major challenge was lack of knowledge on fluidic muscles. Fluidic muscles were developed by Popovic Labs in 2014. To advance the technology the team decided to utilize air, a compressible fluid, to actuate the muscles as it would significantly decrease weight.

3.2 Objectives and Constraints

3.2.1 Objectives

With the initial client statement in mind three objectives were created to design and build an ornithopter to flap in a manner representative of a bird wing and to generate lift from this flapping motion.

The first objective was to create a mechanism that would flap similarly to the motion of a bird flap. The team would achieve this motion in two ways; by incorporating a mid-wing joint and

an angle-of-attack change. These mechanisms would be important in maximizing the lift force on the down stroke and minimizing the downward forces during the upstroke. The second objective was to calculate the estimated lift forces that would be created by the wings. To find the required lift force, estimated weights and required powering system needed to be found. The third objective was to build and test the ornithopter.

3.3 Design Constraints

The team was given $160 for each member, adding up to a total budget of $640. The total purchase of components of the ornithopter must not exceed $640.

The ornithopter must have a certain wing span in order to achieve the required amount of lift force. However, wingspan is limited by the laboratory space and the available space in the testing location. It must be able to be built in the laboratory with available resources and space restraints. Weight and size of the ornithopter must be appropriate for transportation to the field for testing. All components should be able to be manufactured on campus or be acquired through other means within our time and budget constraints.

3.4 Experimental Constraints

The ornithopter must be safe to test and operate. If any failures were to occur during tests or operation, there must not be any projectiles which could cause injuries, deaths, or damage to the surroundings. Pressure inside the muscles must not exceed 100 Psi to minimize the chance of a muscle failure.

The ornithopter must be highly durable in order to withstand forces created during the flapping motion due to large and instantaneous forces created by the wings. The ornithopter must be able to tolerate any crashes during testing. In case of a crash, pieces that are broken must not be impossible to replace without causing large delays to the project timeline. All tests must be possible to replicate.

Availability of required materials such as air compressor is another constraint. The compressor that satisfies pneumatic muscle's air flow-rate and pressure range as well as being lightweight was not commercially available. Available compressors were either too heavy or did not meet flowrate requirements when they were within the pressure range that the team needs.

Another constraint was availability of satisfactory testing space. In coordination with WPI's Sports and Recreation Center Staff, the team was able to secure suitable space for testing which also allowed for flexibility in scheduling necessary tests.

3.5 Revised Client Statement

After completing the initial pressure testing of the muscles the desired pressure and flowrate for a 2 Hz flapping frequency was determined. Extensive research on air compressors was conducted and we were unable to identify a compressor that satisfied the pressure and flowrate requirements while remaining under the projected weight limit.

Three options were created for the continuation of the ornithopter. The first option was to contact a company to design and build a custom compressor for our purposes. This option would cost a significant amount of time and could consume most of the budget. The second option was to design and build a custom compressor ourselves. However, lack of knowledge and time would make it impossible to realize this option. The third option was to have a tethered flight using a

much heavier air compressor that could supply the desired flow rate and pressure. To make this project possible, the client statement was revised as follows:

> *"The goal of this project is to design, build, and test a bio-inspired ornithopter actuated with pneumatic muscles. The goal is to test the flapping of wings, measure the displacement of the ornithopter, and calculate the amount of lift force created by the wings. The constructed prototype does not have to fly. The design should help researchers to observe and analyze the effects of flapping wing and lift generation by the wing"*

The revised client statement states that the ornithopter does not have to fly. Instead, it will be tested utilizing tethered flapping in order to understand and observe the fundamentals of the motion and associated forces. The power source and compressor will not be contained within the ornithopter, instead a pressure line running from an external compressor to the ornithopter will supply pressure and significantly decrease the weight.

3.6 Project Approach

3.6.1 A-Term

The goals for A-Term were to complete initial background research and to begin the design phase of the project. The timeline to complete these goals can be seen in the Gantt chart below.
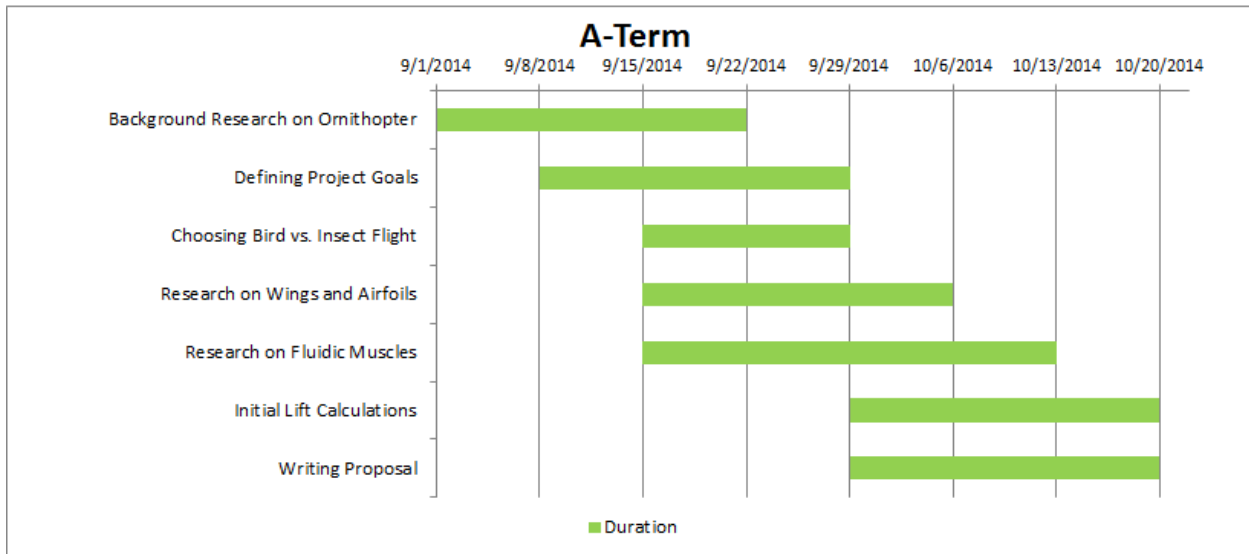
Figure 6: Gantt chart for A-Term

To gain in-depth knowledge for this project the first three weeks were focused on researching the necessary topics for constructing an ornithopter including; previous ornithopter designs, bird physiology, and lift equations. During the second to fourth week project goals were established. Once a base of background knowledge was established a decision was made between replicating bird flight or insect flight. Research on airfoils began in the third week and was continued through to the end of the fifth week. Fluidic muscle research began during week three and continued on into B-Term. During the last three weeks of the term some initial lift calculation were made and the project proposal was written.

3.6.2 B-Term

With the majority of the research complete in A-Term the design of the ornithopter became the main goal for B-Term. The timeline to complete the design portion of the project can be viewed in the Gantt chart below.
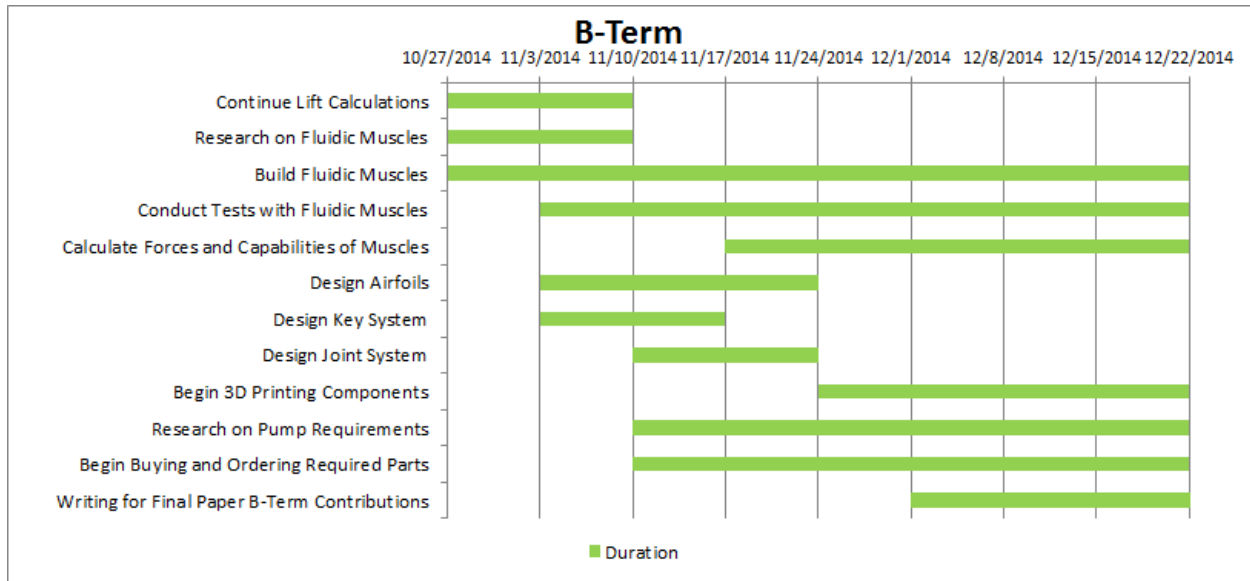
Figure 7: Gantt chart for B-Term

The lift calculations from A-Term were continued throughout the first two weeks of B-Term. Research and construction of the fluidic muscles began in the first week and continued throughout the term. Beginning the second week of the term, tests on the fluidic muscles began and continued throughout the term following developments the team learned from the data collected. The design of the airfoil and key system began in week two and was continued through to the end of week four and three. A joint system for the wings was developed in weeks three and four. 3-D printing of these parts began in week five and was continued throughout the rest of B-Term and into early C-Term. Research into compressor specification and identifying an acceptable compressor began during week three and continued through to C-Term. All other parts required to construct the ornithopter were purchased as needed throughout the term starting during week three of B-Term.

3.6.3 C-Term

C-Term was spent finalizing all designs, completing construction of all parts, assembling the ornithopter, conducting experiments, and analyzing data.
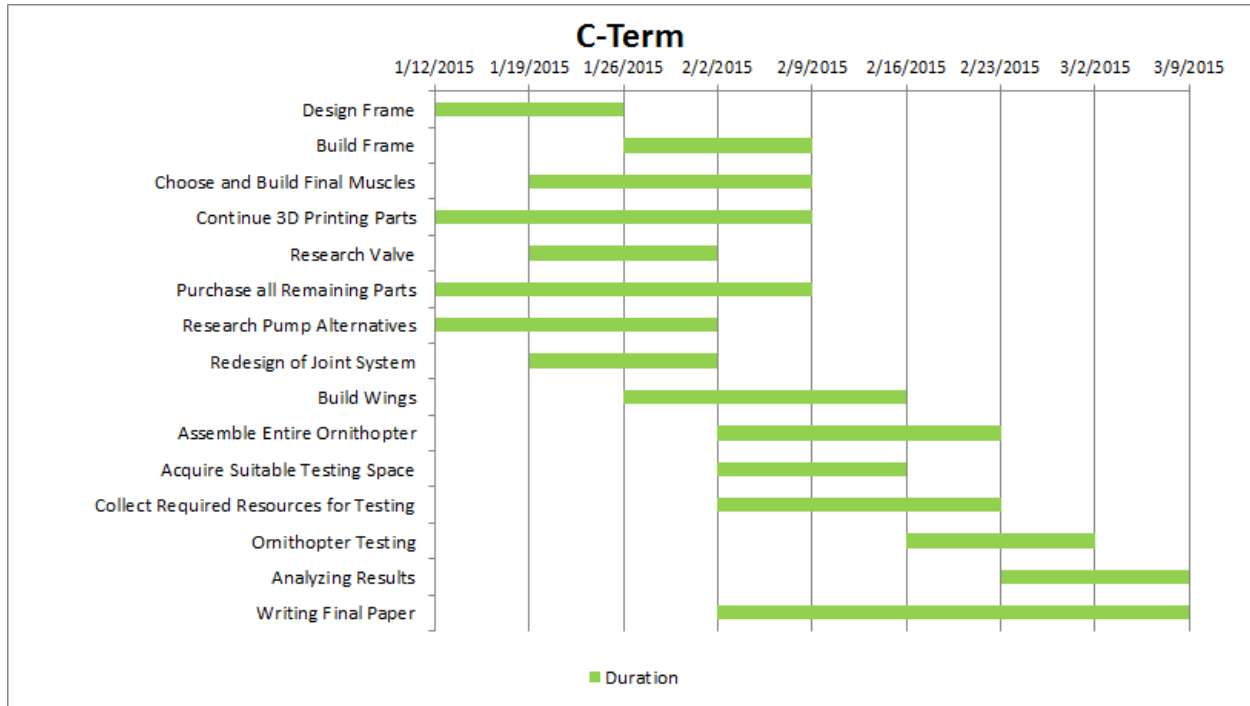
Figure 8: Gantt chart for C-Term

Research into compressors and alternatives, 3-D printing parts, and purchasing additional materials continued through from B-Term and were finalized by weeks three and four. The ornithopter frame was designed in the first two weeks of term and constructed during weeks three. Final decisions on the fluidic muscle system and its construction occurred during weeks two through four. Research into valves and adjustments to the joint system occurred in the second and third week of term. Construction of the wings began during week three and continued on to week five. Assembly of the ornithopter occurred during weeks four through six. A suitable test space was identified during weeks four and five. Tests were conducted during weeks six and seven, results were analyzed in the final two weeks of term. Starting on week four the paper was

completed; sections 3, 4, and 5 were completed and the rest of the paper edited and all sections compiled.

4. Project Design

4.1 Conceptual Designs

There were three main functions focused on for the functionality of the ornithopter. The first was flapping in the vertical plane much like that of a seagull. Powered flapping with sufficient force is the main source of lift for this ornithopter. The second was to change the angle of attack of the wing profiles during the flapping cycle. This allowed for forward propulsion and a reduction of undesired drag during the upstroke. Having this function passively is most feasible to implement. Third, much like changing the angle of attack, a bending motion at a mid-wing joint provides for another way to reduce drag during the upstroke and mimics the actions of most birds.

4.1.1 Wing Profile

In choosing a wing design, lift and functionality with the fluidic muscles were the main concerns. The main need of the profile was to provide lift while moving forward and be compatible with a primarily vertical flapping pattern. Through research it was determined that the closest wing profile to that of a seagull which we were trying to approximate for its flapping pattern is the S1223 airfoil. The advantage of using an airfoil over a flat wing is that lift is generated from air passing over the wing from the forward velocity of the ornithopter without any additional energy input required.

