Worcester Polytechnic Institute

Design and Implementation of an Ornithopter

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April 28, 2016

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Acknowledgements

We would like express our gratitude to Professor Marko Popovic for advising our group throughout this project, we could not have completed our research and design without his assistance and advice. Furthermore, we would like to thank Professor Hossein Hakim and Professor Dmitry Berenson for co-advising our project and providing their wisdom. We would also like to thank the mechanical engineering department for allowing us to use their laser cutter, drill press and 3D printer. In addition, we would like to thank the electrical engineering department for providing several parts from their shop that contributed to the development of the ornithopter. The Recreational Center has also been of help by providing an empty, open room to run experiments and tests. Additionally, we would like to thank Turn 4 Hobbies for supplying the needed gears, battery and other miscellaneous components for our project.

Abstract

The objective for this project is to design and implement an ornithopter capable of short-distance flight. An ornithopter is a robot that flies in a manner similar to a bird by generating flapping wing motion. Ornithopters can be more efficient, cost effective and environmentally friendly in comparison to fixed-wing aircrafts. This ornithopter has been developed by observation of both natural and man-made fliers, as well as previous academic projects. Goals for this project include being capable of maneuvering around and over obstacles by adjusting pitch, yaw, and roll, able to glide for five seconds under its own power, skillful at alternating between flapping and gliding with minimal disruption of flight pattern and being durable enough to withstand impacts with minimal to no damage.

Introduction

An ornithopter is a machine designed to obtain flight by flapping its wings. Ornithopters are essentially designed to mimic the flight of birds. In most cases, ornithopters are built on the same scale as their living counterpart. This span can range from hummingbird sized Nano Aerial Vehicles (NAVs) to ornithopters with wingspans that are large enough to carry human passengers [1]. Ornithopters use flapping and occasionally airfoil wings to obtain enough lift to carry their own weight. This process involves deflecting air downward and creating pressure differences. The flapping must be coupled with a forward velocity that provides a lift force so that the ornithopter is able to fly. Unlike traditional aircrafts such as commercial jets, which utilize turbines and fans to provide thrust, ornithopters use their flapping wings as a source of thrust. On the other hand, both commercial jets and ornithopters use their wing shape as well as their angle of attack to provide lift that in turn, keeps them in the air. The flapping wing design offers many benefits, including improved efficiency, better maneuverability and reduced noise compared to traditional fixed wing and rotary aircrafts [2]. Most ornithopters are created for hobbyist purposes, however, research into mimicking the biological systems of birds could lead to vast improvements in the aerospace market. Some advances include products in the military, research and commercial industries, which would likely extend to a new ideal solution to air travel.

The ornithopter described in this paper has been developed based off of previous work conducted by Popovic Labs at Worcester Polytechnic Institute, in addition to successful industry models. Ornithopter wing test beds, models and research has acted as a source of inspiration to pursue an electronically driven ornithopter that would be remotely and wirelessly controlled. The purpose of creating this ornithopter was to help academia gather data on the physical forces involved in flight with the use of sensors. Additionally, the efficiency of the system has been explored, as well as the practicality in developing an ornithopter. This report chronicles the team's process of creating and testing the ornithopter that has been codenamed RedWing, due to its large and vibrant red wings.

Advantages and Disadvantages of Ornithopters

Ornithopters have advantages over other fixed wing aircrafts. Some of the benefits that ornithopters have are in their potential as transport and surveillance vehicles. The ideal ornithopter would be able to do all the same things as a comparable bird in nature. An ornithopter could have near vertical take offs. This is due to the flapping force potential. This would be especially helpful for surveillance vehicles, Navy aircraft carrier potentials and use in areas with rough terrain. The maneuverability of ornithopters significantly surpasses those of fixed wing aircraft. The agile dynamic maneuvers of birds could outperform those of aircraft and allow for better surveillance and use in hostile environments. Ornithopters can fly at low speeds. Fixed wing aircraft would stall if they tried to run below their limits and it takes professional pilots to be able to handle maneuvers at low speeds without catastrophic results. According to the results flapping would not have stall issues but would only require a slight increase in power requirements over what the optimal values would be. Ornithopters can be more efficient than fixed wing aircraft. The gliding process and lower start time of the flapping compared to jet and propeller engines allows for a real glide as opposed to cruise conditions obtained by jet aircrafts.

Potential Challenges

It was evident that potential challenges would be encountered in the design of a successful ornithopter. Such challenges that were foreseen include initial flight or takeoff, landing, control, recording data, gliding, weight, and budget. It was unknown how the ornithopter would first take flight, whether it would begin on land or be tossed into the air while the wings are flapping.

Landing was another factor to consider, as crashing could bring about damage or complete wreckage to the ornithopter. When considering this, control becomes another potential challenge. Although a remote control would be operating the flapping of the wings of the ornithopter, there are certain factors such as wind speed that cannot be controlled. It is important to anticipate a large error percentage when designing the ornithopter and choosing the motor and materials used. There are several ways to record data but in this case, an ideal scenario to do this would involve an onboard computer that transmits data to a computer and can be received successfully and processed to a readable language. One of the main goals of this project was to achieve gliding, although this is certainly not easy to do. A precise wing angle and speed must be determined so that gliding can occur with the most ideal conditions. Since the final product must not only be able to handle its own weight, but also lift it off the ground, weight was a challenge that would doubtlessly come into play. The original ornithopter design was modeled to be between 750 g and 1000 g, however, the final design was 1690g. Finally, the proposed budget was another factor that had to be considered. Each individual in the team is given a budget of $150 and the team is composed of four people, allowing for a $600 total budget to implement an original ornithopter, while also considering the need to change, modify, or replace components based on performance and damage that could occur during testing.

Background

Introduction to Ornithopters

History of Ornithopters

Although ornithopters have taken a back seat to hot air balloons in the 1800s and helicopters and fixed wing aircraft in the past century, nearly all earlier attempts at flight focused on imitating the flapping wings of birds. The ancient Greek myth of Daedalus and Icarus shows that the idea of humans taking to the air with the help of artificial wings is millennia old. The oldest recorded attempts date back to 60 CE, and portray enterprising individuals crafting wings from real feathers and leaping from tall buildings, with predictably disastrous results. The first reasonably successful of these tests occurred some thousand years later in 1060, when a monk managed to glide approximately 200 yards before his predictably destructive (though non-fatal) encounter with the ground [3].

A notable step forward in ornithopter design came from Leonardo Da Vinci, although it was never properly investigated until the 19th century. Unlike all previous ornithopter designs, where the pilot would move the wings by flapping his arms, Da Vinci's sketches show devices powered by pushing and pulling levers, with a primitive transmission to convert from horizontal to vertical motion. In 1799, Sir George Cayley (likely ignorant of Da Vinci's designs) came to a similar conclusion, theorizing that a man could not be expected to produce lift purely by flapping his arms. He noted that the muscles in a man's arms make up a far smaller proportion of his weight (and that of any flying contraption) than the muscles in a bird's wings. Instead, Cayley argued that an ornithopter reliant on the muscle power of the pilot must take advantage of "his whole strength" [3].

Further ornithopter experiments continued at sporadic intervals well into the early 20th century, although little progress was made in this time. Most prominent of these inventors was Otto Lilienthal, who while better known for his work with gliders was adamant about the potential of ornithopters. He designed and built two ornithopter models using a primitive combustion engine to power the wings, but was killed in a gliding accident before he could properly test his second attempt. Development of Ornithopters dropped off considerably following his death, mostly due to the success of fixed wing aircraft [3].

In 1929, Alexander Lippisch designed a man-powered ornithopter that flew 250 to 300 meters after its launch. In 1942, Adalbert Schmid built a human-powered ornithopter that flew as many as 900 meters, while maintaining a distance of 20 meters off the ground for the majority of the flight. By adding an engine to the device, the ornithopter was able to fly for as long as 15 minutes in duration. A second aircraft built by Schmid was flown in 1947 and has 1 horsepower, more than three times greater than that of his first ornithopter [4].

In 1960, Percival Spencer sent a number of unmanned ornithopters into the air with the use of internal combustion engines with a range of displacement from 0.020 to 0.80 cubic inches, with a wingspan as large as 8 feet. In 1961, Spencer and Jack Stephenson flew the very first engine-powered, remotely piloted ornithopter that was successful. The successful ornithopter is known as the Spencer Orniplave and had a 90.7 inch wingspan, weighed 7.5 pounds, and was operated with a 0.35 cubic inch displacement 2-stroke engine. In order to reduce oscillation of the fuselage, the ornithopter has a biplane configuration [4].

In 1977, Paul MacCready's manned ornithopter, the Gossamer Condor, was able to be flown through a mile long figure eight course in seven and a half minutes. In 1979, MacCready had built another ornithopter, which flew across the English Channel [4].

Kazuhiko Kakuta is a Japanese doctor who was fascinated with birds and other mechanisms capable of flying. With the use of Autodesk 123D Design, Kakuta was able to create 3D printed parts to act as a framework for a hobbyist ornithopter and added carbon fiber rod reinforcements to these parts to construct a stable and balanced flying model. Kakuta's ornithopter consists of a brushless motor, electronic speed controller, receiver, and LiPo battery, and has a servo within the tail to adjust direction during flight [5].

The Hula is a radio controlled ornithopter that was constructed by George Buckley and first achieved flight in September of 2003. Unlike biologically inspired wings based on natural birds, Buckley's ornithopter utilizes hinged struts that are located halfway down each wing. Rather than depending on air pressures and inertia, these wings are twisted with a crank-pin. This category of wings bares many advantages, including balanced and lower wing inertia, less spar weight, lighter support structure, able to handle higher forces, supported by struts instead of a crank, no needed engine torque, better stability, little danger of tips of wings hitting the ground in landing or takeoff, balanced average lift, and less shaking. Many of these characteristics are only beneficial to larger-to-medium scale ornithopters, where weight and structure are of a higher concern in the overall design [6].

In 2005, Yves Rousseau contributed to the field of aviation and was awarded with the Paul Tissandier Diploma. Rousseau processed his first human-muscle-powered flight in 1995, consisting of flapping wings. On his 212th attempt in 2006, Rousseau succeeded in flying his ornithopter a distance of 64 meters [4].

Professor James DeLaurier led a team at the University of Toronto Institute for Aerospace Studies (UTIAS) working towards creating an engine-powered, piloted ornithopter. DeLaurier and his team spent seven years designing, building, and testing their craft. This team made a transmission systems that was able to convert the high-speed rotary motion of a model airplane engine into a relatively slow up-and-down motion. The final version of their ornithopter had a wingspan of approximately three meters. In July of 2006, DeLaurier's device, the UTIAS Ornithopter No.1, made a 14-second flight at the Bombardier Airfield at Downsview Park in Toronto [4].

In May of 2009, students at Massachusetts Institute of Technology (MIT) developed a large scale autonomous ornithopter, which they called Phoenix. This ornithopter was created in order to study the application of controls. The ornithopter was based off of a commercially available ornithopter called the Kestrel. This ornithopter was modified to optimize payload so that the controls system for autonomous flight could be carried. This ornithopter was successful in flying short distances without user input. More information about this project can be found in the Literature Review of this paper, found on page 24 [7].

In 2010, Todd Reichert of the University of Toronto Institute for Aerospace Studies, piloted an ornithopter that he called Snowbird. Snowbird had a 105 feet wingspan and weighed in at 93 pounds. The ornithopter was built using carbon fiber, balsa wood, and foam. The machine was towed by a car until it achieved flight and had a small cockpit below the wings, where the pilot sat to pump a bar with his feet to operate a system that flapped the wings up and down. The ornithopter was able to fly for almost 20 seconds, flying 145 meters with a speed of 7.1 meters per second [4].

Lift theory for Ornithopters

In order to obtain the optimal ornithopter, forward speed, flapping frequency, total flap angle, angle of attack, maximum pitch angle, lag between pitching and flapping, and time steps must either be known or determined using specific equations. It has been observed in MATLAB that using a 40 cm wingspan, 10 cm root chord, and 12 gram mass will result in a varying forward speed between 5 m/s and 10 m/s, a flapping frequency between 4 Hz and 16 Hz with an increment of 2 Hz, and a flapping angle between 30 degrees and 90 degrees. The obtained results exhibit that lift of the ornithopter is most influenced by incidence angle and forward speed, and least influenced by flapping frequency. In addition, thrust is most affected by flapping frequency and forward speed, and least affected by incidence angle. The values also delineate that drag increases with an increase in forward speed, incident angle, and flapping frequency [8].

Simple flapping of the wings of an ornithopter with carefully decided parameters and an overall lightweight design is capable of producing necessary lift and thrust that will allow the device to carry its own weight and achieve flight. Birds use a multitude of mechanisms to modify the vertical flapping motion that they are able to produce. Wingtip strokes of larger birds follow simple patterns like figure-eights, while smaller birds have more complicated wingtip patterns, which become increasingly complicated as the size of the bird is further decreased. Similarly, the aerodynamics for larger birds with slow flapping rates is steadier than smaller birds which possess very unsteady or nonlinear flight. Smaller birds are required to work harder to produce vortices due to an increasing viscous flow regime. Flapping can overall be broken down into three distinct motions. Firstly, flapping itself produces most of the power and the largest degree of freedom. Secondly, there is also feathering or pitching, which is the pitching motion that varies along the span of the wings. Lastly, lead lag is the in-plane lateral movement of the wings. Flapping axis, pitching axis, and the lead lag are also more commonly known as roll, pitch, and yaw. A diagram of these motions along their axes can be seen in Figure 1 below [8].

