Cal Poly
Human Powered Helicopter
Final Design Report

June 10th, 2011

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# TABLE OF CONTENTS

I. Introduction .......................................................................................................................... 2  
   A. Background ......................................................................................................................... 2  
   B. Design Considerations ......................................................................................................... 2  
   C. Ground Effect ...................................................................................................................... 2  
   D. Intermeshing Rotors ............................................................................................................ 3  
II. Project Objectives ............................................................................................................... 4  
III. Project Risks ....................................................................................................................... 5  
IV. Testing Procedure ............................................................................................................... 6  
V. Ground Effect Testing: Single Rotor at Low RPM ............................................................ 7  
   A. Apparatus Overview ........................................................................................................... 7  
   B. Adjustable Stand and Cantilever Boom ............................................................................. 7  
   C. Rotor and Hub Design ........................................................................................................ 7  
   D. Successes ............................................................................................................................ 11  
   E. Low RPM Test Data ............................................................................................................ 12  
VI. Ground Effect Testing: Single Rotor at High RPM ....................................................... 13  
   A. Issues with Higher RPM Tests .......................................................................................... 13  
   B. Solutions to High RPM Problems ..................................................................................... 13  
   C. High RPM Test Data ......................................................................................................... 16  
VII. Ground Effect Data Analysis ......................................................................................... 17  
VIII. Intermeshing Rotors ...................................................................................................... 21  
   A. Design ............................................................................................................................... 21  
   B. Construction ...................................................................................................................... 23  
   C. Issues and Considerations ............................................................................................... 24  
   D. Data and Analysis ............................................................................................................. 25  
IX. Flying Scale Model .......................................................................................................... 28  
   A. Goal .................................................................................................................................. 28  
   B. New Airfoil and Spar Design ........................................................................................... 28  
   C. Airframe Design ................................................................................................................ 29  
   D. Drivetrain .......................................................................................................................... 33  
   E. Control System .................................................................................................................. 36  
X. Plan Forward ..................................................................................................................... 39  
XI. Conclusion and Recommendations for Final Helicopter ............................................. 40
I. Introduction

The following report encompasses the Cal Poly Human Powered Helicopter team’s efforts during the 2010-2011 academic year. The intention of this project is to further the knowledge of human powered helicopter design and to validate an ideal configuration through experimental tests and analysis.

A. Background

The Sikorsky Prize offered by the American Helicopter Society has been the catalyst for many attempts at Human Powered Helicopter (HPH) flight. The requirement to win the prize is a continuous, human powered flight of more than 60 seconds that stays within a 10 meter square box and reaches an altitude greater than 3 meters at some point during the flight. As of 2011, there have been over thirty different attempts. Most of these attempts have not flown or produced anything significant due to serious design issues, fabrication and execution problems, failure to record and publish information, or lack of funding, among other problems. In addition, a large number of the projects are no longer underway because of failure to fly. In fact, only three HPHs have ever achieved flight: the Da Vinci III constructed by students at California Polytechnic State University (Cal Poly), the Yuri I, constructed by students at Nihon University in Japan, and most recently the Gamera, constructed by students at the University of Maryland. All of these successes came after many years of experimentation and the combined efforts of numerous individuals.

B. Design Considerations

Some of the main design challenges for human powered flight include maintaining a very low vehicle weight while achieving the highest power output from the limited energy that a human can produce. From previous research and experiments performed at Cal Poly, it was concluded that the limiting element in using human power is the body’s respiratory system -- the series of organs involved in re-oxygenating blood as it circulates the body. As with any engine, an athlete’s body can only perform within the limits of its respiratory system before reaching exhaustion. For example, simultaneous use of arms and legs to provide power to a helicopter is of little advantage if the body is already processing oxygen at a maximum rate. However, the phenomenon of ground effect is known to reduce the power required for hover during flight at very low altitudes. Unfortunately typical helicopter theory, especially related to low altitude hover, does not entirely apply to the HPH because rotor shape and operational RPM are so drastically different. The HPH relies on rotors that resemble rotating conventional aircraft wings with longer chord, greater camber and twist, and operate at much slower RPM than conventional helicopter rotors. Because the majority of publicly available data relates to traditional helicopter analysis, there is a considerable absence of published experimental data needed to make critical design decisions for an HPH. Therefore, the experiments performed by the Cal Poly HPH Team were done to simulate possible HPH rotor configurations and situations in order to better understand the dynamics of HPH flight.

C. Ground Effect

In studying the past HPH designs, our team realized that the most obvious problem is overcoming the limitations of human power. The best attempt at fighting this was Naito’s Yuri I, a craft that utilized ground effect by running rotors very close to the ground. The success of the Yuri inspired us to study Dr. Naito’s research, and try to understand what made his helicopter so successful. After reviewing Dr. Naito’s research, we identified our areas of work. We came to understand ground effect (GE) as an increase in blade efficiency for rotors operated at less than one radius above the ground. The improved efficiency, or lift to drag ratio, is due to two things:

1. Reduced downward velocity of induced airflow, leading to:
   a. Less induced drag and a more vertical lift vector
   b. Decreased pitch angle and less power needed for hover
2. Reduced tip vortices, resulting in:
   a. Improved efficiency of outboard portion of blade
   b. Reduced system turbulence from ingestion of recirculating vortex swirls

As a result of low altitude hover, the downwash from the wing or rotor blade is deflected by the ground. This deflection reduces the vortices on the tips of the wings and rotors. Because these vortices cause a slight downward and backward drag force on the lifting surface, their depletion allows increases in lift. In a helicopter, this lift is being achieved by power applied to a rotor. Therefore, ground effect should theoretically allow for increased thrust (or lift) from the rotor without a corresponding increase in power input. Ground effect is especially noticeable in the HPHs that have actually flown. The Da Vinci III, Yuri I and Gamera were only able to fly in deep ground effect; in fact the Yuri and the Gamera rotors were only inches above the ground. The Da Vinci rotors were over four feet high, but the rotor length was very large. Ground effect’s influence on HPHs is undeniable, and better designs for HPHs can be achieved by understanding this phenomenon. In Figure 1 below, the in-ground-effect rotor on the left has smaller tip vortices and decreased pitch angle than the rotor out of ground effect seen on the right. The benefits of GE begin around one rotor radius above ground, and then increase exponentially the lower the rotors fly. To reap the greatest benefits, our HPH should fly as close to the ground as possible.