4.1.2 Body Joint

At the section where the wing frame meets the body, a powered range of motion of 40 degrees was desired. Accounting for some inertia as well as desiring a smooth transition between flapping actions, the range of motion for the joint was specified as 5 degrees below level and 45

degrees above level. The upper limit was not as important as this will largely be limited by the muscle extension.

In order to decide on the best design to pursue, decision matrices were constructed for each joint and motion limiting design. The criteria taken into consideration include: mass, durability, functionality, repeatability, ease of manufacture, and several more that had a lower importance factor.

Four design possibilities were evaluated, a motion limited single plane of motion joint, a ball joint with limiting cables, a guiding slot system, and a type of U-joint with stops. Of these design options, the single plane motion limiting joint was selected.

4.1.3 Mid-wing Joint

Through observation of seagull flight, having a wing that bent in the middle was critical for reducing the projected surface area during the upwards flapping. Initial observations provided a range of motion from 0 degrees of bend during the downward flap and a maximum bend of 40 degrees on the upward flap. This allowed for a reduction of forces downward and to maximize the upward forces during repeated flapping.

The same four joint type options were analyzed for this application and again the single plane motion limiting joint was selected for use. The motion of this joint was designed for the wing to be fully extended and flat when flapping down and to allow for as much as a 40 degrees change when flapping up.

4.1.4 Angle of Attack Change

Another major aspect of our wing design was having the angle of attack change for different stages of the flapping as well as over the length of the wing. Changing the angle of attack provides the forward thrust required for sustained thrust as well as reduces the drag on the wing during the upward flap by reducing the apparent area.

Both passive and active methods were considered for this application, however passive methods were preferred as this reduced the amount of energy required to operate the wings for some designs as well as reduced the number of components which reduced weight. There were five total designs reviewed for angle of attack control; a keyed hub and airfoil profile, a double muscle set up, a slot limiting system, a two dowel system, and a shaft within a tube. Of these, the keyed hub setup was selected using a similar decision process.

This design further allowed for the option of having different angles of attack over the length of the wing which allowed the portion dedicated primarily to lift and the portion dedicated to thrust to be easily adjusted during the development stage because each airfoil profile could act independently of each other.

4.1.5 Muscle Capabilities

The type of actuators used for the motion of the ornithopter were made of latex tubing inserted into a tight fabric sleeve. When pressurized, the muscle extends much like a flexible piston. As the pressure is released, the muscle returns to the original length. As the muscle expands it gains potential energy, like an extended spring, which increases the more it is extended and can be rapidly released. In order to characterize the muscles and select specific materials and

dimensions for use knowing the available stored energy and limiting extensions at pressure were needed.

To determine the forces each muscle setup could attain during use, tests were conducted to correlate percent extension to an applied force. Masses were hung from approximately two feet of tubing that were prepared the same as a completed muscle system. As increasing masses were hung from the system linear displacement was recorded and force vs. percent extension was graphed shown below in Figure 9. This information was used to determine the amount of force each muscle could exert on the wing and frame system at different points in the range of motion as well as for different connecting points.

Force to extension id- 1/2, od-7/8

$y = 4E\text{-}05x^3 - 7E\text{-}05x^2 + 0.0169x + 0.0067$
$R^2 = 0.9998$

Data points labeled: 0.0381, 0.05715, 0.0762, 0.09525, 0.1143, 0.13335, 0.15875, 0.18415, 0.20955, 0.23495, 0.2667, 0.301625, 0.339725

Y-axis: ΔL (in)
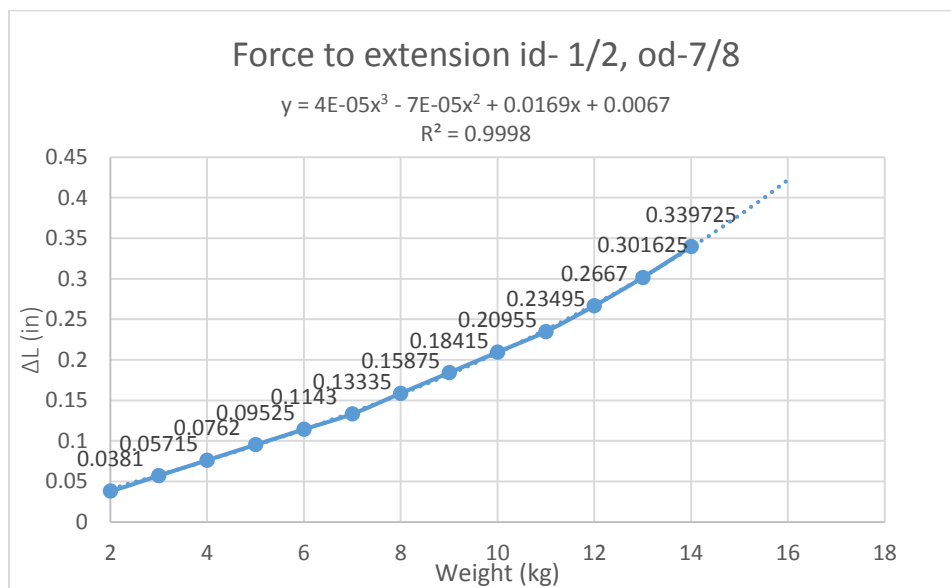X-axis: Weight (kg)

Figure 9: Force to extension for the selected muscle diameters

4.1.6 Actuation System

For the purpose of powering the wings of the ornithopter, hydraulic muscles were first proposed. A pneumatic system, one that had previously not been tested or implemented was also analyzed for functionality and mass requirements. The system was initially specified to operate at

2 Hz continuously, during testing a flapping frequency of 1.8 Hz was achieved. This provided a required frequency of valve operation, two complete cycles per second, as well as to not be a limiting factor for flow rate of fluid in and out of the muscle.

The pneumatic system presented similar operational characteristics with additional benefits. A pneumatic system allowed for an open system without the need to store any liquid in a reservoir on the ornithopter providing for the most substantial reduction of weight compared to previously used closed loop systems. It also allowed for use of a single 3 way valve rather than a multi valve system.

Since large, rapidly contracting forces can be obtained from the fluidic muscles, using them to power the downward flapping motion was optimal. Force, pressure, and extension tests were used to select the placement and connections of these muscles. This was limited by the attainable maximum extension and the minimum force required to provide sufficient torque to the wing about the body joint.

A passive force was used to return the wing to a lifted position when the muscles were inflated. This did not need to be a large force as the wings were constructed to be very light as well as to produce minimal drag when moving to the fully upright position. This was accomplished by attaching small diameter latex tubing to points above the body and connecting the ends to a location near the mid-wing joint. This allowed the tubing to be as long as possible and perform more uniformly during use.

Additionally, the partial filling of the muscles with a rod to take up volume and to reduce necessary flow was considered. This is likely only viable when using compressible fluids because the internal volume change, not the total volume, is needed for muscle function.

4.1.7 Frame Design

For the frame and central structure of the ornithopter, rigidity, stability, and modularity were the top priorities. The frame needed to provide attachment points for the wing joints that were 12 inches apart and provide muscle attachment points 12 inches below the wing joint pivot point. Additionally, the frame needed to provide a structure to contain all operational equipment required inside the ornithopter itself. The two top design concepts were a triangular prism and a pyramid design. Using a triangular design allowed for it to be expandable and provided a stable testing structure. Additionally no special angle bracket systems were necessary and allowed for comparatively less mass. Extensions for additional structures like a tail or repositioned muscle mounts are also easily added with this design.

4.2 Building Prototypes

For many sections of building and testing prototypes, a plastic extrusion based rapid prototyping machine was utilized. Once a design reached its final iteration, final parts were printed in solid PLA plastic for strength and rigidity during testing. This also allowed for lighter weight designs not easily produced with traditional methods like milling or laser cutting.

4.2.1 Airfoil Prototypes

Airfoil prototypes were constructed first to produce the profile of the S1223 airfoil on the scale needed for the design. The following iterations focused on weight reduction, increasing rigidity, and refining the fit between sections of the airfoil. During these iterations, matching whole designs were integrated into this process in conjunction with the angle of attack change prototyping. A final length of just over 13 inches of supported profile was able to be produced and

have additional plastic provide near an inch of extra length to the profile. The hole for this was placed forward of the center of mass of the airfoil by 10% to allow for the passive motion with the air resistance to function properly.
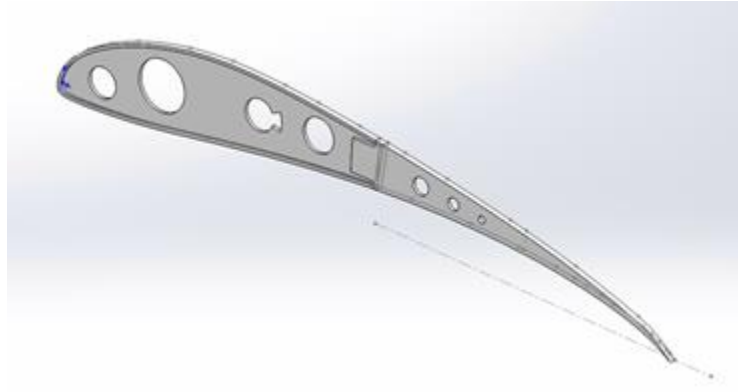

Figure 10: Airfoil prototype sections with keyed hole, connective tab, and reduced material volume

4.2.2 Angle of Attack Change

The angle of attack change system was selected as a key and slot system that needed to keep the airfoil in plane and limit the angular motion of each airfoil repeatedly and uniformly. This was accomplished first by having a set key size on the wing frame and altering the size and angles of the slot in the airfoil. For simplification, later iterations were made to use all the same airfoil parts and only change the size of the key insert. These also were changed to have the slot in the rear of the airfoil profile to allow for smoother motion and protect the more fragile design elements in the case of a front impact to the wing.

Figure 11: Key that fits over the central wing dowel and limits airfoil motion

The desired distal change in angle of attack was designed for 11 degrees and the final prototype during flapping produced a 10 degree change. The loss of a single degree can be accounted for in manufacturing inaccuracies and when a wing covering was added.

During the construction process, design objectives were altered and lift maximization became a priority. For this reason thrust was no longer required and the angular placement of the airfoils was modified to reflect this objective change.

4.2.3 Muscle Placement

Placement of the frame and wing muscle connection points were limited by maximum percent extension from the selected muscles as well as the forces each could exert. Experimentally, a maximum extension of just over 30% was achieved. It is likely that higher muscle extensions may be possible however the compressors available were unable to achieve this.

To simplify the wing model, a single point mass two thirds out from the body was used to approximate the primary force opposing the muscle. The total lift used in calculations was double that of the predicted ornithopter mass.

The two connection points for the muscles to the frame are located on the proximal wing section of the wing and along the lowest frame section. This allows for a maximum of twenty inches out from the body joint and the lower point located 12 inches below the body joint. The attachment points of the muscle on the frame were fabricated to allow for some adjustment and experimentation during the experimentation process.
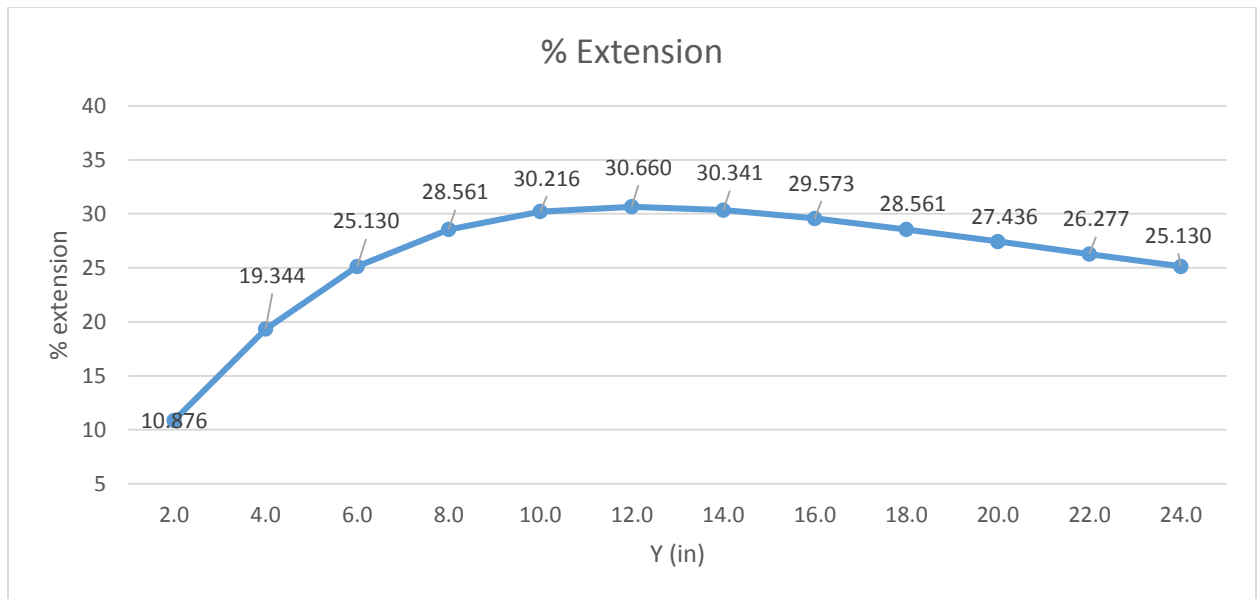
Figure 12: percent extension per distance Y

Within an obtainable range of forces exerted by the selected muscle material, the placement of the bottom attachment was selected to be directly below the body joint and the wing attachment point to be the maximum distance out. These distances are 12 and 20 inches respectively. At these points, the muscle would be required to extent approximately 25%. This provides for a minimum muscle length of 19.5 inches and allows the muscle to move between 5% and 30% extension. Starting at 5% extension provided an initial contractive force from the muscle between the frame and wing.

4.2.4 Custom Muscle Ends

Initial testing of muscle material was conducted using commercially available plumbing fixtures. Although fine to test functionality of the latex, they were both too heavy and did not provide for sufficient locations to be attached to a frame.

To improve this, end pieces were designed to be light weight, function with a single pipe clamp, and have an accessible filling point and attachment points. The filling hole was to be compatible with the 3/8OD tubing of the valve so as not to be a limiting factor in the flow into or out of the muscle at any time. The built in attachment points were specified to hold up to 25kg at any point in time so that failure would be very unlikely for this feature. This strength was verified when testing the muscles for extension and using the same attachment holes.