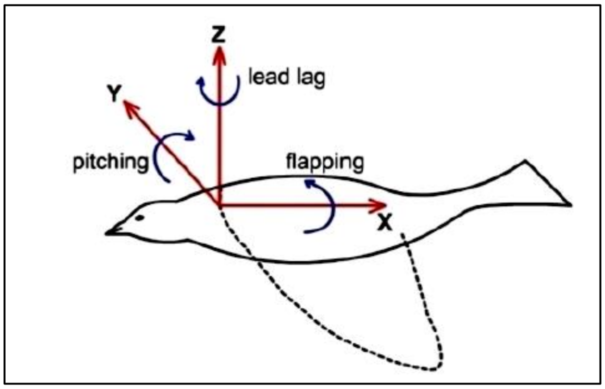

Figure 1: Angular Movements of the Wing [8]

Flapping involves two strokes, which are upstroke and downstroke. During downstroke, the total aerodynamic force is adjusted to a tilt which generates lift and thrust. During upstroke, the angle of attack is positive near the root and can be either positive or negative at the tip depending on the pitching up of the wing. In upstroke, the upper part of the wing produces an aerodynamic force upward with a backwards tilt, producing positive lift and negative thrust. When the angle of attack is positive, the outer part of the wings produce positive lift and drag. Conversely, when the angle of attack is negative, the wings will produce negative lift and positive thrust [8].

Ornithopter Controls

Steering is a vital component to consider when designing an ornithopter. The bird will require a method to control where it goes, or rather which direction it travels. It must not only be able to change direction intentionally, but also be capable of avoiding accidental or unintentional directional changes. Intentionally changing directions is known as maneuverability, while avoiding or reversing unintentional change is termed stability. The tail is known for acting as an effective stabilizer during flight, as well as the dihedral, which is an upward angle of a bird's wings when held stationary in soaring. A third term that bares importance in this setting is agility, which is the ability to turn very sharply. The ornithopter must be able to steer vertically as well as laterally and longitudinally. The vertical movement represents the separation between flight and terrestrial movement. Flying creatures or devices can rotate nose-up or nose-down, which are pitch rotations, or bank so that either the left or right wing is low, which are roll rotations [9].

Ornithopter Applications

Ornithopters can be used by researchers to investigate wildlife more closely and can also be used in the commercial industry for payload transportation. Ornithopters can also have applications in surveillance and are incorporated in several military applications. They are advantageous in this field as they have a low aeroacoustic signature, which is the noise produced by the machine. In addition, ornithopters make suitable small scale aerial vehicles due to their aerodynamic properties. Although small ornithopters may be the victims of wind gusts, they have great potential to execute difficult maneuvers, such as hovering and backward flight. Pioneers in the ornithopter industry have determined that these devices have a plentitude of potential contributions to the science of aerial remote sensing. Defense Advanced Research Project Agency (DARPA), the Pentagon's advanced-research unit, created a nano air vehicle. The NAV is capable of controlled hovering flight with two flapping wings that carry its own energy source and are responsible for propulsion and control. DARPA intends to use the NAV for secret government indoor and outdoor missions in the future. DARPA explains that in comparison to any other small air vehicle, the ornithopter proves advantageous due to its lower Reynold's Number, which expresses the ratio of inertial forces to viscous forces and essentially provides a measurement for airborne efficiency [10].

Avian Anatomy

Birds have evolved over many thousands of years to be able to fly optimally with ease and precision. Avian anatomy is intricate, especially when considering the biological structure of birds.

This complexity is exhibited in birds' hollow bones and many feathers, which illustrate the effort that avian anatomy has invested in trying to minimize weight without demolishing the structural integrity required to handle the forces involved in flight [9].

A bird's power stems from the muscles and tendons that lie beneath its feathers and skin, contributing to some of their most definable features. A bird's tail allows it to change directions during flight [9].

The muscles of birds, which are further examined later in the report, are extremely large compared to their overall mass. The pectoral muscles are the largest muscles of a bird and are essential for allowing the bird to control and flap its wings. The specialized brains of birds allow for their intricate control. By adjusting their wings and tail, aerodynamic characteristics can be modified to achieve maximum lift, higher speeds, and optimal drag [9].

Biomimetics

The definition of biomimetics as described by Raz Jelinek in his book *Biomimetics* is as follows: "the examination of nature, its models, systems, processes, and elements to emulate or take inspiration from in order to solve human problems." Using this concept, the ornithopter was inspired by bird anatomy and behavior as well as physical principles of aerodynamics and mechanics. For the ornithopter, this was shown in many areas of the design. For example, the tail of the ornithopter was inspired by bird anatomy. The tail of a bird is controlled at the base with a small nub or central point of matter [11]. The tail of the ornithopter was created using a custom designed 3D printed part that fit into a servo-based power system at the base of the tail. This structure was able to direct the motions of the lighter fabric and supports. Another use of Biomimetics in the ornithopter design was placing a power system in a location similar to that of the pectorals of a bird, effectively mimicking the muscles which birds use for flapping.

Literature Review

To strengthen the background knowledge on ornithopters, the team has reviewed several scientific publications. The executive summaries of the articles are presented below.

In *Biomimetics: Nature Based Innovation*, editor Yoseph Bar-Cohen proves the influences that nature has had and will continue to have on technology. Biomimetics has played a large role in the development of human flight. Throughout history, birds have inspired such inventors as Leonardo da Vinci to design flying machines, most notably an ornithopter. All of Da Vinci's designs were cataloged in Da Vinci's Codex. Another contributor to the understanding of the flight of birds is Giovanni Alfonso Borelli, famous for his understanding of avian flight dynamics. In Borelli's work *De Motu Animalium*, he describes the way that he believes birds flew and how they are able to control their flight. Borelli's concepts were recognized as being scientifically accurate for 200 years. Otto Lilienthal is another big contributor to the study of avian flight with an in-depth analyses of flight patterns using a "photographic gun" that overlaid images onto a print. He published his results in *Birdflight* as the Basics of Aviation, in other words "lift with an airfoil" [12].

Five methods of flight were also described in this test:

"1. Rowing Flight - Flapping for constant motion

2. Gliding Flight - Rowing flight separated by static wing positions that rely on kinetic energy for forward motion.

3. Soaring Flight - Gliding for extended periods of time so that muscle function is used almost exclusively for balancing

4. Sailing Flight - Soaring using wind deflected by sails of boats or crest of waves.

5. Circling Flight - Using thermal pockets to remain airborne by circling in the rising currents" [12].

The main focus of the Ornithopter project is to mimic the gliding and rowing techniques of flight. The weight to surface area of flight is described in this literature. Demonstrating the importance of reducing weight can be seen by examining the calculations of Karl Meerwein who found that a 200lb man would require a surface area of 126 square feet in order to be considered capable of flight. This calculation was based on the model of a duck flying. Weight also has a correlation to velocity. In general, as weight increase velocity of flight also increases. The equation for relative velocity can be described as velocity = $(\text{weight})^{1/6}$. This function can be used based on the weight versus velocity relations [12].

The flight of birds and the effects on air conditions is another important concept to discuss. The conditions that birds experience during flight are dependent on shape and size, among other factors. The weight of a bird can be graphed against the Reynolds Number, which is a measure of the state of a fluid flow. The Reynolds Number can affect the mechanism of flight of a bird or insect. Laminar conditions are estimated to occur below a 4kg weight. Also the Reynolds Number has a large impact on wing profiles, which varies drastically as the Reynolds Number increases. In *Biomimetics: Nature Based Innovation* the Reynolds Number is plotted with respect to a lift-to-drag ratio. Several wing profiles were correlated to the plot in this section and analyzed per design speculations. For example, pigeon's wing possesses a Reynold's Number of approximately 40,000 with a lift-to-drag ratio of 20. This can ideally be matched with an ornithopter created for mimicking flight of a pigeon, but realistically, the exact parameters are biologically hard to obtain [12].

In addition, stability and control for flight must be taken into account. In traditional aviation, the three directional controls are pitch, yaw and roll. These directions are based on the three axes of motion and allow for controlled flight in 3D space. As described in *Biomimetics: Nature Based Innovation*, birds' use the following tactics and features to control pitch, yaw and roll:

"Pitch Stability and Control

- A long, sturdy, movable flattened tail
- Downward and upward movements of the tail
- Fore and aft movements of the wings relative to the center of gravity

Roll Stability and Control

- Long, broad wings with rounded tips
- sweepback
- Wings asymmetric dihedral like movements
- Twisting the wings in different directions

Yaw Stability and Control

- Long, broad wings with rounded tips
- Tail Rotary Movements
- Twisting and flexing the wings to change drag"

The three directional control axes or methods can be used as a basis for designing the control system of an ornithopter, which would further result in optimal flight [12].

In 2014-2015, "Ornithopter Testbed to Discover Forces Produced by Flapping Wing Movement" by Carlos Berdeguer, Hanna Schmidtman, and Austin Waid-Jones describes how flapping wing patterns can be used to optimize ornithopter designs. The team created a test bed that can be modified to find the wing strokes that allow for the most efficient flight. The system uses a four bar linkage that is modular to allow for varying patterns of motion. The modularity of the system is dependent on a protractor style of design with slots at various locations in place of one of the bars, which allows the linkages to be adjusted. Three motion patterns were studied by the members in this group. The motions consisted of a teardrop shape, a figure eight, and an almost linear pattern. These patterns are only a few examples that can be created using the linkage system, with many more existing options that could be implemented [13].

This team performed several tests using a simplistic wing design. The wing was constructed in the shape of a long rectangle, which was attached to the testbed. The testbed itself had force sensors recording input forces from the wing as it went through its initial motion. The design of the wing skewed the results of the tests due to the similar forces imparted upon the downstroke and upstroke. Due to this occurrence, the patterns were evaluated using the largest downstroke forces as well as the maximum forces. According to the team, the teardrop shape had the most average force. It was noted that: "the teardrop shape, created the highest maximum force and average downforce. Despite this, it also created a significant amount of upward force, referred to as drag. This means that the positive forces, created on the down stroke, were more than negated by the upwards drag." The use of a patterned wing motion was disregarded by the team in the first iteration of RedWing as the mechanism required to create the motion and the added complexity of making the flapping motion be multiaxial would impede on the jointed flapping that was desired [13].

"Theoretical Model and Test Bed for the Development and Validation of Ornithopter Designs" by Alexandra Beando, Christopher Overton, Tyler Pietri, Jesus Chung, and Kevin Ramirez analyzed the optimization of a linear flapping wing pattern. This testbed analyzed the performance of a prototype and devised guidelines for future iterations of ornithopters. One such recommendation was to implement a model that was lighter and had reduced friction. Their hole pattern, which involved drilling out small sections of the chassis without compromising structural stability, was later applied to RedWing in order to reduce weight. The parts used for this ornithopter primarily strayed away from metal-to-metal connections, instead opting for meshing of plastic-to-metal gearing for reduced wearing on the gears [14].

In 2013, "Toward a Biologically Inspired Human-Carrying Ornithopter Robot Capable of Hover" by Nicholas Deisadze, Woo Chan Jo and Bo Rim Seo observed the feasibility of heavy biologically inspired robots capable of hovering. Sensory motor control was thoroughly discussed, as it is crucial in the successful design and implementation of an ornithopter. In addition, bird wing beat frequency is low, which means that birds must continuously adjust their wings during each stroke to remain airborne, change position, hover, land, accelerate, and slow down. Wing beat frequency and stroke angle change throughout flight since wings generate vertical force that is greater than or equal to gravity and horizontal force for forward thrust. Birds achieve flight due to the aerodynamics of their body shape, as well as the muscles they possess. These muscles are described in the following section.

Muscles Involved in Bird Flight:

- "Pectoralis: located at chest; primary muscle that powers wings for flight and is 8-11% body mass and about 60% wing muscle mass. This muscle can keep birds airborne and overcome drag forces. It contains large muscle fibers allowing large muscular movements.
- Supracoracoideus: about five times smaller than the pectoralis and about 2% body mass. This muscle is the wing elevator during upstroke motion and is also the wing supination.

It is very active during slow and moderate flight speeds and during hover. It does not generate much force and is less accommodating to muscular strains.

- Smaller muscles include biceps, brachii, triceps, metacarpi radialis, and carpi ulnaris. These muscles are lightweight, deform less, absorb less energy, output lower power, and are involved in flight, although they are not able to generate enough force to support body weight or overcome drag. They help orient and control wings during flight by maneuvering and maximizing energy by changing wing geometry to maximize aerodynamics of flight" [15].

In addition to their muscles, birds use primary feathers to generate lift and thrust during flight; they are aligned to reduce drag forces on the wings by up to 25%. Birds are able to generate pressure gradient across wings when flapping to produce upward lift force. During downstroke, feathers are held tightly against each other to prevent air flow through wing. During upstroke, feathers separate in horizontal and vertical directions to allow air passage in between. Secondary feathers are shorter and wider and don't generate any thrust, but help to produce lift forces in flight. In birds, upstroke kinematics and aerodynamics vary with flight speeds, while downstroke remains rather consistent. Birds usually enter slow speed flights in takeoff and landing and have wings positioned nearly vertical to maximize generated lift forces. This method of flight is often referred to as gliding. In fast speed flights, wings in downstroke have slight forward movement and upstroke has no propulsive backward flick while wings moves relatively slowly. In flapping wing flight, birds alter wing beat frequency, wing angle of attack, and stroke amplitude; this provides high maneuverability, ability to fly at low speeds, and high power and aerodynamic efficiency. Lift and drag forces determine flight energy efficiency, flight speed, and maneuverability of the flying body. The Strouhal Number is terminology used to describe the efficient cruising locomotion, which requires a value between 0.2 and 0.4. Birds adjust wing beat amplitude and wingbeat frequency to maintain a constant Strouhal Number. The tail of a bird at low speeds acts as a splitter plate and lowers parasitic drag up to 25%. The tail is also involved in lift production by preventing flow separation and is important for flight stability and control. Wing Loading is known as the ratio of weight of the flying object to the wing area and describes actions of gravitational and inertial forces against aerodynamic forces [15].

In the 2014-2015 academic year, “Fluidic Muscle Ornithopter” by Alphan Canga, Michael Delia, Alexander Hyman, and Angela Nagelin, focused on creating a large scale ornithopter which would use pneumatic “muscles” to control the movement of the wings. This team chose to model their ornithopter after a Herring gull, after research into the flapping motions of various birds and insects suggested that the gliding abilities of a seagull would make it the most efficient bird to emulate. They selected the S1223 airfoil as the most appropriate shape for their wings. They furthered their imitation by adding a joint in the middle of each wing which would allow them to change both surface area and angle of attack on the up and down strokes, improving flapping efficiency and maneuverability [16].