![Figure 1. Comparison of tip vortices in relation to height above ground.](image)

D. Intermeshing Rotors
The Yuri I had four rotors, and was the most stable and successful flying HPH. However, the large structure needed to keep the four rotors from colliding with each other had to be made very, very light. This meant the structure was not very robust and collapsed after a minor impact between rotors. If the structure size requirements could be reduced, the remaining structure could be made much more robust and could withstand forces from a control system, without an increase in craft weight (compared to previously flown helicopters). In addition, if the rotors could be brought together, it would also decrease the amount of material in the drivetrain as well as reduce complexity and weight. To accomplish this, the rotor blades would have to intermesh or spin inside of each other like gears that do not touch, otherwise obvious disaster would occur. The question is then whether a drive train could be designed to ensure that the rotor blades don’t hit and if intermeshing rotors come with any thrust or instability penalties that would have to be considered before using them on a full size helicopter.
II. Project Objectives

Though going for the prize and attempting to get a full scale aircraft off the ground is very enticing, simply considering the nine years it took to loft Da Vinci III indicates attempting full scale flight in our one year time frame would be foolish. Ultimately the goal, not just for our team but for the HPH project at Cal Poly, is to bring home the Sikorsky Prize to our university. For this to happen, we know it is critical we understand as much as possible about HPH dynamics and accumulate the data into a pool of knowledge that future teams can use. Though the results may seem less glorifying, we aim to be part of a bigger success and help lead the way to the prize. We must finish this year by answering questions that have yet to be understood and leave the next team with a clear starting point from which to continue.

The key reason for the success of Yuri I was the research of project leader Professor Naito who followed up a series of full-size vehicle failures with testing of scale models to build a new helicopter. In the course of this research, he decided on the final configuration of the Yuri based on its low power requirements and its inherent stability. This example inspired the efforts of this year’s Cal Poly team that decided to test various aspects of HPH dynamics to determine an optimum design for an HPH.

For Fall Quarter, our design objectives changed continuously while we researched, but eventually became clear and specific. At first, our goal was to rapid prototype several small scale helicopter rotors that we could test for thrust characteristics in a fixture similar to that used by Dr. Naito. After narrowing our goals to building a working control system and learning the influences of ground effect, we decided to pursue much larger scale models that could be configured in different ways. This flexibility in design allows us to fully quantify the impact ground effect has on different rotorcraft. Thus, large foam airfoils were cut and used in place of the much smaller sized plastic rapid prototype models.

By the end of Fall Quarter we had gathered a set of low speed ground effect data, which led to several objectives for Winter Quarter. First was to re-confirm the results of our tests from Fall Quarter using our single rotor test system at higher RPM and documenting the results in a formal report. The next goal was to determine the effects of intermeshing two rotor blades and create a drive system that could keep the two rotors synchronized.

Following suit, goals for Spring Quarter were determined at the end of Winter Quarter. As the intermeshing tests were cut short by a test malfunction and two destroyed rotors (discussed later in the Intermeshing Rotors section of this report), our first and immediate goal was to finish testing both rotor configurations and perform the data analysis needed for future reports. Additionally, our second goal was to design and build a scale autonomous model that can function as a proof of concept for the research conducted in prior quarters, and serve as a platform for demonstrating a control system. At the end of the school year, we have three quantifiable outcomes: research describing the influence of ground effect on low RPM rotorcraft, the benefits and disadvantages of intermeshing HPH rotors, and a flyable scale model to test control systems and craft stability.

In future quarters, following HPH teams will have all our test data, reports, suggestions, and a flying model at their disposal. This information will hopefully serve as a basis for continued research. This team, or teams following, can then start constructing the full size helicopter that will lead Cal Poly to winning the Sikorsky Prize.
III. Project Risks

The greatest risk in attempting any new feat is failure. In the case of the Cal Poly Human Powered Helicopter team, the ultimate failure would be not making progress towards obtaining the Sikorsky Prize. However, it should be noted that even our mistakes can be used as learning tools for future teams. We feel the greatest immediate risk to Cal Poly’s success would be failing to pass on what we learned over the past year to future Cal Poly Human Powered Helicopter teams.

Our team is fortunate in that the research and design completed this year can be passed on to future Cal Poly teams to ensure the lessons learned and hard work accomplished are not lost. Many of the students on our team will be graduating at the end of the year and therefore the knowledge and experience gained may not be readily available to future teams. We plan to do all that we can to pass this information on, but inevitably some of the minor details will be lost year to year.

Additional risks lie in what we would like to accomplish by the end of the year. The current plan for this year has us designing, building, and testing a scale model of an HPH design that can sustain controlled hover for one minute. While constructing such a model was achieved - and a control system tested - whether the model and control system will accurately scale to full size is another matter entirely. Although dimensional analysis was performed to ensure a consistent Reynolds number between the full scale and model helicopter, the scalability of HPH models has proved extremely difficult for other teams in the past. Therefore, the design for a scaled control system presents a large risk of not actually working on a full scale HPH.

There are also risks of failure due to equipment issues. For example, we obtained initial data with the double rotor test structure in the form of very large thrust measurements. However, in the middle of these tests, the battery in the scale died. When we obtained a new battery and ran another test, our results were much lower than originally obtained. After running several other tests at the same height, we realized that the scale becomes extremely inaccurate when the battery is low. This is something to note with any of our equipment, as it can be inaccurate without our knowing about it.

In the actual building process of the scale model, there were many risks that make the project bog down. The biggest risk – in terms of deadlines - has been obtaining materials. Delays in obtaining materials occur frequently and have high impact on our progress. When a test stand was required to perform intermeshing testing (discussed in the Intermeshing Rotors section of this report) several delays were encountered. After agreeing on the aluminum box frame structure for the boom, we were required to wait several weeks for delivery. In a similar fashion, unexpected long lead times on things as simple as the blue EPS foam used to make model rotors set us back again. The best way to prevent such delays would be to predict how much of certain materials will be required and then preorder them. This seems fairly obvious, but there are times when rushing to get things done will clutter foresight and by the time someone needs materials, they won’t be able to get them. Spend some time really thinking ahead to what may be needed to accomplish your goals. There is the risk of ordering unnecessary and excessive materials, but this is a reasonable risk when the time lost due to not having those materials is eliminated.

We feel that by writing this document and having several members available for next year’s team to work with, we have minimized both our immediate and long term risk of not passing on the valuable lessons we learned this year. We have been exceedingly fortunate in avoiding massive disasters on our project and in having a great team dynamic to work with. We wish next year’s team, and all future Cal Poly HPH teams, the best of luck and feel the rewards of success far outweigh the risk of failure.
IV. Testing procedure

The procedure for acquiring data across all testing platforms is very similar. The first step before the rotor(s) was connected to the boom arm is to set the angle of attack of the rotor blades to the desired pitch. This was accomplished by the use of a wooden jig that was designed to have a negative profile of the airfoil on one side and flat on the other. The negatives left over from the hotwire airfoil cutting were saved and substituted for the wooden jig when the switch to Eppler 399 airfoils was made (discussed later). When the jig was mated with the top of the airfoil, an inclinometer was used on the flat surface of the jig to measure the desired angle. The rotor assembly was then attached to the motor output shaft via set screw.

The test fixture was located in a large clear space so that there was no risk of the rotor blades impacting anything, and the air flow could be allowed to circulate around the rotor properly. A power source (an Agilent Technologies N5747A rack mount unit and later a Mastech HY3030EX) was connected to the motor via wires that ran along the length of the boom arm, and the fulcrum axle was adjusted to the desired height. The hanging scale was attached to the back end of the cantilever arm. The power source that was used could display the voltage and the current for simple calculation of power input. The fulcrum was adjusted to the desired height for testing (see Figure 2 below).