The ends were then 3-D printed with custom settings to ensure they were air tight to any measurable degree. The muscle end used for filling was altered to allow for filling from the side of the fitting. This was the most feasible option and caused the least interference with the angular motion of the muscles.

Figure 13: Filling end for muscle with end attachment hole

4.2.5 Muscle Control

The motion determined for use in the ornithopter called for continuous motion propelled by a pneumatic system. This meant that an open system would be used and that the only two actions needed would be filling or emptying the muscles. Speed and repeatability were additional high priority aspects. From the initial design specifications, the valve was required to complete a

minimum of two complete cycles per second and operate using an amount of power that could consistently be supplied.

An electrically operated three way valve was selected for the complete control of the pneumatics on the ornithopter frame. This allowed for a single 12 volt signal to actuate the filling or emptying processes of the muscles. Using an open system also allowed for a single pressure line to be run to the valve and the emptying to be done directly into the atmosphere.

4.2.6 Motion Limiting Joints

The joints selected for use with the ornithopter wings were designed to provide a pivot point in a two dimensional plane as well as to limit the angular motion. The angles were determined from observational data collected from seagulls in flight.

After initial geometric functionality was established, several iterations were produced and tested to increase the durability and improve the fit of the joints. Problems with various parts cracking out under high impact were addressed.

During the construction of the central frame, the decision was made to switch to metal hinges with attached sections to only limit the lower limit of the flapping at the body. This allowed for an increased upper flapping angle when inflating the muscles during testing with all other aspects remaining the same.

The mid-wing joint remained unchanged and functioned between the 0 and 40 degree motion for which it was designed without noticeable deviation. After initial tests, an angle of as little as 20 degrees was observed to function much better for the assembled ornithopter. The changing of the maximum bending angle as well as a reduction in impact when reaching the end of the range of motion was accomplished using neoprene for a bumper material. The addition of a

bumper material at the points of contact in the joints allowed for a smoother transition in motions at the limits of the joints. The added cushion also put less stress on the joints when contact was made and in part helped to reduce the chance of failure.
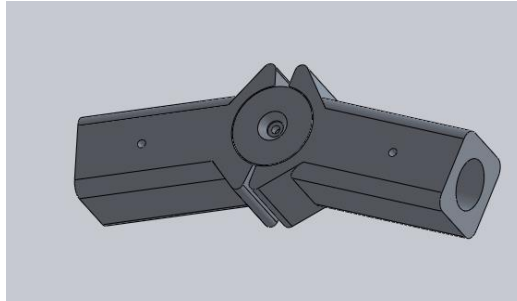

Figure 14: Motion limiting joint for between two dowels in the wing

4.2.7 Frame Development

The design constraints of the frame required a rigid structure on which to mount the wings, muscles, and necessary pneumatic system components. Additionally, minimizing the mass of the frame and allowing for potential expansion was desirable.

A minimal wood frame constructed using gusset plates in the shape of a triangular prism with extensions proved to be the most viable. No special connections were necessary and using wood allowed all sections to be glued for rigidity. Further expansion of this frame is also easily accomplished for additions such as muscle mounting or aerodynamic features. The wings were successfully attached pivoting 12 inches apart with sufficient muscle attachment structure 12 inches below an outstretched wing. The valve and all pressure lines were held in place within the confines of the frame and easily extended out to the controlling units.

5. Experimental Setup

5.1 Muscle Experimental Setup and Measurements

To establish elongation of the latex materials, the muscles were first constructed as designed and left open to atmospheric pressure. The top of the muscles were attached to a secure holder and various masses attached to the bottom. The masses were plastic jugs filled with water to amount to either 1 kg or 2 kg and gathered together using a hook at the bottom muscle connection. These masses were hung freely above the floor. Each trial increased the hanging mass by 1 kg. For each mass, the distance between the two hose clamps of the muscles was measured and recorded for analysis. This process is detailed in the image below.
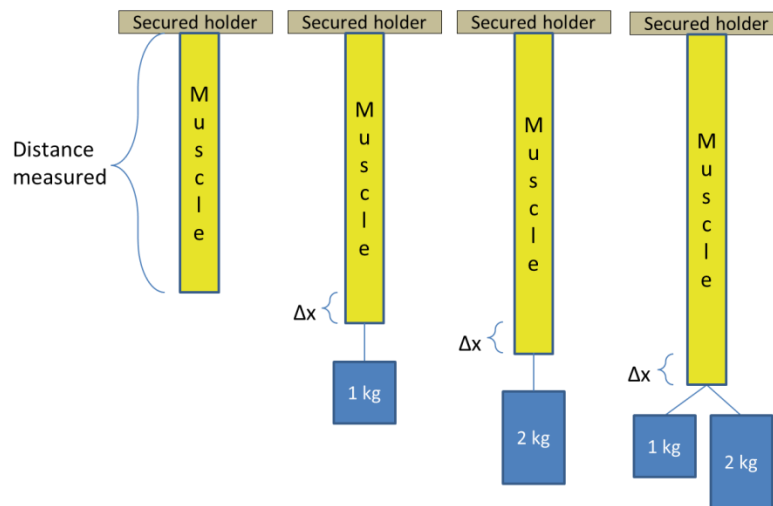

Figure 15: Test setup for Force to Muscle Elongation test

For pressure tests, 3-D printed PLA end plugs were fit to the ends of the latex tubing and secured using hose clamps. Fabric sleeves were secured by inserting them between the hose clamp and latex tubing at the time of assembly. 3/8 inches OD tubing was secured inside of the PLA sections using J.B.Weld to obtain a secure and airtight junction. For supplying pneumatic pressure, a portable air compressor with a maximum pressure of 100 Psi and a built in pressure regulator

was used. For testing, the compressor was connected to the muscle tubing using pneumatic fittings for an airtight connection. The top connection of the muscle was attached to the top of a vertical metal pole and the bottom, with the pressure connection attached, was allowed to hang below. To get to each pressure point for the purpose of data collection, the pressure regulator was opened until that pressure was reached. Then the muscle extension was measured between pipe clamps being held straight to prevent any deflection. After a measurement was obtained, the regulator was then opened up to the next data point and the process repeated until the last data point was collected. For multiple tests the muscle were completely deflated and the next test was restarted from ambient pressure. This process is shown in the figure below.

Figure 16: Muscle testing setup

5.2 Ornithopter Experimental Setup

The tethered ornithopter was hung from a frame constructed with two regulation volleyball poles and 12 feet of one inch diameter electrical conduit held horizontally and secured with adhesive. The ornithopter was balanced at the end of a spring with a constant of 120 N/m. The spring constant was determined by adding a weight to one end of the spring while tethered, measuring the extension created by the weight, and then using Hooke's Law to calculate the spring constant. The ornithopter test setup can be seen in the following image.
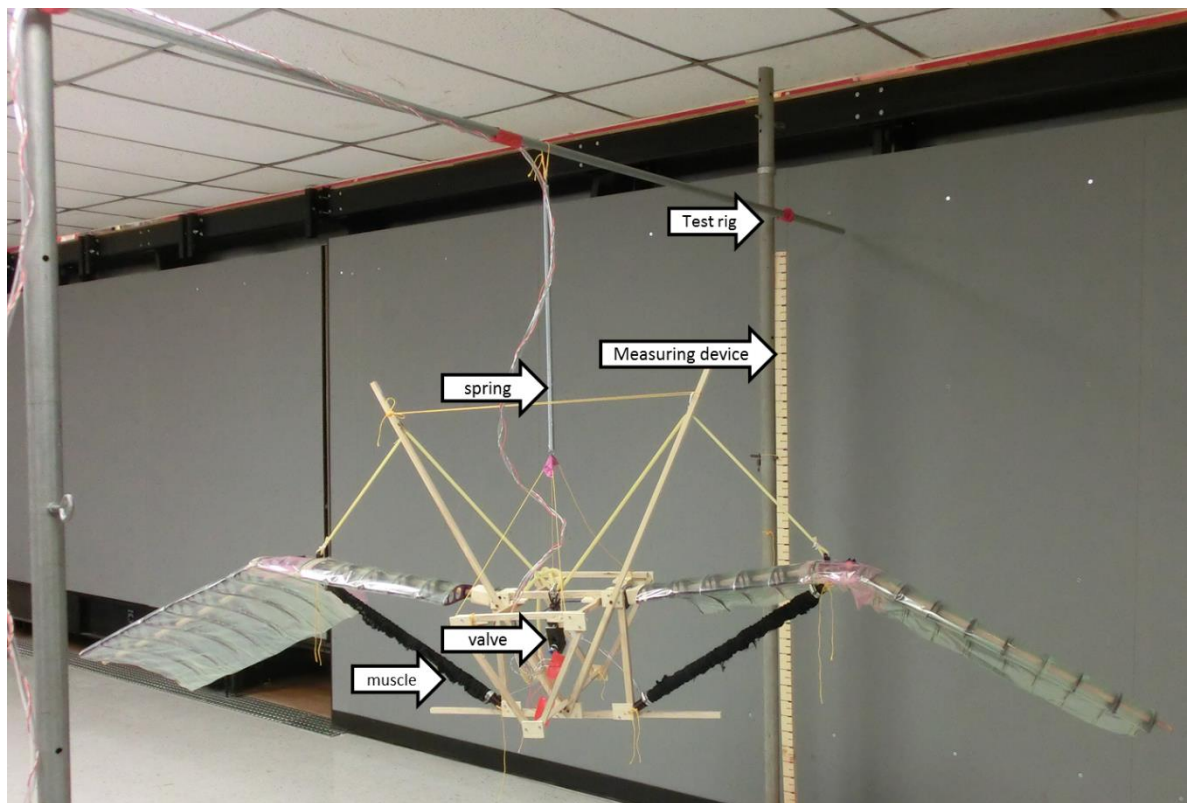

Figure 17: Ornithopter Test Setup

The muscles were pressurized using a 100 Psi portable air compressor with a built in regulator to raise the proximal section of wings to 40 degrees above the horizontal. A variable power source set to 12 volt DC was used to supply power to operate the valve during testing. Once the wings were raised to this position the ornithopter was first stabilized. Then the pressure was remotely released from the muscles for a quick and powerful down stroke. The swift downward motion of the wings created a lift force allowing the spring to compress. This change in length was analyzed to quantify the lift generated. For some tests multiple pressure releases of the muscles were made consecutively so that the motion of multiple flaps could be studied. For the sake of ensuring results could be measured and not altered by the spring force, only the first down stroke was analyzed in the cases where data was taken from tests. The pressure was regulated manually to match experimental muscle conditions and obtain specific muscle extensions that could be held indefinitely in position ready for actuation. This was accomplished using the built in pressure regulator in the compressor available for testing. Much higher pressures were selected in multi flap tests in order to provide the highest flow rate possible with our compressor setup to the system. These components are shown in the image below.
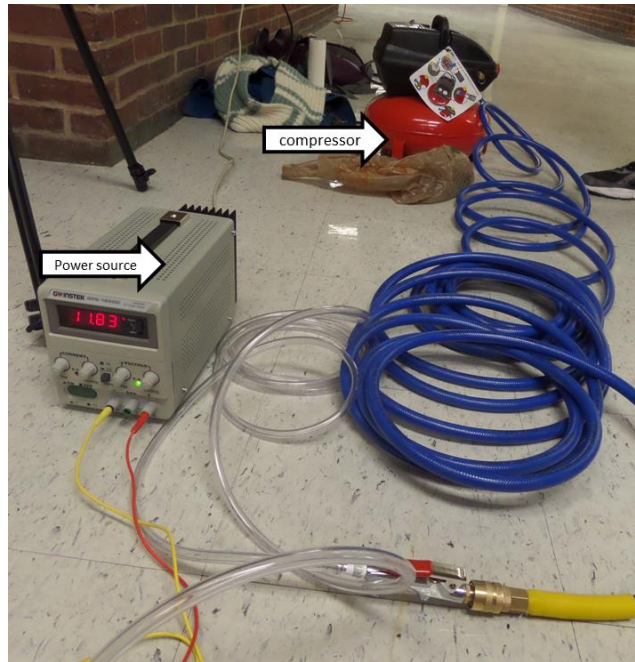
Figure 18: Power and pressure supply for testing

To record data, the team used two different cameras borrowed from WPI's Academic Technology Center. The two cameras used were a SONY Lens G and an Exilim. The cameras were positioned to record data on tests and were operated at the same time so each test would have multiple viewpoints. This allowed different motions and measurements to be studied on the same test, result, and timeframe. The Exilim camera was chosen for its ability to record at a higher framerate of 240 fps. This gave the team the ability to move the videos frame by frame to measure precise motion and record the time associated with the motions. The videos were exported to Adobe AfterEffects studio to be analyzed in a frame-by-frame manner.

The final weight of the ornithopter was determined to be 26.2426 N (2.676 kg). This includes all parts of the mechanism that were tethered to the spring during testing including muscles, the frame, the wings, and smaller associated parts. This does not include the larger parts that were not considered in total weight including the power source and the air compressor.

6. Results

6.1 Muscle Results

6.1.1 Extension and Force from Cross-Sectional Area

Initial force calculations per cross sectional area were conducted to narrow our selection process because a wide range of diameters and wall thicknesses are available for latex tubing. This was done by hanging known half kilogram masses from the material and recording the corresponding extension. The amount of force at different extensions was approximated for available latex tubing and then extrapolated to predict to forces available from tubes with greater material cross sectional area. Of the numerous options available from McMaster-Carr, the top four candidates for muscles were purchased for testing.

Table 1: Force to doubling length of various sizes of latex tubing

Id (in)	od (in)	Wall thickness	OD area	ID area (in^2)	total area(outer-inner)	Force to doubling length (kg)
1/4	3/8	1/16	0.11	0.05	0.06	3.00
1/4	5/8	3/16	0.31	0.05	0.26	12.88
0.125	0.75	5/16	0.4415625	0.012265625	0.429296875	21.46
3/16	7/16	1/8	0.15	0.03	0.12	6.13
1/4	5/8	3/16	0.31	0.05	0.26	12.88
5/16	9/16	1/8	0.25	0.08	0.17	8.59
3/8	3/4	3/16	0.44	0.11	0.33	16.56
0.5	0.875	0.1875	0.601015625	0.19625	0.404765625	20.24
1	1.25	0.125	1.2265625	0.785	0.4415625	22.08

6.1.2 Extension under Tension

Testing the extension and force of the latex tubing was conducted by assembling muscles and hanging known masses from each while keeping the ends open to atmospheric pressure and

allowing for just the forces from the latex to be quantified. This was conducted in 1 kg increments. The behavior of these muscles was noted to be close to linear.