Ultimately, this team had trouble limiting the weight of their ornithopter, and were unable to get it off the ground. Part of the problem was an inability to acquire an air compressor light enough that placing it inside the ornithopter would be practical. Their muscles were also unable to flap the wings quickly enough. Their results made a convincing argument that hydraulic and pneumatic muscles are probably not the most practical choice for an ornithopter given available resources [16].

"Design and Construction of an Autonomous Ornithopter" by Zachary John Jackowski documents the process of creating an ornithopter for research purposes. Jackowski, a student at MIT, documents the process that he undertook to create an ornithopter from scratch. The goals of Jackowski's project was to create an autonomous ornithopter that could help to improve understanding of flapping wing flight. Jackowski's ornithopter was designed for survivability and to be able to hold a large payload of sensor equipment. This ornithopter was named Phoenix and used rigid wings as opposed to jointed wings. The model was constructed with heavy, yet durable components. The Phoenix's original design was based on a commercially available ornithopter, the Kestrel. This model used a rigid wing structure and had a tail that acted as a rudder to steer. The use of a tail rudder to control movement of the ornithopter is supported by the success of Jackowski's ornithopter, as well as the Kestrel. Jackowski provided insight into the types of sensors and computer controllers that would be most helpful in the design iteration of RedWing. The use of micro ball bearings as opposed to sleeve bearings was also observed due to Jackowski's design. Jackowski's successful design for the Phoenix additionally supported the assumptions and the mathematical conclusions that were found while designing RedWing [7].

Methodology

Project Goals

To be considered successful, the MQP team will create a final ornithopter model that will meet or exceed the following goals:

1. Be able to fly under its own power in a controlled fashion in the pitch, yaw and roll directions to avoid obstacles with a larger surface area than an equivalent 1m x 1m square for a duration of at least 30 Seconds.

2. Be able to glide for 5 seconds under its own power, which is defined as not flapping and remaining in flight within a 90 deg range or 45 deg in either direction from the x direction parallel to ground upon start of glide.
3. Be able to transition from flapping to gliding and back to flapping with minimal disruption of flight pattern.
4. Durable enough to withstand impacts and/or a short repair time if failure occurs.

Preliminary Design

The design process for the RedWing ornithopter began by narrowing down flight mechanics by studying flight patterns and anatomy of organisms, particularly flying birds. Previously developed ornithopters provided various methods of flight, which were thoroughly researched and analyzed. The three main types of flight that were considered were rigid wing flight, jointed wing flight, and patterned wing flight. Different sizes were also considered for the three wing types. Some assumptions were made based on trends observed in the natural world. For example, the small ornithopter size that resembles a Robin with a wingspan of approximately 40 cm was based on data found about the Robin population. This Robin design would require a very fast wing beat frequency, thus limiting the possibility of using passively jointed wings or pattern wings as these motions take time to be completed during the wing stroke. The pros and cons of these types of flight and pros and cons of the sizes were listed out. Based on the listing, a jointed wing on a medium sized bird would be best suitable for this design. A conclusive list of pros and cons can be seen in Appendix B.

Calculations of Dimensions

Once the decision for the design had been chosen, the specifications for the ornithopter needed to be determined. To implement modeling of bird flight, mathematical calculations were conducted based on fluid dynamics and physics. Models provided by the advisor of the RedWing ornithopter, Professor Popovic, were used as a basis for determining wing length and width. These equations were used to account for adequate thrust and wing beat frequency based on an assumed mass and velocity for the ornithopter. Several conservative estimates were used to ensure that the calculations would take into consideration the losses of efficiency throughout the system. The process for calculating specifications can be seen in the section below.

First, the constants were set.

- Coefficient of Drag (C_D) = 2
- Density of air (**ρ**) = 1.225 kg/m^3
- Acceleration due to gravity (G) = 9.81 m/s^2
- Maximum angle wing makes with respect to body (**θ**) = 0.5236 radians

The coefficient of drag was set as if the wing was a flat plate. This was done because the velocity of the wing is in the Y direction with respect to the direction of travel of RedWing. In addition the surface area of the wing when looking straight at RedWing's beak produces negligible drag. Therefore the only source of drag will come from this flapping motion.

Then, values were set for certain parameters.

- Wing span (b) in meters was set based on the size of a number of birds.
- Chord length (c) in meters was set based on the size of a number of birds.
- Weight (M) in kilograms was set based on the size of a number of birds.

Finally, values were calculated.

- Drag force (Fd) was calculated with the following equation:

$$\text{Fd} = \rho * C_d * \text{c} * \frac{b^3}{3}$$

- Angular Momentum (**ω**) was calculated using the following equation:

$$\omega = \sqrt{\frac{M*G}{Fd}}$$

- The time for the downstroke (T) was calculated next:

$$T = \frac{1}{(\omega*\theta)^2}$$

- The torque (□) of the wings was then calculated:

$$\tau = \rho * \omega^2 * C_d * c * \frac{b^4}{8}$$

- Power (P) in watts was calculated:

$$P = \tau * \omega$$

- Power (P_{hp}) in horsepower was calculated:

$$P_{hp} = P * 0.00134102$$

After several iterations using sizing from birds, the set parameters were adjusted to obtain values that would be more realistic when the team was manufacturing the system. The team's calculations are presented below for the proposed sizing, a full table of calculations can be found in Appendix D.

Table 1: Parameter Calculations for Realistic Values

B (m)	M (kg)	C (m)	Fd (N)	**ω** (rad/s)	T (s)	**τ** (Nm)	P (W)	P_{hp}
0.50	0.62	0.33	0.033	9.24	0.113	4.14	38.3	0.051

RedWing Design

RedWing was developed based on the anatomical structure of birds. Birds have a light skeletal system, while also having powerful musculature. This anatomy was carried over in creating the ornithopter.

The main concern with creating the ornithopter is how the force will be distributed along the wing during upstroke and downstroke. It was desired to use material for the wing supports that would provide both strength and flexibility, while still keeping within budget. It was concluded that the wings would be fixed without a joint for simplicity. Calculations were performed that varied the feasibility of the size and design of the wings. This process began by sketching out design iterations. A linkage system, as seen in Figure 3 below, was used to both enable the desired wing motion and reduce weight of the ornithopter. There would only need to be one motor running which had a small fixed metal gear along the shaft that meshed with two larger plastic gears with a 9:1 ratio. These plastic gears were connected to the aforementioned linkage which not only reduced the amount of electrical equipment required, but also guaranteed that the wing beats would be synchronized when there were no obstructions. The materials used for the wings were carbon fiber rods and 3D printed ABS plastic. The carbon fiber was used to mimic the bones of the wings. The ABS plastic was used as the connectors of the rods and linkages.

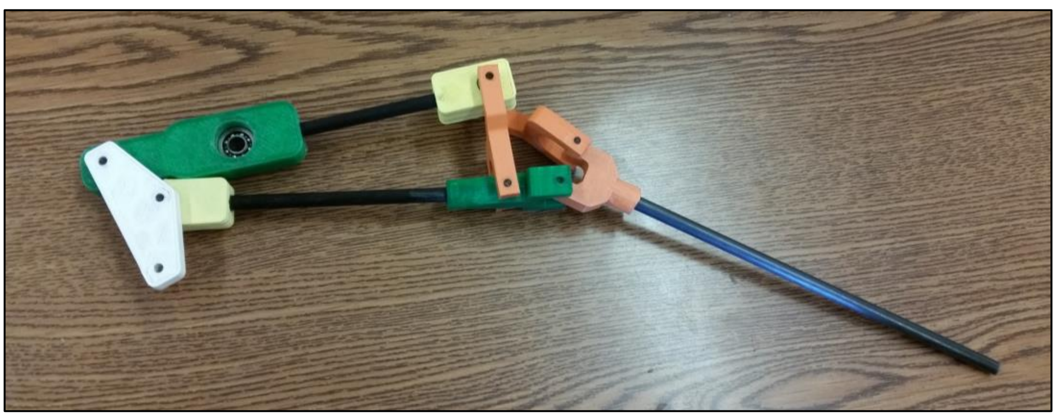

Figure 2: 3D Printed Linkage with Jointed Motion

The first wing design was formed used custom designed computer aided design (CAD) modeled parts that have been 3D printed. These parts acted as joints connected to carbon fiber rods. This body, however, proved to be unstable as it could not handle the power delivered by the motor and would disconnect every time the flapping motion was initiated. The increased number of joints and the uneven surfaces of the 3D printed parts also produced an untenable amount of friction, forcing the team to switch to a simpler linkage design.

The next design for the frame of the wings was formed using aluminum bars that were purchased from a local Lowes hardware store. These commercial parts were in the hobby section of the store. They had holes in 0.5in. intervals along the rods of different sizes. This was ideal for allowing the design of the system to be modified so that the four bar linkage could adjust and allow the team to find an optimal wing stroke. The bars were connected to create the "bone" of the wings. Using a four bar linkage design that connected the "bone" of the wings to the motor using gears as the power transmission system, the wings flapped up and down. The connection between the gears and the bone was another metal rod. 6/32" machine bolts were used for connecting all these components. Lock nuts held the components in place when regular nuts fell off from the vibrations of the system. Nylon spacers of varying sizes were used to ensure enough clearance between parts. Washers were used both to reduce friction between moving parts and also as smaller spacers for components. For simplicity, the jointed wing design was removed from the system during testing. While the joint was included, there were mechanical issues that resulted in part failure.

The next iteration of the design incorporated reinforced connectors between the wing bars and the gears, and a reinforced cross bar, which can be seen in Figure 3 below.

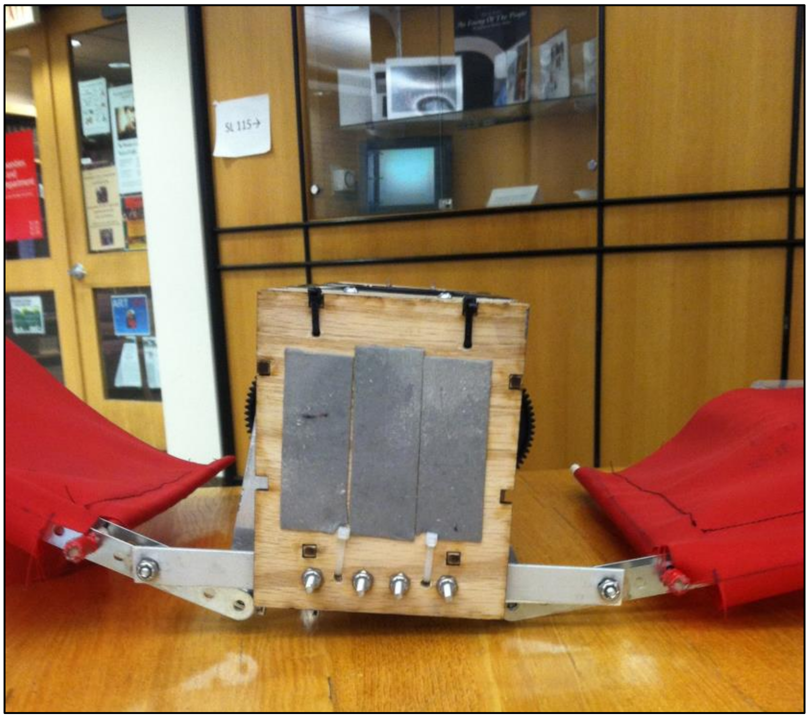

Figure 3: Wing Structure with Aluminum Struts

The following iteration added a planetary gear with the sun gear attached to the motor providing an increase in torque. The size of the wings were increased as well. The wing struts of the ornithopter were covered in a ripstop nylon in this design iteration. The nylon provided an adjustable angle of attack which created a more desirable lift force. The nylon wing coverings were cut in the rough shape of the wing, with protruding flaps along the top and sides. The intention of this design was to provide structural support that could withstand the force of RedWing's wingbeats, while also being removable and reinstallable with relative ease. This was done by stitching loops into the fabric which could hold the aluminum struts and carbon fiber rods in place, positioned such that the two structural support materials would only allow movement in perpendicular directions. The "bones" in this design were used to secure the nylon in the appropriate position. The carbon fiber rods that extended from the "bones" added additional rigidity and support. This implementation can be seen in Figure 4.

The wings could be assembled or taken apart in a few simple steps by removing and replacing the carbon fiber rods. On the other hand, when the wing was properly fabricated, the nylon would hold everything in place during tests provided that the material did not tear and the structural supports remained intact. This characteristic made the wing design described very beneficial in the comprehensive structure of the ornithopter.

The system dynamics portrayed in this section herald several advantages, however, there were also several noteworthy downsides. The ease of dismantling this structure was partially belied by the difficulty of constructing the wing coverings and the need to create an entirely new covering each time the wing length needed to be changed, or the supporting struts had to be repositioned. The aluminum bars as well as the nuts, bolts and spacers that held the wings together added a significant amount of weight to the system as a whole, and caused the structure to be more flexible than what was desirable. Finally, adjusting the angle of attack of the wings added complications and difficulties to the design, such as the sudden need to use a different material in place of the wing coverings or struts.

Figure 4: Fabric Wing Covering

In the final design iteration, attention was focused on reducing weight and improving rigidity. This was accomplished by replacing the aluminum bars that acted as the original wing struts with a single wooden rod for each wing, reducing the number of rods and supports that would be required. The struts along the wing and the pocketed wing coverings were replaced with a single triangular piece of nylon designed to reach from the wingtips to the body of the bird. This design had easier preparation and installation in comparison to the complicated loops and flaps integrated in the previous wing coverings, which allowed for testing as a proof of concept with minimal risk. This setup additionally allows for the angle of attack to be easily alterable since the base of the wing cover was attached to the body of the bird below the level of the wing struts, creating an optimal upward angle from the back of the bird.

