

Design and Construction of an Autonomous Ornithopter

by

Zachary John Jackowski

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Mechanical Engineering

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In order to better study the control of flapping wing flight we have developed a large scale ornithopter called the Phoenix. It is capable of carrying a heavy (400 gram) computer and sensor package and is designed specially for the application of controls research. The design takes special care to optimize payload capacity, crash survivability, and field repair abilities. This thesis covers the design process of both the mechanical and electrical systems of the ornithopter and initial control experiments. We also show that it is possible to stabilize the machine in pitch with a simple PD controller through experimental testing.

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I'd like to thank Russ Tedrake, Rick Cory and the other members of the Robot Locomotion Group not just for the facilitation of this project, but for the much more important education in the world of research and robotics I received during my two years on the project. Their support and the environment of the lab have been one of the biggest influences of my academic career so far and despite my well known joking cynicism the atmosphere of excitement and progress in the lab has been very inspirational.

I'd also like to thank my dad and mom for everything they've done along the way. Despite my time spent in endless engineering classes most of the design intuition and skills I find most valuable have come from years spent working on everything from flintlock rifles to competition dragsters with my dad. Sometimes in opposition to this, my mom's unwavering support has been the most important thing that has kept my education and research career going in the right direction.

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Chapter 1

Introduction

Natural fliers like birds and insects have captivated the minds of human inventors through history. The ease and grace with which they take to the air vastly surpasses the state of the art in aircraft and their control systems.

This is not to say that modern aircraft designs are ineffective, they are excellent in many respects. Propellers and turbines are very efficient methods of producing thrust and airfoils efficiently produce lift. A Boeing 747 achieves a dimensionless cost of transport (energy used divided by weight times distance) of 0.1, equivalent to a soaring albatross [14], and does it with amazing reliability, but it will never match the maneuverability of the albatross.

The problem mirrors legged versus wheeled locomotion well. Wheels provide a stable, easy to analyze, and very efficient way of getting around with the sacrifice of a large amount of agility. Legs are notoriously difficult to control and current implementations are energy inefficient [2] and flapping wing flight parallels this well. The unsteady fluid dynamics of flapping wings are poorly understood and it's difficult to get an ornithopter (the term used henceforth to refer to a flapping wing vehicle) to maneuver as desired.

Interest in the design and control of ornithopters has grown in recent years as interest has grown in the area of Micro Aerial Vehicles or MAVs. These small flying machines have struck the imaginations of many as ideal platforms for a variety of tasks including systems monitoring and surveillance where a swarm of tiny agents would be

unobtrusive and have better access to confined areas than larger flying vehicles [6].

This thesis covers two years of work on the Phoenix ornithopter project, a 1.8 meter wingspan flapping wing flying robot, picking up from just after proof of concept work performed at the lab. From that point on two hardware revisions were produced of the Phoenix, one in summer 2007 and one in summer 2008. In the time between these summers flight testing and analysis was performed. Sustained steady level flight under computer control was finally achieved in August 2008.

Chapter 2

Project Purpose

Perhaps the first question that must be asked about the project is what it has to do with Micro Aerial Vehicles and why the work is a reasonable research direction, especially because a large ornithopter bears little resemblance to the kinds of miniature machines many researchers are focused on. While it is true that at a 1.8 meter wingspan the Phoenix isn't a step toward the resolution of the problems that currently plague MAV research like energy storage and actuator miniaturization, it is a big step toward solving the problems that these projects will encounter soon, those of control. Even though the Phoenix is many times the size of MAVs under development we conjecture that the problems inherent in stabilizing and coaxing agility out of them are retained in large part with the scaling up.

Working with a much larger robot allows us to sidestep the problems of miniaturization and instead work on the problems that interest the Robot Locomotion Group specifically, those of dynamics and control. Instead of working in series with researchers attempting to build the miniature machines we are working in parallel with comparatively easy to build hardware and off the shelf electronics to lay the groundwork on the dynamics and control work which will be central to the next steps in these projects. This is not to say that the dynamics will be the same, they may be as far apart as the differences between how a hawk and bumble bee fly, but the body of work covering the control of any sort of flapping wing flight is extremely small so any conclusions reached will be valuable additions as work moves forward.

This research is also performed in parallel with fixed wing flight research in the Robot Locomotion Group's Agile Flight Project. Rick Cory along with Woody Hoburg have been making amazing progress in the area of agile fixed wing flight [3, 8]. Their work in free flight system identification and control over trajectories involving extreme angles of attack focuses on perching maneuvers. This research is both being applied directly to fixed wing unmanned aerial vehicles [12] and also has the aim of developing methods and software tools to work with the Phoenix ornithopter and further improved ornithopters to follow.

In order to become familiar with manually controlled ornithopters and get an intuitive feel for the problems at hand we purchased plans for a hobbyist designed machine. The Kestrel [9] is based on the Park Hawk design by Sean Kinkade [10] and represents the best of available designs in terms of performance and reliability. With the designs in hand lab staff member Stephen Proulx built and the machine was successfully flown the Kestrel ornithopter along with lab member Derrick Tan, an expert radio control pilot.

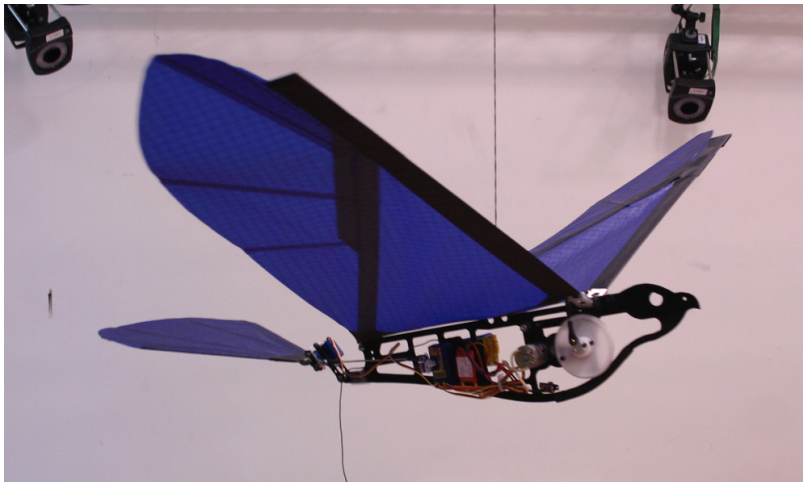


Figure 2-1: The Kestrel ornithopter.

Satisfied with proof that an RC ornithopter can be built at all, far from a forgone conclusion at the start of the project, the project needed to be extended into new territory. Instrumentation was required to acquire the data needed for analysis and the eventual implementation of a controller. Instrumentation could be done either

onboard with sensors like an inertial measurement unit or offboard with the Vicon motion capture system at the lab.

The Vicon environment available provides excellent data and is easy to set up, but is too small to capture free flight data for the 1.17 meter wingspan vehicle with its capture area of approximately 3x3x2 meters. In order to use it a scaled down ornithopter would have to be built, but this presented large problems at the surface because we were already using some of the smallest commonly available RC components in order to keep the weight of the Kestrel low enough to fly well in the first place. Scaling down would require even smaller servo motors and would completely rule out the possibility of any onboard control later because of the reduced payload capacity.

The manual flight testing conducted with the Kestrel qualitatively showed it has very little excess weight capacity which could be used to accommodate a sensor and computer package. This leads to two options, either make an extremely light and small sensor package, or increase the payload capacity of the ornithopter to handle the weight of the sensors commonly used in the lab. A preliminary analysis of the payload and carrying capacity showed it would be feasible to make an ornithopter large enough. In addition to the advantage of using a computer and sensors we are already familiar with a larger vehicle would have slower dynamics which would be easier to analyze and control when the project is advanced. Increased payload to accommodate the weight would also allow the expansion of the system with the addition of more sensors further down the line and improved performance if the computer was also downsized.

Chapter 3

Related Work

Ornithopters have been a relatively obscure area of research in comparison to fixed wing aircraft and field of ornithopter design is sparsely populated. Much of the research done has been performed by hobbyists such as Sean Kinkade. Kinkade is the designer of a wide range of radio controlled ornithopters both smaller and larger than the Park Hawk that the Kestrel is based on and holds a patent on the design [10]. Even though these machines have been designed both the ornithopters and plans are exceedingly hard to obtain. Both original designs and designs that build on Kinkade's that build are in progress in the hobbyist community but very little work has been published. Ornithopter designs in similar form factors that focus on adding additional degrees of freedom to the wings have been published [1] in addition to a variable amplitude wing design produced by the Robot Locomotion Group previously.

An extensive analysis of the wing design used here has been performed with a motion capture system by Robyn Harmon of the Morpheus Lab at the University of Maryland which explains many of the aerodynamic properties of this type of ornithopter [7]. The Morpheus Lab has also been working with the simple kinds of ornithopter control presented here [13]. Paralleling this work similar results have been shown by the University of Arizona working with a 74cm wingspan ornithopter [11]. Both of these projects make use of a very limited onboard computer in order to be lightweight enough to fly.

James Delaurier's work forms much of what has been accomplished in larger scale

ornithopter design and analysis. A project to build a piloted ornithopter [4] has been ongoing for many years and as of July 8, 2006 achieved several seconds of sustained flight [5].

Chapter 4

Project Requirements

When examining what is required to build a robot ornithopter a layered system becomes apparent.