Using the collected data as shown in Figure 9, the latex tubing ½ ID, ⅞ OD was selected for use because it was capable of producing the necessary force over the range of extension, could reach a usable extension, and minimized the amount of airflow required to attain an extended pressure.

For the selected tubing the testing was limited to 14 kg because the available hose clamps were not able to be made sufficiently tight around the muscle ends. In order to remain safe and not create a danger in the lab, this test was not conducted above this point. Because all of the other muscles performed in the same manner there was no need to redo this experiment.

6.1.3 Pneumatic Pressure Testing

Testing with pneumatic pressure was conducted using purpose designed 3-D printed end caps and a general purpose compressor with pressure gage. Each of the tubing diameters were assembled into muscles and tested to correlate pressure and extension. This was done by increasing the pressure in 10 Psi increments and recording the distance between end clamps of the muscle. The process was repeated several times for each muscle and an average taken to use in calculations for use on the prototype.

Calculations were performed to estimate the pressure that would be required to match the extensions attained in the hanging mass test. If the inner diameter of the tubing was to remain constant, then the required pressure for elongation would be much higher than that measure in

pressure tests. Calculations not considering internal cross-sectional change indicated that 226.88 Psi would be required to elongate this muscle. In testing with the muscled manufactured with this material, only 70 Psi produced the same extension. This difference is likely because the inner diameter increases when the material stretches as well as pushes out to the limits of the fabric sleeve. The larger inner diameter exerts a larger force to extent the muscle from the same pressure.
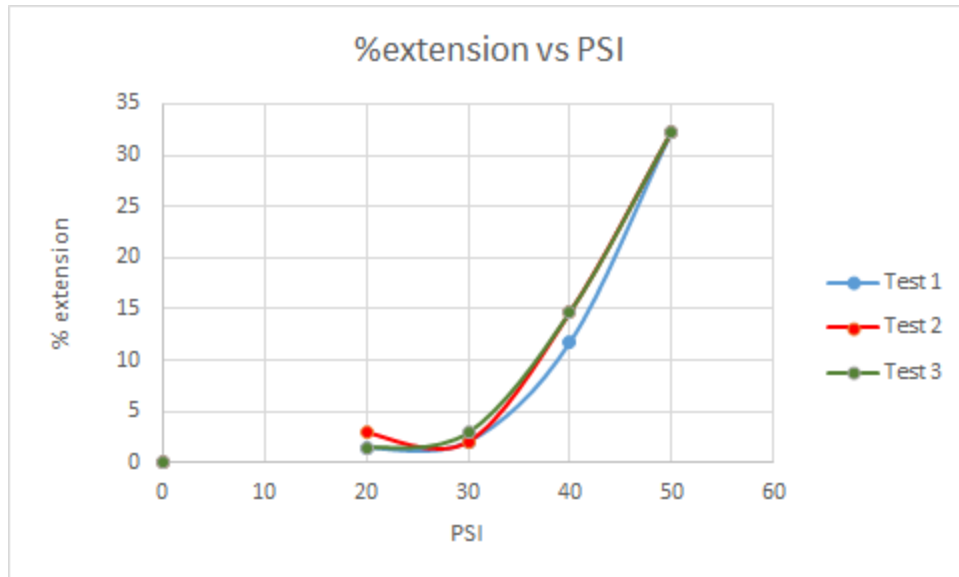

Figure 19: Extension vs. Pressure for fluidic muscle

One anomaly not expected was experienced in Test 2 in Figure 19 above. Before extending, the length of the muscle decreased. This may be due to the latex expanding radially until limited by the fabric sleeve over the complete surface. This would cause the muscle to behave more like a McKibben muscle until reaching this limit. It is important to note this because a shortening of the muscle is not desirable for this application. In tests with other sleeves, this was not observed even when using the same latex material, so is likely due to the evenness or tightness of these sleeves around the latex.

6.2 Ornithopter Results

6.2.1 Defining the Center of Gravity

The motions of the center of gravity was important in discerning if the ornithopter generated enough lift to raise itself. A SolidWorks model was created to study the center of gravity at specified positions of the up stroke and the down stroke. The center of gravity is positioned as referenced to the midpoint along the top horizontal dowel of the chassis. Angles of the proximal wing section and distal section were measured every 10 frames or .04 seconds. The down stroke occurred over a period of .45 seconds and the upstroke for a period of .35 seconds. The entire flap occurred over a period of .8 seconds, a frequency of 1.8 Hz. Flapping frequency was limited by the flow through the air compressor's built in pressure regulator. These angles were applied to the SolidWorks model as seen in Figure 20.
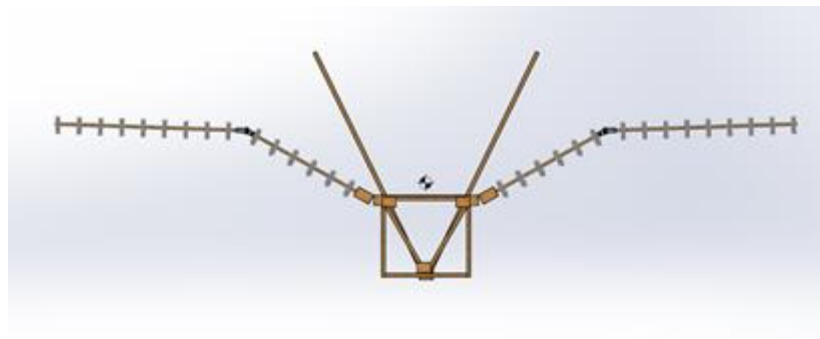

Figure 20: Center of Gravity in relation to the ornithopter

6.2.2 Center of Gravity Motion

The position for the center of gravity changes its vertical location depending on which angle the wings are positioned in. To observe how this location changes over time, the position of the center of gravity relative to the top of the ornithopter frame was plotted using the angles of the wings obtained during a continuous flapping test. These angles were measured, relative to the

horizontal, every 10 frames from the high speed camera used to record the ornithopter wing motions.

The start time for the position graph and following velocity and acceleration graphs was taken to be the point that the muscles first begin to be filled. Because some of the experimental data collected likely had some introduced error, a polynomial trend line was created for the position graph and derived to obtain the velocity and acceleration of the center of gravity. The experimental data starts at zero as this is the start location for this experiment, however in using the best fit function for position, the appearance of an initial below zero starting point is created.
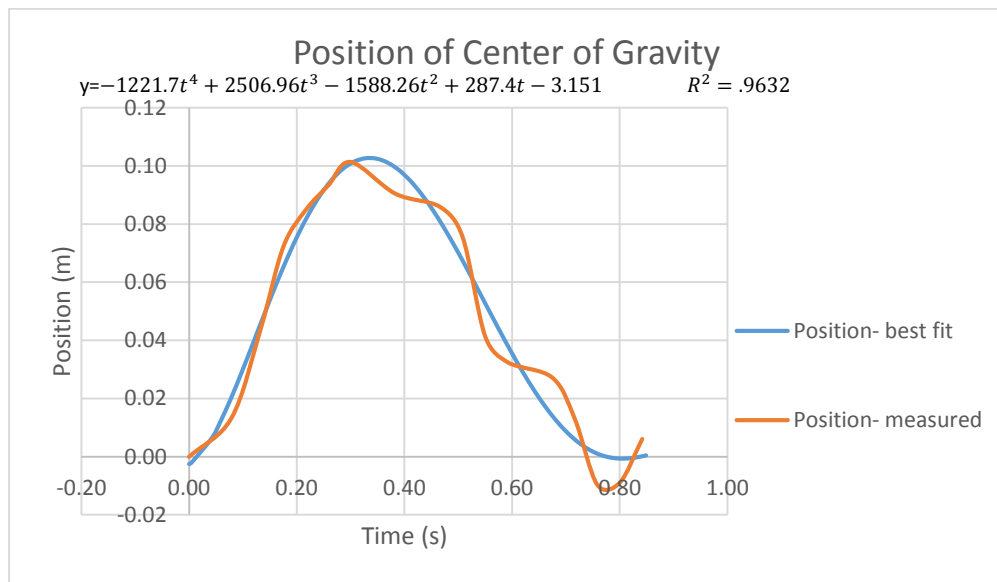

Figure 21: Center of Gravity change over one flap

The position graph was derived first to get the velocity change of the center of gravity, as seen in Figure 22, and then a second time to derive the acceleration as seen in Figure 23. The Equations for the position, velocity, and acceleration can be seen below:

$$position = -244.34t^5 + 626.74t^4 - 529.42t^3 + 143.7t^2 + 3.151t - .098 \quad [1]$$

$$velocity = -1221.7t^4 + 2506.96t^3 - 1588.26t^2 + 287.4t - 3.151 \quad [2]$$

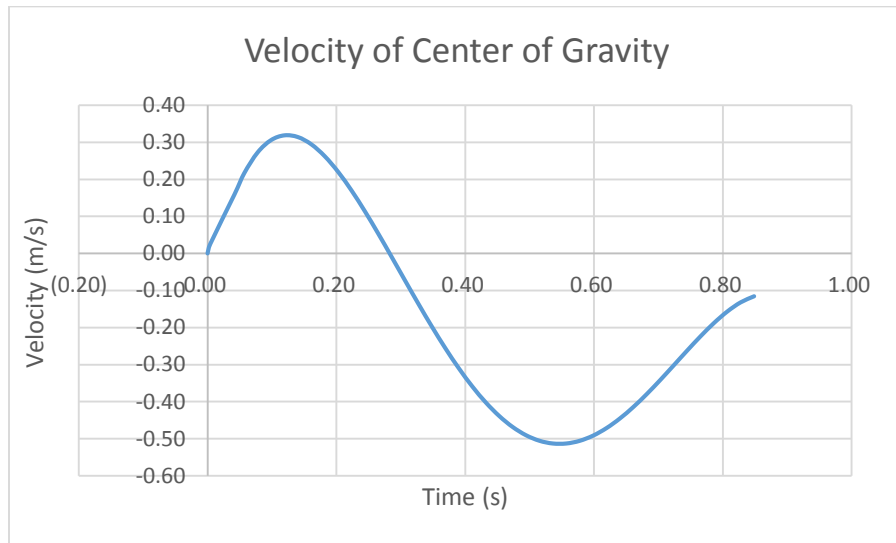$$acceleration = -4886.8t^3 + 7520.88t^2 - 3176.52t + 287.4 \quad [3]$$

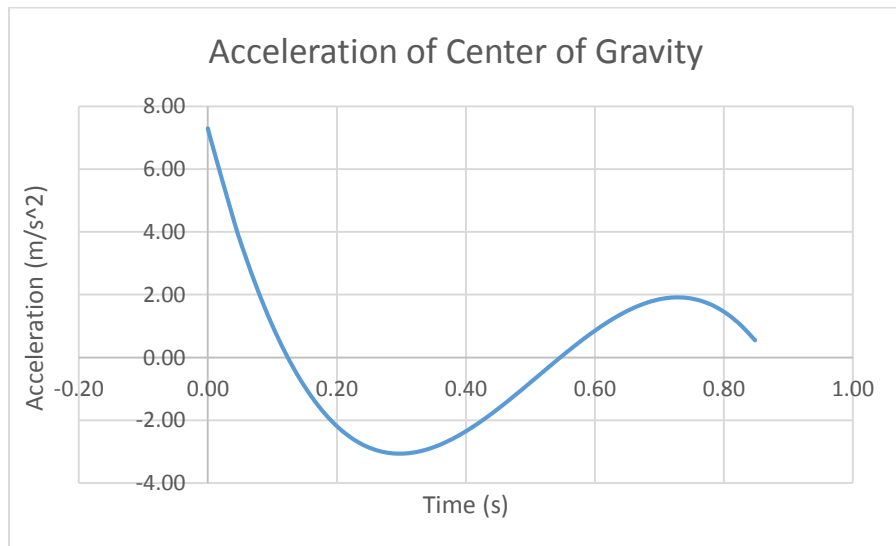*Figure 22: Velocity of the Center of Gravity over one flap*

Figure 23: Acceleration of the Center of Gravity over one flap

6.2.3 Angle of Attack Change

In order to create a motion similar to that of a bird, our wing sections passively changed their angle of attack during the flapping cycle. This change allowed for a greater projected surface area during the down stroke than on the upstroke. Using a high speed camera we were able to track this motion and qualify the expected change from the design and manufacturing.

During the up stroke the angle of attack rests at 10 degrees as seen in Figure 24 and remains in this position throughout the entire upwards motion. During the down stroke the angle of attack decreases to 0 degrees in order to maximize lift. If it was desirable to create a forward thrust the angle of attack on the down stroke could be decreased further below level.