Body Design

The body of RedWing served several functions. It provided structural support for the overall system and increased longevity of RedWing during crashes. The body was designed to absorb most of the impact during a crash and ultimately survive. In addition, the body provides a space for more delicate components to be mounted securely and housed safely. The microcontroller, wireless receiver, gear and linkage system, sensors, and other electrical components were mounted along the body without damage and connected to one another using male-to-male banana cables. The tail is also secured to the body behind the center of gravity, allowing for greater directional control.

The body of RedWing was first implemented using a large section of laser cut acrylic formed into a streamline box design that housed the motor, the electronic speed controller (ESC) and the battery. The acrylic structure survived many courses of testing but eventually became prone to failure. In order to provide a more stable structure, pine wood was selected as an alternate material composing the body. This decision based off of the wood being less brittle and more resistant to the vibrations throughout the system during run-time. Additionally, the wood housing was less expensive and easier to manipulate. The body was initially constructed using custom ACAD designs that were then laser cut into the desired material. The requirements for the body consisted of durability and strength, ability to enclose or shelter the components of RedWing and to be competently accessible for repairs. A rectangular box was first designed, that had pegs and slots that fit together similar to a puzzle. These components were drilled into in order to produce appropriate gaps for the attachment of the motor, shafts and cross bar utilized for the wing linkage. This initial design can be seen in Figure 5 below.

Figure 5: Original Wooden Housing for Ornithopter Body

The next iteration of this housing was scaled up in order to more easily contain the components internally, while also providing external space for sensors, the battery switch, tail, and microcontroller. The body of the housing was modified so that slots were cut into the inner supports, which allowed for bolts and nuts to be fastened. This implementation held the body to the internal structure, which provided for more overall stability. This stable housing construction was successful in enclosing the more delicate components and the motor and new gearing was set to match the new design. The setup of this model can be seen in Figure 6 below.

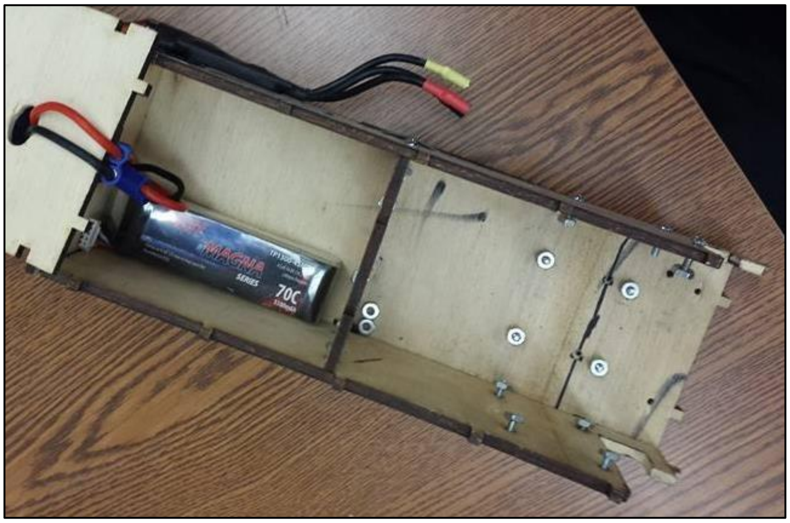

Figure 6: Internal Housing for Components with Bolt and Nut Setup

The final housing was able to hold up to the stresses of the system and contain all of the components, while also protecting them from impact during testing. To assist with the protection process, a crafting foam was attached to the bottom of the housing. The foam acted as a damper against hard landings to the ground and other surroundings. For frontal impacts, a balsa wood nose cone or head was attached to the forward most section of RedWing. Although this component would likely take damage during a crash, it would prevent damage to the housing and vital components contained internally. The head was attached to the body with double-sided tape so that it could be replaced or repaired easily without affecting the design as a whole. The customized balsa wood nose cone can be seen in the Figure 7.

Figure 7: Nose Cone for RedWing

For the final iteration of housing, the team ultimately decided to proceed with pine wood housing due to some of the unfavorable properties of acrylic that have been previously mentioned. The new design, however, acted as more of a framework than housing. In the previous rendition, the body weighed approximately 470g, which made the wooden body almost 31% of the weight composing the ornithopter. Although an all-encompassing housing ensured safety of the components, it was obvious that the housing was creating extraneous weight and space. The new design utilized the side walls incorporated in the previous designs, but omitted the top, while the bottom was secured with fabric rather than wood in order to eliminate some of the weight. The new body weighed 247.81g, representing approximately 22% of the total weight. This housing model was implemented in the final design iteration of the ornithopter.

Electrical Specification

The electrical components incorporated in the design of RedWing were carefully selected to provide optimal conditions, while also being safe to handle. A brushless outrunner motor was used due to its efficiency and high power-to-weight-ratio, which is an essential component to take under consideration when creating an apparatus capable of achieving flight. With the motor being the most critical component in the design, components such as the battery and ESC were chosen to mesh with the motor ratings and specifications. The final motor used was selected based on its performance. Most favorably, the motor provided high power and a modest amount of torque, while also being reasonably lightweight.

The motor was attached to an ESC. This device allows the brushless motor to take in signals allowing for a range of output and not just an on or off state. The ESC for RedWing was attached to the motor and then was routed through the microcontroller so that signals being sent to the receiver could be modified before being sent to the motor via the ESC.

In the configuration of the Ornithopter, the distribution of signals plays a vital role in successful flight. The remote controller transfers a signal implemented by the user wirelessly to the receiver, which then transmits this signal to both the Arduino or microcontroller and the servos. The Arduino receives an additional signal from the sensors. In turn, the Arduino transmits the user-implemented signal to the motor controller and the SD card interface. The battery transmits power to the motor controller, which is able to transmit the original signal to the motor. After the motor receives the signal, it begins to turn, causing the fixed gear to turn and the following gears to rotate, causing the wings to flap and the overall contraption to gain lift. A diagram framing these signal distributions was implemented using Multisim and can be seen in the figure below.

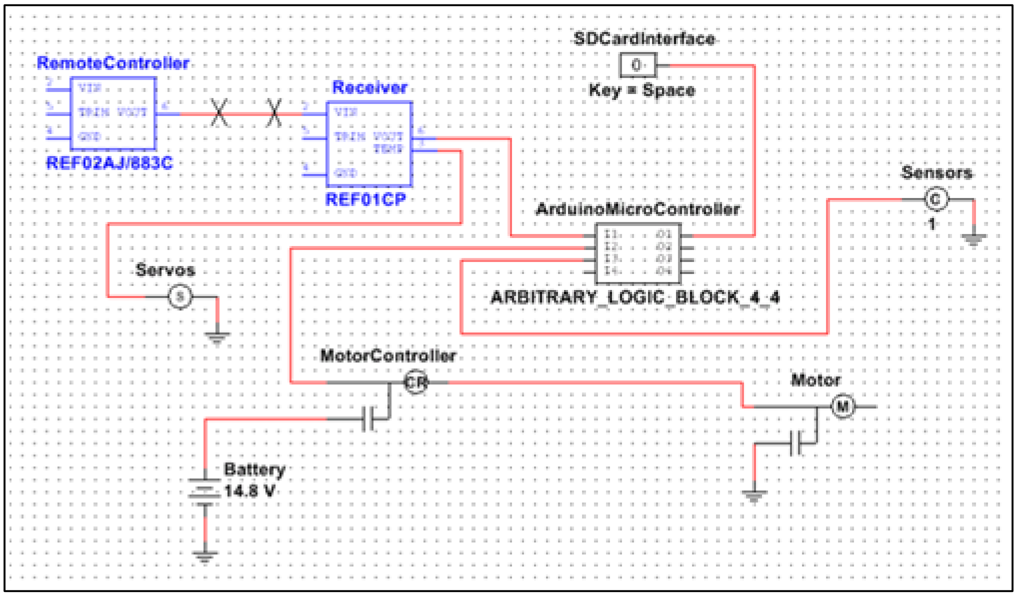

Figure 8: RedWing Signal Distributions Implemented in Multisim

In layman's terms, the motor is connected to the ESC, which is further connected to the battery. Since the battery is capable of supplying 14.8V it is important to take safety precautions. When dealing with this amount of power, it was decided that a mechanism should be integrated into the design that will be able to shut everything off when necessary. The battery needed to be disconnected in two cases: when testing is complete and when the battery needs to be charged. This device proved to be very useful considering that the only way to disconnect the battery was to pull out the wires by hand, which was both inconvenient and carried a small risk of electrocution. A high-current switch was added in between the ESC and battery in order to account for the possibility of such dangers. For this switch, the toggle pointing upward indicates that it is on and power is being supplied by the battery, while the toggle pointing downwards, as it is Figure 9, indicates that it is off.

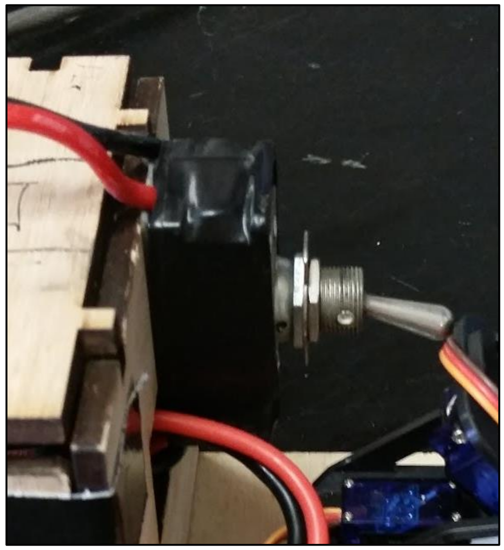

Figure 9: On-and-Off Switch Setup for Battery

Motors

The first motor selected was a Turnigy Park450 Brushless Outrunner 890kv. An outrunner was chosen because it had higher torque values than a standard brushed motor. As much torque as possible was needed to move the wings. The outrunner 890K was rated for 425g–850g aircraft which matches the theoretical weight that RedWing would have. The motor also had a very low weight at only 67g [17]. This motor, however, was unable to provide the torque and power that was needed to turn the gears and flap the wings of the ornithopter.

The second motor tested with the design was the Turnigy Aquastar 2842-2800KV Water Cooled Brushless Outrunner Motor. This motor was slightly heavier at 138g but also more powerful and capable of supplying significantly more torque [18]. After redesigning the ornithopter to be at a larger scale to suit this motor, it proved to be a better, more reliable choice. The arrangement utilized in this design is termed “dual cranks.” Although this setup adds weight to the overall design, it also improves efficiency by making the wingbeats more symmetric [12]. With the use of this motor in a dual cranks setup, the necessary rotary motion is provided, which can then be converted to an oscillating wing motion in order to flap the wings and create lift. The motor described in this section and implemented in RedWing can be seen in the Figure 10.

Figure 10: Turnigy Aquastar Brushless Outrunner Motor

Gear Implementation

RedWing initially utilized a total of three spur gears, with the addition of a planetary gear. The gears are used to gear down the motor and provide enough torque to flap the wings. The gear reduction is dependent on the chosen motor and the desired characteristics of the ornithopter. In this design, the gears were arranged so that two large 68 tooth plastic gears would turn simultaneously with the activation of the motor, which had a small metal nine tooth gear fixed on the shaft. These gears had a 9:1 gear ratio, respectively. The planetary gear itself had a 5:1 gear ratio.

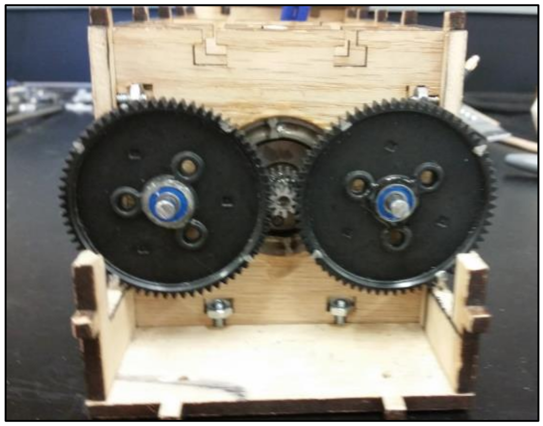

Figure 11: Dual Crank Gear Arrangement with Fixed Motor Gear (9:1 Gear Ratio)

During several tests, the flapping motions of the wings seemed to not be synchronized. This problem was attributed to the gears skipping teeth while the motor was running. Initially, the larger 68 tooth gears were assumed to be loose and wiggling out of the connection. To further understand what was happening, the team borrowed a high-speed camera and took a video of the motor and planetary gear turn the drive gears without the wings attached. The preliminary viewing of the footage seemed to suggest that the two 68 tooth drive gears did not slip. However, the planetary gear and drive gear appeared to wiggle while the motor was running. Upon viewing the frame-by-frame of the high-speed camera, it did not appear as though any of the gears were skipping, and that although the 9 tooth drive gear was wobbling, it never slipped from the other gears.

The issue was determined to be due to the links of the four bar being of incompatible sizing. The motion of the bars was not symmetric which caused the issues with misalignment. This was corrected by better modelling the linkage and recreating the linkage.

The next iteration of the gears had the input gear meshed with a single plastic drive gear, so the two drive gears would turn symmetrically. The gear ratio was the same for this setup. The system ran well except for the interference between the planetary gear ring and the pins holding the input shafts to the gear. The gear ratio for this system was too low for the large wings that were implemented with this design. The gear ratio was increased.

The new gear system was created using the previous planetary gear system and a new compound gear setup. The compound gear train was a two stage setup with an 8:1 gear ratio. This combined with the 5:1 of the planetary gear gave an overall gear ratio of 40:1. This setup worked for powering larger wings for a minimal amount of time before the teeth of the compound gears began to break. This caused skipping and was not a fixable problem in the time constraints of the project. The layout of the gear setup is presented below in Figure 12.