At the base is the mechanical ornithopter system which has the main requirement of flying acceptably. Acceptable in this most preliminary case is defined as being able to sustain flight in calm conditions. Key to this is the ability to carry all the additional weight of the sensors and computer. Branching out from this base requirement are several secondary requirements. Because this is a controls research platform it can be expected that the ornithopter will end most of its flights with crashing at least at the beginning stages, this makes crash survivability of great importance in addition to it being a reliable machine in less severe conditions. An emphasis is placed on designed points of failure to isolate damage to parts easily replaced in the field. In addition to this all of the systems need to be easy to tie into the computer controller.

The sensing and computing equipment which is taken along for the ride with the mechanical platform is usually considered secondary, but is key to the intended research use for the ornithopter. In order to measure as much of the ornithopter's state as possible to perform the desired system identification and control sensors are needed. The absolute position of center of mass in space isn't important at this stage because it isn't a factor in the dynamics, however the orientation of the body and the position of the wings and tail in relation to the body is very important. In addition to the sensing of this data a computer is required to log and eventually process it into

commands to be sent to the actuators. Ideally this computer would have sufficient computational power to implement advanced control algorithms unlike many small scale autopilots based on microcontrollers.

Even though the project requirements are pretty straightforward and simple, the engineering process to realize them required many iterations to develop them into final specifications which further required design iterations to produce a realization of those specifications. The design was broken down into several minimally interconnected sections.

Chapter 5

Electronics

While the electronics on the ornithopter aren't a critical system as far as the mechanical function of the machine performs they do make up the one of the most important specifications for the project, the minimum payload capacity. Because the rest of the sizing and design of the ornithopter depends on this the weight of the computer, interface equipment, sensors, and battery must be determined first.

5.1 Computer

The selection of the computer to base the rest of the system on is one of the defining decisions of the design process because it makes up the largest amount of additional payload weight. Because the scaling of the robot depends on the payload capacity needed the computer choice will have a long chain of effects down the design process. Two main computer options were selected early on, one for its ease of programming, the other for its light weight.

A PC/104 form factor computer was the initial choice guided by its previous use in the lab on other robots. The single board Diamond Elektra has an onboard analog to digital converter, ethernet network interface, x86 processor equivalent to a Pentium 2, and most importantly complete driver support for the Matlab XPC realtime kernel. This software hooks in with Simulink and Matlab on a host computer for fast and user friendly control system development. On the downside, the computer is heavy

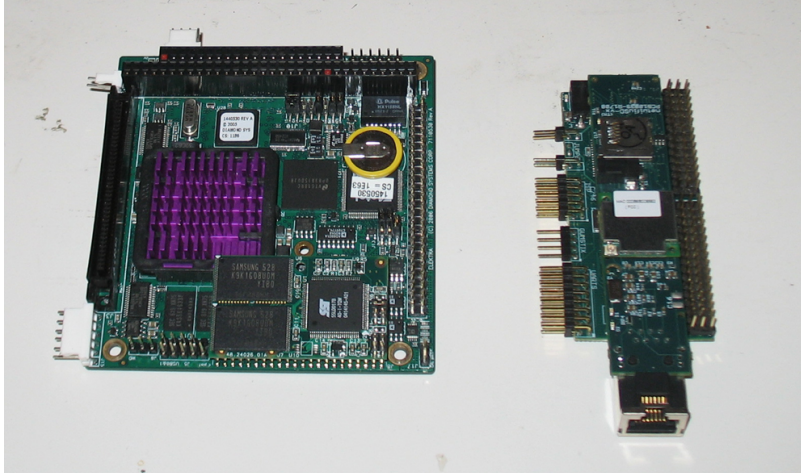


Figure 5-1: Two of the computers used in the project. On the left is the Elektra and on the right is the Gumstix.

by itself, 106 grams, but on top of that it needs additional IO boards to interface with the servos and any wireless communication which add even more weight.

In contrast with the Elektra is the Gumstix system, an ARM based computer which runs the OpenEmbedded Linux distribution. The system is much more compact and lightweight, the set of boards weighs 43.5 grams, includes the necessary IO equipment to interface with the servos and a wireless networking module. The major cost in this option is that development for the system is vastly more difficult. The software development environment has a steep learning curve, the operating system and drivers are unreliable, and all of the software needs to be written in C.

In the course of development both systems were used, first the Elektra, which the initial design was based around, and later the Gumstix on the second revision because of the unmanageable weight of the Elektra system.

5.2 Battery

The battery used is a three cell lithium polymer pack, the standard for high performance machines like airplanes on this scale because it has the best power and energy to weight ratios available. Power density is the main concern at the initial stages of the project because flights aren't expected to last for long which would make

power output the limiting factor for the battery. A lithium polymer battery can be discharged at up to 10 times its capacity (commonly referred to as 10C) with specially selected batteries capable of continuous discharge up to 25C which makes it able to deliver the short bursts of power that the ornithopter needs to flap during short test flights.

Lithium phosphate batteries produced by A123 were also investigated because they have similar characteristics but the cell sizes available at the time were too large to make a suitably lightweight pack at the correct voltage. Since then a smaller series of cells has become available, the 18650, which matches the application well. Four cells would produce a pack at 13.2 volts at 156 grams. This works out comparably to the lithium polymer pack with two important advantages. The cell price of the lithium phosphate batteries works out to a pack at about half the price of the lithium polymer pack. In addition to this the lithium phosphate cells are much less sensitive to overcharging which causes lithium polymer batteries to violently explode. Because of potential cost and safety advantages of the lithium phosphate cells over the lithium polymer cells they may be further investigated in the future.

Because the current draw from the motor wasn't yet known a standard battery, 1200mAh at 11.4V and 93 grams, was chosen for the weight calculation. Eventually a three cell 2200mAh battery pack was selected for actual use.

5.3 Sensors

Ideally full state information for the ornithopter would be available to the control system, but because sensors are a significant part of the weight budget only those of immediate need to the control system envisioned were included. Orientation and velocity are typically used to describe the state of an aircraft because the body's position doesn't generally play a part in the vehicle dynamics. This of course discounts environmental effects like wind and obstructions.

The MicroStrain 3DM-GX1 is the standard orientation sensor used by the lab and is widely used in the field. It's a fully integrated gyroscope, accelerometer, and

magnetometer sensor package that performs the sensor filtering and fusion onboard and communicates orientation and acceleration over an RS232 data line. It was chosen as the primary sensor for the ornithopter because of its reliable and accurate performance in addition to its small and lightweight construction. The sensor package is fully integrated onto two small boards with all surface mount construction, making it surprisingly light at 25.8 grams for the amount of equipment packed onto it.

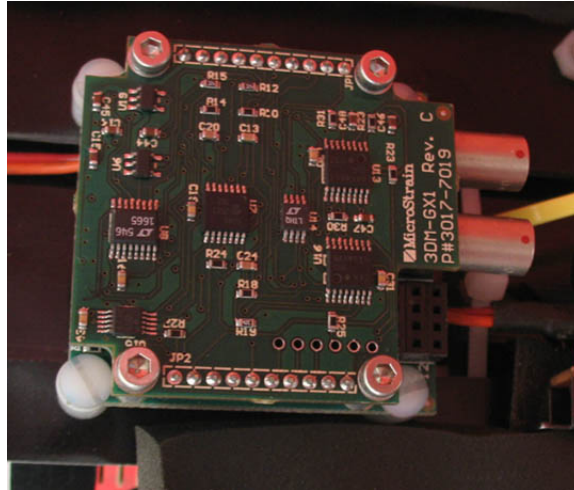


Figure 5-2: The MicroStrain 3DM-GX1 IMU used to sense orientation.

While velocity information is theoretically available from the sensor through the integration of reported accelerations in practice that method is extremely prone to drift and a pitot tube or hot wire velocity sensor is a much better sensor for the application. Both of these could be added at a later point at a small weight cost but because the very first control experiments would only be using pitch data in a single-input-single-output fashion the decision to maximize flying performance by minimizing weight was chosen.

This also applies to the position data that will eventually be needed for autonomous flights over longer distances and involving turns. There are many extremely lightweight GPS units that can be integrated at a later time for a small weight penalty once initial performance concerns are worked out.

5.4 Hardware Interface

There are three main elements to the control system interface: the servo motor controller, drive motor controller, and communications to systems offboard the robot.

Conventional hobby servos like those used on model aircraft use a pulse width modulated signal with a period of about 40hz and a pulse width of between 1 and 2 milliseconds which corresponds to the desired absolute position of the servo's output drive. Because the computer system's main interface is over RS232 serial, a converter is needed. Serial to PWM converters designed specifically for controlling hobby servos are widely available because of their widespread application in robotics. For this project the Pololu Micro Serial Servo Controller was chosen because of its extremely small size and weight; the smallest available at about one square inch and about five grams. The device uses a custom programmed Microchip PIC microcontroller to receive serial data and produce the PWM signal. While a similar device could be produced custom for the project the advantage over the already extremely small size and weight of the Pololu controller would be very small.

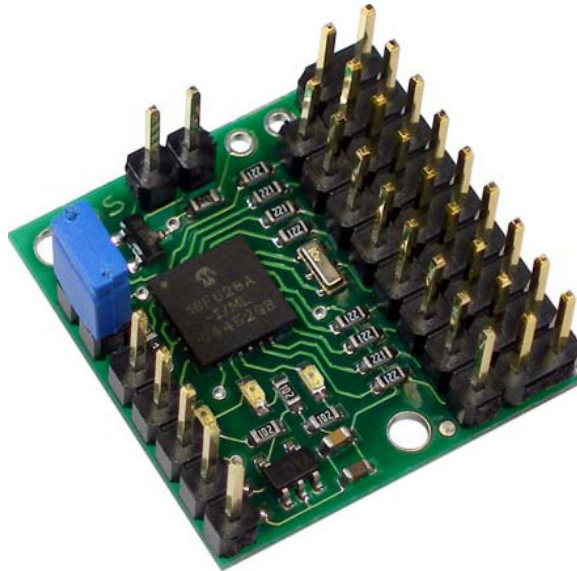


Figure 5-3: Pololu servo controller board used to convert RS232 output from the computer to PWM control signals for hobby servos.