![Figure 2: Twin blade single rotor model attached to test stand and boom arm.](image)

The motor was turned on and run up to the appropriate voltage and current. Determining the rotation speed was also relatively simple by using an Extech optical tachometer to measure the RPM of the rotor blades. When the motor was running steady, the force scale was zeroed and the motor was shut off. The difference in force measured by the scale was recorded as the lift produced by the rotor with the mechanical advantage of the cantilever arm. After each test, the boom was raised a few inches and tested again. These points were recorded and analyzed later for better understanding ground effect.
V. Ground Effect Testing: Single Rotor at Low RPM

At the start of Fall Quarter, our focus was tuned to finding a way to choose the best rotor configuration for a human powered helicopter. In pursuit of this goal, several questions arose: if the lift to power ratio increased exponentially as height is decreased, where is the ideal height that balances GE efficiency gains with constructing a feasible and controllable aircraft? What rotor configuration and number of blades is best in GE? To answer these questions we sought empirical data on low flying rotors. Unfortunately there is very little data on such rotors, as all conventional helicopters require an engine, transmission, cockpit, and skids to attach below the rotor. These constraints eliminated the need for engineers to study GE below a half rotor radius above ground; actual flight below that height did not physically occur. Though some HPH teams have collected some data on the matter, we did not have access to it nor confidence in the numbers we had seen, so we set out to gather our own.

A. Apparatus Overview

After some brainstorming, we narrowed down a general plan to construct several scaled model rotors and run them with an electric motor at various heights. In order to measure the lift at the rotor hub without interference from the rotor blades, a cantilevered test fixture was constructed to suspend the rotor so that the motor was mounted at the longer side of the boom arm and counter weights were hung from the shorter side. The aluminum boom arm was mounted on a shaft with bearings at the fulcrum and supported by a variable height structure. A digital scale was connected above the boom at the end opposite the rotor to measure the lift force created at the rotor hub. Thrust was determined by multiplying the scale reading by the mechanical advantage of the boom.

B. Adjustable Stand and Cantilever Boom

Using readily available materials, the boom arm was constructed from eight foot lengths of 1/8 inch aluminum bar stock and fastened with blind rivets. The initial boom required several revisions, adding stiffness to resist bending under the model weight, and torsion created from slight imbalances while spinning the model. The wooden frame that suspends the boom arm contains a fulcrum with a ½ in. steel axle was designed to allow ground effect testing at heights from 2.25 inches above the ground to 4 feet above the ground (see Figure 3 below). The height was extended to 8 feet by placing the test structure on a 4 foot solid surface.

Figure 3. Profile sketch of the test stand and boom arm.

C. Rotor and Hub Design

Initially it seemed that rapid prototyping was the best method for producing many blades, as it was fast, sophisticated, easy, and machines were available to us. After preparing airfoil models for the machines, we discovered this method would be too expensive and would greatly limit the size of our models. With the prototyping machines on campus offering lengths of less than a foot, we would either have very small models or a complicated
design to connect the blades in pieces. Very small models would also become dangerously thin, likely leading to fragile rotor blades not ideal for high speed testing.

In order to increase our model size we decided to construct each wing from a solid foam airfoil, a hollow cylindrical carbon spar, and Monokote, a low-drag thin sheet covering. With the help of the Design Build Fly team at Cal Poly, we learned how to cut airfoils using a CNC hot wire foam cutter. The foam rotor blades were to be cut from a block of 4 foot by 1 foot by 1 inch solid blue aero-foam with a 5 foot by 5 foot CNC hot wire cutter (seen in Figure 4 below). We decided on four foot lengths for the blades because our foam stock was available in this size, which happened to be just under the limits of the hot wire cutter.

![CNC hotwire machine used for cutting all airfoils.](image)

From the direction of an aerospace graduate student who previously worked on the HPH blade design, we chose a symmetrical airfoil, NACA 0009, since it would allow us to run the rotor with no pitch angle, creating no lift, and determine the power requirements for a no-lift condition. The no-lift power, or power to overcome profile drag of the rotors, is an important value used in interpreting the results we planned to obtain. The NACA 0009 symmetric airfoil with an 8.5” chord was programmed from a text file. The foam was set in a secure level position and the wire start position was calibrated by visual estimation. The wire was run at 25 Volts and 5 to 6 inches per minute. The wire speed and temperature were tuned such that the foam would not excessively melt if the wire moved too slowly, and such that the wire would not bend if the temperature was too low. The airfoil text file was modified to include a 0.42 inch diameter hole for the spar shaft along the length of the blade, located at one third of the chord length from the leading edge. Through some practice we managed to cut several well shaped rotors (see Figure 5 below).
Carbon fiber arrow shafts (.42 in diam.) were selected for tube spars. As the available shafts were less than four feet long, each spar was made of two shafts connected with three inch aluminum rods and an epoxy bond. The spars were cut to length and then bonded into the cutout channels of the blades. Next the blades were sanded and covered with MonoKote heat shrink wrap for a smooth finish (Figure 6) with a 1 to 2 inch overlap allowance. A small iron was used to seal the covering to the wing by tacking the middle, then corners, then smoothing out the wrinkles.

Once covered, the rotors were connected to a precisely machined aluminum hub, donated by Muller Machine. The hub uses eight pinch bolts to allow independent pitch adjustment of each rotor and a set screw to attach the motor shaft (see Figure 7 below). The blade pitch angle was set using a wooden jig that contours the shape of the airfoil on one side, and is parallel to the airfoil center line (chord) on the other. Placing an inclinometer on the flat, parallel side of the jig allowed for measuring pitch. The rotor was assembled from two wings and the hub. The wings were balanced using a typical model helicopter balancing procedure where small strips of electrical tape were laid in layers on the inside top surface of one wing to make the Center of Gravity (CG) radius the same length for both
individual wings. Then, the assembled two-blade rotor had lead weights inserted into one of the airfoils at its CG to make the complete rotor balanced longitudinally.

Figure 7. Rotor hub allows for independent pitch adjustment.

With a complete twin blade rotor assembly (see Figure 8), we next tackled the task of powering the model so that we could measure the critical parameters. Several motors were purchased based on scaling analysis of Da Vinci III rotor speeds, power, and size. Though scaling precisely to an actual HPH was not critical to our ground effect testing, it provided a starting point and led to gear reduced motors with speeds of 50 to 300 rpm. With a power input of less than 9 Watts, these motors (see Figure 9) did not have nearly enough power to spin the mass of the rotor at their maximum speeds. All of our test data was collected using the 24V, 300 rpm motor which operated at no more than 60 rpms under load.

Figure 8. The test stand allowed for collecting lift data in very deep ground effect.
Figure 9. Twenty-four volt, 300 rpm electric motor mounted at boom tip, attached to rotor hub.

