PROJECT #DJO - 0211

Design of a Remote Controlled Tether System for the WPI Kite Power System

A Major Qualifying Project Report
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Abstract

The goal of this project was to modify the current WPI kite power system by developing a wireless system in order to remotely control the trailing edge lines of the kite to control its angle of attack and side-to-side motion. This is the first step in developing a spooling line kite power system. Kite powered systems, compared to wind turbines, have the potential to more efficiently harness the power of the wind because it has the capability to access stronger wind velocities at higher altitudes, which will in turn provide more renewable energy and diminish the negative effects that other energy sources have on the environment. Previous WPI MQP teams had to control the kite using manual control lines attached to the kite and a rocking beam which turned a gear train and generator. The current project team made new modifications which include the design and development of a control box placed beneath the kite that includes two motors, gear boxes, transmitters, and two spools in order to remotely control the length of the trailing edge lines. Both of these developments were rigorously tested in the field as well as in the lab. Lab tests included experimentation with the motors and gears to change the trailing edge line length. Field tests included determining a maximum weight for the control box and testing the control box performance.

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Acknowledgements

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1. Introduction

The goal of this project is to develop a new concept to more efficiently harness the power of the wind. The world today is more dependent on energy than ever before and unfortunately the Earth’s non-renewable resources are continuously being depleted. Due to the diminishing non-renewable resources, an emphasis has been placed on finding alternative energy sources. Non-renewable energy sources, such as coal, oil, and natural gas, have been the stable source of present day energy production. Unfortunately, these current sources of energy are being depleted and will one day run out. For this reason, it is important to turn attention to discovering and improving renewable energy sources.

Renewable energy sources are sustainable and will one day efficiently provide for the world’s energy needs. Sustainable energy means that energy needs are met now without stopping people in the future from meeting their needs[11]. There are several benefits to renewable energy. First, this type of energy can utilize local, available resources such as the sun or wind. Next, it can create local job, revenue, and income opportunities[7]. Also, these renewable energy systems can be sited close to the load requirement which would offset the need for costly grid extension as well as being able to expand production as demand warrants[7]. Most importantly, having efficient modes of renewable energy would reduce the need for fossil fuel imports.

In the past decade, an increasingly popular source of energy has been wind power. Globally, long term technical potential of wind energy is believed to be five times the total current global energy production[11]. Wind power is the conversion of wind energy into electricity and mechanical power to do everyday tasks[11]. The most popular modern technologies used today to harness this power consist of wind turbines, and wind mills. Wind power is one of the fastest growing energy sources because it is cost competitive in a variety of grid, off-grid, and remote applications[11].

The desire for renewable energy and the uses of renewable energy will vary across countries as seen in Figure 2. Renewable energy continues to be comparatively expensive for developing countries that need it the most[6]. World Energy Outlook 2004 predicts that under "business as usual," energy needs through the year 2030 will increase 60%[7]. Fossil fuels at the time of this prediction accounted for 86% of energy use, as seen in Figure 1. The cost of wind power will continue to be steadily driven by technology development; however, as the wind power industry grows, the number of premium wind sites with easy access dwindles[7]. For this reason, new technology with access to stronger, higher altitude sources of wind will have to be developed, such as the use of kites.

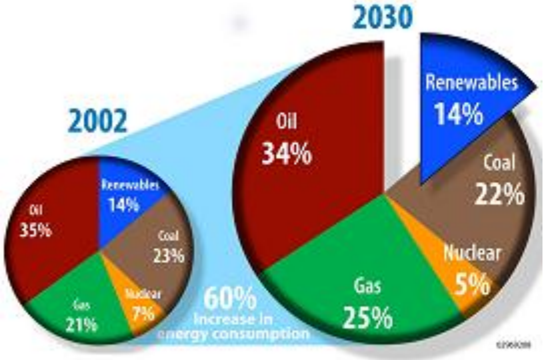
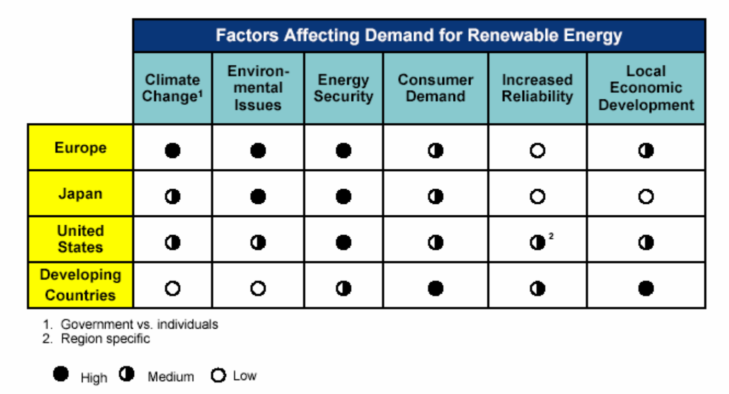