Figure 24: Angle of Attack change

The angle of attack changes rapidly at the start of the down stroke. In 0.133 seconds the airfoils shift from 10 degrees to 0 degrees.
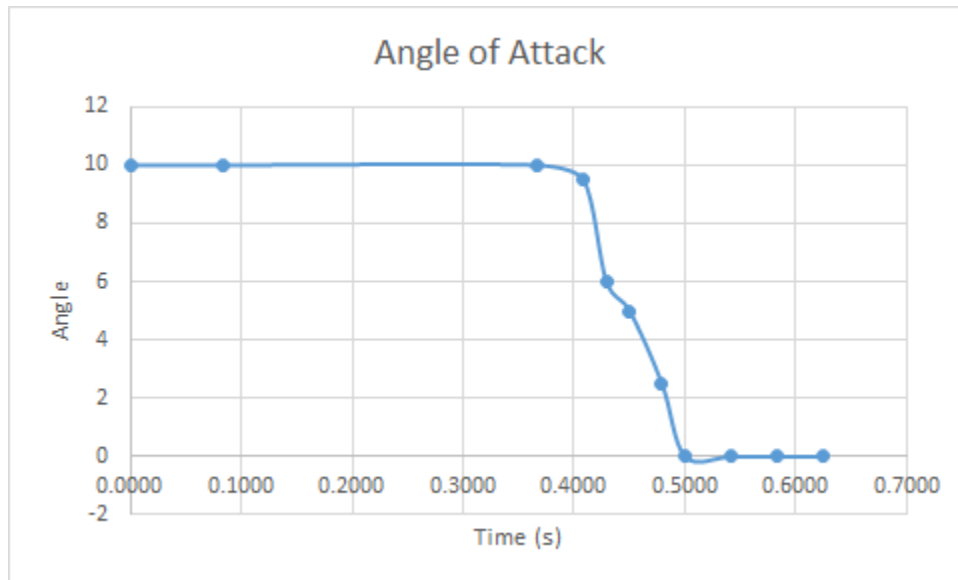
Figure 25: Angle of Attack change over time

6.2.4 Wing Angular Motion

By examining the motion of the wing during a test, new information can be analyzed regarding the angular motion of the wing throughout the flap. Using a video taken from the high speed camera, the frame and associated elapsed time were recorded and the angles of both the proximal and distal sections of the wing were determined. In Figure 26 below, the representation of the measured angle is shown. The proximal angle is determined in reference to the ornithopter frame while the distal angle is in reference to the proximal wing. This was done to show that the distal angle would, at some point during the motion of the flap, reach 0 degrees signifying the wing is completely extended in the down stroke.
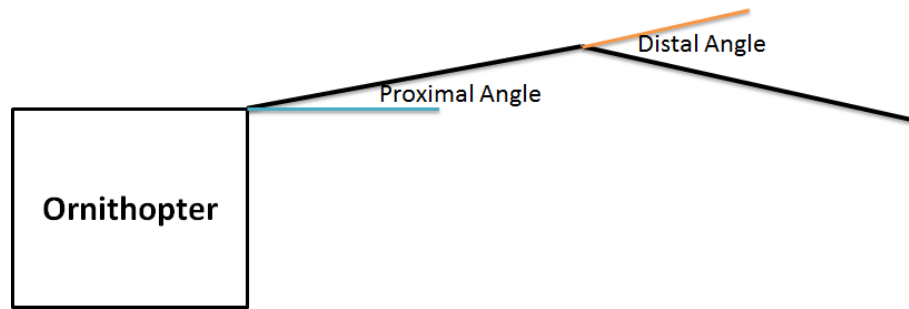
Figure 26: Diagram showing the measurement of angles

The angles determined from the videos were determined against time and are displayed in the Figures below. Angles for both the proximal and distal sections of the wing were both found. Best fit polynomial curves were determined for both sets of data and had significant R^2 values associated with the curves. The angles collected and determined from the corresponding video were recorded in degrees. The results were converted to radians as the following analyses relate to angular motion including angular velocity and angular acceleration. The start time of data was taken to be the point that the muscles first begin to be filled.
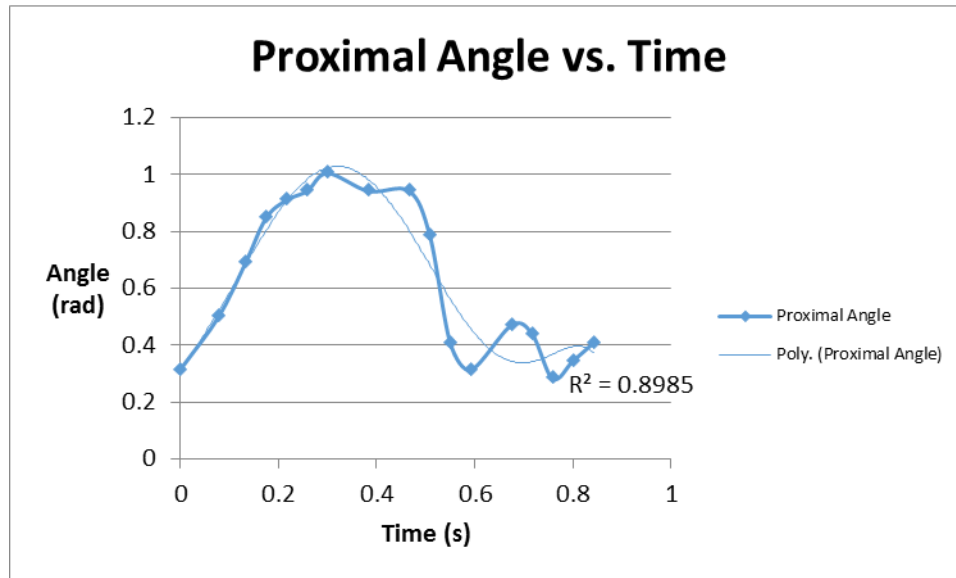
Figure 27: Proximal Angle vs. Time

The best fit line was found using a polynomial trend line with the equation:

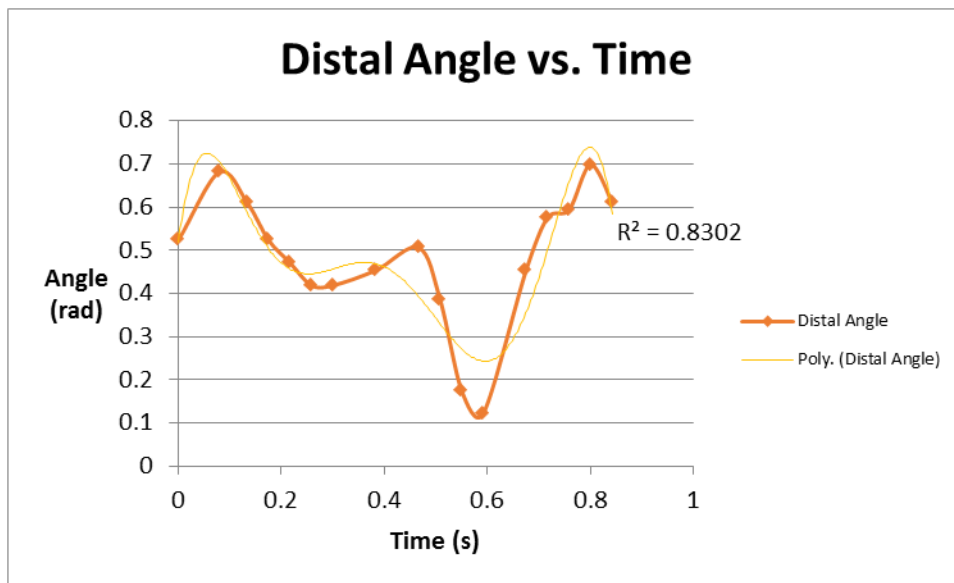$$\Theta_{proximal} = -134.98t^6 + 275.67t^5 - 168.92t^4 + 21.416t^3 + 2.1972t^2 + 2.4451t + 0.311 \qquad [4]$$

Figure 28: Distal Angle vs. Time

The best fit line was found using a polynomial trend line with the equation:

$$\Theta_{distal} = -596.02t^6 + 1477.4t^5 - 1374.6t^4 + 596.13t^3 - 120.01t^2 + 8.7349t + 0.5199 \qquad [5]$$

While the data collected and displayed in Figure 28 suggests that the angle did not fully extend during motion as it does not decrease to an angle of 0 radians, there are certain factors which must be considered. Factors include an error in measuring the angle in the video as motion may have occurred in between recorded frames, the angle the video was recorded at may have skewed visibility of the wing, and the manufacturing of the wing and joint as well as the assembly of the components which may have limited the motion of the wings while flapping.

The derivatives for the best fit curves for the proximal and distal angle vs. time were found to determine the angular velocities and accelerations of the wing sections. These results are displayed in the figures below. These analyses share in depth details on the angular wing motion and give a better understanding of how the forces affect the motion created.
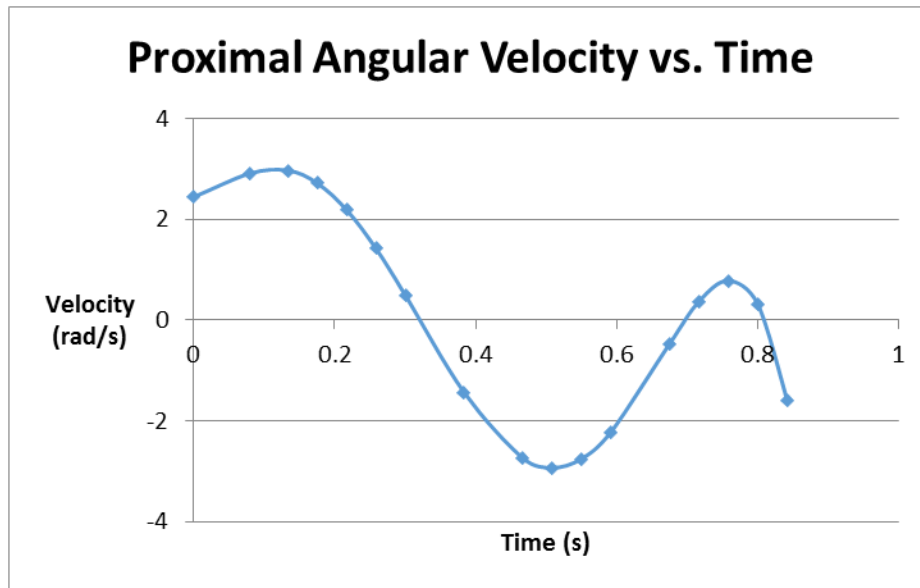
Figure 29: Proximal Velocity vs. Time

The proximal velocity is represented by the equation:

$\omega_{proximal} = -809.88t^5 + 1378.35t^4 - 675.68t^3 + 64.248t^2 + 4.3944t + 2.4451$ [6]

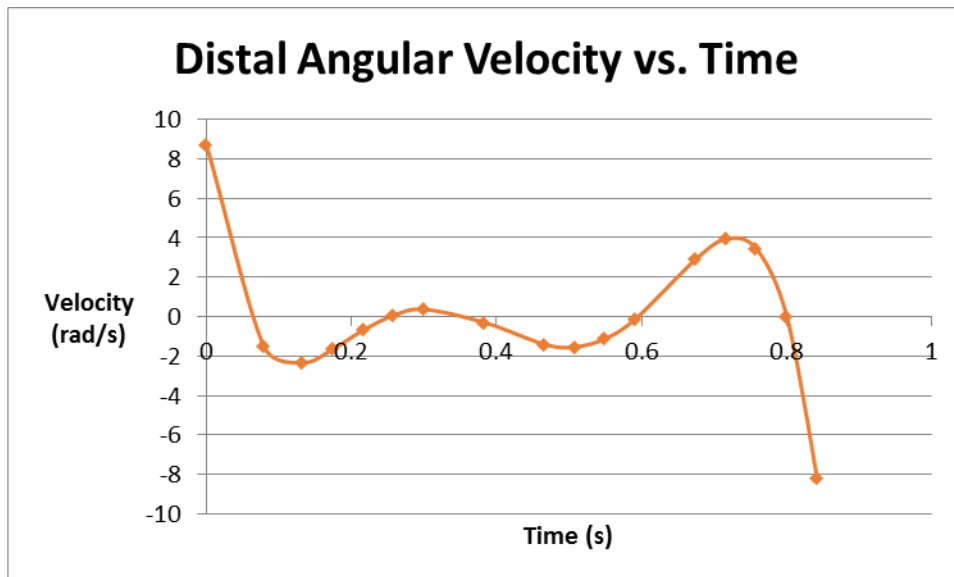*Figure 30: Distal Velocity vs. Time*

The distal velocity is represented by the equation:

$\omega_{distal} = -3576.12t^5 + 7387t^4 - 5498.4t^3 + 1788.39t^2 - 240.02t + 8.7349$ [7]

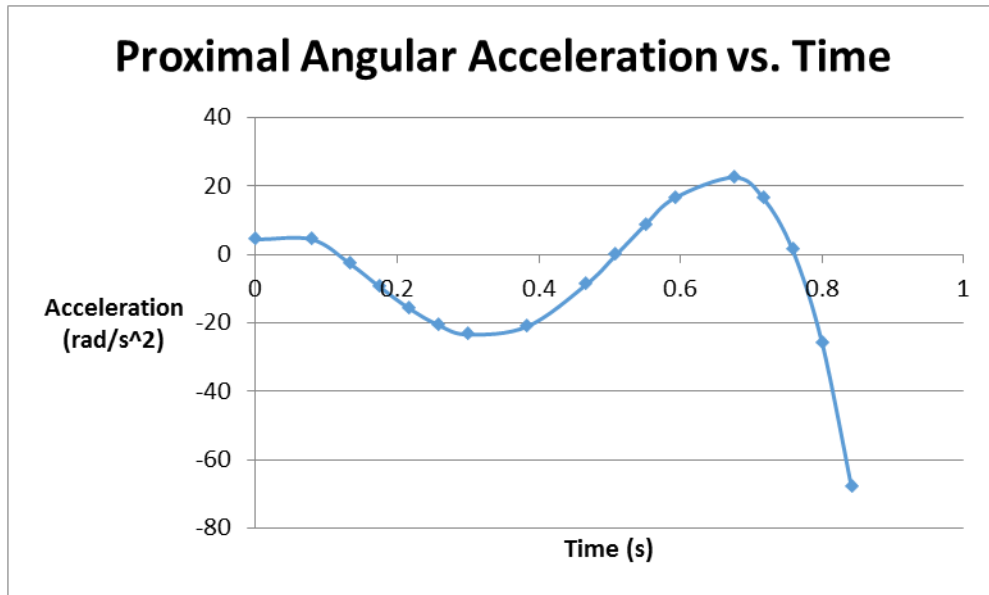*Figure 31: Proximal Acceleration vs. Time*

The proximal acceleration is represented by the equation:

$$\alpha_{proximal} = -4049.4t^4 + 5513.4t^3 - 2027.04t^2 + 128.496t + 4.3944 \qquad [8]$$

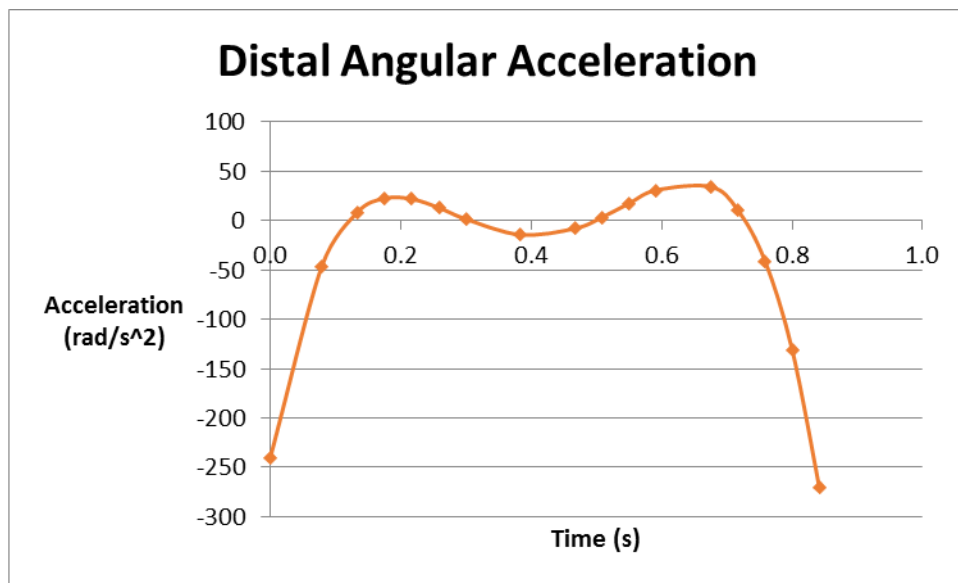*Figure 32: Distal Acceleration vs. Time*

The distal acceleration is represented by the equation:

$$\alpha_{distal} = -17880.6t^4 + 29548t^3 - 16495.2t^2 + 3576.78t - 240.02 \qquad [9]$$

6.2.5 Change in Position from Lift

Lift was measured utilizing a spring with a spring constant of 120 N/m to measure the forces generated. The spring constant was measured and described in the ornithopter experimental setup in section 5.2. A high speed camera was used to capture the change in length of the spring throughout the down stroke.