The actual test flights conducted are a combination of radio control and computer control, both for procedural and safety reasons. While testing different controllers

it's desirable to be able to control the robot via a conventional radio controller, either in full or just specific channels like the throttle while the computers handles the control surfaces. It's also used to guide the robot into initial conditions where it's safe to switch over to the computer controller. There are multiplexers designed for the specific purpose of robot control in which the signal source selected is controlled by a separate PWM input from the same radio receiver that traditionally controls the servos. A digital output line is also connected to the control computer so that the control loop can be initialized correctly once control is switched over. The multiplexer used on the Phoenix is the RxMux board made by Reactive Technologies which weighs about 30 grams. Since the time of the original design Pololu has released a new servo signal multiplexer that would fit this application much better with significantly size and weight savings over the Reactive Technologies board.

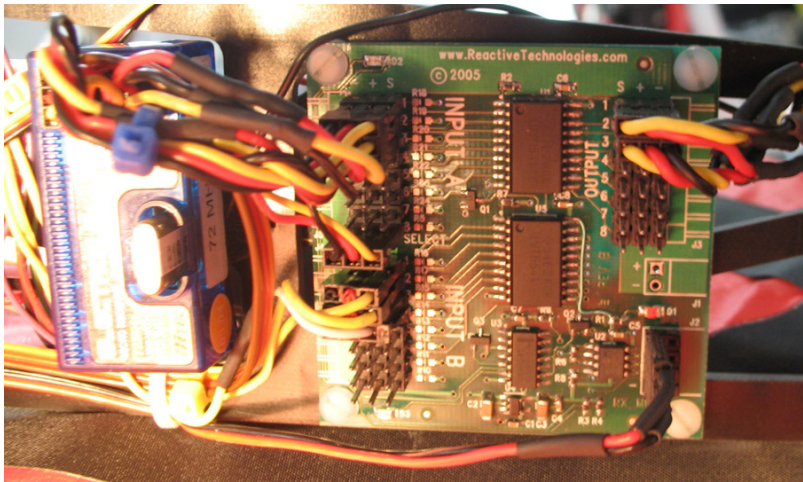


Figure 5-4: Servo signal multiplexer to switch between remote operator and automatic control. Next to the multiplexer board is the radio receiver in blue.

The drive motor controller sits between the serial to PWM servo controller and the motor and uses that signal to control a high current driver suitable for the power requirements of the large motor. This is again a standard radio control airplane part and a JETI Model Advance 30 brushless motor speed controller was chosen for this application because of its past use in the lab. The speed controller is designed to handle 30 amps of current which was considered to be an upper bound of power required, about 300 watts at the 11.4 volts the battery pack runs at, and weighs 35

grams.

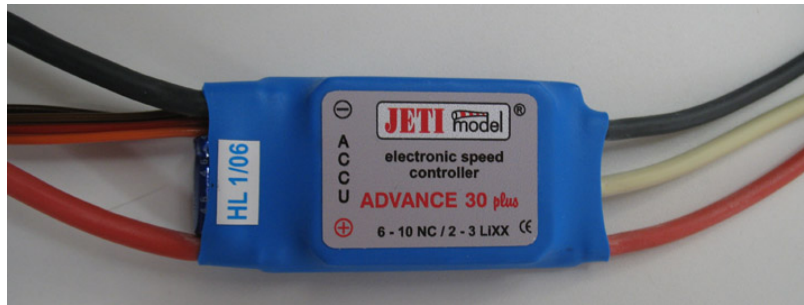


Figure 5-5: Main drive motor speed controller. Converts the PWM control signal into the appropriate waveform to drive the high current brushless motor.

5.4.1 Wireless Communications

The last major piece of interface equipment is on the other side of system, communication between a base station computer and the robot. While a standard 802.11 network link is desired the PC/104 based system running XPC Target doesn't support a USB wireless transceiver. This problem can be sidestepped through the use of a wireless bridge which connects to the wired ethernet on the computer making the connection transparent to the system. An Asus WL-330g, the smallest device capable of the job at the time, was used. This allows data to be offloaded and control system parameters to be changed without hooking an umbilical cable up to the robot.

The fact that 802.11 wireless networking is the widely used standard in retrospect has led to many unforeseen problems. The extremely high proliferation of wireless networks in the Stata Center and around the MIT campus results in several access points overlapping on all channels in most areas. This overlapping coverage produces interference that causes latency problems and dropped packets from qualitative experience. While measures can be taken to increase the strength and directionality of the desired signal it doesn't seem to make much difference with respect to the problems experienced. Depending on the fragility of the protocol used results of these latency issues and dropped packets can range from insignificant to catastrophic, the best example of this being the communications used by the Simulink XPC system

which completely fails in the presence of any dropped packets.

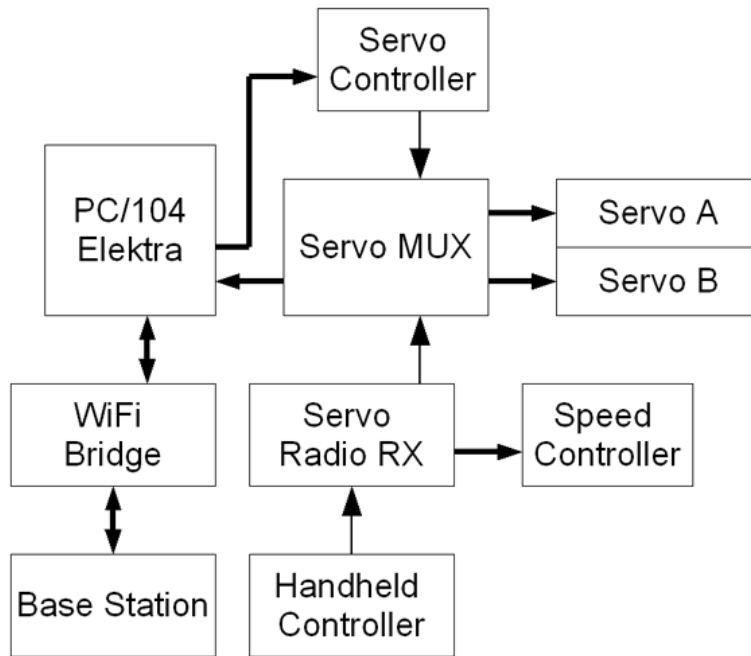


Figure 5-6: Block diagram of the overall electronics system configuration.

Chapter 6

Wings

The wing design chosen for use for the Phoenix is a proven design by Sean Kinkade and is used throughout his line of ornithopter designs which shows that it scales well. Working from the years of development on this wing design allows the focus of our project to be on the parts we have more experience in such as the gearbox, electronics, and controls. The wings have a triangular support structure made from carbon rods. A main spar runs along the leading edge of the wing and a strut connects from the rear of the ornithopter's body to a point near the tip of the main spar. From this strut there are several smaller carbon rods that project to the edge of the wing which are somewhat free to move. This results in a fanning motion from the trailing edge of the wing that produces thrust while the leading edge is flapping up and down which directly contributes a part of the lift in addition to the conventional lift coming from airflow over the wing. [7]

Working from the specifications of the Kestrel ornithopter and the new payload capacity necessary an approximate size for the scaled up wing was found based on the wing loading. With its 0.22 square meter wing area and overall weight of 395 grams the Kestrel has a wing loading of $1.78 \frac{kg}{m^2}$. Scaling to a larger machine that even the size of is known is a pretty difficult proposition, but a few assumptions can be applied to clean up the situation. The payload fraction, or amount of payload divided by the overall weight of the ornithoper is assumed to be constant. For the Kestrel this number is 0.334 with a payload of 132 grams. The 132 gram payload was

estimated by looking at the difference between the weights of onboard components like the batteries as equipped and the maximum weights allowed (using lithium polymer batteries vs nickel metal hydride for example). The estimated required payload for the Phoenix is 400 grams which, using the same payload fraction, comes to a total weight of 1197 grams. With this weight in order keep the same wing loading as the Kestrel the Phoenix will need a wing area of 0.672 square meters. By scaling the original Kestrel wing the desired wingspan comes to about 2 meters. The actual wingspan used in the design was shortened to 1.8 meters in order to make the ornithopter easier to handle through the lab with the option left open to increase the wingspan with longer spars if necessary.

The wings are of similar construction to a modern kite. The fabric used is $\frac{1}{2}$ oz polycarbonate coated ripstop polyester which provides excellent strength and resistance against tearing for very little weight. The sections where the wing interfaces with spars or the ornithopter frame are constructed from Dacron fabric which is glued to the polyester fabric to form pockets and reinforced sections, for the most part directly scaled up from the Kestrel's wing design. Instead of stitching the fabric which creates stress concentrations in the fabric gluing is the preferred construction method now. The gluing is done with the application of a very thin double sided tape called Very Highly Bonding by 3M. The tape is applied with the backing still on to one piece of fabric and worked into the surface for full contact, then the backing is pulled away and the mating piece of fabric is applied.