Figure 1: Energy Source Usage



	Factors Affecting Demand for Renewable Energy					
	Climate Change[1]	Environ-mental Issues	Energy Security	Consumer Demand	Increased Reliability	Local Economic Development
Europe	●	●	●	◑	○	◑
Japan	◑	●	●	◑	○	○
United States	◑	◑	●	◑	◑[2]	◑
Developing Countries	○	○	◑	●	◑	●

1. Government vs. individuals
2. Region specific

● High ◑ Medium ○ Low

Figure 2: Energy Demand by Country

Wind power dates back to the first windmill built by Charles F. Brush in 1888. As the 21st century began, fossil fuels were relatively cheap, but as the century wore on, rising concerns developed over energy security, global warming, and fossil fuel depletion[1]. These concerns led to the wind power industry increasing at a growth rate of about 30% per year since 2003[1]. There are several positive aspects of wind energy. First, and most importantly, wind power generates electricity without by-products such as harmful pollutants or gases being produced such as greenhouse gases like carbon dioxide or methane. It is also one of the cheapest forms of energy and does not involve the use of non-renewable energy[12]. Finally, wind is a never ending resource. For these reasons and many more, it is important to investigate ways to harness the wind to produce energy.

Wind turbines are currently the most well known technology for harnessing the power of the wind. The power these machines produce is directly connected to the size of its rotor, meaning that the larger the rotor the more power that can be produced. However, this poses a problem because in order to make turbines larger, the cost for developing and constructing drastically increases and it becomes harder to find a suitable area to construct these very large pieces of equipment. These are some reasons to look for alternative technology to wind turbines.

As with all wind power based technology, turbines do not produce constantly and their performance varies based on the wind. Wind turbines tend to produce large levels of noise comparable to the noise level of a car traveling 60 miles per hour[1]. Another main concern of the increasing number of wind turbines is wildlife disruption. In order to install a wind turbine, vegetation would have to be removed and there have also been incidents of birds being killed by the turbines[1]. It also takes a large amount of power to start up a turbine which means there would have to be power stations close by to produce enough energy to start a turbine or replace the turbine if the turbine is not producing sufficient amounts of power[1]. Wind turbines are also unable to access the strongest winds which are located at high altitudes. At higher altitudes, higher velocity winds can be accessed. The power generated by wind is proportional to the velocity of the wind cubed as seen in the equation below. For this reason, higher altitutdes are ideal for harnessing higher wind velocities which will in turn produce more power.

$$P = \frac{1}{2}\rho V^3 A \tag{1}$$

Due to the location of these higher velocity winds, the use of kites to harness this energy is more sufficient and feasible than constructing wind turbines in these locations. At higher altitudes, wind velocities are higher, making power generation more efficient. The equation below shows that wind speed increases following a 1/7th power law where V is velocity and y is the height, while the subscript 0 denotes a reference condition[3].

$$V = V_o \left(\frac{y}{y_o}\right)^{1/7} \tag{2}$$

The goal of this project will be to develop a control box as well as a motor and spool system to remotely control the trailing edge lines of the kite Previously, the generation of power has been dependent on a rocking arm concept (Figure 3). This mechanism will be replaced by a spooling line concept (Figure 4). The spooling line concept will harness the power more efficiently by eliminating the intermediate steps that are involved in the rocking arm system. By eliminating the rocking arm structure and replacing it with a remote controlled spindle, the efficiency of the system will improve. There will no longer be any need for counterweights to make the beam change position. The A-beam structure pictured below will no longer be needed. Instead, the kite will be directly anchored to the ground and the trailing edge lines will be altered via remote control.