Aiming to collect data from a height definitely out of GE down to the lowest we could run the blades without dragging on the floor, measurements were taken from heights above six feet all the way to the ground. Throughout each test, the thrust was measured at the same power input, 8.16 Watts. The angular speed was consistent at 54 rpm, and the blade pitch angle was set at about five degrees. It was important for balancing the rotor that the pitch angle was the same on each blade, but the actual angle was somewhat arbitrary as it would remain constant throughout the testing.

D. Successes
Our first tests with the single rotor were a complete success. There were very few problems with the boom and testing procedure, and the ones that did occur were easily fixed. First, we had issues with the scale turning off at inopportune moments during testing, but a change in operating procedure rid us of the problem altogether. In addition, the boom as built was very susceptible to torsion, but we were able to reduce this by adding more bracing to the structure. As soon as these problems were fixed, we started to collect data. This provided a good basis on which we founded our other research.
E. Low RPM Test Data

Table 1: Original boom single rotor test data sample

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VI. Ground Effect Testing: Single Rotor at High RPM

To verify our test results from the single rotor boom, we decided to test the rotor blades at higher RPM. By utilizing the existing stand and structure we felt it would be very easy to re-test under different conditions. However, we soon encountered many issues that prevented the next round of tests from being performed.

A. Issues with Higher RPM Tests
First we had to find a motor that could turn the rotor blades faster. Our original motor could not spin the blades as fast as we wanted, upwards of 200 RPM. Our options were to either change the gearing on the motor or locate a new motor. Trying to limit costs and avoid lead time on a new motor shipment, we sought out more readily available sources.

Next, at higher speeds, the rotor blades became very unstable, coned (bent upward lengthwise) excessively, and almost hit the test boom several times. Some of these difficulties arose because the blade’s single carbon tube spars were not nearly stiff enough. Additionally, when we built our first rotor blades we had incorrectly placed the spar around the third chord position (spare location is 1/3 of the chord length from the leading edge), which contributed to blade instability because it was not located at the aerodynamic center. When the spar is located at the aerodynamic center, the pitching moment does not change with the angle of attack. At most points on the airfoil the moments are dependent on angle of attack and a small deviation away from the aerodynamic center can cause a pitching moment that is intensified at higher angles of attack. The unstable moments can cause a flow induced ‘flutter’ that forces the blade to alternatively shed a turbulent vortex on top and then on bottom of the airfoil, changing the lift force produced. When the lift force varies as the rotor spins the wingtip bounces up and down like a wave; this phenomenon is called ‘galloping flutter’. The flutter effect can be reduced by proper location of the spar. The most stable place for the spar is at the quarter chord, the aerodynamic center for symmetrical airfoils. There the moments on the airfoil are independent of angle of attack, so a minor change won’t cause large disturbances in the rotor blades.

Finally, we encountered numerous problems with the boom. The boom we originally constructed had been rapidly assembled with aluminum and rivets and had not been built for large loads. This worked for the small motor we used for our initial tests, but it could not take a heavier motor and faster rotor blades. The structure would wobble, especially when the blade RPM matched the natural frequency of the boom, which prevented us from taking accurate measurements.

B. Solutions to High RPM Problems
Each of these problems had a unique solution; first for the motor, after a little experimentation, we found that we could easily mount our rotor to an AC variable speed power drill and turn the rotor fast enough (see Figure 10 below). The power drill could raise the RPM of the rotor tremendously, so we modified it to operate from a controllable power source and interface with the boom mount. However, this installation had problems of its own, mostly with regulating the current and the voltage. The permanent solution was to modify our planned boom design for the next series of tests to be compatible with a single rotor configuration.
To fix the boom instability we built a new boom that was more rigid and resisted the torsional instabilities that the previous aluminum boom encountered. Using the dimensions of our first stand, we constructed a second single rotor boom from one inch boxed steel (see Figure 11 below). This boom was far more robust than the first one and could accommodate the more powerful motor. Later, when we built our intermeshing test fixture, we removed the mount for one of the rotors used it to test single blades in ground effect. However, our tests with the old boom and drill motor were not wasted because our experiments brought to surface problems that had escaped our notice during our initial tests and enabled us to make corrections.
The biggest improvement was made to the airfoils. To make our future rotor blades stiffer and more stable, we shifted the spar to the quarter chord and added a second spar for structural support located slightly behind the main spar about which the airfoil will rotate for setting angle of attack (see Figure 12 below). In comparison tests with single spar rotors, the double spar rotors coned significantly less. The new blades were applicable to any future test we could do and we started producing them exclusively.

Figure 12. Airfoil comparison – single versus double spar.
C. High RPM Test Data

Our Data was almost the same as the data we collected the previous quarter. This was very significant as we were using a different fixture, motor, and rotor blades, yet the results were the same. This implies that no matter the configuration, ground effect will have the same influence, and offer similar benefits.

Table 2. Improved boom, single rotor test data sample

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VII. Ground Effect Data Analysis

In theory, the same power input to the electric motor should result in the same rotational rate for the rotor, everything else being held constant. This was verified using a digital laser tachometer and found to be the case. Once the rotor reached a steady state, the thrust of the rotor was measured using the digital force scale. This was repeated many times at various heights above the ground. The results of the testing showed that large increases in thrust can be seen at very low heights above the ground, as much as 150% (see Figure 13 below).

![Figure 13. Thrust increase versus normalized height above ground.](image)

For comparison of the results of this experiment to theoretical models by Hayden, Free-Vortex theory, Knight, and Cooke, a common parameter for ground effect called the ground effect coefficient \(K_p\) was calculated. The ground effect coefficient relates the thrust, induced power and profile power such that,

\[ K_p = \frac{\text{Thrust} - \text{Profile Power}}{\text{Induced Power}} \]  

where the thrust was measured directly with a hanging scale at the back end of the boom (as seen in Figure 14 below), the profile power was determined by running the experiment with the rotors set at zero angle of attack \((\alpha = 0)\) so no lift was produced but the power required to run the fixture could be measured. The Induced Power was determined by setting the ground effect factor \((K_p)\) equal to one, where in theoretical models \(K_p\) converges, representing out of ground effect (OGE) operation. Once determined, the Induced Power was applied as a constant in the analysis, as well as the Profile Power. For in ground effect (IGE), \(K_p\) is variable and directly related to the
measured thrust. The power was measured in watts and the thrust measured in pounds. Because the major benefit of ground effect is increased rotor efficiency, the coefficient tells how much less power will be required for a given amount of thrust.

![Figure 14. Hanging scale for thrust measurement.](image)

The test with the rotor blades made it abundantly clear that ground effect plays a role in helicopter flight, especially for human powered helicopters. The increased thrust at low altitudes has no doubt kept the few flying HPH’s off the ground, but the rapid decrease in thrust when climbing indicates that a HPH trying to achieve 3 meters (where the rotor will be much higher off the ground) will prove to be very difficult.