Selecting the correct wing spars for the scaled up version was one of the larger engineering leaps of faith because not only do they have to be strong enough to not break, but the wings rely heavily on their compliance to produce the kinematics that have been experimentally found to produce the best performance. In order to try to match the motion of the Kestrel wings with the much larger Phoenix wings the moment of inertia of the wing spar was scaled linearly with the torque at the shoulder. This is because in the case of a beam bending due to a moment acting on the end, the static situation most closely modeling the ornithopter, deflection at all points grows linearly with the moment applied. The scaling relationship for this moment is



Figure 6-1: A section of the wing material with the 3M VHB adhesive tape applied.

obtained in the gearbox design section further on, applied here, leading to the desired moment of inertia four times greater than that of the spars of the Kestrel.

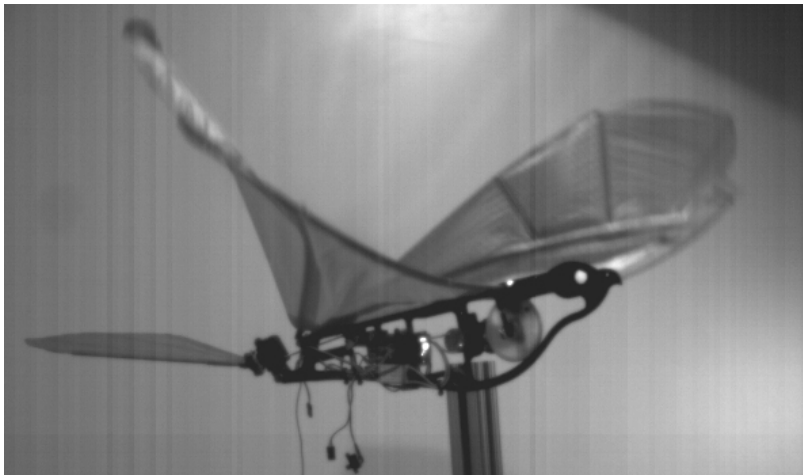


Figure 6-2: A frame of high speed video taken of the Kestrel which shows the amount of wing spar flex in normal flight.

The insertion ends of the wing spars are a somewhat difficult engineering problem because they are the point at which the driving torque is exerted. While the spar is easily able to handle the torque, any piece attached to the end to drive the spar will create a stress concentration that will create a point of failure. In addition to this the spars need to be able to be removed from the shoulder assembly both for assembly of the wing and when they break. In order to distribute the loading along a length of the spar instead of concentrating it at a point an extremely stiff rubber was

used to make a threaded connector that screws into a delrin shoulder. This connector allows the spar to flex and because it is soft it is unable to create a significant stress concentration, instead relying on a large area of lower force to exert the torque on the spar.



Figure 6-3: The compliant wing spar end assembly.

Chapter 7

Gearbox

The most critical part of the ornithopter is the drive mechanism the converts the electric power from the battery to the flapping motion of the wings. This system is the most complex to design and fabricate because it must withstand very large forces which reverse direction several times a second while at the same time being extremely light and durable. Because of the loads it must be made from metal which makes it beneficial to perform careful analysis and trim as much weight as possible.

The drive system can be further broken down into four sections, the electric motor, a gear reduction stage, a linkage to convert the high torque rotation into a reciprocating motion, and the connection to the wing spars. While a highly integrated design is needed in order to maximize the power to weight ratio, the analysis of these parts breaks down well.

7.1 Load Case Development

In order to figure out what loads the gearbox needs to be designed for the torques to be exerted at the wing shoulders need to be known. While a relationship for scaling the torque from the Kestrel ornithopter can be created, the actual torques on the Kestrel need to be known too. Because the gear ratios and motor characteristics are known these torques can be found by measuring the current through the electric motor and calculating the torques at each point in the transmission to the wings.

With the ornithopter frame fixed a shunt resistor was used to measure the maximum current at full throttle through the brushed DC motor that flaps the wings. This represents the maximum loading seen by the transmission. An oscilloscope was used to measure the voltage across the resistor over time along with the voltage across the motor. With this data it was found that the maximum torque at the motor is 0.00832 Newton-meters and that the wings flap at 6hz in the conditions during measurement. This torque at the motor is translated through the 97.8:1 ratio gearbox and the flapping linkage to produce 4.43 Newton-meters at the shoulder.

With the torque at the shoulder of the Kestrel and the new wingspan needed by the Phoenix the one piece that remains is the scaling relationship between wingspan and torque at the shoulder. This is accomplished with a relatively simple analysis. The torque at the shoulder is the product of the distance to the center of pressure (moment arm) times the force produced by the pressure on the wing concentrated at that point. Because the wing loading is being fixed for this scaling process and the wings are roughly square the force increases with the square of the wingspan. In addition to this the distance to the center of pressure increases linearly with the wingspan as long as the wings remain loaded in a similar fashion along their span. This suggests that the torque on the shoulder will grow with the cube of the wingspan. The new design calls for a wingspan 1.56 times longer than that of the Kestrel and so the shoulder torque is expected to be 3.79 times higher or 7.78 Newton-meters.

The rate at which the wings need to be flapped is also important to selecting gearbox components. While exact data to base this on isn't available a video of a similarly scaled ornithopter based on Kinkade's design was found which the flapping frequency could be roughly estimated from. Compared to the Kestrel known to flap at 6Hz the ornithopter in the video was judged to flap at about 4Hz, roughly in line with an inverse scaling of flapping frequency with wingspan.

7.2 Drive Linkage, Wing Joining Gears and Spar Mounts

In order for the forces on the wings to balance each other out to produce only thrust and lift rather a rolling and yawing moment the wings need to move together in the same motion. This can be accomplished in a couple different ways, either by having a second, opposite four bar linkage which is the strategy used on the Kestrel, or with a set of gears that slave the motion of one wing to the other similar to the design in Kinkade's patent [10].

In the case of the Kestrel it made sense to have two separate linkages because the lightly loaded gearbox was able to be built directly into the fiberglass frame of the ornithopter and was configured longitudinally so setting up two linkages that don't interfere with each other is relatively easy. Combined with the fact that they don't need to be very strong because of the small scale making two linkages from lightweight and cheap materials is the natural choice. One major downside to the configuration is that the rotation of the crank and wing are on different axes which means the links need to have additional degrees of freedom to accommodate the 3D motion. This is accomplished with plastic ball joints that are common to model airplanes but creates a major source of broken parts in practice because the joints are not designed for such loads.

With the vastly increased load in the Phoenix gearbox a different strategy is required. The linkage movement must at very least be kept in plane so that proper bearings can be used at the joints instead of ball joints, this means that the linkage must be longitudinal which in turn means that having two opposing linkages is much harder to make work. Luckily slaving one of the wings to the other is also an option. By putting gear teeth on the shoulders they can be made to turn with each other with very little extra weight over just moving one wing. With one linkage driving both wings at the same time the loads on it are slightly more than doubled, but since the motion is in plane the problem is reduced to a relatively simple problem of selecting suitable bearings and designing the links to be lightweight and strong in the right

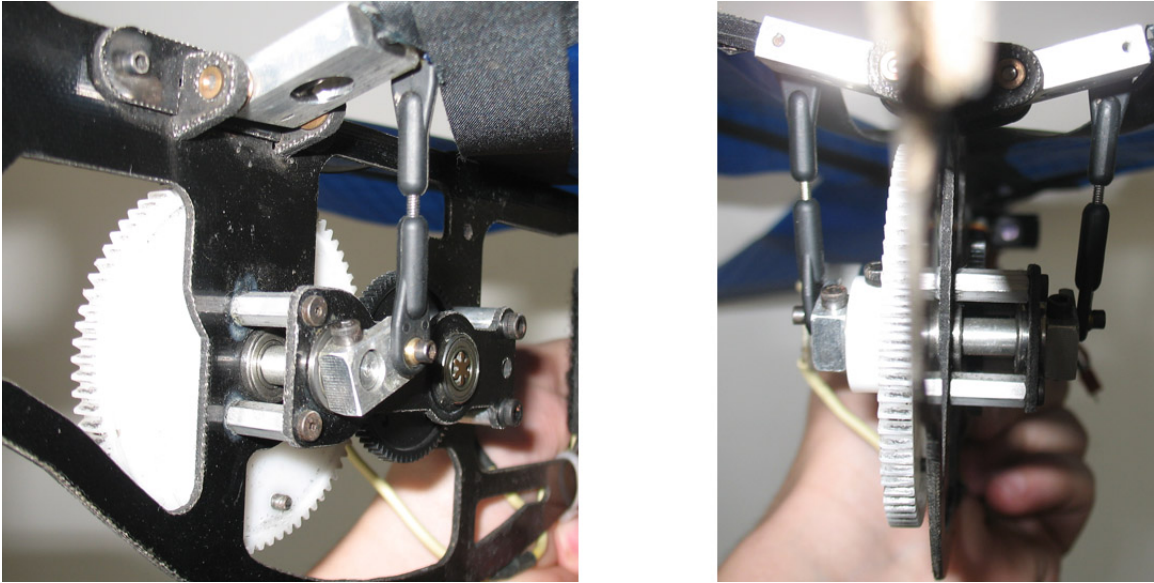


Figure 7-1: Side and front view of the Kestrel gearbox. Note the longitudinal configuration of the reducing gears and the matched linkages on either side. The shoulder and crank rotate about different axes, plastic ball joints allow this 3D motion to take place.

directions.

The linkage was designed to match the wing trajectory of the Kestrel with the wing lifting 30 degrees above the horizontal and 20 degrees below. Flat links constructed from titanium allow them to be designed to be strongest in the directions that matter and extremely lightweight overall. The geometry of the linkage was determined using the Solidworks COSMOSMotion package and then the links were optimized using COSMOSMotion FEA. The links were also analyzed for buckling because their flat structure is very susceptible to it, the load factor of 8.3 predicts that buckling will not occur.