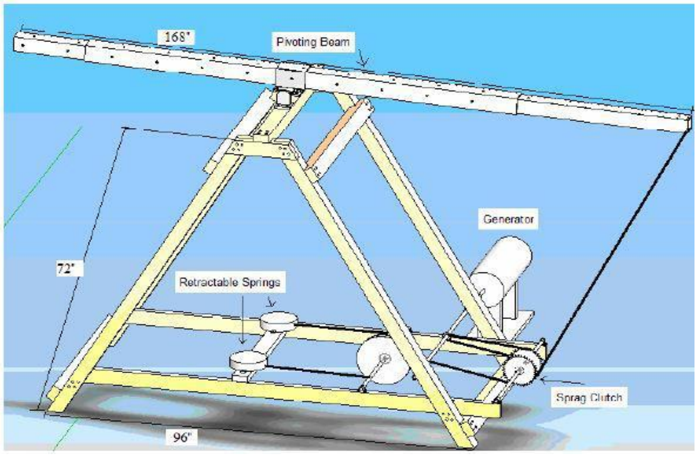


Figure 3: Rocking Arm Concept

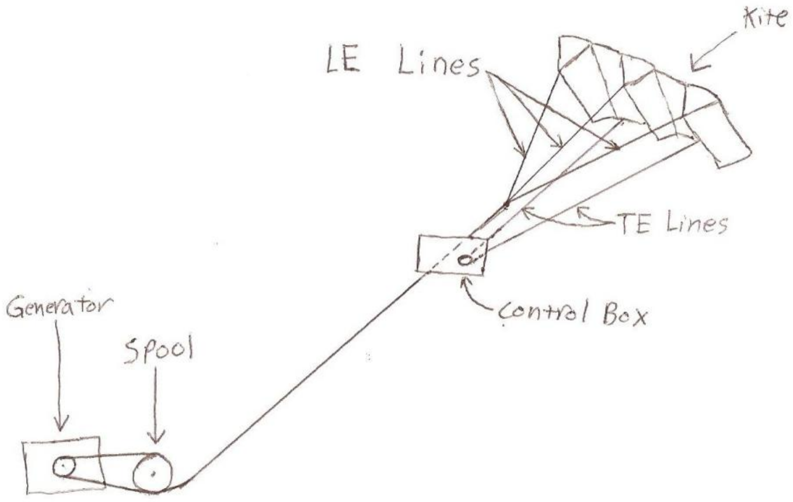


Figure 4: Spooling Line System Concept

The kite's trailing edge lines will be controlled by using a motor to power a rotating shaft located in a control box connected to the main tether of the kite. By being able to remotely control the trailing edge lines rather than manually adjusting them, the kite will be able to be adjusted in order to more effectively stall the kite depending on the wind direction.

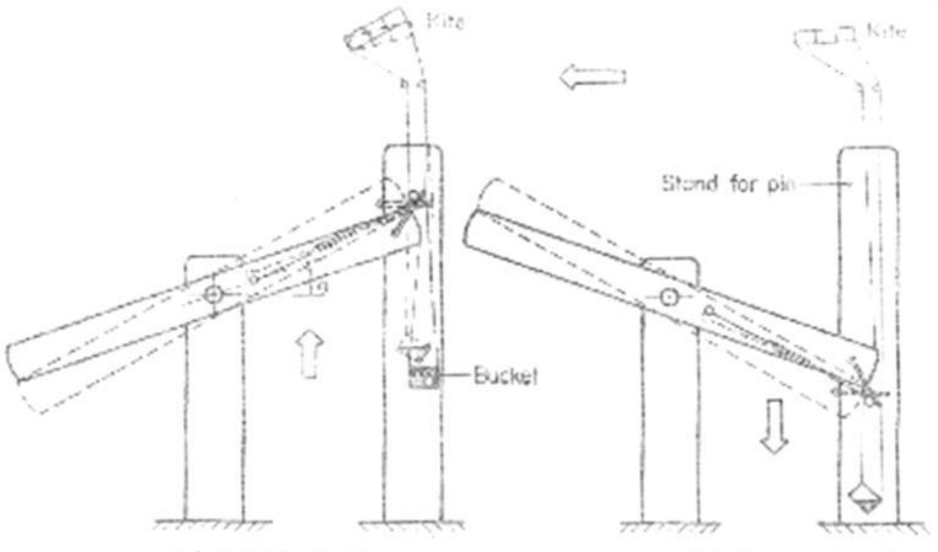
1.1 Background

For many centuries, the wind has been used by humans to generate mechanical power. Kites, although less popular than windmills, have been used for a variety of purposes throughout the world. Since early times, the people of the South Sea Islands adopted the practice of using kites for fishing, which is still used today. The Chinese, and later Europeans and Americans, often used kites for recreational, scientific, and military applications[6].