Ground Effect means that it will be much easier, in fact beneficial, for the HPH to remain at low altitude throughout its flight where less power will be required. This explains how a helicopter like Yuri I was able to fly for a significant length of time. With this knowledge, accomplishing a 60 second flight seems possible. The only remaining obstacle is to climb above 3 meters. An ideal flight plan to win the Sikorsky Prize would be to hover deep in ground effect for most of the flight until the end, when the pilot makes a single determined effort to climb above 3 meters.

However, the rapid loss of ground effect benefits when gaining altitude presents a daunting challenge. The next step is to research how ground effect’s advantage can be extended. This can be done using different rotor blades, appropriately positioning the rotor and possibly by manipulating ground effect to give a spurt to fly above 3 meters.

Other tests that could be done include using cambered airfoils and blades with twist or taper to determine how or if ground effect changes.
Figure 15. Comparison of ground effects data for 50 RPM (Fall data) and 150 RPM (Winter data) rotor test speeds.

Figure 15 seen above shows the original ground effects testing data and an additional curve for rotor tests conducted at a higher rotational speed. The shape of the ground effects curve was found to be very much the same as that found from initial testing, with the only exception being that at very low heights above the ground the higher speed data shows a larger increase in thrust produced. This result is consistent with initial expectations for the high speed testing, due to the fact that larger vortices are produced from the tips of the rotor and ground effect can lessen the aerodynamic disadvantages associated with these.
A slightly more physical representation of the increases in lift as a function of both RPM and height off the ground can be seen in the surface plot below (Figure 16). This plot clearly shows maximum lift can be obtained by spinning the rotor as fast and as close to the ground as possible. The tapered edges show the interesting characteristics of ground effect. Based on the data, these tapered edges imply the same amount of lift is generated at low RPM close to the ground as when spinning three times as fast high above the ground. As it takes much more power to produce the same amount of lift at high elevations, this further supports the theory that ground effect is a very critical element that needs to be utilized as much as possible.

![Surface Plot of Thrust as a Function of RPM, Height. Full Quadratic](image)

**Figure 16.** Surface plot of thrust as a function of both RPM and height above ground.
VIII. Intermeshing Rotors

In order to support two rotors, for the purpose of intermeshing, another test stand and support structure needed to be built. These new fixtures needed to be robust and versatile, as they will be used in repeated testing and eventually passed on to the next HPH group.

A. Design

Going in, we had several requirements for our new test fixture. First, we wanted the new test fixture to use as much of the original as possible in order to reduce construction time. Next, the intermeshing system had to be easily modified so testing could go faster and smoother between cycles. Finally, the structure had to be strong, stiff, and stable so we could collect reliable data.

The basic boom design holds two rotors on a long rail out front. The rotor mounts slide across the front rail to adjust the percentage the rotors are intermeshed. This front rail is fixed to two parallel rails mounted on bearings sized to accept a ½ inch steel shaft. The wooden frame constructed for the single rotor tests was widened to fit the considerable larger boom assembly and fulcrum shaft. Lastly, two multi-functional members were fixed perpendicular to the outer rails to give structural support and solid mounting locations for the motor and drive train components. The entire boom and fixture assembly can be seen in Figure 17 below.

Figure 17. Two rotor boxed aluminum boom and structure. The rail closest to the front of the boom will hold both rotors and the middle two rails will support the motor and drivetrain components.
To intermesh two rotors at high speed, the rotation must be closely synchronized to prevent collision. A drivetrain was designed to turn the rotors with the correct timing and in opposite directions. The system needed to achieve high speed rotation, maintain a constant phase difference between rotors, adjust to various rotor spacing configurations, and adapt to single or multiple rotor systems. Additionally, other motors or gear/sprocket combinations should be easily added into the system. To localize weight near the fulcrum and allow for sliding adjustability, a chain drive was selected to transmit power to the rotors. To reverse the rotor rotation, two nylon gears were selected to mesh at the drive sprockets. ANSI #25 chain was used for its small size and smaller pitch. 1/2 inch shafts were chosen to provide stiff power transmission to the rotors. Open caged ball bearings were pressed into the aluminum bearing mounts for tight and low friction movement. The motor was selected because of its high power output of 1/7 hp with a speed ratio of 1:16 to attain 300 rpm (see Figure 18 and Figure 19 for drivetrain components and detail). It is useful to note that any CNC and manual machine operations were performed in on-campus student facilities.

Figure 18. Drivetrain detail – note the nylon gears near the bottom of the photo.
This system was very flexible and allowed us to mesh the two rotors in and out without affecting the synchronization. In addition, to test our single rotor we removed the other blade, disconnected its gearbox, and ran the test fixture. This modification was simple and easy to do, meaning that we did not have to substitute the two booms we built, which would have been time consuming and difficult.

As this entire structure utilized many different and sometimes hard to acquire parts, it was very important to give ourselves plenty of leeway when ordering each individual component.

B. Construction

The boom itself was constructed from several box aluminum girders (see Figure 20 below). These were held together with a large number of plates, angle brackets and screws. We reused the stand from the first test fixture, although we widened it to accommodate the new boom. We also made changes to the mount for the force scale, and later added Kevlar thread to brace the boom and the stand.
C. Issues and Considerations
The boom construction went forward quite smoothly with the exception of a few small issues. The first issue we had to address was fixing the bugs in the drive train. When we built the boom and turned it on for the first time, we found that the rotor blades were not synchronized and would have hit each other after a few rotations. It turned out that the shafts were slipping inside their mounts. To ensure the rotor blades did not slip, we milled flats onto the shafts for set screws to secure them into place.

Our next issue was trying to adjust and balance the fixture as the new twin rotor boom was much heavier than our previous single rotor stand. To fix this problem, we added counter weights to the rear of the structure until the oscillations diminished at operating speed.

Our last issue would cripple our structure and end our tests for winter quarter. We had mounted the force scale with Kevlar thread which was adjusted in length for each test and clamped in place. During testing, the clamp released and allowed the unsupported boom to fall back towards the ground directly onto the rotors. One rotor hit and broke the spars between the hub and root of the blades. This ended our testing until new rotors could be constructed. To ensure this doesn’t reoccur, a new stand was created to hold the test boom with a load cell attached to a threaded rod (Figure 21). This setup was more rigid and allowed for more detailed and accurate data collection. Additionally, the load cell offered the added benefit of easy calibration. Now the thrust read was the actual amount created by the rotors, already adjusted for the mechanical advantage of the boom. LabJack DAQ software was used to collect lift values.