Hooke's Law and Newton's second law of motion were utilized to calculate the lift force created. Figure 33 shows the change in spring length for 6 trials. On average the ornithopter was able to rise 0.1238 +/- .01475 meters from its initial position and generate 15.4 +/- 1.77 N of force. The time scale for these 6 tests was .19305 +/- .03012 seconds. Trial 3 is most representative of the average, occurring over .204 seconds and achieving a maximum rise of .1333 meters.
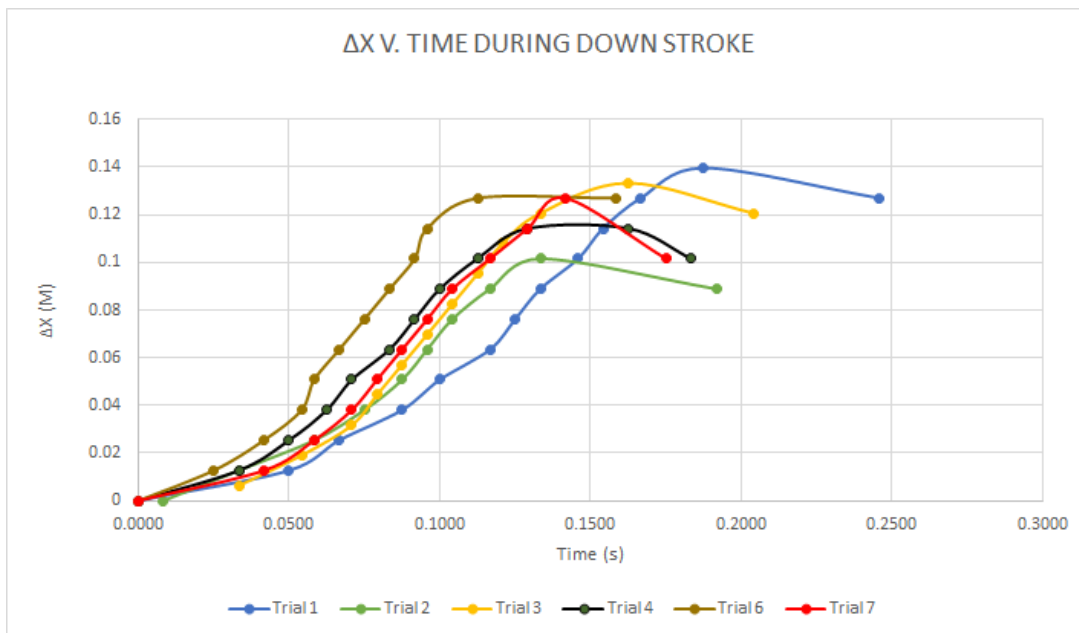

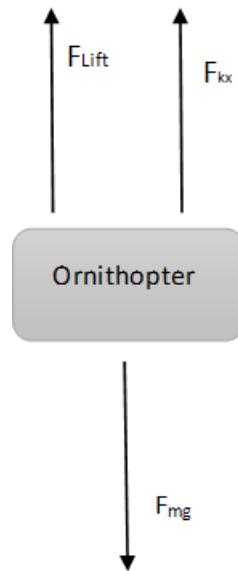*Figure 33: ΔX during down stroke*

6.2.6 Determining Lift Force

Figure 34: Free Body Diagram of Forces acting on Ornithopter

Lift force was calculated utilizing Newton's Second Law, F=ma. All forces acting on the ornithopter are described in the free body diagram in Figure 34. The following equation was used to determine the lift force.

$$F_{lift} = ma - F_{spring} \qquad [10]$$

In the equation above F_{lift} is calculated as the mass of the ornithopter multiplied by its acceleration and the opposing force of the spring. F_{spring} is proportional to the displacement from the equilibrium defined by the ornithopter hanging from the spring while at rest. Figure 35 shows the lift force and angular velocity through a single down stroke. A maximum lift force of 18.77 N (1.9 kg) was achieved during the first 0.004s and a minimum of 11.9 N (1.2 kg) at 0.1625 s. The average lift force over the down stroke was 15.4 N (1.57 kg), 58% of the total mass. A maximum angular velocity of the proximal section of the wing was calculated to be 95.3 deg/s at 0.112 s and a minimum velocity of 75.5 deg/s at 0.2042 s. The average angular velocity for the down stroke was 89 deg/s.
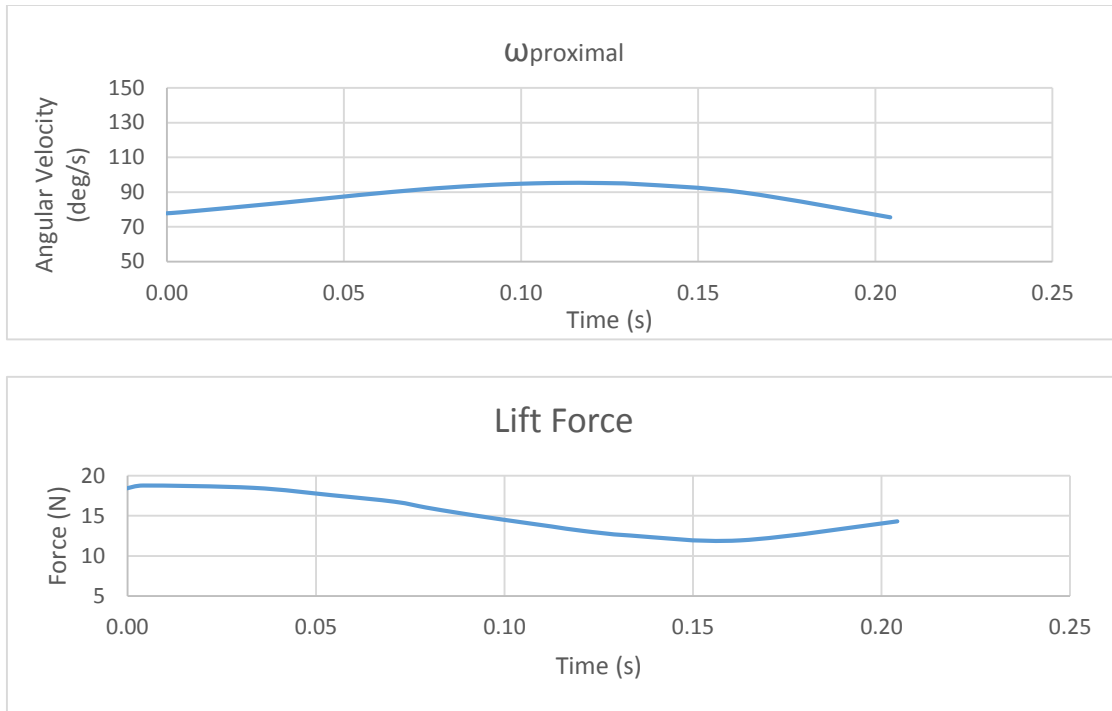
Figure 35: Lift force and Angular Velocity through the down stroke

6.2.7 Determining Sustained Flight

An important aspect of this project was its focus on maximizing lift. The team tested the ornithopter specifically to measure the amount of lift generated by a single flap of the wings and prove its ability to create lift. Throughout the project, the team aimed to solely maximize lift which could be done by ignoring thrust and any forward velocity created by a flap of the wings. With the results collected and analyzed proving the ornithopter's ability to achieve lift, the team was then able to use the data to suggest the system's ability to create sustained flight if thrust is now considered. This suggests the greater application of the research and results collected in this project by suggesting the ornithopter could achieve flight if alterations were made and it had the ability to

create the necessary thrust and forward velocity required. This leads the project to the future step

of achieving autonomous flight in an ornithopter using fluidic muscles.

After collecting results and using the necessary information. The team was able to use

Bernoulli's Lift Equation to calculate the velocity necessary to achieve lift.

$$L = \frac{C_l * \rho * A * v^2}{2}$$ [11]

Bernoulli's Lift Equation
L = Lift (N)
C_l = Coefficient of Lift (1.6, unit less)
ρ = Density of Air (1.2041 kg/m^3)
A = Area (.4032 m^2)
V = Velocity (m/s)

The coefficient of lift was determined by finding the angle of attack and position of the

wing of the ornithopter during the majority of a flap. The coefficient of lift varies based on the

angle and can be seen in Figure 36 below. The optimal angle of attack was determined using

XFLR5 software considering the forces generated by the wing. The software produces the graph

showing a coefficient of lift of 1.6 at approximately 5 m/s which is what was used as a constant in

the calculations for the Lift Equation. The density of air and the area were both found and remain

constant in the equation allowing for the velocity to be solved for. This equation will show results

for only one wing and the result will be doubled to account for total lift generated both by wings.
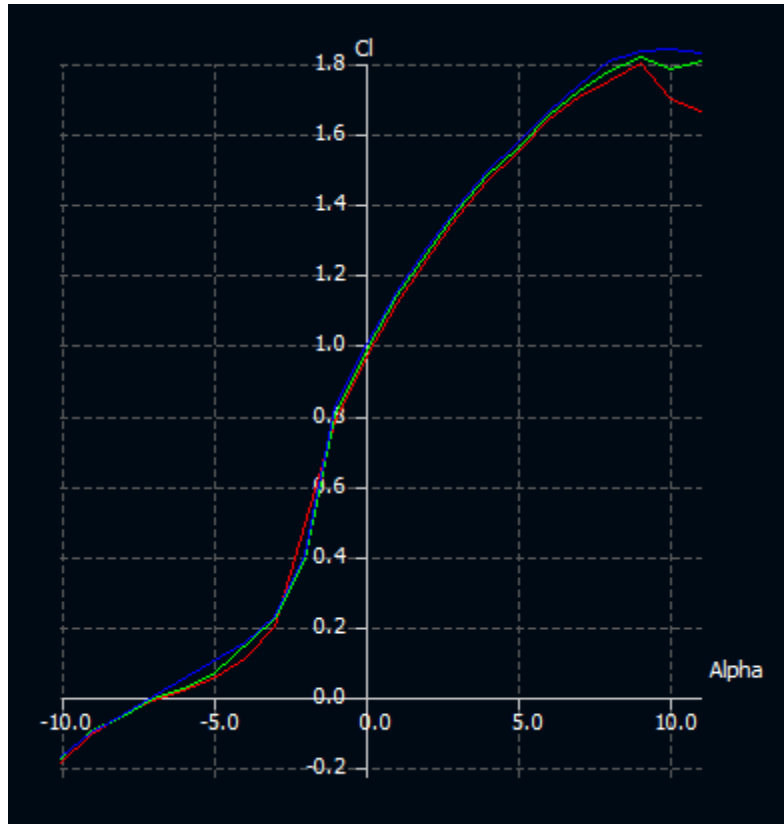
Figure 36: coefficient of lift against angle of attack from XFLR5 software

The lift the ornithopter needs to generate is at least equal to its weight. For our calculations we assumed its ability to lift the exact amount of its own weight, allowing the system to sustain flight. The weight of the mechanism is 2.676 kg (26.2426 N).

First, the team calculated the lift generated from the wings based on velocity when the ornithopter is not flapping and generating any lift of its own. Using the Bernoulli Lift equation the necessary velocity could be determined. For our 2.676 kg system, it would require a velocity of 5.8123 m/s to generate enough lift for flight. Next, the team considered the average amount of lift the ornithopter was able to generate from one flap of both wings. This average 15.4 N of lift is equivalent to 58% of the total mass. This was used as opposed to the maximum measured lift, 18.77 N, because the average force can be applied more reasonably than just a maximum force.