In the early 1800s, George Pocock incorporated the mechanical energy generated from kites into his invention, the "Charvolant". The Charvolant was a buggy powered by two kites controlled by spools mounted to its front, and could easily travel as fast as the horse-drawn buggies of the time[7]. M. L. Loyd[8] developed a governing set of equations detailing crosswind kite motion. Loyd modeled kites after an aircraft wing moving in a circular orbit downwind of its teather's origin. In his investigation into the possibility of effectively harvesting energy from kites, Loyd indicated that 45MW of power could be generated by a 2000m^2 kite flying at an altitude of 1200m. He also found that power produced in a crosswind mode increases with the square of a kite's lift to drag ratio, and stated that more advanced technology could allow a kite to produce up to twenty times the power output of a turbine[8].

Dr. J. S. Goela also performed research and development on harnessing energy from kites in the 1970s and 1980s. Previous kite power MQP teams have employed Dr. Goela's ideas in the design of their projects, and he has also served as a technical consultant since WPI's first kite power project began in 2007. Goela developed his own set of equations governing the motion of kites while at the Institute of Technology at Kanpur. He used these equations to predict the potential power generation of a kite, and confirmed Loyd's result that a kite's power output is maximized when it moves in the crosswind direction[9]. Goela's experiments included wind tunnel tests on several kite models, which provided insight into the effects of wind loading on kites[10].

Goela also analyzed the steady state motion of a kite and derived relative efficiencies of the kite system by simplifying a kite's motion into two parts, ascent and descent. During ascent, the kite rises and produces power, and during descent it falls to its original position. He noted that the kite system's power coefficient is maximum when the lift to drag ratio on the kite is large. He also observed that the power coefficient reaches a minimum when the kite descends directly against the wind. Goela also investigated practical applications for his kite model, and developed a system where a kite would lift a bucket of water vertically in a well (Figure 5). This system is comprised of a balanced beam on a pivot with spring-loaded assists. The springs are used to vary the angle of attack of the kite as the bucket is emptied and filled at its highest and lowest points, respectively. This variation in the angle of attack allows the kite to ascend and descend to drive the system[9].



(a) Upword stroke (b) Downword stroke

Figure 5: Goela Spring Mechanism View 2 [9]

Some start-up companies are advancing kite power technology by developing ways to effectively generate electricity using kites. KiteGen, based in Milan, Italy, has been in development since 2007, and is developing two kite power systems. One model tethers a kite with two lines to two ground-based drums that are connected to electric drives (Figure 6). The wind force on the kite unravels the drums, which causes the electric drives to act as generators as they are driven by the spinning motion of the drums. When the maximum line length (about 300m) is drawn out by the kite, the drives act as motors to recover the kite, which uses only about 12% of the generated electricity. The kite motion is controlled by a complex system of ground and on-board sensors and control software that can adjust the roll angle and lift coefficient of the kite. This spooling line configuration is estimated to produce about 40kW of power through the electric drives.

KiteGen is also working on medium to large scale generators using their "carousel configuration" (Figure 7). In this setup, several kites, controlled by their own steering units, are attached to arms of a vertical axis rotor. The steering units are programmed to maximize the torque each kite exerts on its arm, causing the rotor to spin about its axis and turn an electric generator. For a given wind direction, the kites can produce energy for about 300 degrees of rotation, and only a small fraction of energy is spent dragging the kites against the wind for the remaining 60 degrees. Simulations have estimated that this configuration could be scaled up to generate almost 1000MW at as little as one-sixth of the cost per megawatt-hour compared to fossil resources[11].