The wing shoulders have three functions, forming the second fixed point of the main drive linkage, driving one wing to match the motion of the other, and providing an attachment point for the wing spars. Both wing shoulders rotate on titanium shafts supported by miniature ball bearings. These bearings are commonly used in small machinery, most notably model cars, and are available cheaply in almost any size, these coming from Boca Bearing. The miniature bearings are lightweight and small allowing the overall gearbox size to be kept to a minimum.

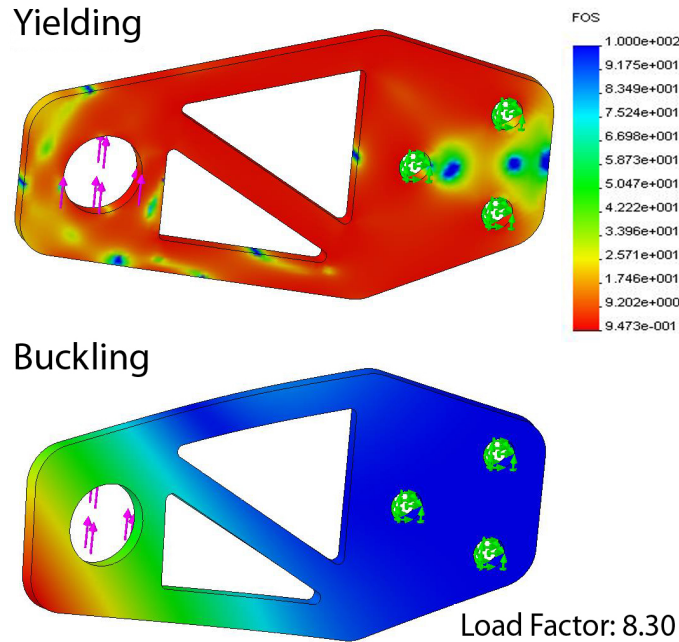


Figure 7-2: Sample yield stress and buckling analysis results from FEA performed on the linkage components.

The shoulder piece itself is machined delrin and has a threaded end to accept the screw in spar discussed in the wing section. The threaded wing spar is essential because it allows the spars to be quickly changed out when they break and allows for the compliant rubber of the spar end to mate with the shoulder which must be much more rigid. A set of pins join the delrin piece to the aluminum gear that drives the other wing in addition to the rocker link that drives both wings. The gears that connect the wings were selected using the Lewis formula for gear tooth strength to find the the most lightweight gears that fit the form factor of the gearbox. Stock gears were ordered and waterjetted to the desired shape so that the precise gear teeth wouldn't have to be machined.

7.3 Motor Selection

The main drive motor is one of the most important parts to be selected because it makes up one of the major weight components of the drive system. The highest power density possible is desirable for obvious reasons, but second to that is a high

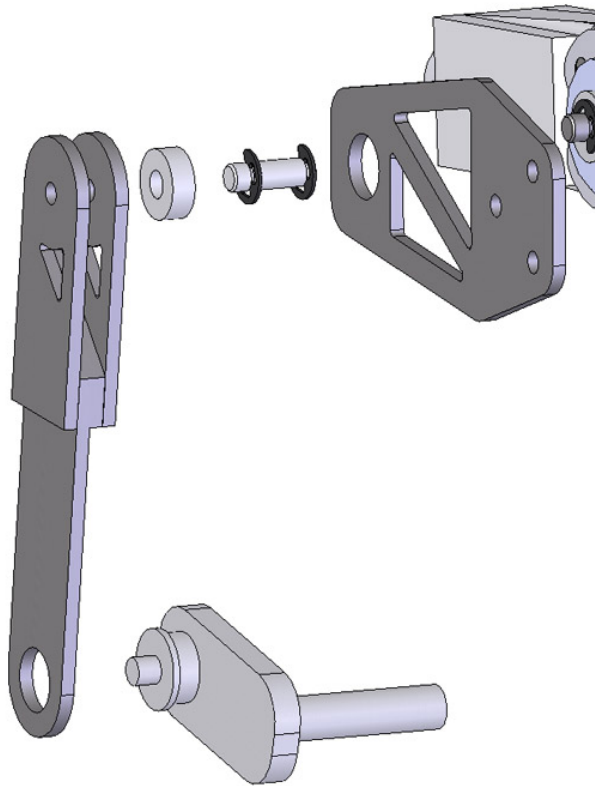


Figure 7-3: Exploded view of the four bar linkage the drives the wing motion. Notice the planar motion in comparison to the Kestrel's linkage and ball bearings at every joint.

torque density. This is because gear reductions require both additional weight and space in the transmission. The gears need to be able to handle large torques so they also must be strong and hence large and heavy. Several types of miniature high performance motors are available for model airplanes but one in particular sticks out for this application, the brushless outrunner, which is primarily used in direct propeller drive configurations because of the high torques supported.

A brushless outrunner motor is essentially an inside out version of the conventional brushless motor, instead of the coils being placed around an internal rotating magnet assembly the coils are wound around a stationary internal post and the magnets are mounted on the outside motor housing which is free to rotate, shown in figure 7-6. This puts the magnets that the electromagnetic force created by the coils acts on as

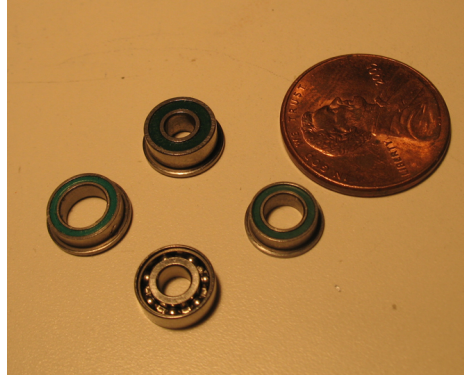


Figure 7-4: A sampling of the micro bearings used in the flapping transmission.

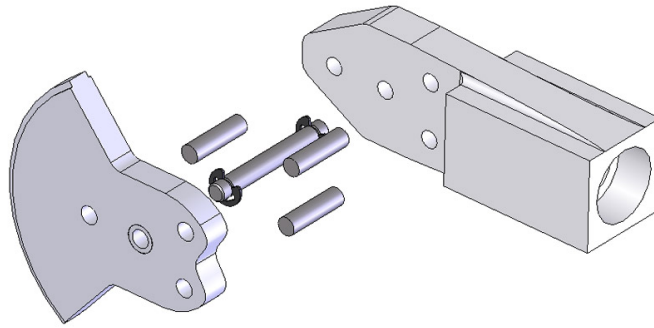


Figure 7-5: An exploded view of the wing shoulder assembly. Pins connect the delrin spar receptacle to both the driving gear and the drive linkage rocker.

far away from the axis of rotation as possible. This creates the largest amount of torque possible in the space constraints of the motor.

The two outputs from the motor and gear reduction system are already known, the torque transmitted down through the drive linkage becomes 17.7 Newton-meters and the desired speed of 4hz becomes 240RPM. Sadly this does not fix the variables enough to select a motor or design a gearbox right off the bat because a wide range of gear ratios and motor windings are available. Rather than simply fixing a design parameter with no basis to proceed, some reasoning about the system was done.

Because of the large torque required at the transmission output a steep gear reduction will be required along with large strong gears in the stage close to the output. A gearbox with two reduction stages of the maximum possible ratio was



Figure 7-6: The brushless outrunner motor used in the ornithopter gearbox taken apart to show its unusual configuration. Notice that the outside can of the motor rotates rather than the coils inside.

designed as a starting point. In this case the maximum reduction at each stage was limited by the strength of the gear teeth, what was kept in stock by the supplier, and what could be packaged feasibly into a transmission. At the end a maximum of a 24:1 reduction was achieved which made motor selection very easy. The 240RPM output shaft speed through the 24:1 reduction becomes a target of 5760RPM at the motor shaft. At the maximum voltage across the motor of the 11.4 Volts of the three cell LiPo pack the desired motor speed constant comes out to $505 \frac{RPM}{V}$.

The electric motor speed constant is inversely proportional to the motor's torque constant, a measure of the amount of torque produced per unit current. Because of this relationship it makes sense that the small lightweight motors desired for this application will have high speed constants. Windings available on even the the highest

torque motors suitable start well above this speed constant because of their inability to produce a large amount of torque in such a small space. The law of conservation of energy when applied to this case shows that for the same energy output the speed of the motor must increase if the torque produced decreases.

With these specifications the field of possible motors became very small. The selection of windings available in the brushless outrunner motors used in model aircraft is quite limited because of the specialized application but a motor that fit the desired specifications closely enough was found. The PJS 3D 1200 motor, conveniently used in previous experiments in the lab has a speed constant of $848 \frac{RPM}{V}$ and a torque constant of $0.01126 \frac{Nm}{A}$. The expected torque required at the motor shaft of $0.7375Nm$ requires $65A$ of current through the motor. While this current seems too high the options to lower it, either by adding a gearbox stage or using a heavier motor are as unpalatable as handling the high current. This decision was one of the major engineering compromises of the project but the stacked safety factors in the gearbox loading and conservative scaling estimates used so far make the predicted loadings especially brutal at this stage. The decision to go with the PJS 3D 1200 motor and deal with the consequences of high current was made with the option of using a larger motor if testing indicates the necessity.

7.4 Gearbox Frame

The gearbox frame is a component whose performance, not just existence, is critical to every function of the gearbox. The distance between the gears and hence the quality of their meshing depends on the accurate construction and stiffness of the frame. The quality of the gear mesh is of utmost importance because the flapping motion puts periodically reversing loads on the gears and backlash in that case leads to very fast tooth destruction in addition to sloppy wing motion at the highest and lowest parts of the stroke. The pursuit of accuracy and stiffness can quickly lead to a very heavy and expensive construction.