The average lift is determined from the upward forces created during the down stroke, not including the upstroke. The down stroke accounts for 56% of the total cycle of a full flap. Considering this, an average lift of 15.4 N was added to the data and it was determined that a velocity of 3.7361 m/s would be required to generate enough lift for sustained flight. This proves that the ornithopter built in this project would have the ability to sustain flight if it constantly produced the average amount of lift and was able to maintain a constant forward velocity of 3.7361 m/s during flapping while remaining a self-contained system. This data can be shown in the graph below.
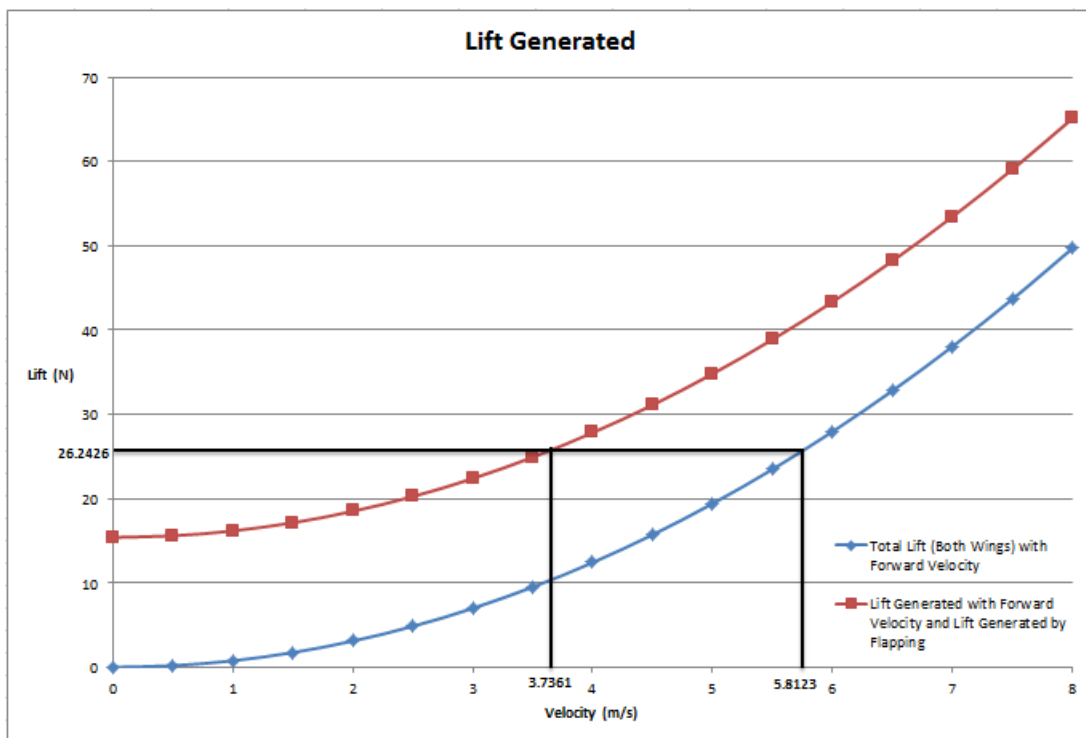

Figure 37: Lift Generated Utilizing Bernoulli Lift

From this graph, the results show that if the average lift is added to the total lift, sustained flight can be achieved with a minimum velocity of 3.7361 N. If the velocity of the ornithopter was at this value, the lift force contributing to the sustained flight from the flapping would be 15.4 N,

while the lift force contributing to the sustained flight from the total lift with forward velocity would be 10.8426 N. This accounts for 58.7 % and 41.3 % respectively of the total lift of 26.2426 N minimum required to sustain flight, and is the result that would be expected. If Bernoulli Lift and lift generated from flapping contributed equally, a velocity of 4.4526 m/s would be required. The total lift generated would be 30.8 N.

This assumes the additional lift applied in this graph created by flapping would be constant, which is not the case during the flight of the bird. This amount added is instead just the average lift generated by flapping. As previously shown in our results, the lift generated during flapping varies. During flapping, it is likely that the velocity does not stay constant either. While this is important in consideration of the results and conclusions drawn from our data, it would suggest that sustained flight could be possible under these conditions, and a future version of the ornithopter would have to be developed to create forces that achieve both the constant lift and velocity required as determined through these calculations.

7. Conclusions and Recommendations

This project signifies a step forward in proving applications of the fluidic actuated muscles as it was the first to consider and implement air as the fluid to actuate the muscles. The group originally began researching air as a viable fluid for the system to make the overall design lighter in any possible way. Adjusting and improving the main system within the ornithopter appeared as the right place to implement these ideas in designing a lightweight system. The total weight of the system was determined to be 26.2426 N (2.676 kg), a weight that was close to expected and planned for by the team considering the different elements that would be incorporated into the ornithopter excluding the components that were not in the enclosed system, including the compressor and power source.

Air, being a compressible fluid at certain pressures that were practical to contain and achieve, proved it was able to change the length of the muscles considerably. After testing the muscles built for the system, it was determined that a change in length of at least 30% could be achieved and would do so reliably with each extension at the specified pressure. The muscles themselves proved to be durable when constructed correctly and functioning within a reasonable operating pressure range. The limiting factor of the muscles was the fabric sleeves around the muscles which occasionally failed above certain pressures. Using a stronger fabric in the future would be an improvement as it could reinforce the strength, reliability, and extension of the muscles as it could likely sustain a greater pressure range during operation.

The ornithopter developed in this project proved capable of creating a lift force, proving a new application for fluidic muscles. From testing, the flapping of the wings was able to create an average lift force of 15.4 N during the down stroke. While this did not generate enough lift to overcome the ornithopter's mass, it does show the potential and promise for future related projects.

This MQP also did not account experimentally for thrust or forward velocity which should be considered for future adaptations of the project. Assuming the average lift created during the down stroke could be maintained throughout the cycle, the ornithopter would be able to achieve enough lift for sustained flight if it could reach or be supplied with a minimum constant velocity of 3.6309 m/s. Further work could lead to the development of an enclosed system that could generate enough lift for sustained flight. Fluidic muscles have a growing range of applications and this project demonstrates their potential.

This project also developed a new motion for the wings not previously seen incorporated in an ornithopter. Research was done to study the flight of birds. Choosing a common bird to study, the group focused on the seagull and a specific airfoil design was selected using the S1223 airfoil profile. This airfoil was modeled and 3-D printed for application in the ornithopter. The motion of a seagull's wings during flight were mimicked in the wing design. Instead of using a single uniform surface during flapping, this ornithopter changed the wing shape by incorporating airfoils, adding a mechanism to change the angle of attack, and added sections of the wing. Also included in the design were joints that limited the motion of the wing sections during flapping and ensured a soft stop. This new wing system effectively simulated the flapping seen in a seagull. This method developed to change the angle of attack naturally in flight and will prove beneficial to future designs and in the future development of ornithopters. While it has not yet been proven that the fluidic muscles are practical to create sustained lift, the muscles did prove to be an effective system in creating the motion seen in the wing system.

One difficulty experienced throughout the research of the project was the availability of compressors that could supply the necessary pressure with a flowrate high enough to support flapping of the wings by expanding the muscles and able to be a self-contained system. A custom

compressor would have been required to meet the specifications determined by the group. The solution implemented in this project was to use an off-board air compressor, but a future team could spend time developing their own compressor system if their intention is to create a self-contained system that is capable of flying autonomously. This idea will have to determine the output of a compressor against the weight it adds to the system. A heavier compressor requires even greater power, and as shown throughout this project, weight is a considerable factor in creating a flying system and must be given priority in designing an ornithopter. The compressor options researched for the project are detailed in Appendix C.

The designed ornithopter may also be suitable for gliding where it can convert the potential energy to kinetic energy that will give the required forward speed for flight. Flapping during gliding could increase the range by providing extra lift forces and thrust or provide for directional control. Muscles are practical for the type of motion desired.

In a self-contained system utilizing a compressor system, a power supply will also have to be incorporated. Again this adds considerable weight that must be compensated for by the operation of the compressor. For continuous and sustained flight, a strong and lasting power supply is necessary unless other solutions can be determined. The valve in the system that employ a compressor in a self-contained system must also be able to operate at the pressures which the compressor system supplies. The valve also plays an important part in containing the pressure and allowing the muscles to function as required.

If autonomous flight is desired, future projects would need to spend time developing additional control for the muscles. This may include additional mechanical systems and may also add more muscles to the wings to attain a greater control. This may also require additional research on controlling an individual muscle especially if using compressible fluids like air in the future.

While autonomous flight using this system was not obtained, this project shows the potential of fluidic muscles to generate lift. Fluidic muscles show potential for future applications. With further improvements this technology has the potential to achieve the goal of sustained flight.

Bibliography

(2014). Retrieved from Clear Flight Solutions: http://clearflightsolutions.com/

A Dirigible and Zeppelin History Site. (n.d.). Retrieved from airships.net: http://www.airships.net/zeppelins

Anderson, J. D. (2002). The airplane, a history of its technology. *American Institute of Aeronautics and Astronautics*.

Beerinder, S. (2006). *Dynamics and Aeroelasticity of Hover Capable Flapping Wings.* Retrieved from http://drum.lib.umd.edu/: http://drum.lib.umd.edu/bitstream/1903/6663/1/umi-umd-4119.pdf

Burns, J. (2014, September 18). *Robotic Birds of Prey to Patrol the Skies*. Retrieved from psfk.com: http://www.psfk.com/2014/09/robotic-flying-birds-airports-landfills.html

Damian, A., Chirilean, I., Gudea, A., Stan, F., Dezdrobitu, C., Irimescu, I., & Burian, Ş. (2011). Anatomical Features of Bones Directly Involved in the Act of Flying in the Homing Pigeon and in the Common Pigeon. *Bulletin UASVM, Veterinary Medicine*, 1-8.

Diesadze, N., Jo, W., & Seo, B. (2013, April). Toward Biologically Inspired Human-Carrying Ornithopter Robot Capable of Hover. Worcester: Worcester Polytechnic Institute .

Dumont, E. (2010). Bone density and the lightweight skeletons of birds. *Royal Society B.* http://rspb.royalsocietypublishing.org/content/early/2010/03/13/rspb.2010.0117.full.pdf html.

Ebrahimi, A., & Mazaheri, K. (2012). Aerodynamic Performance of the Flapping Wing. In J. C. Lerner, *Applied Aerodynamics* (pp. 177-192). InTech.

Ebrahimi, A., & Mazaheri, K. (2012). *Aerodynamic Performance of the Flapping Wing, Applied Aerodynamics.* Intech.

Effraimidis, D. (2014). Hydro Artificial Muscle Exo-Musculature. *Worcester Polytechnic Institute*.

Effraimidis, D., Jennings, B., McCarthy, G., & Corso, N. (2014, May). Hydro Artificial Muscle Exo-Musculature. Worcester: Worcester Polytechnic Institute .

Ehrligh, P., Dobkin, D., & Wheye, D. (1998, January 1). *How fast do birds fly.* Retrieved from Stanford.edu: http://web.stanford.edu/group/stanfordbirds/text/essays/How_Fast.html

Elrilich, P., Dobkin, D., & Wheye, D. (1988). *The Birder's Handbook: A Field Guide to the Natural History of North American Birds.* New York, NY: Simon and Schuster.

Festo. (n.d.). *SmartBird- bird flight deciphered*. Retrieved from festo.com: http://www.festo.com/cms/en_corp/11369_11437.htm#id_11437

Goodheart, B. J. (2011). Tracing the History of the Ornithopter: Past, Present, and Future. *The Journal of Aviation/Aerospace Education & Research, 21*.

Grap, C. (2003). *Leonardo da Vinci*. Retrieved from flyingmachines.org: http://www.flyingmachines.org/davi.html

Grauer, J., Hubbard, E., Pines, D., & Humbert, J. (2011). Testing and system identification of an ornithopter in longitudinal flight. *Journal of Aircraft, 48*, 660-667.

Hedenstrom, A., & Alerstam, T. (1995). Optimal Flight Speed of Birds. *The Royal Society*.

Ho, S., Nassef, H., Pornsinsirirak, N., Tai, Y.-C., & Ho, C.-m. (2003). Unsteady aerodynamics and flow control for flapping wing flyers. *Progress in Aerospace Sciences*, 635-681.

Jackowski, Z. J. (2009, June). Design and Construction of an Autonomous Ornithopter. Cambridge: Massachusetts Institute of Technology .

Lilienthal, O. (1911). bird flight as a basis of aviation. new york: http://www.lilienthal-museum.de/olma/edokvo38.htm.

Liu, T., Kuykendoll, K., Rhew, R., & Jones, S. (2006). Avian Wing Geometry and Kinematics. *AIAA Journal*.

Moelyadi, A. A., Putra, H. A., & Sachs, G. (2013). Unsteady Aerodynamics of Flapping Wing of a Bird. *Engineering Technological Society* , 47-60.

Mueller, T., & DeLaurier, J. (2001). *An Overview of Micro Air Vehicle Aerodynamics.* American Institute of Aeronautics and Astronautics.

Ornithopter. (n.d.). Retrieved from Dictionary.com: http://dictionary.reference.com/browse/ornithopter

Owano, N. (2014, September 3). *3D-printed robotic birds of prey are undergoing trials*. Retrieved from phys.org: http://phys.org/news/2014-09-3d-printed-robotic-birds-prey-trials.html

Project Ornithopter History . (2008). Retrieved from Ornithopter.et: http://www.ornithopter.net/history_e.html

Prummel, W., Brinkhuizen, D., & Zeiler, J. (2010). Birds in Archaeoloy. *Proceedings of the 6th Meeting of the ICAZ Bird Working Group in Groningen.*

Rashid, T. (1995). *The flight dynamics of a full-scale ornithopter (Unpublished master's thesis).* Toronto, Canada: University of Toronto .

S1223 - Selig S1223 high lift low Reynolds number airfoi. (n.d.). Retrieved from airfoil tools: http://airfoiltools.com/airfoil/details?airfoil=s1223-il

The Wright Brothers - First Flight, 1903. (2003). Retrieved from eyewitnesshistory.com: http://www.eyewitnesstohistory.com/wright.htm

Tobalske, B. W. (2007). Biomechanics of bird flight. *The Journal of Experimental Bology*, 3135-3146.

Tumlison, R. (n.d.). *Skeletal Adaptations of Birds for Flight.*

Van Breugel, F., & Lipson, H. (2005). Evolving buildable flapping ornithopters. *GECCO*.

Wegener, P. (1997). *What makes airplanes fly?: History, science, and applications of aerodynamics.* New York, NY: Springer-Verlag.