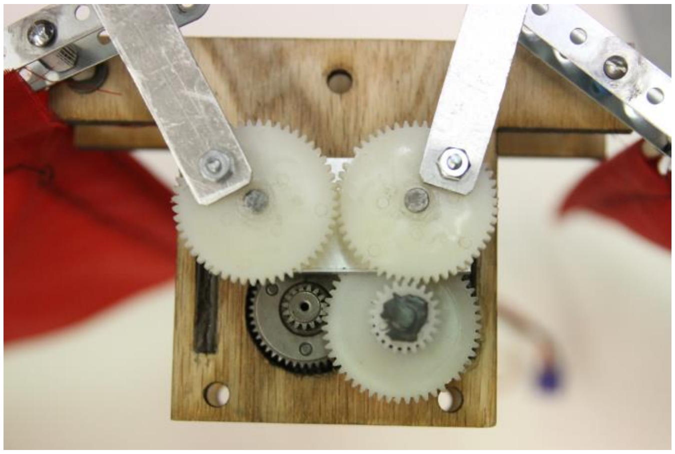

Figure 12: Final Gear Arrangement

Battery

The battery selected was a Thunder Power Magna series 1300 mAh 4S 14.8V 40A 70C LiPo, which are typically used in RC applications such as hobbyist ornithopter designs [19]. Since birds use their stored body fat as their means for providing energy for flight, it is impossible to achieve the same results using a battery. Birds are capable of storing seventy times more energy than even the best battery. This is why birds are able to fly long distances, while an ornithopter would be lucky to stay in the air for a half hour. The battery that was chosen has a lower weight compared to most 4S batteries of its kind. Although not as efficient as energy released from stored body fat, the battery implemented in RedWing has an energy density of about 0.14Wh/g. This battery can be seen in the figure below. The flight time for the ornithopter was conservatively estimated to be 30min.

Figure 13: Thunder Power Magna Series 1300mAh 14.8V LiPo Battery

Electronic Speed Controller

The controller needed to run the outrunner motor was an E-Flite 40A Brushless Electronic Speed Controller (ESC) [20]. The controller has connectors for the battery, the receiver and the motor which can be seen in Figure 14 below.

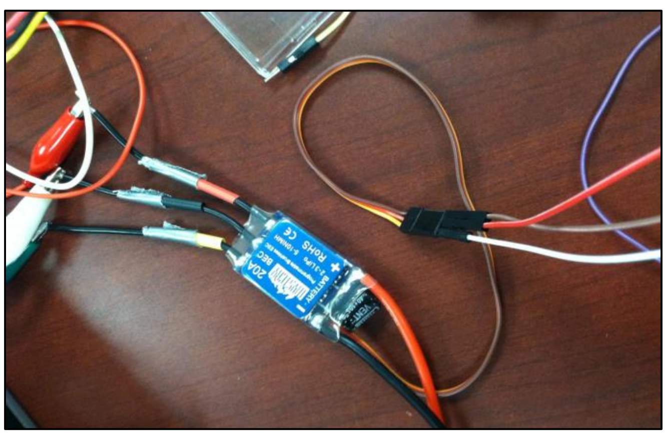

Figure 14: Electronic Speed Controller (ESC)

R/C Controller

The Remote Controller used to transmit commands to RedWing was a Turnigy 2A TGY-I6. This controller was initially chosen because it was available to the group at no cost. The performance provided by the controller has been sufficient and it is likely that the same controller or a similar model would have been purchased, had it not been provided. The controller has a fairly standard set of two joysticks, each with two degrees of freedom, two dials, and four switches. It has six signal channels, mapped by default to all four joystick directions and the two dials, although this was adjusted to include one of the switches. These channels send information via pulse width modulated signals which could control a servo or motor directly, or be read in by a digital port on an Arduino. The receiver counterpart to the controller is very lightweight and did not have any significant issues with interference from anything on or around RedWing during testing [21].

Figure 15: Turnigy 2A TGY-I6 RC transmitter and receiver

Onboard Computer

A Sparkfun Redboard was used to handle low level commands, read sensor data, and log relevant information for debugging. The Redboard is extremely similar to an Arduino Uno, identical except for a different type of USB port (mini-B on the Redboard, compared to a larger type B on the Uno) and some cosmetic differences. Like the Uno, it is equipped with an ATmega328 microcontroller. The Redboard was chosen over a “real” Uno or other official Arduino boards because it already belonged to a member of the team, and the number of ports and slightly reduced size made it an excellent fit for the ornithopter. Although not technically correct, this device is colloquially referred to as an “Arduino” in other sections of the paper [22].

Although using an onboard computer is not strictly necessary for flight, and it does slightly increase the total weight of the bird, it provided several significant advantages. First off, it proved far easier to program than the controller itself, allowing the team to quickly and easily adjust the signal being sent to the drive motor. It also allowed the team to read, record, and react to data from various sensors. To record sensor data, the team used a micro SD card reader and several high capacity Micro SD cards.

Sensors

A Pololu MinIMU v3 Gyro as an accelerometer/gyroscope/compass. The primary purpose of this sensor data was to provide the team with retroactive information about RedWing's performance. Sensors can be implemented in biological and artificial systems through a feedback-control system, which is able to process sensory data and send commands to the motor system. This characteristic of sensors makes them a beneficial tool for data collection [23]. Potentiometers were considered to measure the current position of the wings, but were not actually implemented in the final iteration of the design. Potentiometers could have been used to provide retroactive data on how fast the bird was flapping. Additionally, they could have been used to obtain real time feedback while attempting to adjust the position of the wings for gliding.

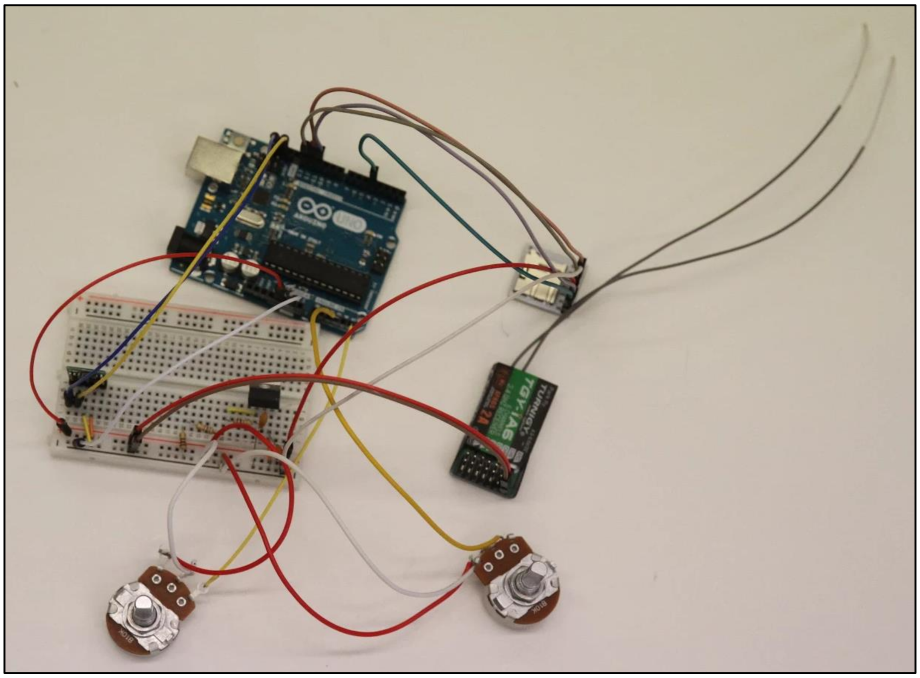

Figure 16: Circuit for Sensors, Receiver, SD Card Reader, and Arduino

Servos

RedWing utilized a Mallofusa Pan and Tilt with Mg995 Servos Sensor Mount for the Arduino Robot Set, which also included a Mallofusa cable tie. These servos will be used to control the pitch and yaw motions of the tail, which will contribute to generating lift while also acting as a stabilizer [24]. The tail is designed in a similar manner to that of the wings. A 3D-printed connector was designed in SolidWorks and is used to hold three carbon fiber rods in angled positions and connect to the pan and tilt mount. The rods are coated in the same nylon used for the wings. The servo, 3D-printed connector and tail can be seen in Figures 17, 18 and 19.

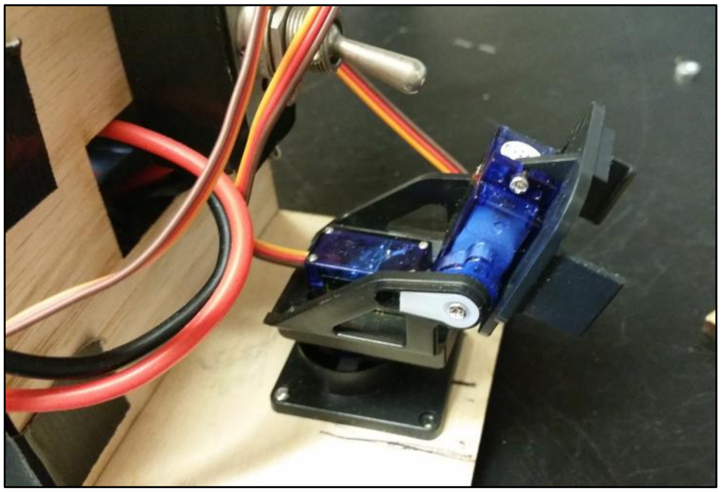

Figure 17: Mallofusa Pan and Tilt with Mg995 Servo Sensor Mount

Figure 18: CAD Designed and 3D Printed Connector for Tail

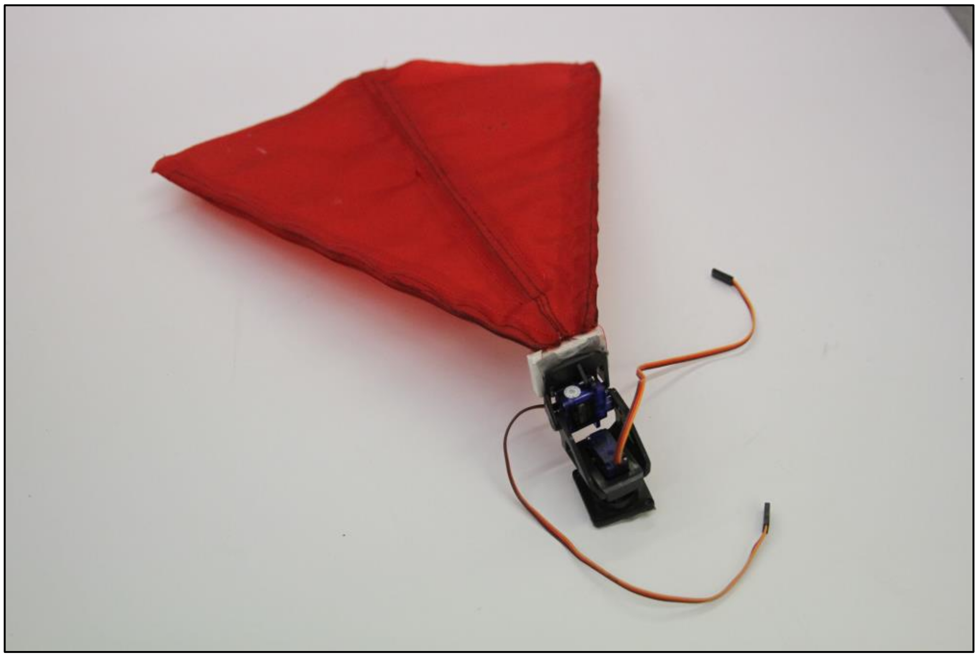

Figure 19: Ornithopter Tail Capable of Pitch and Yaw Motions

Software Specifications

The software implemented in the design provides simple and straightforward instructions that direct the Arduino to perform certain commands and transmit them to the motors and other components. The custom code used for this project was written using a variation of C++ specially designed for the Arduino, which was on-board RedWing, and interfaced with the receiver, motor controller, sensors, and SD card reader.

Drive Motor Control

The signals from the remote controller to the drive motor were first fed into the Arduino, which filtered out anomalous values and scaled down the final signal to approximately 30% of the initial input. This allowed for full operation of the RC controller interface, while additionally scaling down the motor to run at speeds that the gears, linkage and wings could handle safely.

Sensor Data to SD Card

A Serial-to-SD card reader adapter was used to convert signals from the Arduino into standard I/O and file manipulation commands. The program can create and write to files on an SD card with information that is useful for debugging, as well as for providing test results during experiments. This implementation allows for a surplus of data to be recorded, including the current motor power, acceleration in the x, y and z directions, and potentiometer values for wing positions. Furthermore, the transmission can be started and stopped effortlessly by flipping a switch on the controller. The configuration organizes data by using a timestamp denoting the amount of time since the program first began to run. For reference on the software specifications, see Appendix A for more details.

Wings to Glide Position

Using a potentiometer mounted to the pivot point of RedWing's wing, the Arduino was able to determine the current position of the wings at every point in time during testing. This information is beneficial as it could have been used as feedback for a proportional control based positioning algorithm, which would slow the wings and gradually move them into a predetermined position chosen for optimal gliding performance. This is not a conventional proportional control situation because the wings cannot reverse direction, and must instead complete an additional flapping motion to move the wings back into position if they overshoot. Thus, the actual algorithm for positioning these wings should be fine-tuned through trial and error, with ideal speeds and stopping points worked out and the self-correction algorithm included as insurance.

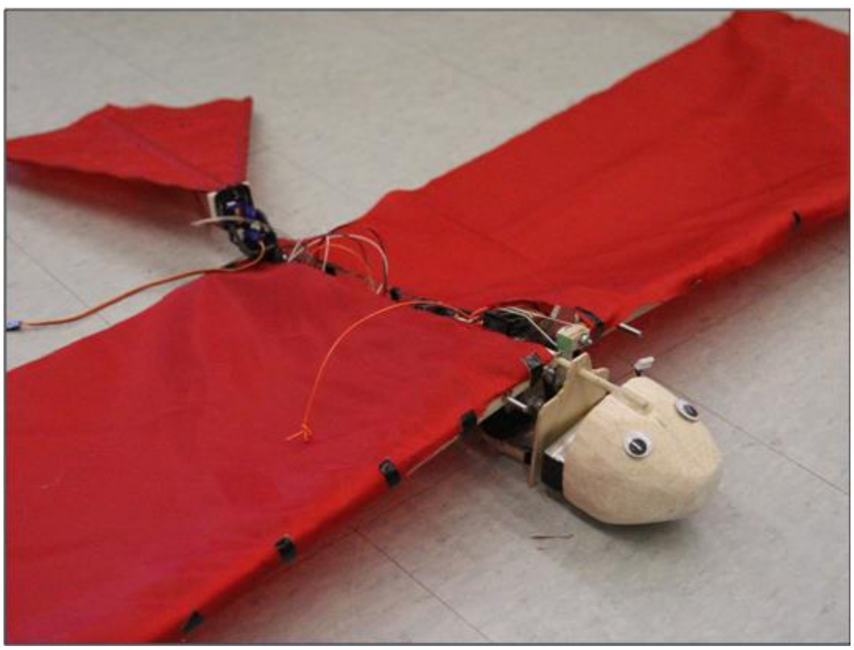

Figure 20: Final RedWing Design

Experimental Results

Design Iterations

As each design was created, a testing phase was conducted. The testing process varied as designs changed. The process was iterative in order to get to a conclusive, optimal design.