In order to make the frame as lightweight as possible a titanium sheet design was

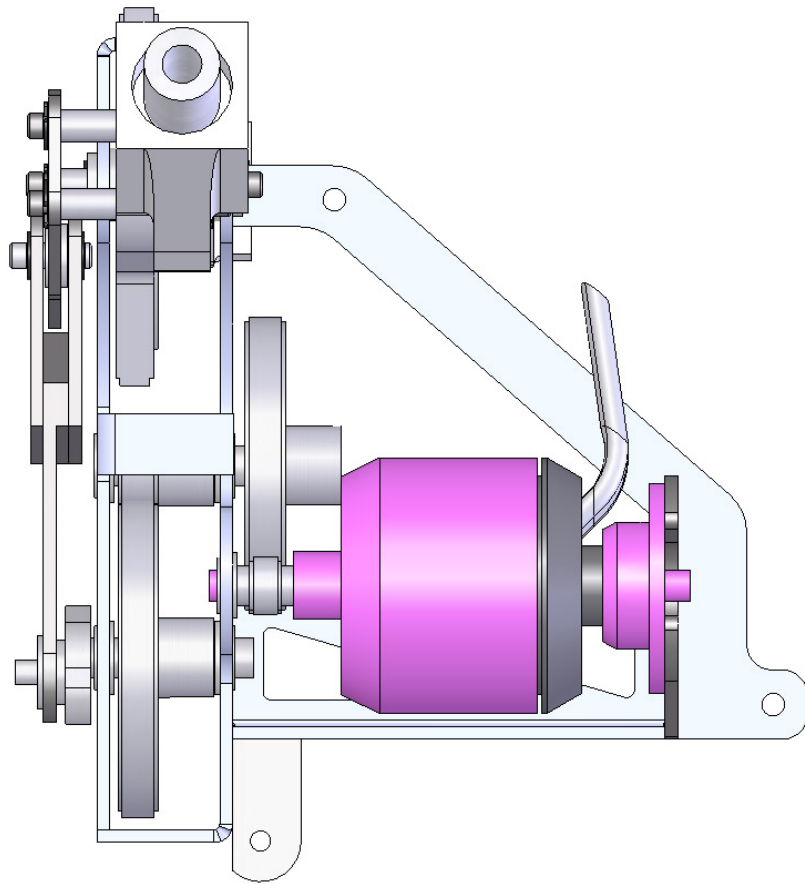


Figure 7-7: Side view of the complete gearbox showing the motor mounted and the configuration of the transmission gears.

chosen. The process of designing a complex frame in CAD, cutting it out with a CNC waterjet cutter, then bending and welding the structure together is very inexpensive and fast because little time is spent machining large amounts of material away. By paying careful attention to the design of box and truss structures and how they are bent from the parent sheet surprising stiffness can be achieved and with the addition of tabs that guide assembly and welding the entire process is very fast.

The key to making the process come together is welding the individual pieces together. In order to make the strongest and cleanest welds the Tungsten Inert Gas (TIG) process is used. This welding process relies heavily on the skill of the operator to guide the torch and apply the right amount of heat to the part in the form of an arc between a tungsten electrode and the base metal inside an inert



Figure 7-8: The welded titanium gearbox frame which holds all of the drive components together. Bent and welded sheet construction produces a strong, lightweight, and inexpensive part.

argon atmosphere. Titanium is extremely susceptible to atmospheric contamination when heated so special steps outside the normal welding process must be taken. Titanium welding is often performed inside a completely purged glovebox for this reason. Without one available additional shielding gas can be applied and attention not to let the areas of the part exposed to the atmosphere heat up too hot must be observed.

The accuracy of the bearing pocket placement comes from cutting out the holes undersize on the waterjet cutter and once the bending and welding of the frame is complete they are reamed to their finished sizes. The reaming process is performed

with the frame mounted in the vise of a milling machine, by using the machine's table to move the part to the correct hole locations they can be machined accurate to less than a thousandth of an inch.

When finished the entire frame weighs a total of 58.1 grams and stands up to both the high internal forces of the gearbox and large amounts of external abuse, usually from impacts to the ground during crashes. Because large shock loads are expected from frequent crashes a protective face plate is attached to the main frame by several screws. Made from much cheaper thin fiberglass laminate it's intended to flex and absorb the shocks and break instead of the main frame breaking. Multiple faceplates can be kept on hand during testing sessions and replaced quickly whereas the main frame is cut from much more expensive material and would take hours in the lab to transplant.

Chapter 8

Tail

The tail section of the ornithopter is responsible for both of the controllable degrees of freedom aside from the ability to throttle the drive motor. The tail of the Kestrel is set up with one servo directly connected to the tail at an angle and another further up the body which rocks it via a linkage. Mounting the rudder servo at an angle is important because with a single control surface the elevator and rudder are naturally coupled, moving the rudder servo makes the tail also move in the vertical direction unless it's at zero angle where it doesn't have any control authority anyway. With the tail at an angle to the rudder servo it allows the servo to hold into the zero angle position with respect to the ornithopter body and while the tail stays near the trimmed position for horizontal flight. This causes the tail to move in a bowl shaped trajectory decoupled from the elevator action and is much easier to control by a human pilot. It does not solve the problem when the elevator servo moves the tail out of the trimmed horizontal position, but being able to exploit that is a big advantage where it applies.

A second point to make about the Kestrel tail is that the linkage for the elevator servo appears to be unnecessary but serves two important purposes. First is that the servo range of motion is much larger than what is necessary for the tail. By using a linkage not only does the range of motion get reduced but the mechanical advantage allows a smaller servo to be used. In addition to this, the servo, a major point of weight on the ornithopter, is moved forward in the frame. While not obviously an

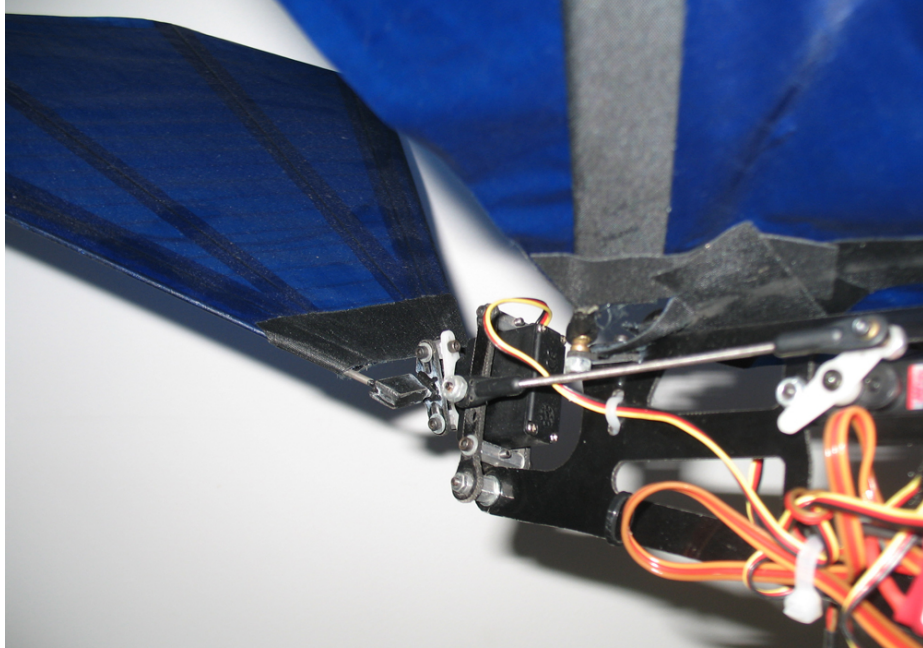


Figure 8-1: The tail section of the Kestrel. The tail uses a clever configuration to decouple the elevator and rudder actions

issue it becomes important once the center of gravity must be placed because the frame ends up rear-heavy.

The tail of the Phoenix is designed with computer control in mind and so doesn't use the configuration the Kestrel exploits to make human control easier, but it does use the same tail fan design. The servos are directly joined to each other so that as little weight is spent on linkage and mounting as possible, again using lightweight welded titanium construction. At a glance it can be seen that the tail cannot follow the same path as the Kestrel tail, but it should be able to act similarly aerodynamically. Because of the large surface area of the tail and the fact that tail is attached directly at the servos output horns very high torque HiTec 5995TG servos with titanium gearsets were chosen. The high strength gears are much less likely to be damaged in the event of a crash that impacts on the tail and come at a slight weight savings over lower torque servos with a steel gearset.



Figure 8-2: The tail section of the Phoenix. In contrast with the Kestrel the servos are directly joined in an effort to simplify the mechanism and save weight.

Chapter 9

Main Frame

The main frame of the ornithopter is a surprisingly simple component from a design standpoint. Because the flapping mechanism is contained fully within the gearbox frame the main frame of the machine serves mainly to provide mounting locations for the rear wing mounts, electronic components, battery, and tail assembly. There are two directions to go with the frame design, either a single flat plate which relies on its own thickness for stiffness, or a three dimensional design made from much thinner material that gets its stiffness from the truss-like structure.

If the frame had to be very stiff the second option would make for a much lighter and stronger option, but in this case the frame really doesn't have to be very stiff in all directions. The rear wing mount actually holds the frame from flexing in the direction a sheet would be most weak because the wing spars form a very large and stiff triangle. What this amounts to is that while the more complicated structure is often the higher stiffness and lower weight option it doesn't come with much advantage in this case. The flat frame is vastly easier to design and fabricate and may even be lighter.