Appendix A: Design and Construction of the Physical Model
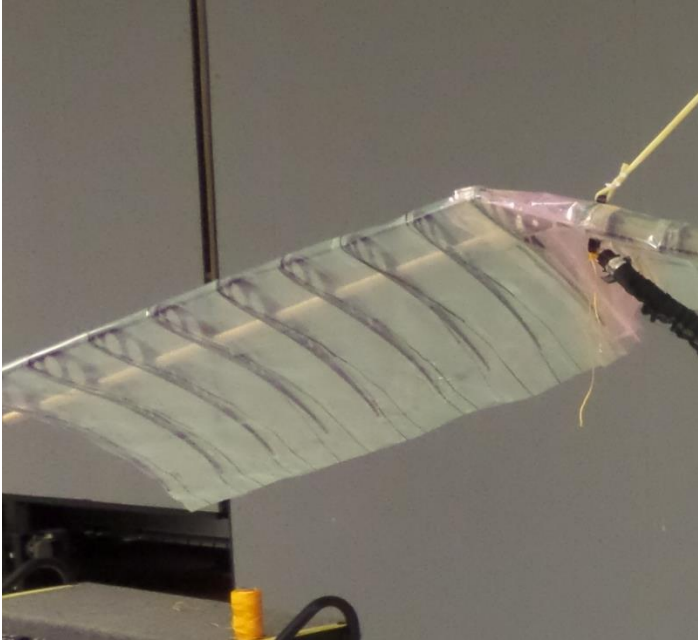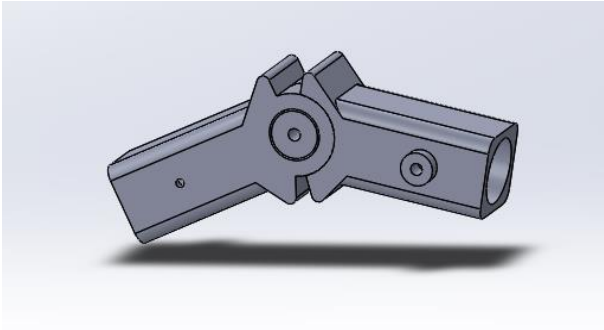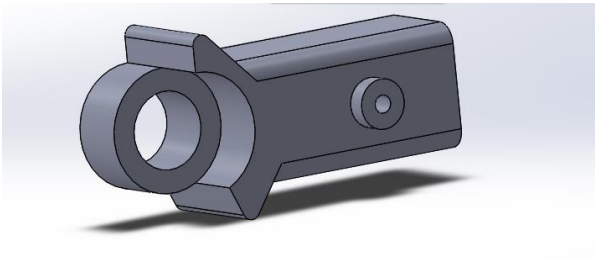
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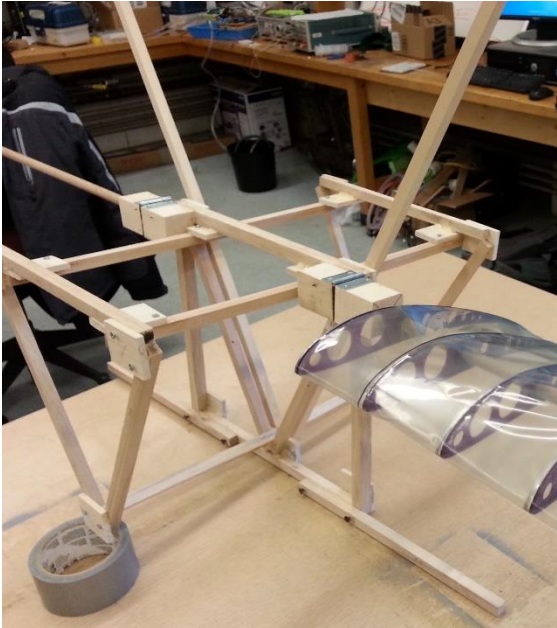
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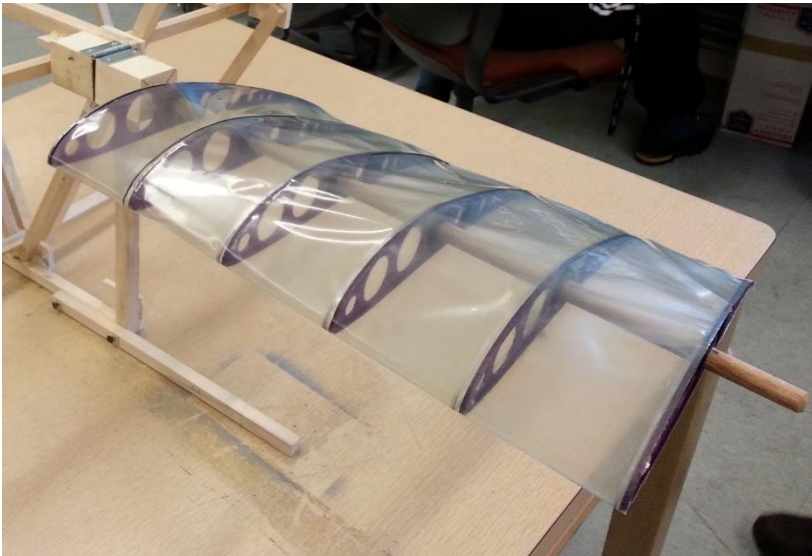
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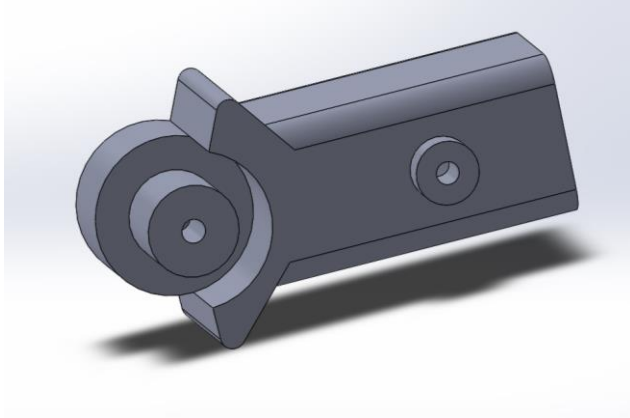

Joint Design:

Joint Assembly

Central Frame Construction:

The frame was constructed using primarily ½ inch poplar square dowels, ¼ inch thick poplar board, and held together with select screws and gorilla glue. The screws were mainly for holding all sections in place during the gluing process, however become permanently stuck once the glue cures.

Construction was done first by creating the three triangular frame sections and ensuring they were level. Then dowels running the length were attached and fastened to these sections to form the central frame. Mounting blocks were also glued and screwed to the central frame.

Wing Construction:

For the construction of the wing, ½ inch round oak dowels were cut to 0.486 meters for the proximal section and 0.694 meters for the distal. Airfoil profiles, keyed hubs, backing washer, and joints were printed in PLA plastic and any imperfections filed off and fit together. The Two wing profile sections were glued with super glue and clamped to form a single, rigid profile. To attach the airfoil to the wing frame, super glue was used to adhere first the keyed hub to the dowel. Then

the airfoil profile was put in place and the backing washer glued to hold the assembly in place and allow for smooth motion for the angle of attack change.

Mylar plastic covering was adhered to the wing profiles using contact cement. The sheet was stretched over the wing to avoid wrinkles and secured to the contact cement coated areas. All excess material was cut away once the glue was fully dry.

The joints were assembled and glued to the dowel ends using gorilla glue and clamped in place until the glue set. They were set so that they bent in a perpendicular plane to that of the zero degree angle of attack position of the wings. This provided for them to flap the wing only up or down and not forwards or backwards in any way.

Appendix B: SolidWorks Model

In order to fully understand the motion of the center of gravity a SolidWorks model was constructed. All parts of the ornithopter were modeled according to the physical dimensions of their construction. These parts can be viewed below in the Bill of Materials.

General assembly of the ornithopter occurred in many subassemblies. These were created to reflect the actual construction of the physical ornithopter. The airfoil assembly was created, then put into the distal and proximal wing assemblies. These smaller assemblies were then added to the full assembly along with the chassis.

Bill of Materials

| ITEM NO.	PART NUMBER	QTY.	Weight (kg)
1	Frame_outter_dowel	12	0.027215
2	joint	9	0.009072
3	Frame_support_dowel	2	0.040823
4	bottom support	1	0.040823
5	joint block	4	0.068039
6	Wing_dowel	2	0.081646
7	Proximal dowel	2	0.018144
8	S1A.front	30	0.009072
9	S1A.back	30	0.004536
10	WingKey_V1.a	30	0.000907
11	Joint_A1_V3	1	0.009072
12	Joint_B1_V3	1	0.004536
13	distal dowel	2	0.027215
14	Joint_A2_V3	1	0.009072
15	Joint_B2_V3	1	0.004536
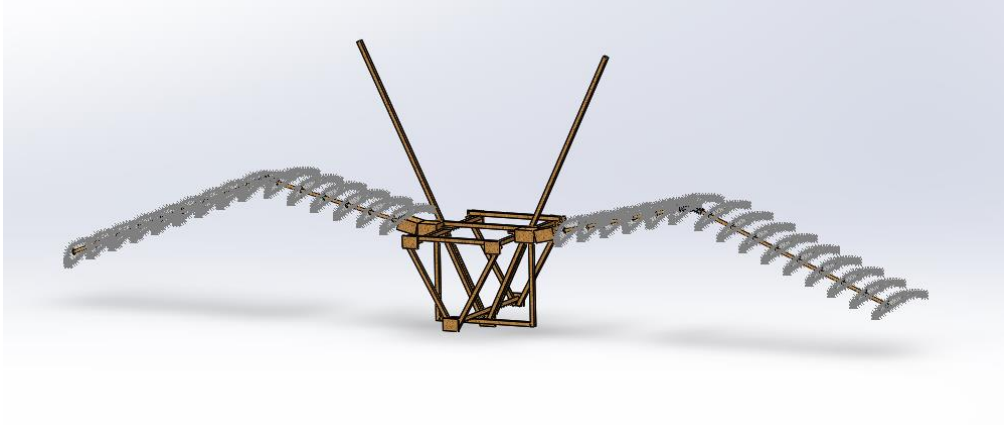
Full Model of Ornithopter (sans muscles)

Ornithopter Chassis
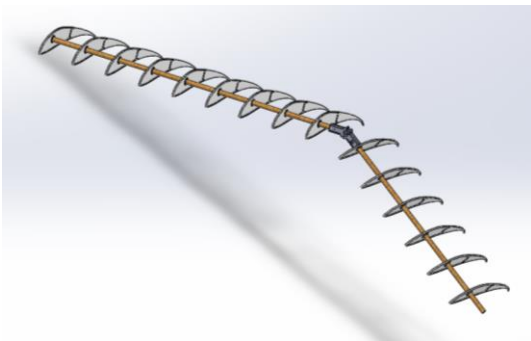
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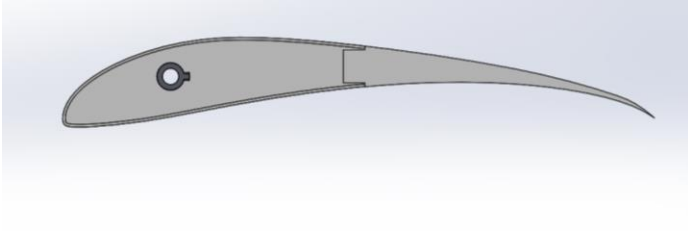
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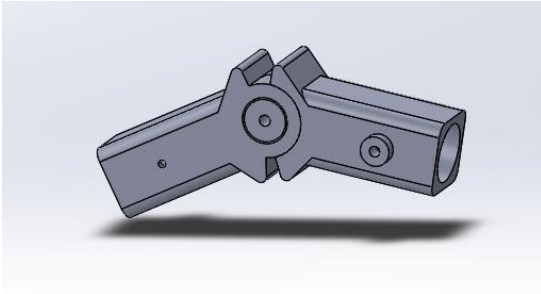
Joint Assembly

Appendix C: Compressor List

The following table details several compressors that were researched during the course of the project. For varying reasons, these compressors were not feasible for the project and those reasons are detailed briefly in the table. Some compressors were purchased but did not operate as expected, therefore they were unusable. This is also specified in the table.

The specifications for the compressors were determined throughout our research by different calculations. The minimum Psi required from a compressor was determined from pressure tests to be 60 Psi which would be the standard operating pressure used for the muscles. A maximum of 100 Psi would be required for the abilities of the muscles implemented into the system. All calculations were made assuming the weight of the entire system would be 2.882 kg or 6.3 lbs, which was accurate considering the final weight of the ornithopter once it was manufactured and assembled. The allowable compressor and system weight determined were an additional 2.27 kg or approximately 5 lbs. Weight was a considerable factor in determining compressors that could meet specifications. While some compressors met other requirements, weight was an important consideration that prevented the implementation of several options. Cost also became a limiting factor in options for compressors. Several compressors including ones not listed in this table were too expensive considering the budget available for the project. Another factor that affected the available options was the flowrate that each compressor could supply. It was determined that a minimum of 2.49 L/min was required for operating the muscles in the desired motions. Most compressors that fit within our budget and met other specifications did not meet the required flowrate.

The chosen compressor was a 1/3 hp compressor running on 120 V AC. This includes a 3 gallon storage tank filled by the compressor unit operated by a pressure valve. This unit was external from the flapping wing mechanism allowing for tethered testing.

Compressor List					
Source	Cost	Max psi	Weight (lbs)	Notes	Link
Home Depot	$54.99	230	9.3	Too heavy	http://www.home
Grainger	$1,073.00	135	189	Too heavy and expensive	http://www.graing
Grainger	$4,730.00	1500	34	Too heavy and expensive	http://www.graing
Home Depot	$59.97	60	5	Too heavy, not enough max pressure or flowrate	http://www.home
Home Depot	$59.97	160	5.2	Too heavy	http://www.home
WalMart	$60.99	150	10.8	Too heavy, flowrate is not great enough	http://www.walma
Air Compressors Direct	$24.00	260	3	Flowrate is not great enough	http://www.aircon
Air Compressors Direct	$29.99	120	3.5	Flowrate is not great enough	http://www.aircon
Advanced Safety Devices	$19.95	250	2	Flowrate is not great enough	http://www.safety
Power Equipment Direct	$69.99	230	11	Too heavy	http://www.power
Power Equipment Direct	$17.57	120	3	Flowrate is not great enough	http://www.power
WalMart	$47.94	160	7.45	Too heavy	http://www.walma
WalMart	$73.01	150	6.15	Too heavy	http://www.walma
MSC Direct	$198.53	75	N/A	Max psi not great enough	http://www.mscdir
Harbor Freight Tools	$9.99	250	1.3	Purchased, would not operate properly	http://www.harbor
Harbor Freight Tools	$29.99	100	4.1	Purchased, would not supply greater than 40 psi of pressure	http://www.harbor
Ace Hardware	$26.99	250	N/A	Purchased, would not supply greater than 60 psi of pressure	http://www.aceha
Amazon	$23.39	N/A	3	This is a blower, not a pump or compressor	http://www.amazo
Harbor Freight Tools	$69.99	160	10.5	This is an air tank	http://www.harbor
Amazon	$26.40	150	N/A	Flowrate is not great enough	http://www.amazo