Figure 21. A revised steel test stand offered more rigidity and precise height adjustments through a linked set of lead screws, and an Omega S-type tensile load cell allowed for accurate data collection.
D. Data and Analysis

Table 3. Improved boom, twin rotor, no intermeshing test data

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Table 4. Improved boom, twin rotor, intermeshing test data

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*Blades destroyed when contact was made with the ground
Table 5. Eppler 399 cambered airfoil intermeshing test data

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<td>192.1</td>
<td>96.05</td>
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To calculate the percentage of rotor intermesh, the length of blade overlap was divided by the distance between hubs such that,

\[
\% \text{ intermesh} = \frac{\text{rotor length} \times 2 - \text{hub to hub distance}}{\text{hub to hub distance}} \times 100 \, .
\] (2)

for many different intermeshing percentages (see Tables 3-5). Unfortunately, the test fixture malfunctioned during the test of full intermesh, or 65 %, but complete data was collected for two rotors with no intermesh. After building a new, better test stand the testing was continued. The test blades were changed to those that were eventually going to be used on the flying model, the Eppler 399 with 0.85 carbon spars. More information on the design and construction of these rotors is located in the Flying Scale Model section of this report. The testing results can be seen in Figure 22 below and the data collected in Table 5 above.
Figure 22. Thrust variance for different percentages of intermeshing and various normalized height ratios.

The trend in the above figure shows a decrease in thrust as two rotors are intermeshed, and the decrease is consistent regardless of the rotor’s height above the ground. However, closer examination of the trend shows that the percent decrease in thrust from completely separated to completely intermeshed was very small (see Tables 6 and 7). This indicates that the intermeshing of the rotor blades doesn’t significantly decrease the thrust the blades produce. The implication of this effect is very important to the design of a quad rotor HPH: by moving the blades closer to the center of the structure the amount of material and weight decreases significantly and structural stiffness is increased. At the same time, the rotor diameter and disk area is held constant without any significant loss in lift. The big takeaway here: intermesh the blades to save weight and increase stiffness.

Table 6. Intermeshing thrust loss at 16.25in height

<table>
<thead>
<tr>
<th>% Intermesh (%)</th>
<th>Ave Thrust (lbf)</th>
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<tr>
<td>79.08</td>
<td>10.94</td>
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<tr>
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<td>12.93</td>
<td>11.88</td>
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<td>2.39</td>
<td>11.2</td>
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</table>

Percent Difference: **2.30%**

Table 7. Intermeshing thrust loss at 11.25in height

<table>
<thead>
<tr>
<th>% Intermesh (%)</th>
<th>Ave Thrust (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.41</td>
<td>12.48</td>
</tr>
<tr>
<td>28.53</td>
<td>12.24</td>
</tr>
<tr>
<td>1.42</td>
<td>13.08</td>
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Percent Difference: **4.60%**
IX. Flying Scale Model

A. Goal
The ultimate goal for this year was to design and build a scale HPH model that would serve as a test-bed for various methods of control. In addition, we wanted the helicopter model to be able to sustain flight for at least 60 seconds in order to more accurately compare its flight characteristics to full scale Human Powered Helicopters. Keeping these goals in mind, we set out to design a model that would take advantage of the information we had gained through our ground effect testing and our intermeshing testing.

B. New Airfoil and Spar Design
The first step in designing an effective scale model was to select and build new airfoils that would produce more lift, more efficiently for our slow rotational speeds. Recall that the previous testing airfoils we used were NACA 0009 symmetrical airfoils with a 9% maximum thickness. While these worked well for testing ground effect and allowed us to easily measure the profile power required for rotation, a more appropriate cambered airfoil was now needed. After some research on available human powered vehicle airfoils, the Eppler 399 was selected for its highly cambered shape, 14.8% thickness and the fact that it matched our speed range well. The length of the blades was left unchanged (due to size limitations on the foam wire cutter) as was the chord.

One problem with the much thinner NACA 0009 airfoils was that space for a spar was limited. This meant that it was necessary to use a small diameter (0.42 in OD) carbon arrow shaft as the main structural member in the wing. At higher speeds (greater than 60 RPM) a significant amount of coning at the tips of the rotor blades was observed. To remedy this situation a second spar of the same outside diameter was added to the airfoils. While this worked ok, a better solution was needed for a stable flying model. The much thicker airfoils allowed for a spar up to 0.85 in OD which would help to eliminate blade coning (due to the larger cross-sectional moment of inertia). In order to save time and money, 5 foot carbon fiber unidirectional tubes were made in house at Cal Poly. For more information on the design, construction and testing of the unidirectional carbon tubes used in this project see Independent Research: Composite Spar Manufacturing for use on the Human Powered Helicopter.

Figure 23. 0.85 in OD unidirectional carbon fiber rotor blade spars.
C. Airframe Design

After new airfoils had been sized and selected for use in further intermeshing testing and on the scale model, a frame needed to be designed to hold the rotor(s). Based upon previous research and other Human Powered Helicopter designs, we decided that a four rotor architecture would offer the most stability and give us the best opportunity to fit a functioning control system. As previously stated, taking maximum advantage of ground effect and blade intermeshing was of high importance due to the research findings from previous quarters. With this in mind, a solid model was created of the proposed structure and sized to allow a high degree of intermeshing (see Figure 24 below).

![Figure 24. Solid model of quad rotor, intermeshing helicopter design and proposed control surfaces.](image)

The model was important for determining an appropriate size for the actual structure to be built, but other than that not much time was spent using it. After a size was chosen, a manufacturing method was selected. It was clear from the very beginning that the support structure needed to be very light and very stiff to ensure that our rotor blades could produce enough thrust to carry it aloft. For this reason carbon fiber was selected as a building material. A large amount of dry (containing no resin) woven carbon fiber cloth was donated to the team and this cut the cost of producing such a structure significantly. The largest expense in creating the structure was the purchase of room temperature cure epoxy called the West System (sourced from Aircraft Spruce).
To make the structure stiff (particularly the arms in bending and torsion) a core material was required to increase the cross-sectional moment of inertia without using many layers of carbon fiber. The same blue EPS foam that was used to create the rotor blades was incorporated as a core material due to its availability and the fact that we still had a large amount on hand. Honeycomb core was also considered, but the thickness required was not on hand and achieving a good surface finish over the porous material would have proven more difficult. The blue EPS was cut into four, 3in high x 1.5in wide x 60in long sections to form the “arms” of the structure (see Figure 25 below).

![Figure 25. Foam arms being test fit with the rotors.](image)

The foam offered the additional benefit of acting as a “tool” to form the carbon over. Long strips of cloth were laid so that the fibers were oriented along the length of the arm (0° direction) and perpendicular to the length (90° direction). This was done on the top and the bottom of the beam to provide bending strength/stiffness. Torsional strength and stiffness was achieved through a single large piece of carbon cut so that the fibers were oriented at ±45° angles and wrapped around the entire beam so that only one seam can be seen on the bottom of the arm. It is important to note that the above “lay-up” was performed all at the same time, rather than allowing the West System epoxy to cure after each layer was applied. Epoxy was placed on the dry carbon and then evenly distributed as best as possible. 0.010in thick high-gloss plastic was used as a backing to the carbon fiber as it dried. This material will not bond to the carbon fiber and easily pulled away after the part cures, leaving an excellent surface finish. The plastic was worked with a squeegee to remove bubbles trapped in the carbon. The backing also allowed the arms to be encapsulated by four pieces of steel (caul plates) which were then wrapped with heat shrink tape to apply pressure to the arm. This ensured that no bubbles/imperfections were present in the final structure and an excellent strength-to-weight ratio could be achieved (see Figures 26 and 27 below).
Figure 26. Caul plate installation.