Because the frame is really just a collection of mounting locations for the rest of the components it's relatively easy to design. The one major specification that must be paid attention to is the location of the center of gravity. Because the data needed to work out the correct location theoretically isn't available this was also scaled up from the Kestrel where the location was experimentally determined from flight testing to

be about 4 inches behind the main wing spar. If this is scaled linearly with wingspan the desired center of gravity should be about 6 inches behind the main spar.

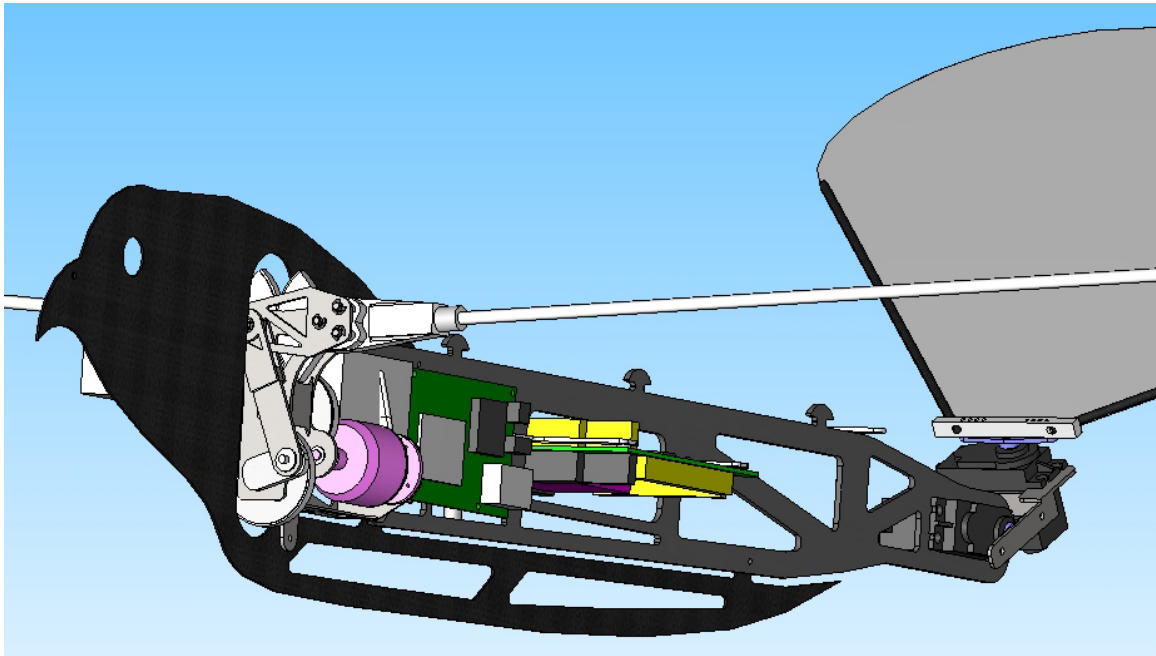


Figure 9-1: A rendering of the Phoenix in the process of placing all of the components for the correct center of gravity.

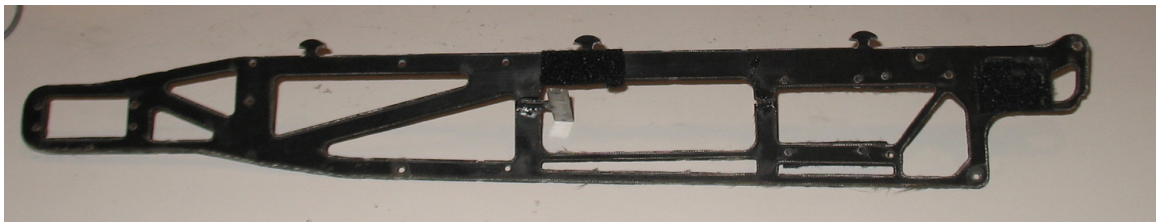


Figure 9-2: The main frame of the ornithopter. It is fabricated from a stiff carbon fiber plate and provides mounting locations for all of the machine's subsystems.

In order to facilitate the locating of all the parts the weights and sizes of all the components were modeled in Solidworks and component configurations were iterated until the center of gravity was in the right location. This turned out to be more difficult than expected because the machine tends to be rear heavy with all the computer computer equipment distributed on the frame. In order to counteract this the main battery back was moved in front of the gear box, a less than ideal option but necessary to get the balance right. The completed machine weighs 1200 grams.

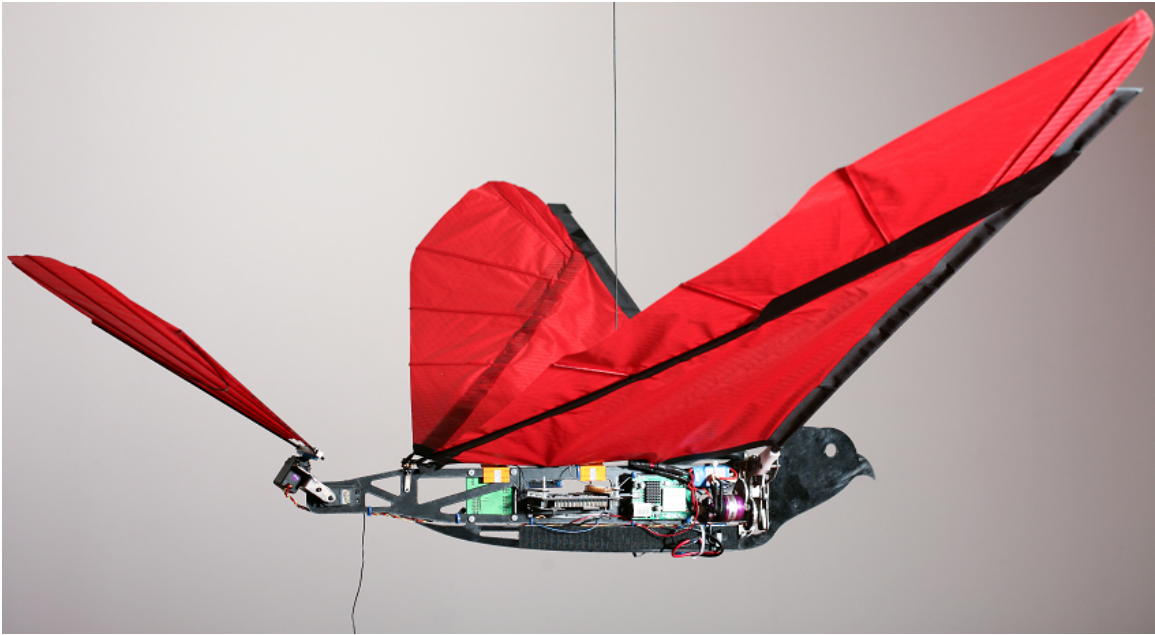


Figure 9-3: The completed ornithopter.

Chapter 10

Control System

For the very first flights a PD control was selected for several reasons. First because of its widespread application in conventional aircraft autopilots, second because it's very simple to establish reasonable starting gains and tune by hand. The proportional and derivative action is easy to visualize and intuitively understand which is very important in this case where making as few tests as possible is desired and catastrophic failure isn't. Applying PD control to pitch was the first step taken because the other degrees of freedom are relatively passively stable and pilots had little luck controlling the ornithopter in pitch themselves. It isn't obvious that a simple PD control should work with a an ornitopter because of the vehicle's periodic dynamics from flapping. One way of looking at the situation is that the controller needs respond to larger changes in pitch rather than the fast motions due to flapping. In order to accomplish this the time constant of the controller can be adjusted so that the response to fast changes in pitch is minimized.

The control system used on the successful flights so far is written in C and runs on the Gumstix computer at 40Hz. 40Hz is the target update rate because it's the maximum that the servos can take commands since the frequency of their variable duty cycle pulses is 40Hz. The pitch and derivative of the pitch come directly from the inertial measurement unit and do not undergo further filtering. In tests so for the desired pitch has been set to a constant value approximating what has been seen in manual flights but this can easily be changed as progress is made.

Controlling yaw has not been implemented yet and will require a somewhat more clever strategy of servo control because the area of the tail presented to the airflow changes with the position of the elevator servo.

A proportional control on the throttle with altitude as an input has been attempted. The reasoning behind this isn't full altitude control but to enhance the level flight by bumping up the throttle a little bit when the ornithopter experiences a drop in altitude. A sonar range sensor was added to the Phoenix to sense altitude but the data has been too unreliable to hand control of the throttle over to the controller because of the sensor's inherent unreliability and the sine errors introduced by the robot pitching and rolling that must be accounted for. An alternative being investigated is an extremely sensitive atmospheric pressure sensor in combination with acceleration data from the IMU.

Chapter 11

Testing

Many test flights were conducted with the finished Phoenix ornithopter, first with an equivalent weight and distribution payload under manual control to determine whether the machine would actually be able to fly. Initial tests showed that sustained flight was possible but the robot was exceedingly difficult to control and quickly crashed. Later tests with a PD control on the elevator to stabilize pitch qualitatively showed promise but difficulties with gearbox and wing spar reliability plagued the testing process.

This process of breaking things during testing is an essential part of the design process and leaps of progress were made during this time in tracking down problems and implementing design solutions to them. Parts of the gearbox like the connection between the final rocker link and the shoulder were a common point of failure and received stopgap design revisions until enough changes accumulated for a full design iteration of the machine. Changes were incorporated into the gearbox design, the electronics package switched over to the much lighter Gumstix based system, and the frame was reconfigured to balance the new weight distribution properly.