The first trial of testing involved the use of the original Turnigy motor. The ESC was connected in series with the motor, which allowed for examination of the responsiveness of the motor when it was controlled by a user-input command. This process proved to be simple and successful, as the connection between the remote controller or transmitter and receiver was quickly attainable and the results were immediate.

A linkage system that incorporated 3D printed components and carbon fiber rods was designed and fabricated. The linkage was mounted to a temporary stand and connected to the Turnigy motor, which brought about a great deal of resistance for the motor to overcome. The linkage mechanism in this design had many contact points, resulting in a lower overall efficiency due to friction. For this reason, the linkage configuration was discarded for an alternative mechanism. The Park450 motor was also abandoned as its potential power did not meet the initial design goals for this project.

The AquaStar motor replaced the previous motor and became the center point in the design process. The new configuration of the ornithopter involved the use of several commercial parts that are traditionally used in RC cars. Construction of these prototypes allowed for constructive testing on the housing, linkage, and power system, simultaneously. During the first test trials, the acrylic housing with the 32 pitch 9 tooth drive gear connected to the AquaStar motor was used to drive the two 68 tooth gears, which formed the ground bars of the linkage system. Numerous gear combinations were purchased and investigated in order to test feasibility. The 9 tooth and 68 tooth gears were chosen due to their high gear ratio, which was set at 7.56:1. For testing purposes, the system was mounted without the fabric wings, having only the modular hobby metal to allow for easy adjustment in spacing. The metal wing struts could flap successfully using the AquaStar motor. Unfortunately, the motor ran far faster than the system could handle and catastrophic failure of the acrylic holding the gears and motor occurred. The results of this test were used as a basis for confirming that the motor would have more than enough power to run the ornithopter linkage as desired. The feasibility of the linkage was confirmed with this design as well as the motion of the wing beam matching the theoretical flapping motion.

The next iteration of testing incorporated several key links in the system, which were replaced with thicker metal. While this added to the weight, the structural support that this setup added was necessary for the system to run. The motor was attached to the linkage, similar to the first round of testing. During operation, the design held together but experienced issues with the tolerance of some of the vital parts that caused recession of the gears and links. This vibration greatly lessened the efficiency that the system originally had. It was also found that the AquaStar motor would need to be geared down significantly as it was still running far too fast for the system to handle. By gearing down the motor, a greater amount of torque would be provided to the linkages, which would be beneficial. This increased torque would also allow for larger wings to be attached to the ornithopter.

Using a planetary gear attached to the AquaStar motor allowed for the placement of larger wings. In addition, a larger housing made of pine was used for this iteration of testing to account for the larger wings. Additionally, the shafts for the crankshaft gears were replaced with steel that could not bend or buckle. The new gear ratio increased to 37.78:1. This significant increase allowed the motor speed to be increased to roughly 20% of its maximum performance, where previously only 10% was being used. It was determined that testing flight with this prototype was feasible and an experiment was conducted that allowed for a measurement of performance throughout the system design.

Zipline Experiment

The first experiment conducted on RedWing consisted of suspending heavy duty fishing line across Harrington Auditorium, which acted as a zipline. Three eye-hooks were added along the top of RedWing in order to attach it to the zipline. The purpose of this test was to determine how much forward acceleration was produced by RedWing's wings. One meter intervals were marked along the gymnasium floor using metallic tape in order to easily and quickly mark how far the bird traveled in each trial. The speed at which RedWing traveled was another factor that was analyzed. These values were calculated using the distance and time measured for each trial. It was initially decided that RedWing would first be released with no power being supplied for three trials, then with 5% power for three trials, 10% power for three trials, and 15% power for three trials. At the end of these trials, with a total of 12 trial runs, averages for each grouping would be taken and compared. These tests were monitored using video in order to validate time and distance estimates and to supply concrete material for future use. It was expected that RedWing would travel a limited distance without power being supplied to the motor. In contrast, when the drive motor was powered and that power was increased, the RedWing's speed was expected to increase in turn. The line had a small amount of slack, meaning that gravity would help pull RedWing towards the center of the line. During these trials, one person recorded the test runs using a high-quality video, one person controlled RedWing, one person timed how long RedWing progressed forward before stopping, and one person released RedWing from the initial starting position. The following table shows the results received for this experiment.

Table 2: Zipline Experiment

Trial	Distance (m)	Time (sec)	velocity (m/sec)
no flap 1	3	6.38	0.470
no flap 2	3.5	7.07	0.495

7% flap 1	3	5.48	0.547
7% flap 2	4	5.12	0.781
7% flap 3	4.5	4.98	0.904
7% flap 4	4.5	4.59	0.980
7% flap 5	5.5	5.19	1.060
mean no flap	3.25	6.73	0.483
mean 7% flap	4.30	5.07	0.848

It is important to note that during the eighth trial run, after increasing the power to 10%, RedWing malfunctioned and testing had to be postponed. The data collected shows that there is an increase in velocity while the wings were flapping. The mean increase in velocity was 75% from the no flapping to the flapping tests. There is reason to believe that these numbers may be skewed. As can be seen in the data, the distance of flights increased in almost every test. Causes for this could be that the fishing line used to create the zipline was being stretched and thus allowing RedWing to slide along farther on each successive run. This would mean that the flapping of RedWing may not have contributed to the forward velocity at all. Another effect that may have skewed the results comes from the flapping motion creating an upward force. This force could have made RedWing create slack in the line, when it came down due to gravity it created a higher velocity on the line than before.

In order to alleviate this issue, the fishing line would need to be replaced by a material that would not stretch or deform to the same extent. A material that could work is a paracord line. To have less variables in testing the line would also be held taught and set at a downward angle. This would allow for the same basic tests to get the velocity of RedWing and compare flapping and non-flapping runs. Alternatively a pulley system could be used to allow for RedWing to glide along the fishing line as originally intended.

Further Experiments

Using a Vernier Force Sensor set to the large force option of ±50 N, RedWing's force was measured during flapping. These test trials were arranged by attaching the force sensor to a bar that ran perpendicular to two vertical bars mounted to stands of the same height. RedWing was suspended about its center of gravity, using a string that ran from the sensor's eyehook attachment. The force sensor read a flat rate while RedWing was static. Using the software LoggerPro, the sensor data output was zeroed. Using this value, the final weight of the ornithopter was verified. During flapping, data was recorded continuously over time. Unfortunately, the flapping process did not allow for a steady state system. RedWing pitched about its center of gravity, causing the system to be off-balance, which resulted in bucking. The flapping mechanism caused gears to skip during run-time, resulting in an asymmetric wingbeat. Since this complication occurred consistently for about 7.5 seconds of flapping, a true steady state was not achieved. The results of these test trials are shown below, which included 10 runs. The average of the maximum downward force that the ornithopter applied during these tests was 11.22 N. This value was less than that of the average weight of the ornithopter, which was set to be approximately 16N under gravity. Additionally, the net force was also very low, which averaged to be about 0.273 N. This value was in part due to fact that the upstroke of the ornithopter corresponded to a jolt or fall, which applied a much higher force to the sensor that was not caused by just the force from the upstroke alone. Even with this complication in the data, the result is encouraging as the value displays that there was an overall net force produced and it was likely much greater than 0.273 N. Compared to the theoretical calculations, which can be seen in Appendix D, it was obvious that there were many losses contained in the system. It was also noted that the force data collected by Logger Pro may have reached a hard limit in some trials. This can be seen below in Figure 21.

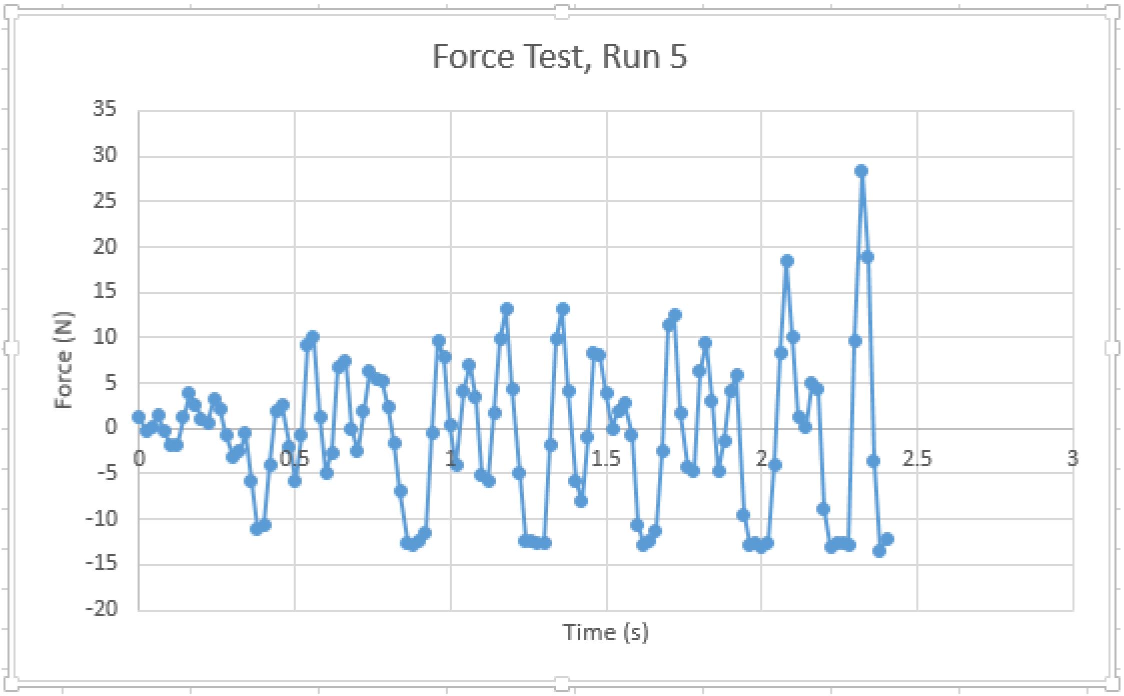

Figure 21: Force Test Results with Vernier Force Sensor

The force results imply two different results, that the force is either constant for a small amount of time at the bottom of the downstroke or that the force sensor was reaching a limit where is was unable to measure the force applied. The first result would be very promising, as it would mean RedWing was no longer pulling on the force sensor and lifted fully for a fraction of time. The second result, however, would skew the data that was obtained and impact the results. The rest of the data would imply that the force is constant at the end of the downstroke as the sensor cannot view when the weight of RedWing was lifting with more force than gravity could apply. As the sensor could read a positive 28N, it can be determined that the latter is correct.

RedWing was tested solely from a static initial condition. With lift being a function of velocity, the total lift of an ornithopter must take into account the forward velocity as well. Calculations were done in order to find the resulting velocity versus power required to lift the ornithopter and can be seen in Figure 22.

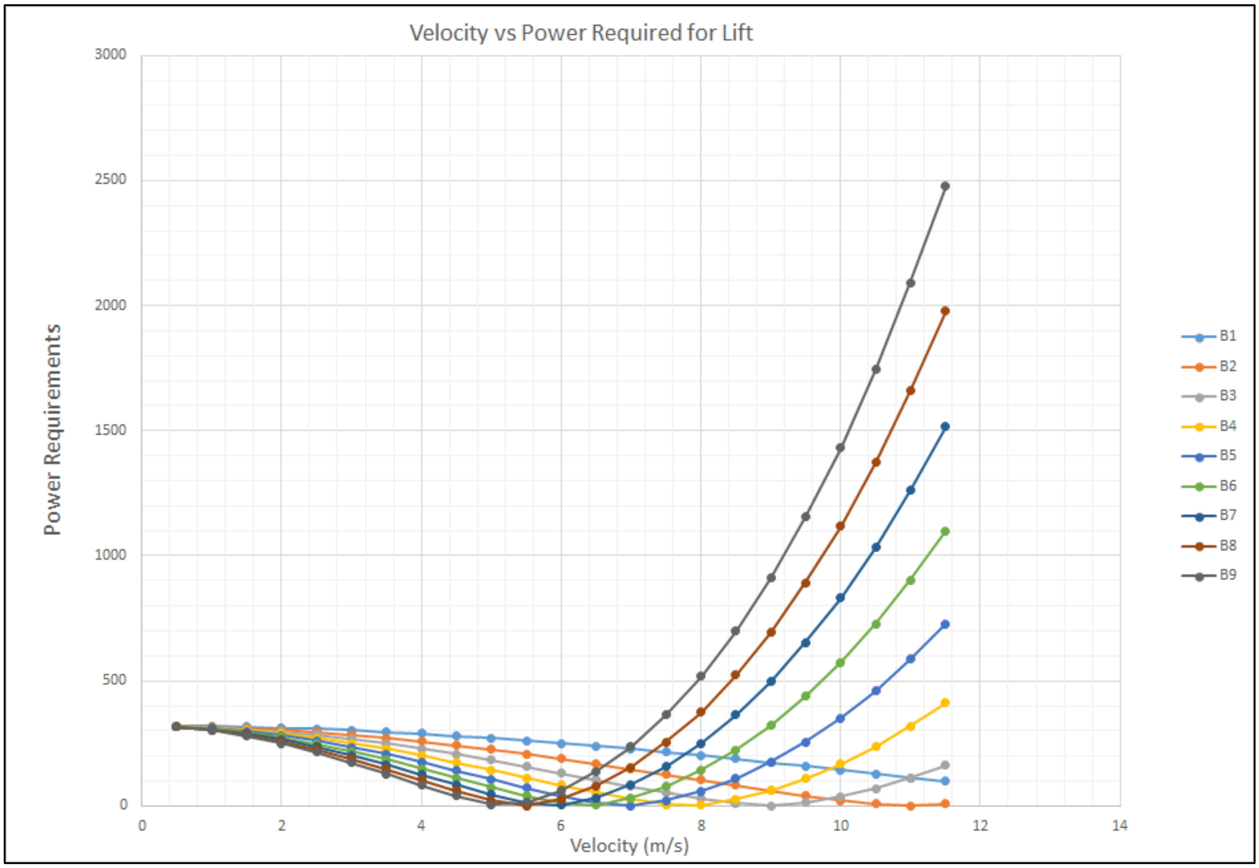

Figure 22: Velocity vs. Power Required for Lift with Varying Wing Spans in Meters

The graph in Figure 22 shows that there is a forward velocity where power goes to zero. Forward velocity is largely due to the thrust created by flapping. The power referred to in this graph and in the calculations is the total power required to flap the wings that create the thrust for forward velocity. At the point where the power of the ornithopter goes to zero, the lift becomes equal to its weight. This means that the ornithopter could stop flapping as the lift generated by the forward velocity is enough to sustain flight without additional thrust input from flapping. In the situation where power is zero then the efficiency of the system would be its highest. The ornithopter would be able to glide at the velocity that has the zero power value, then when the velocity dropped below that optimal velocity that wings could flap to reach that forward velocity that requires no power input. The base calculations for this graph appears in Appendix D. The numbers for the wingspan were set constant for each wing span graph while velocity was set to be at increments between 0.5 and 11.5 m/s.