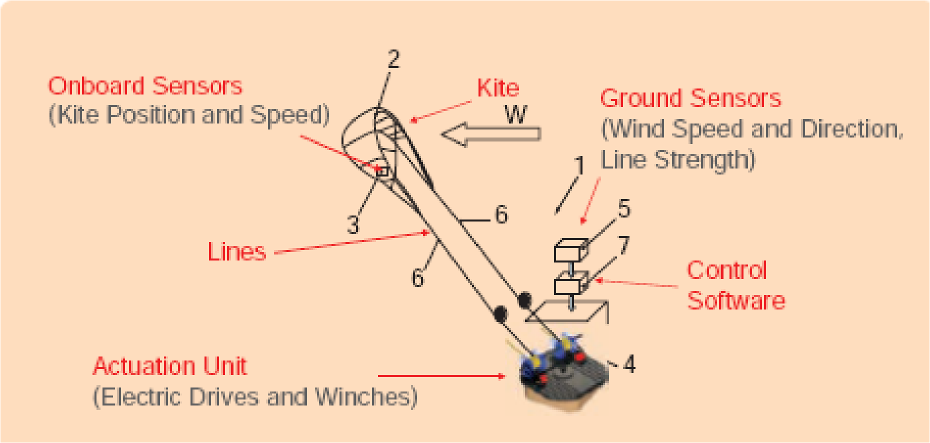


Figure 6: KiteGen "Yo-Yo" Configuration [11]

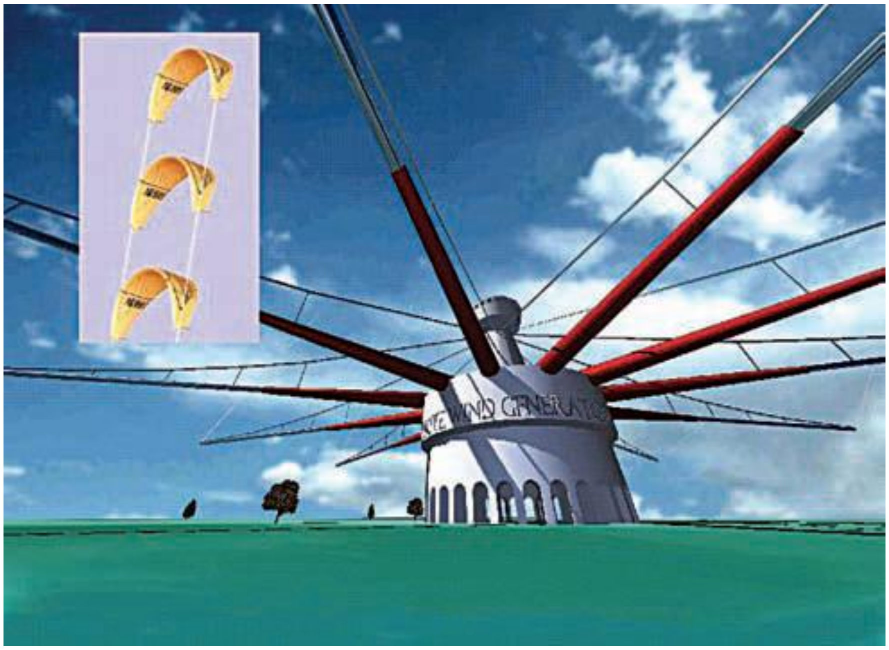


Figure 7: KiteGen Carousel Configuration [11]

Highest Wind LLC, based in Newmarket, New Hampshire, is another company that is pioneering the use of kites to generate electrical power. Similar to KiteGen's yo-yo configuration, the Highest Wind Energy Glider System uses a 40 foot by 40 foot glider tethered to a generator on the ground to produce power through its rising and falling motion (Figure 8). The glider produces power as it rises to altitudes between 700 and 1200 feet, and then descends when its tether automatically reels in the kite line. This cycle repeats itself every 30 seconds, and continuously produces 30kW of power. The generator and remote control unit are housed in a power trailer, and an aerie launch/landing platform is placed on the ground between the power trailer and the glider so that the glider may rest on it when conditions are poor. Highest Wind LLC is advertising its system for locations with winds too weak for wind turbines to be effective since the glider will be able to access stronger winds 1000 feet above the ground. Highest Wind plans to start selling their Energy Glider System in late 2011[3].

Figure 8: Highest Wind Energy Glider System [5]

1.2 Previous Project Work at WPI

Previous MQPs have done a great amount of research and have built on the rocking arm concept that was previously mentioned. The first team to work on the Kite Power project at WPI in 2006-07 developed the rocking arm design after researching and studying various possible concepts. The design used a rocking arm on a wooden A-frame structure that used the weight of the rocking arm to stall the kite and create a downward stroke. A large kite-boarding kite was chosen for the project after many types of kites were tested. The power was produced using a sprag clutch system which produced power in the rocking arm's upward stroke. The project team evaluated a Pumpjack, Sprag Clutch, or a combination of the two as possible systems and determined the combination that was most suitable for the project.[14]