Figure 27. Caul plates with cured carbon fiber arm inside.
Once the arms were built they needed to have bearings assembled into the ends for the rotor blades to spin in. A large hole was cut in the top and bottom surfaces of the carbon of each arm, 1.25in from the end. This hole was then filled with two layers of carbon cloth that extended out of the hole and onto the top of the structure, while the remaining empty space within the hole was packed with resin and chopped carbon fiber. This ensured a strong support for the bearings and “tear-out” prevention (see Figure 28 below).

Figure 28. Bearing cutout hole prior to carbon fiber filler (top), ball bearing ready to be installed (bottom left) and reamed press fit hole for the bearing.

Curved shear webs were created to give a large structural surface in the middle of the helicopter to mount control systems, batteries, an electric motor, landing structure, etc. (see Figure 29 below).

Figure 29. Carbon beams with foam shear webs glued in.
Once the foam base was all assembled and checked for all critical dimensions, the foam was bonded using 5 minute epoxy. A single layer of carbon fiber cloth cut on the ±45° was placed around the edges of the shear web, four total (one for each edge) and pressure was applied using the foam shear web negatives and a significant amount of weight (see Figure 30 below).

![Image](image_url)

**Figure 30. ±45° plies after being cured around the edges of the shear webs.**

Finally, the top and bottom pieces of 0°-90° carbon were placed on the structure, wetted out and covered with plastic/weights. The completed fuselage measures just under 10ft diagonally (along the length of the arms), is extremely stiff and weighs in at just 7lbs.

### D. Drivetrain

The drivetrain for the flyable scale model was designed to be a both robust and lightweight. Due to the fact that the rotors on the model were going to be intermeshed, the drivetrain also needed to operate as a very reliable timing mechanism. To accomplish this, 3/8in wide rubber timing belts were chosen to transmit power to the rotors. The long lengths required for the belts made them difficult to find in closed loop form, therefore open belts were purchased and joined together to form the correct length. The process of joining the belts was particularly challenging. Several different types of epoxies, glues and RTV were tested, however all of these products proved to be too stiff to withstand the many revolutions over the timing pulleys. The solution was to cut a long diagonal at the point which the belts needed to be joined. A small amount of super glue was applied to hold the belt together for handling purposes and then the two halves of the joint were stitched together using 50lb breaking force Kevlar string. The string was knotted every few teeth so that there was redundancy built in (if one section of string broke, several others would still hold the belt until it could be fixed). See Figure 31 below.
Figure 31. Belt stitching on the top and bottom. Notice how the stitches on the bottom stay in each tooth and are pulling the two pieces of belt together.

Timing belts were chosen because they can maintain a phase difference between rotors while remaining lighter than a chain drive. Once they were cut to appropriate lengths and securely stitched, we then selected appropriate pulleys that matched the belt pitch and offered the gear reduction we desired. Four lightweight plastic timing pulleys were mounted on top of steel 5/16\textsuperscript{th} inch shafts that fit through the bearings and were fixed to each hub. These driven pulleys contain 44 teeth (see Figure 32 below).

Figure 32. 44 tooth final drive pulley at the end of a carbon arm
One of the most important design requirements of the scale model is all four rotors are to spin together, two counter-rotating to the other two. This is important to balance the torque driving the blades; otherwise the helicopter would have a tendency to spin wildly out of control. In order to accomplish this using a continuous drive, four belts had to be utilized, two of which were twisted once to reverse rotor direction. Using four belts meant that there had to be four drive pulleys mounted to the output shaft of the brushless DC motor that powered the system. As these driving pulleys were stacked, their corresponding driven pulleys had to be located at the same height directly opposite to ensure belt slippage didn’t occur. This was accomplished by firmly attaching the driven pulleys to the ends of the shaft with setscrews and utilizing plastic collars to prevent the shaft from slipping within the bearings. The drive pulleys chosen contained 15 teeth, for a drive ratio of 2.93:1 (see Figure 33).

Possibly the most crucial element in the scale drivetrain is the brushless DC motor powering the system. After more than two quarters testing, we understood the motor had to be capable of producing large amounts of torque at low RPM, while being robust enough to handle the current draw necessary to get the rotors moving. It was decided to use a Rimfire .32 outrunner brushless DC motor. This is a medium size motor designed for use with R/C aircraft. This motor was countersunk into the carbon and foam airframe so there was room for all four driving pulleys to be stacked above its surface. As this motor is designed for high RPM, continuous output situations a planetary gearbox was mated to the motor output shaft to greatly reduce the driving RPM. This was necessary to ensure correct rotor speed and to eliminate the gear teeth from slipping on the timing belts, which would cause the rotors to eventually collide. The planetary gearbox used was a small 6.7:1 reduction. This coupled with our final drive pulleys gave a total reduction of 19.6:1.

Once assembled, each successive belt was arranged 90 degrees relative to the one below it. This provided the drivetrain with an even dispersion of belt tension and prevented excess stress on any one part. To maintain tension across all belts, an adjustable idler pulley was added in line (see Figure 33 below).

Figure 33. 15 tooth central drive pulleys with belts installed.
Although this system could have worked well, several problems were encountered. First, the motor produced a significant amount of torque after adding the gearbox reduction. This was desirable (and incidentally it was required to spin such large rotors) however the belt tension required to prevent slippage with this system was very great. This presented problems with loading up the motor too much at start-up. Additionally, whenever belts come into play belt stretch is almost always an issue. This became especially problematic due to the fact that a true tensioning system (other than idler pulleys wedged in the belts) was not incorporated. For these reasons, among others, the drivetrain is being rebuilt using ANSI #25 chain and nylon drive sprockets. The chain is far more robust, will last longer, is cheap, will eliminate slippage and can be easily adjusted to any size. The negative side is that it weighs a small amount more and will be noisier. Noise is of little concern to us however and the helicopter blades/motor are capable of supplying many times more thrust than the weight of the craft (approximately 3:1 thrust-to-weight ratio). In the end this decision was an easy one to make, as it will increase the reliability and longevity of the model a great deal.

E. Control System

To determine what type of control system would best work on a full scale quad rotor HPH, many existing aircraft control systems were analyzed and considered. The 1980’s Cal Poly team experimented with radio controlled flaps at the tips of the DaVinci II rotor blades. According to Chad Frost, an active team member at the time, the flaps did affect the translation of the helicopter, but the lag in response after a control input was performed made guiding the helicopter in the desired direction too difficult. A computer controller could overcome this challenge, but would involve adding sensors, electric actuators, and a generator to power electronics – overall a great deal of undesirable complexity and added weight.