With velocity being such a significant portion of lift the team calculated the forward velocity the ornithopter would need to travel at to obtain flight given the current net lift being generated. The values used matched the values for the ornithopter that was used for the force sensor testing. This was the second to last iteration and had a wingspan of only 1.35m as opposed to the 2m wingspan of the last iteration. The value for the forward velocity calculated to achieve lift equal to drag for the ornithopter used was 5.52 m/s. Figure 23 shows the curve of the velocity vs the lift force provided by flapping and forward velocity. The horizontal line is the weight of the ornithopter calculated from the mass times gravity. The intersection point is where the lift equals the drag.

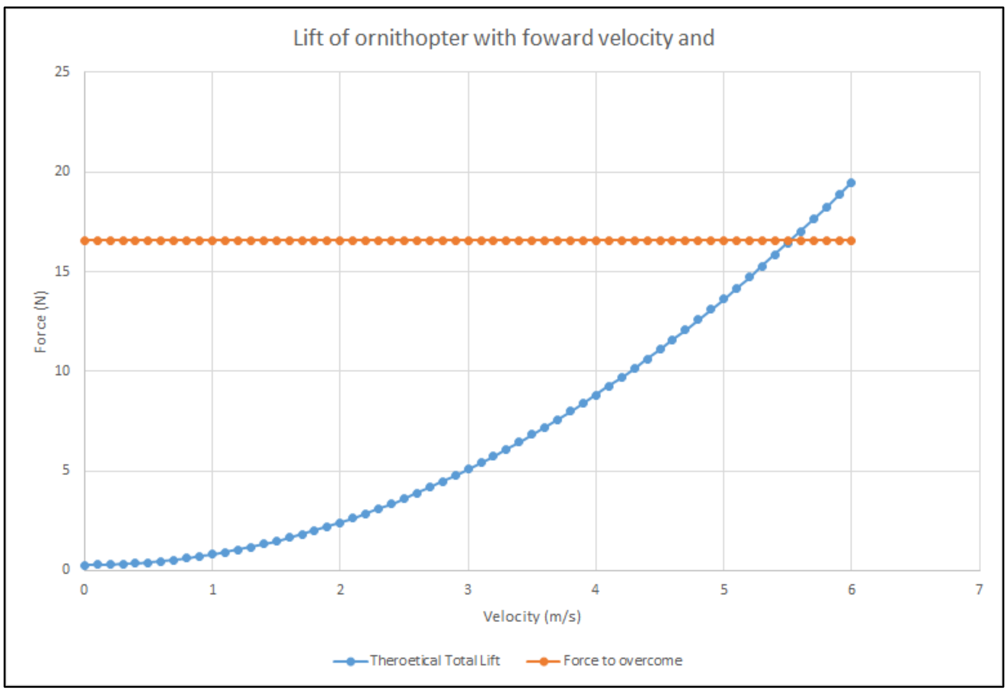

Figure 23: Force vs Velocity Graph

Conclusions

The original goals of the ornithopter were to do the following tasks:

1. An ornithopter that can be flown under its own power in a controlled fashion in the pitch, yaw and roll directions to avoid obstacles with a larger surface area than an equivalent 1m x 1m square for a duration of at least 30 Seconds.
2. Be able to glide for 5 seconds under its own power, which is defined as not flapping and remaining in flight within a 90 deg range or 45 deg in either direction from the x direction parallel to ground upon start of glide.
3. Transition from flapping to gliding and back to flapping with minimal disruption of flight pattern.
4. Durable enough to withstand impacts and/or a short repair time if failure occurs.

The team was able to accomplish the first goal with the use of the tail mounted on the servo mount. This tail mount was controlled with the transmitter. The control process was responsive and provided a significant moment about the center of gravity of the ornithopter. This was shown in qualitative tests where the tail was mounted on the ornithopter and moved side to side, and up and down. The motion of the tail was enough to cause the whole ornithopter to shift its position when placed on a surface.

The ornithopter could possess the ability to be placed into a gliding position. The transmitter is capable of sending signals to the receiver which are intercepted by the Arduino and can trigger code to stop the motor the next time the wings reach a gliding position. The position of the wings can be measured using a potentiometer that would be able to send resistances that would correspond to angles of the wings to the Arduino. The ideal gliding position would consist of the wings facing parallel to the ground. The duration of time that the ornithopter can glide could be determined essentially as a function of time. The glide duration was unable to be tested analytically because the ornithopter was not able to fly in the end. Therefore, the goal for glide duration was not accomplished. Similarly, the process of gliding to flapping with no distribution to the flight pattern was not accomplished or tested as the ornithopter never was able to sustain flight.

The ornithopter was made to be both durable and interchangeable with its selection of components and materials. The final goal was successful as drop tests from varying heights did not break or damage the configuration. The components are fairly easy to replace and are commercially available components aside from the housing in the final design.

The goals of this MQP were not met as the final prototype was not able to accomplish all of the goals. Perhaps most importantly, the ornithopter was not able to fly due to its inability to carry its own weight. This result was disappointing as the main function of the ornithopter was to fly. The previous ornithopter projects produced by Popovic Labs have increased the knowledge in the field of study. This team's ornithopter, RedWing, was able to take information and knowledge from the other projects and attempt to create a working model.

Recommendations

Based on what has been encountered in the ornithopter design experience, many recommendations could be expressed for future development in a similar project. Below is a listing of all of the recommendations that have been concluded in order for future projects to better position themselves to be able to create an optimal ornithopter.

1. Complete material analysis on the best materials for the ornithopter based on weight, structural stability, damage resistance, and cost. This would be essential to find the optimal material for the ornithopter. The stress on the material could be calculated using a CAD software package. As the forces applied to the system are dependent on the wing size and fixturing, using CAD would allow for modifications to be made easily. The main tests

needed would be displacement as the flexing of a material would easily throw off the gears meshing of the system. Keeping in mind manufacturability is key.

2. Optimize linkage to have the least frictional force. Many different variations of a flapping wing linkage exists. More in depth analysis of the frictional forces and the velocity of the linkages would be important for making an optimized wing beat system. The four bar linkage system is an easy and efficient means of creating the motion but a slider crank or more complicated system with more degrees of freedom for patterned wing motions could be used. Software such as Working Model, Linkages, or Matlab can be used to collect data.
3. Being able to optimize the power system to minimize weight but still keep all functionality is important. The battery used for RedWing was light for the capacity it holds. However, the capacity was estimated to be enough for a 30 min. flight time. This flight time was more than necessary for the testing that would be needed. Saving 50 grams on a battery would be a huge savings for the ornithopter as a whole.
4. Create a more robust sensor system. The proposed sensors in RedWing include an IMUl and 2-4 potentiometers. Adding more sensors adds weight and complexity but the potential data is invaluable for future work. It was suggested that a strain gage could be used on the ornithopters wings to measure the flexion of the wings. This could provide more information about the passive change in angle of attack. Variations in wing sizing and shapes could then be tested in action to find the best wings for lift.
5. Research further the best way to create a net positive lift. The RedWing used a passive angle of attack change but other methods of generating a positive lift can be used. For example creating lift using a jointed wing can create the lift needed because it reduces the surface area that is creating drag on the upstroke and then maximizing the area on the

downstroke. The jointed wing method was used by Festo in creating the Smartbird [25]. It is possible to create a linkage to have this jointed wing motion be driven and can be passively done through gravity and normal forces. This was demonstrated by the team during early prototype phases. The linage was discarded by the team as it was creating too much friction and weight too much for the gains that it gave but an optimized version could be created to make this method more feasible. Another option is using the airfoil shape of traditional fixed wing aircraft to generate lift through the change in pressure of the fluid flowing over the airfoil. Many different airfoil designs are available. Research into the most ideal shape based on lift to drag ratio and stall condition would need to be done. Software like XFLR5 can be used to model the airfoil in the conditions that the ornithopter would be flying in.

6. Carefully select the motor and power transmission system after creating the linkage, or vise-versa. The power needed to have an ornithopter fly is the most important aspect of the robot. A plot of the flapping speed to wing size and the provided lift over time while flapping would be the best way to find a motor that had the torque to be able to drive the wing size and be able to do so fast enough. Commercial motors like those from Pololu that have built in gearboxes would be very helpful in making sure that the ratios were accurate, would increase reliability of the motor and gears, and would mean that fixturing the gears and their shafts for a custom gearbox would already be done so that time would not be wasted on machining to very high precisions. Another advantage would be that the specs of these motors are all available, unlike many hobby motors.

The team encountered many problems with the “medium sized” bird that was designed in the earlier iterations of the project. The size of the final prototype had a 2m. wingspan, which was calculated to be the desired area needed to lift the weight of RedWing. This wingspan is not a medium bird’s wingspan. The scaling of the ornithopter is very important for the power requirements and performance, as well as the way that the mechanisms are designed. After discussing the design and producing quick calculations of the wing area to the lift force that had been obtained, it was observed that the relationship was nonlinear due to the upscaled wingspan increasing the force almost exponentially. Therefore, a larger ornithopter would be theoretically more efficient and easier to manufacture. However, given the resources and area available to the future project teams, it could be considered that a much smaller ornithopter be created. Scaling down allows for the building materials to be less expensive and the housing to be much lighter as it does not have to contend with as much structural stability. The lighter models can also be tested in the wind tunnel provided by WPI in order to check for forward velocity versus lift values. The smaller scaled models also have a much higher gliding potential as compared to larger and heavier ornithopters.

The RedWing ornithopter was not a successful prototype, however, it contributes to the proof of concept designs of other ornithopters. The information gathered during this experience could serve as a base for future ornithopter designs that would be capable of flight and gathering data to create the most efficient possible biomimetic system.