The following year, the 2007-08 MQP team focused on constructing the design that was developed the previous year. The prototype that was built by this project team used a sprag clutch that was adapted from a rowing machine and included a sliding control mechanism that was able to control the motion of the kite, a flywheel for continuous power creation, and a gear train with a gear ratio of about 6:1. An arm lockout mechanism and safety padding were also added to improve the safety of the structure. The mechanism was built by mounting and attaching the kite to the rocking arm which is on top of the A-frame structure and utilizing nylon cords to connect the kite to the gear train and sprag clutch. To control the motion of the kite, a control mechanism was created. The control mechanism consisted of a pivoting center arm that moves side to side as the kite moves to either direction, side control arms that in effect rotate the control bar with respect to the kite, and a slide that allows the entire mechanism to be moved in and out and allows for lateral control at all angles of attack, this can be seen in Figure 9. When the kite is lifted by the wind, the rocking arm is also lifted, and a nylon cord pulls on the sprag clutch which turns the gear mechanism. The mechanical energy created by the gear mechanism is then converted to electrical energy and stored via a battery bank. Once the kite reaches its maximum upward position, the sliding mechanism, which is tethered to the kite, slides downward and stalls the kite. This allows for a counterweight to swing the rocking arm back to its original position. The slider is also returned to its previous position, creating a cycle.[15]

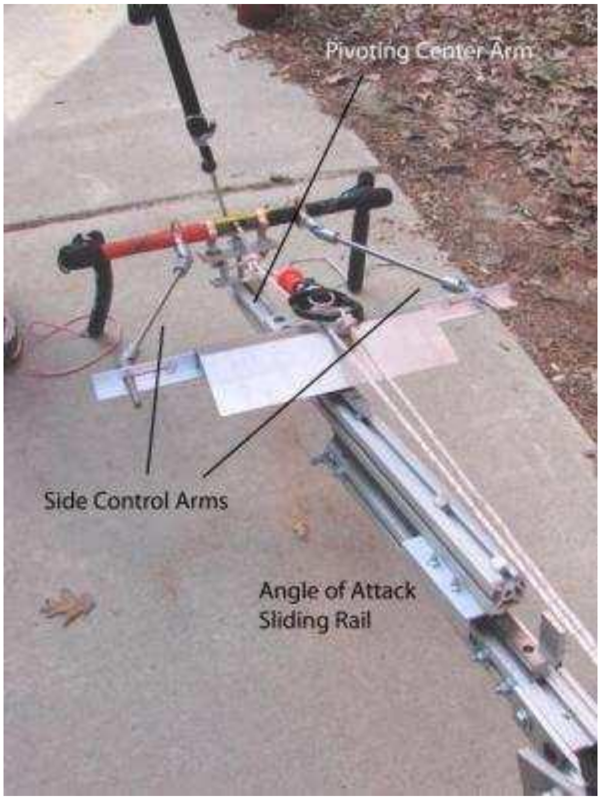


Figure 9: Control Mechanism

The next Kite Power team focused on improving the system by adding instrumentation to measure the mechanics of the Kite Power system. This instrumentation included a force meter used to record the force that was being exerted on the kite, an inclinometer that measured the angle of the rocking arm, a torque meter for the system, and magnetic ring and pick-up to measure the rotational velocity of the gear assembly. The team also added additional safety precautions, such as reinforcements for the A-frame structure and acrylic covering for the gear mechanism.[13]

A pair of MQP teams made additions to the Kite Power system in 2009-10. One of these teams focused on designing and constructing a dynamometer for the Kite Power system. The dynamometer was introduced as a breaking mechanism; as the wind speed increases the dynamometer slows the rotational speed of the system by exerting force on the main shaft. It consists of a rotor that will replace the main shaft of the system and rod that is attached to the A-frame structure and applies force to the rotor. The system also allows for gear additions to the power conversion system down the road.[16]