Also considered were swash plates and variable pitch rotor blades that are used by modern engine-powered helicopters, but soon abandoned for weight and complexity considerations. Reactionary force systems such as propulsion jets used on spacecraft were then considered, but deemed unusable as they would violate the energy storage rules outlined in the Sikorsky Prize.

The most feasible control systems were narrowed to either control surfaces/flaps or pilot weight shifting. Having the pilot shift his or her weight to counteract drift may work on a single rotor craft such as DaVinci, but would likely detract from the pilot’s ability to produce power. As the current direction for the team is to build a quad-rotor ground effect machine, a more inherently stable craft, shifting the pilot weight would seem ineffective in counteracting drift. This was illustrated in some of the Yuri I attempts, where the pilot was leaning out of the cockpit to counteract drift, but without success.

With all of these considerations, focus was directed towards a system of strategically placed control surfaces that could both generate reaction forces on the craft when properly angled, and redirect induced airflow in order to shift the lift distribution of the entire helicopter. Through some experimentation with holding wing sections below and above a spinning rotor on a test stand, it was determined that a vertical airfoil should be cantilevered over the area of intermesh in each quadrant. Doing so allows the control surface to see the greatest downward velocity, giving maximum control authority (see Figure 34 below).
By deflecting the control surface in one direction, additional air is funneled to one rotor thus increasing airflow through it, increasing lift and pitching the helicopter in the desired direction. With two control surfaces each in the x and y directions, the helicopter can theoretically translate in any direction by mixing the degree of control surface deflection in the x and y. The surfaces are placed symmetrically about the craft and linked to deflect the same amount for any level of input. This way the moments induced on the control surfaces are balanced about the center of the craft. With servo mixing available in the Radio Controller, the control surfaces can also be deflected in the opposite directions to create yaw control.

Placing the control surfaces below the rotors would allow for greater control authority as the induced airflow below has greater velocity than above. However, a below-the-rotors location would require the landing gear to be longer, and raise the starting height of the craft, diminishing the benefits of ground effect. Though quite feasible on an electric motor-powered model, maximizing ground effect on a full scale HPH will likely prove more critical than slightly improving the control system effectiveness. For this reason the control surfaces were located above the blades. Further tests should include varied sizes of control surfaces, as well as relocating them below the rotor blades.
Figure 35. HPH model control system consisted of four vertical symmetrical airfoils cantilevered over the area of rotor blade intermesh. Powered by electric servos the blades can be deflected 15 degrees in either direction.

As this model and control system is a proof of concept test, much thought will be required to translate this control method from RC actuation to human powered actuation of a full scale helicopter, where weight is critical. It has been considered in the design of this control system that any control surfaces that do nothing to generate vertical lift are effectively dead weight. Limiting such dead weight is a driving design constraint on any HPH. Creating very lightweight airfoils for control surfaces is an attainable task, especially when stiffness to fight coning is not required. The greatest challenge in implementing this method may be devising a linkage system that can interface with a human pilot so they may quickly sense and carry out the correct inputs, without detracting from their primary focus of delivering power.
X. Plan Forward

Nine months ago, our initial objectives were as follows:

1. Determine the best rotor/blade configuration to maximize ground effect
2. Design and model a working control system
3. Design and model an efficient drive-train system

After further research and experience with our first twin-blade rotor model, our ideas of what was obtainable and worth pursuing within the scope of the Sikorsky Prize have slightly shifted. After our secondary tests with a larger motor, improved rotor blades, and new test fixture, we are satisfied with the data, results, and knowledge we have achieved over these past three quarters. We know the experience we have gained is valuable and even the failures and setbacks are important to our progress. Though there were difficulties in creating the first rotor model and understanding how the data could properly be interpreted, we are confident we can move forward with our model testing while yielding valuable results. Apprehensive of spreading our attention too thin, we took count of what major shortcomings kept DaVinci III and Yuri I from reaching the ultimate goal, and hope future teams continue to study those complications in greater detail.

The complete model HPH manufactured this year is intended to focus attention on making the aircraft hover in a controlled, predictable manner, even if only in deep ground effect. This scale model will also confirm the influence ground effect has on an actual vehicle. Hopefully then, power required to reach full altitude can be measured. With this in mind, and the one minute mark still unconquered, we feel this model HPH, controllable during sustained flight, will be profoundly beneficial to future teams pursuing the Sikorsky prize.

Currently, there are several major tasks awaiting those who seek to pursue this prize. Much more testing and research is required in designing the optimum control system. We have begun the process and hopefully delivered the tools and equipment necessary for this research to continue. Once a concept is established, it is crucial to begin understanding how everything will translate to the full scale craft. Our scale models seek to provide the basis on which these concepts are proven, but how exactly they can be implemented in full scale and powered by human energy still must be discussed.

Additionally, a large benefit of manufacturing scale models is the use of a continuous drivetrain. There has yet to be a full scale HPH attempt that utilizes a continuous drive system and all HPH crafts rely on spools of thread to spin their rotors. These spools must be machined to extremely precise standards to ensure all rotors in this intermeshed configuration are properly timed. A lightweight continuous drive system that can be operated by pilot would be a tremendous accomplishment itself, and could provide the structure around which a successful HPH can be built.

Finally, there is a very long list of aerodynamic considerations to be addressed for full size craft. A repeatable method for dynamically balancing rotors is necessary in isolating rotational vibrations from influencing flight. Optimum rotor shape and design will require more attention as well. If the full 3 meter height is to be achieved, all aspects of flight and design will have to be optimized. These aerodynamic considerations will couple directly with manufacturing. While things may look promising on paper and in theory, manufacturing may be the greatest challenge of all.
XI. Conclusion and Recommendations for Final Helicopter

Our big recommendation from testing ground effect is that the future HPH should be able to utilize ground effect as much as possible. A recommended flight profile would be to stay in low ground effect operating at low power for most of the one minute flight and using all power to gain height in the last seconds of the one minute goal. Our recommendation for multi-rotor configuration is that the blades can be intermeshed almost completely together with little thrust penalty while yielding weight reduction and structural/drivetrain benefits.

This Cal Poly senior project was created to further develop the understanding of human powered rotorcraft flight, and more specifically, how best to successfully complete the requirements set forth through the Sikorsky Prize. The current team of engineering students has spent the 2010-2011 academic year learning all we can about the problem, discovering new information, and attempting to plan for future efforts. We believe we have narrowed the focus of our study enough so that valuable information gained will be passed on to future teams. Our team is ambitious, and we believe the Sikorsky Prize is achievable through hard work, research, and lots of testing. We feel our efforts put forth this year will be judged a success if future teams can build upon the knowledge we have gathered and add new insight into the challenge of designing a human powered helicopter.

Although, there are still many things that need to be considered before flight can be achieved, we believe we are making progress towards an attainable goal. There are still many avenues of research that present opportunities for Cal Poly to make sustained human powered helicopter flight become a reality. We look forward to watching this progress continue and bearing witness to the next time Cal Poly makes history in human powered helicopter flight. With much anticipation we wait for Cal Poly students to once again turn the eyes of the world skyward.