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Appendices

Appendix A

Code

```
/**
 * @author Rick Wight
 *
 * Program does the following:
 * - reduce power to main drive motor to 30% of input
 * - Read sensor data from gyro/accelerometer/compass and potentiometer
 * - write sensor data to an SD card in .CSV format
 */

#include <SPI.h>
#include <SD.h>
#include <Wire.h>
#include <LSM303.h>
#include <TimeLib.h>
#include <Servo.h>

Servo wingMotor;

// arduino pins associated with each pin on the SD card reader
// ordering is backside left to right
const int CS = 4; // may switch to 10
const int DI = 11; // aka MOSI
// VCC = 3.3v
const int sck = 13; // aka CLK, SCLK
// GND = GND
const int DO = 12; // aka MISO
// CO = unused

const int potPin = A0; // potentiometer pin
const int switchPin = 9;
const int recieverControlPin = 7;
const int pwmContPin = 5;

unsigned long startTime;

LSM303 compass;

time_t t;

File aFile;
char fileName[13] = "LOGGER00.TXT";

int potVal;
int switchVal;

boolean sensors = true;

unsigned long contVal = 0;
```

```
int delayCycles = 0;

int oldContVal = 0;

int inputMin = 996;
int inputMax = 1996;
int outputMin = 1030;
int outputMax = 1300;

boolean recievingSignals;
boolean shouldPrint;

int motorVal = 0;

int oldTime = 0;

boolean writing = false;

// make a new file with a new name
void makeNewFile() {
  boolean gotFileName = false;
  int i = 1;
  while (!gotFileName) {
    fileName[6] = i/10 + '0';
    fileName[7] = i%10 + '0';

    if (!SD.exists(fileName)) {
      gotFileName = true;
    }
    else {
      Serial.print(fileName);
      Serial.println(" already exists");
    }
    if (i > 99) {
      Serial.println("too many files");
      break;
    }
    i++;
  }

  Serial.print("found file name: ");
  Serial.println(fileName);

  aFile = SD.open(fileName, FILE_WRITE);
  if (!aFile) {
    Serial.print("Could not open file ");
    Serial.println(fileName);
  }
  else {
    Serial.print("opened new file ");
    Serial.println(fileName);
    aFile.close();
  }
```

```
  aFile = SD.open(fileName, FILE_WRITE);
  if (!aFile) {
    Serial.print("Could not reopen file ");
    Serial.println(fileName);
  }
  else {
    Serial.print("reopened new file ");
    Serial.println(fileName);
    // print column headers
    aFile.println("T,Ax,Ay,Az,Mx,My,Mz,Pot,MV");
    aFile.close();
  }

  writing = true;
  Serial.println("end of makeNewFile()");
}

// write to an existing file
void writeToFile() {
  String timeString = (String(hour(t)) + ":" + String(minute(t)) + ":" +
String(second(t)));

  if (sensors) {
    compass.read();
  }

  aFile = SD.open(fileName, FILE_WRITE);
  if (aFile) {
    aFile.print(timeString);
    if (sensors) {
      //aFile.println(report);
      aFile.print(",");
      aFile.print(compass.a.x);
      aFile.print(",");
      aFile.print(compass.a.y);
      aFile.print(",");
      aFile.print(compass.a.z);
      aFile.print(",");
      aFile.print(compass.m.x);
      aFile.print(",");
      aFile.print(compass.m.y);
      aFile.print(",");
      aFile.print(compass.m.z);
      aFile.print(",");
      aFile.print(analogRead(potPin));
      aFile.print(",");
      aFile.println(motorVal);
    }
    Serial.print("Opened ");
    Serial.println(fileName);
    aFile.close();
  }
  else {
    Serial.print("error opening ");
    Serial.println(fileName);
  }
```

```
}

void runMotor() {
  contVal = pulseIn(recieverControlPin, HIGH);

  if (contVal > 10 && contVal <= 1000) {
    motorVal = contVal;
    recievingSignals = true;
  }
  else if (contVal > 1000 && contVal <= 2000) {
    motorVal = map(contVal, inputMin, inputMax, outputMin, outputMax);
    recievingSignals = true;
  }
  else if (contVal <= 10) {
    if (recievingSignals) {
      recievingSignals = false;
      shouldPrint = true;
    }
    else {
      shouldPrint = false;
    }
  }

  if (recievingSignals) {
    if (!shouldPrint) {
      Serial.println("regained connection with remote");
      shouldPrint = true;
    }
  }
  else {
    if (shouldPrint) {
      Serial.println("No signal from remote");
    }
  }

  wingMotor.writeMicroseconds(motorVal);
}

void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);

  pinMode(switchPin, INPUT);
  pinMode(recieverControlPin, INPUT);

  Serial.print("Initializing SD card...");
  if (!SD.begin(CS)) {
    Serial.println("Card failed, or not present");
    return;
  }
  Serial.println("card initialized.");

  Wire.begin();
  compass.init();
  compass.enableDefault();
```

```
  t = now();
}

void loop() {
  // put your main code here, to run repeatedly:
  int newTime = millis();

  runMotor();
  switchVal = pulseIn(switchPin, HIGH);

  boolean switchOn = (switchVal > 1500);
  if (switchOn) {
    if (writing) {
      // write to an existing file
      writeToFile();
    }
    else {
      // create a new file
      Serial.println("Switch on!");
      Serial.print("switchVal = ");
      Serial.println(switchVal);
      makeNewFile();
    }
  }
  else {
    if (writing) {
      // stop writing
      writing = false;
      Serial.println("Switch off!");
      Serial.print("switchVal = ");
      Serial.println(switchVal);
    }
  }
  oldTime = newTime;
}
```

Appendix B

Design Brainstorms

Jointed wing mechanism
-The following is a linkage design system that mimics a jointed wing.
-Include specs of all materials used (motor, battery, sensors, etc..)
-Include implemented coding

Small Ornithopters

1. Robin sized jointed wings
   Unique idea that has little documentation allowing for testing and data collection.
    a. symmetric linear wing motion (up and down)
        i. pros
            1. simple mechanism

            2. not much variation from larger scale design
            3. smaller internal parts so there is less weight in the body
        ii. Cons
            1. little control over moment if turning occurs
            2. forces created by wings may not be enough to overcome added weight
            3. gliding may be limited to short spurts of flight *may be able to program controller to automate gliding such that as long as a minimum velocity is held the ornithopter will be locked in gliding position and will not receive wing flap inputs only directional.*
        iii. Alternative iteration includes a non linear velocity curve of the wing
    b. patterned wing motion (teardrop, elliptical, figure-eight etc.)
        i. Pros
            1. more complicated than linear motion
            2. better forces provided by flapping
        ii. Cons
            1. Harder to control position and orientation for gliding
            2. likely need a twisting feature of wings to allow proper flight
            3. larger space for linkage system
    c. Independent wings (single motor with servos for each wing)
        i. Pros
            1. better control over movement
            2. More power if configured correctly with servo motion
        ii. Cons
            1. added complexity to design, construction and software
            2.
    d. Independent wings (independent drive motor for each wing, no servos)
        i. Pros
            1. better control over movement
            2. More power
        ii. Cons
            1. requires more wing position sensors
            2. wings would be more likely to become unaligned
            3. larger power supply
    e. One-to-many wing motion (elastic potential energy transfer)
        i. Pros
            1. Produces fast flapping motion

Large Ornithopter

1. 2m wingspan (Harbor Seagull)

Documentation is accessible and several variations exist so idea is not as unique. Novel application or function is important to design. *jointed wings are basically requirement for larger scale as the membrane wings would need excessive speed to perform properly and this results in large stresses at the larger size*

a. Linear wing motion
    i. Pros
        1. easier to construct than small scale ornithopter
        2. less affected by environmental conditions like wind
        3. larger wings allow better balance to overcome weight of body
    ii. Cons
        1. more weight due to larger motor and battery

Other ideas:

1. Servos: can adjust the wing's angle when they are not flapping (up and down) or adjust position while flapping which would add to complexity.
2. Multiple wings, one jointed, one static
3. Swooping or sinusoidal motion for gliding
4. Part airfoil, part flexible material wings for ideal AoA

Appendix C

Weights of parts:

Arduino Uno	19.22g
Turnigy Aquastar Motor w/ brass adapter	208.03g
Pan-tilt mount and servos	41.53g
Brushless ESC	44.87g
Planetary gear	98.39g
14V LiPo Battery	144.97g
9V Battery	42.00g
Receiver	7.207g
Potentiometer	12.121g

One wire	.747g
Polulu IMU	1.074g
Switch	66.91g
Bird head	41.10g
68 tooth drive gears	60.18g
Tail	13.2g
Total weight	782.549 g

	Early Wood Housing	Final Wood Housing
Face (place for bird head)	60.05g	
Sides	112.13g	121.13
Bottom	85.75g	-
Top (including fishhooks)	140.377g	-
Motor mount plate	15.07g	38.76g
Planetary gear support	17.75g	52.74g
Structural support element	16.64g	-
Back plate	22.03g	-
Pan-tilt platform	(included in weight of bottom)	35.18g
		-
Housing weight	469.797g	247.81g
Wings	263.83g	147.04g
Total weight of frame	733.627g	394.85g

Appendix D

Calculations

Coefficient of Drag(Cd)	density of air(rho)	Gravity (G)	Theta						
2	1.225	9.81	0.5235987756						
	Wing Span(b)	Weight(M)	Chord length(c)	F = rho*Cd* c *(b^3/3)	w = sqrt((M*G)/(F)	Time for downstroke	Tau = rho * w^2*Cd*c*(b^4/8)	Power(Watts)	Power(Horse Power)
American Crow	0.5	0.62	0.33	0.0336875	13.43680322	0.07793502172	1.1404125	15.32349836	0.02054911777
Blue Jays	0.43	0.1	0.135	0.00876564675	10.57894895	0.09898880848	0.15818625	1.673444263	0.002244122225
Bald Eagle	2	6.3	0.6	3.92	3.97065126	0.2637344563	46.35225	184.0486199	0.2468128802
Albatross	3.4	10	0.3	9.62948	3.191781006	0.3280919177	125.0775	399.2199888	0.5353619893
Popovic	3	100	2	44.1	4.71644972	0.2220308947	1103.625	5205.191822	6.980266337
Firewing	0.1524	0.113	0.0889	0.0002569812822	65.6784628	0.01594430665	0.0633524895	4.160894125	0.00557984224
Modified	0.6	1	0.4	0.07056	11.7911243	0.08881235789	2.20725	26.02595911	0.03490133169
Large	0.75	1.5	0.5	0.172265625	9.242316169	0.1133046665	4.13859375	38.25019193	0.05129427238

Saftey factor	M (kg)	G	wings (b)	Constant	Vx (m/s)	Cl	Cd	Rho	L	W	Wing Area (cm)	Lift force (N)	Omega (rad/s)	Period (s)	Frequency (Hz)	Torque (Nm)(both wings	Power (W)	Adjusted power (W)
set value	set value	constant	set value	set value	set value	set value	set value	set value	SQRT(M*0.64+W))/2	(6/11)*L	L*W*100*100	b*.5*Vx^2*Cl*Rho*L*W	SQRT((3*M*G-Lift Force)/(Cd*Rho*(L*2)^2*L*W))	(2*PI/3)/Omega	1/period	(Rho*Omega^2*Cd*W*(L^4/8))*2	Torque * Omega	Power*4*(1/0.2)
3	0.75	9.81	1	0.5	2	1.75	2	1.225	0.42123813	0.22976625	967.8631	0.414971	11.3437533	0.18462982	5.416243	0.57018606	6.46804998	129.361
3	1	9.81	2	0.5	2	1.75	2	1.225	0.47395116	0.25851882	1225.253	1.050654	10.2575037	0.20418175	4.897597	0.84065149	8.62298578	172.45972
3	1.25	9.81	3	0.5	2	1.75	2	1.225	0.52056303	0.28394347	1478.105	1.901212	9.42732364	0.22216222	4.501215	1.13503198	10.7003138	214.00628
3	1.5	9.81	4	0.5	2	1.75	2	1.225	0.56280163	0.30698271	1727.704	2.963012	8.76295614	0.23900554	4.184003	1.44858063	12.6938486	253.87697
3	1.75	9.81	5	0.5	2	1.75	2	1.225	0.60170666	0.32820363	1974.823	4.233527	8.21345951	0.25499549	3.921638	1.7776285	14.6004797	292.00959
3	2	9.81	6	0.5	2	1.75	2	1.225	0.63796139	0.34797894	2219.971	5.710876	7.74759559	0.2703284	3.699204	2.11919306	16.4186508	328.37302
3	2.25	9.81	7	0.5	2	1.75	2	1.225	0.67204336	0.3665691	2463.503	7.393589	7.34497021	0.28514685	3.506965	2.47076366	18.1476854	362.95371
3	2.5	9.81	8	0.5	2	1.75	2	1.225	0.7043019	0.38416467	2705.679	9.280479	6.99160589	0.29955852	3.338246	2.83017207	19.7874477	395.74895
3	2.75	9.81	9	0.5	2	1.75	2	1.225	0.7350017	0.40091002	2946.695	11.37056	6.67754505	0.31364747	3.188293	3.19550897	21.3381551	426.7631
3	3	9.81	10	0.5	2	1.75	2	1.225	0.76434901	0.41691764	3186.706	13.663	6.39546683	0.32748119	3.05361	3.56506703	22.800268	456.00536

0.5*(C_d)*\rho*A*cos(\theta)*(v*sin(\theta))^2

Cd	Rho (kg/m^3)	winspan (b) m	Chordlength (c) m	Mass (m) kg	angle of attack (theta)	velocity (v) m/s	Gliding lift (N)	Induced Lift (N)	Total Lift (N)	Force to overcome
2	1.225	1.3208	0.33	1.69	0	4.5	10.81215135	0.273	11.08515135	16.5789
2	1.225	1.3208	0.33	1.69	0	4.6	11.29803074	0.273	11.57103074	16.5789
2	1.225	1.3208	0.33	1.69	0	4.7	11.79458881	0.273	12.06758881	16.5789
2	1.225	1.3208	0.33	1.69	0	4.8	12.30182554	0.273	12.57482554	16.5789
2	1.225	1.3208	0.33	1.69	0	4.9	12.81974093	0.273	13.09274093	16.5789
2	1.225	1.3208	0.33	1.69	0	5	13.348335	0.273	13.621335	16.5789
2	1.225	1.3208	0.33	1.69	0	5.1	13.88760773	0.273	14.16060773	16.5789
2	1.225	1.3208	0.33	1.69	0	5.2	14.43755914	0.273	14.71055914	16.5789
2	1.225	1.3208	0.33	1.69	0	5.3	14.99818921	0.273	15.27118921	16.5789
2	1.225	1.3208	0.33	1.69	0	5.4	15.56949794	0.273	15.84249794	16.5789
2	1.225	1.3208	0.33	1.69	0	5.5	16.15148535	0.273	16.42448535	16.5789
2	1.225	1.3208	0.33	1.69	0	5.6	16.74415142	0.273	17.01715142	16.5789
2	1.225	1.3208	0.33	1.69	0	5.7	17.34749617	0.273	17.62049617	16.5789
2	1.225	1.3208	0.33	1.69	0	5.8	17.96151958	0.273	18.23451958	16.5789
2	1.225	1.3208	0.33	1.69	0	5.9	18.58622165	0.273	18.85922165	16.5789
2	1.225	1.3208	0.33	1.69	0	6	19.2216024	0.273	19.4946024	16.5789
2	1.225	1.3208	0.33	1.69	0	5.526213771	16.30581274	0.273	16.57881274	16.5789

Wooden bird weight:

733.627 + 782.549 = 1516.176g

Percent weight of wooden body:

(469.797/ 1516.176) = 30.98565%

Acrylic bird weight:

782.549 + 349.85 = 1132.399

Percent weight of acrylic body:

(247.81 / 1132.399) = 21.88%

Angular velocity of wooden bird:

$\omega = \sqrt{6mg/NC_d\rho(LLL)(W)}$

$= \sqrt{6(1.516176)(9.81)/2(2)(1.225)(2*2*2)\ (.33)}$

$= \sqrt{(89.242/12.936}$

= 2.627 rad/s

Lift Force:

$F = \frac{1}{2} NC_d\, \rho\omega^2(L^3/3)(W)$

$= \frac{1}{2}\ (2)\ (2)\ (1.225)(2.627)^2\ (8/3)\ (.33)$

= 14.88N

Force of the ornithopter:

F = mg

= (1.516176)(9.81)

= 14.87N