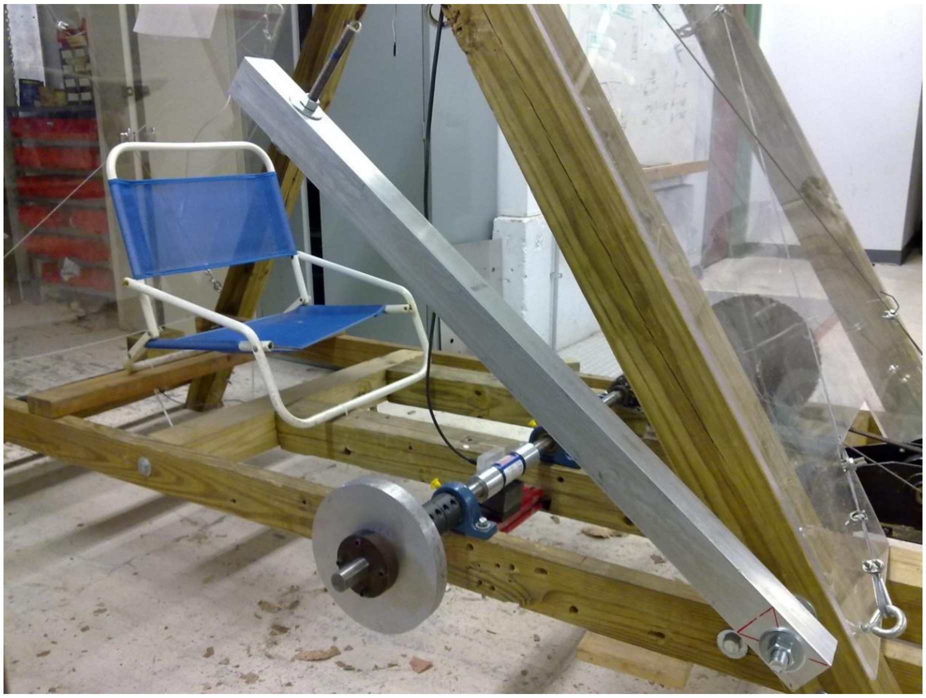


Figure 10: A-frame structure with Dynamometer

The second team focused on making several improvements to the entire Kite Power system. The improvements included using a sled kite which is larger and more stable than the kite-boarding kite that was used for the previous projects. Mechanical improvements to the safety of the system were made by creating a new device to immobilize the arms of the system for transport, set-up and take down; this was due to the fact that the current system bent significantly under forces that could be seen in the field. Other mechanical improvements included removing the stabilizing component of the stall system, lowering the weight on the end of the arm and allowing for the slider to be shortened. This decrease in the weight of the slider increased the movement of the slider, making it easier to stall the kite. The ability to add specific amounts of weight to the slider was added by including a spacer that can be removed and replaced with weights; this allowed the slider to adapt to different sized kites. The instrumentation used for data acquisition was refined; this included the development of a method to measure kite tether tensions. This was done by adding a load cell that moves freely as the kite tether changes its elevation angle due to wind forces; this allows the load cell to calculate tension accurately. Thorough tests of the new system design were performed in the lab and in the field. The entire rocking arm system can be seen in Figure 11 below.[5]

Figure 11: Rocking Arm System

1.3 Project Objectives

The goals of this year's project are as follows:

- Develop a remote controlled sled kite capable of having the trailing edge lines adjusted from a ground-based station
- Test the remote controlled system in the laboratory and during field tests

The main goal of this project was to develop a remote control system to adjust the length of the trailing edge lines in order to control the kite's angle of attack and side-to-side motion. This control system was thoroughly tested in the laboratory as well as during field tests. The results of these tests were analyzed and compared to past year's project groups to assess the overall productivity and improvement to the mechanical system. The development of the remote control system is the first step towards the development of a new kite power demonstrator at WPI based on a spooling line concept.

2. Design Methods

2.1 Control Box

To give the kite power system the potential to generate more energy, a new design was implemented for the system. This new design requires the motion of the kite to be controlled from the ground. A remote controlled kite will make controlling the kite easier and allow for more design options for power generation in future work, for example, the spooling line concept. In order to implement this control, a remote-controlled control box was designed to be attached to the kite. The control box is designed to wind and unwind the trailing edge lines of the kite. By controlling the kite's trailing edge lines, the control box is able to increase and decrease the angle of attack of the kite, causing the kite to increase or decrease its altitude. This system will give the kite more freedom of motion, allowing it to take advantage of the wind's energy.

The length of the two trailing edge lines will be changed by two spindles that will be located inside the control box. These spindles will be powered by a pair of motors which will be remote controlled using a motor controller and transmitter.