This second revision Phoenix took its first successful semi-autonomous flight on August 18, 2008 by traveling about 30 yards in steady, level flight before being shut down manually to avoid hitting MIT's Building 18. A PD control stabilizing pitch was applied to the elevator with the throttle set at a fixed point by a remote control operator. The throttle setting was taken from a successful manual flight. The con-

troller gains and pitch set point were initially set to a response that seemed to mimic a human pilot and tuned over the course of several tests. At the end of the flight flapping power is shut off and the wings passively enter a high dihedral which causes it to quickly glide to the ground while maintaining roll and pitch stability.

Steady state flight data from one of the successful test is shown below, note that the length of time is only about two seconds because the section containing initial conditions is excluded and the area used for testing is small. Longer tests are planned but have not been conducted yet. The data shown covers nine wing beats.

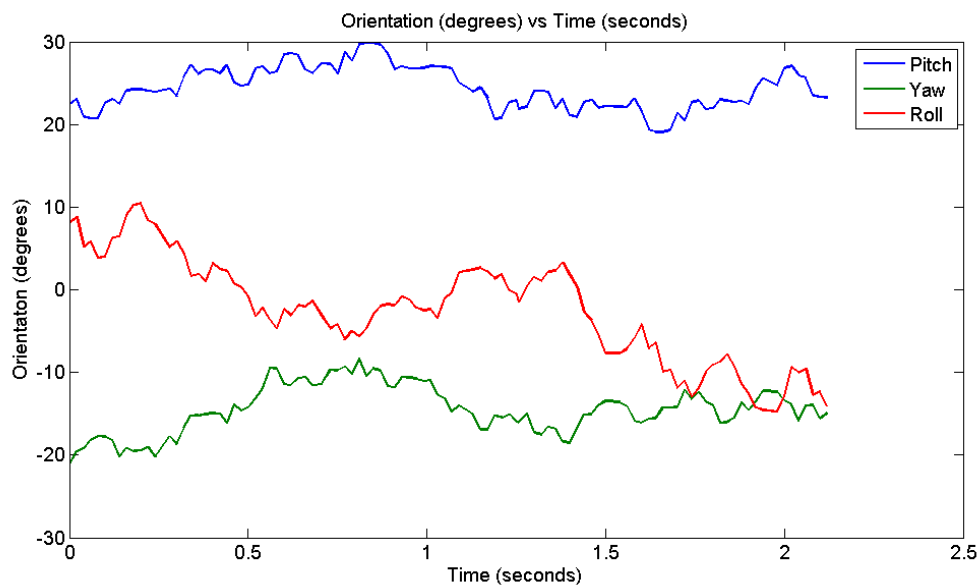


Figure 11-1: A slice of orientation data taken from flight after initial conditions have died out.

The graph of orientation shows pitch maintained with small variations, most likely caused by environmental conditions and the action of the wings flapping. Both roll and yaw are uncontrolled but are expected to be somewhat passively stable. The trend in roll shown in the data seems likely to be caused by a difference between the wings such as a weakened spar or out of trim tail.

The torque plot in figure 11-2 is based on current into the speed controller as measured over a current sense resistor. It shows peak torques in the 0.35 Newton-meter range which is about half the maximum predicted. The peak torque seen here isn't the peak torque that can be produced however, because the throttle was

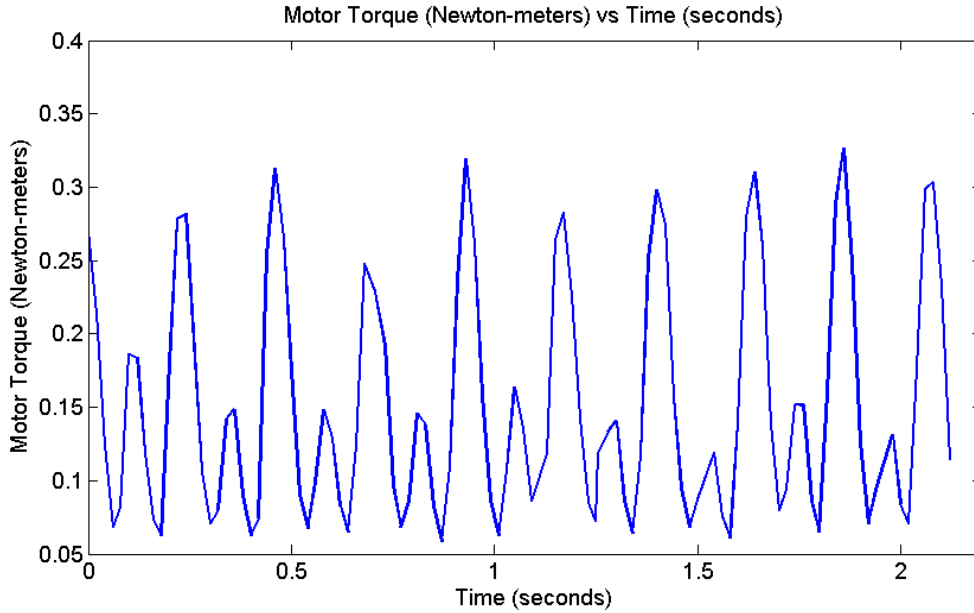


Figure 11-2: Torque from the main drive motor based on current into the speed controller. Notice the periodic variation at about 4Hz with a high torque peak on the downstroke and low torque peak on the upstroke.

set at about 70% of maximum for the steady level flight. Two factors complicate measurement above this point. First is the speed controller is only rated for 30 amperes so going above this level results in the speed controller shutting down. Second is that throttle settings near maximum excite a second mode in the motion of the wing spars and sets up a standing wave instead the desired flapping motion. Both of these problems will be subject of further investigation.

Because both current and voltage are measured it is simple to look at the power it takes for the ornithopter to fly. While efficiency isn't an immediate goal it's obvious that the current realization of the ornithopter and its controller is an extremely inefficient way to fly. An estimated forward velocity of about $4\frac{m}{s}$ based on total time of flight and distance covered combined with a vehicle weight of 1.2Kg shows a very rough unitless cost of transport of about 30.

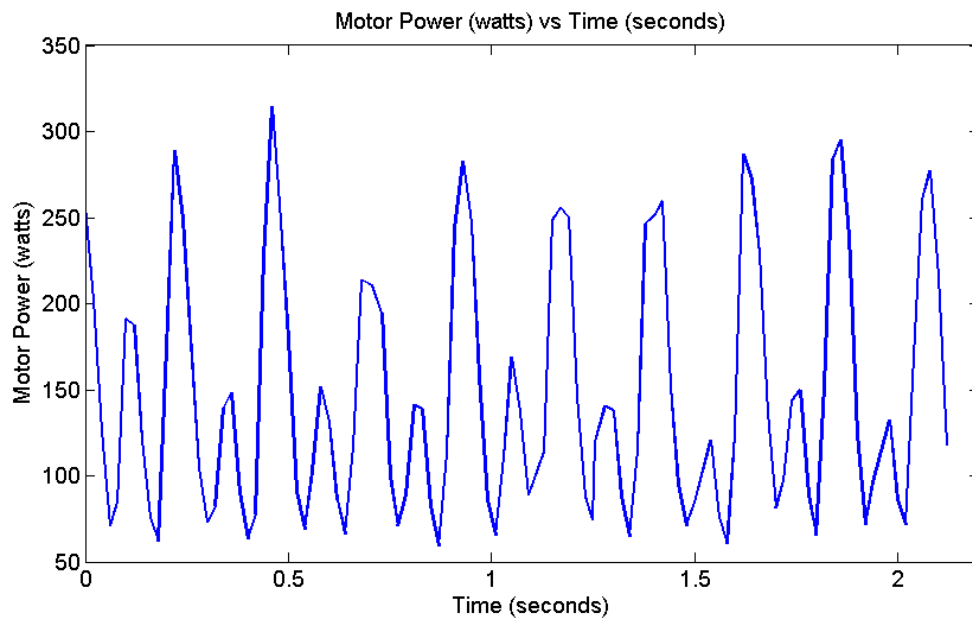


Figure 11-3: Power consumed by the main drive motor. Mean power is 147 watts.



Figure 11-4: Several frames from the video of the first successful semi-autonomous flight of the Phoenix. The robot maintained steady level flight until shut off to avoid impacting the building. The author (in blue) is handling the throttle set point and controller switchover while graduate student John Roberts (green) launches the robot.

Chapter 12

Conclusion

In this paper the case for the construction of a large scale ornithopter suitable for control systems research is motivated. Performance and weight constraints imposed by the computers and sensors desired onboard make it difficult to work with the smaller platforms currently available, let alone micro UAVs currently in development. In order to work with the dynamics and controls of a flapping wing flying vehicle while these future targets are currently in development a scaled up version has been designed and constructed. With its larger payload capacity it's capable of carrying a fully equipped computer and high-end inertial measurement unit with the option of future additions of GPS or other more exotic sensors.

The ornithopter was designed from the ground up with the needs of research in mind. All components have been designed to be as lightweight and high performance as possible so as to maximize payload capacity and are intended to fail in predictable and field repairable ways. Examples of this are the screw in wing spars and replaceable face plates. In addition to this all parts of the ornithopter are simple and inexpensive to fabricate and assemble.

Manual and initial autonomous flight tests have been conducted and show that the ornithopter is capable of sustained flight with a full load of electronics and can be stabilized by simple controllers in common use in aircraft. Flight tests have also shown that the planned points of failure work as expected and allow repairs to be quickly accomplished in the field.

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