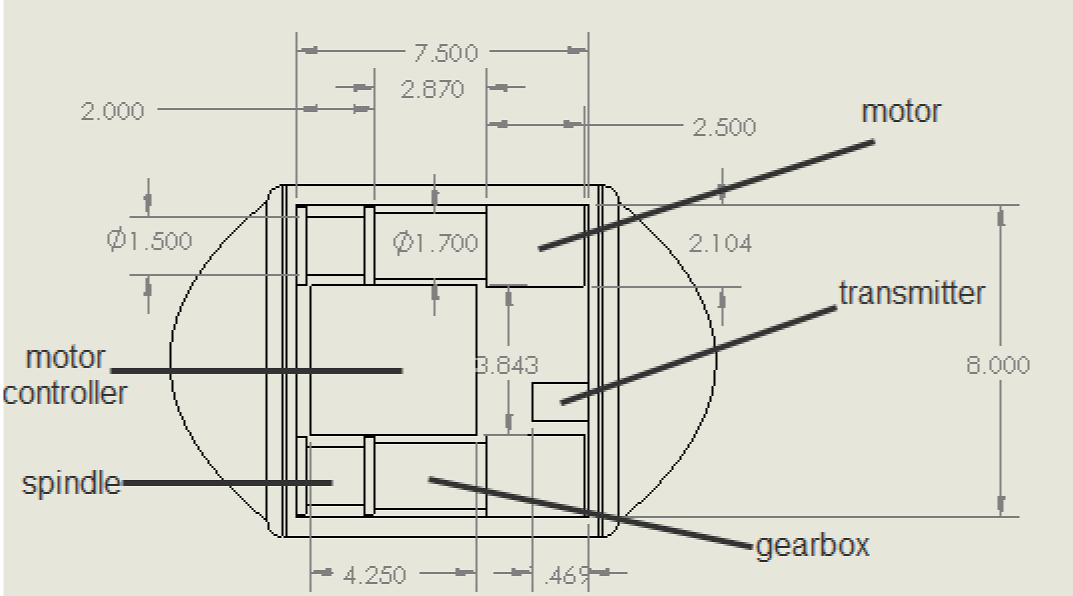


Figure 12: Control Box- Labeled SolidWorks Drawing

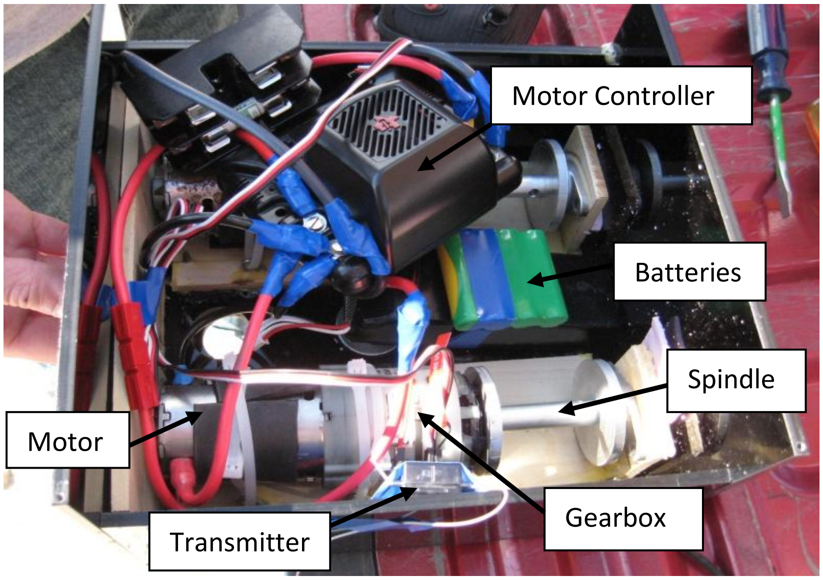


Figure 13: Final Layout of Control Box Components

The first step of this improvement was creating a control box design. This control box would be the protective casing that would house the necessary components to assemble the remote control system. Some of the designs discussed included a layered concept where the box would be made up of six circular sections stacked vertically with spaces between each section to allow air to flow through the structure and create more lift. A second design concept was a rectangular box shape with streamline airfoil shapes attached to two opposite sides of the rectangle. After considering both options, the second design was chosen due to its simplicity compared to the first design. The control box was designed using the CAD program SolidWorks. A drawing of the selected design can be seen in Figure 12 above.

Next, the control box had to be manufactured. Due to the function of the control box, a lightweight material was necessary that would be strong enough to contain the necessary components inside of it. After speaking about our material requirements with Neil Whitehouse of the Mechanical Engineering department at WPI, we were referred to a company called Plastics Unlimited located in Worcester, MA. After discussing our necessities with the company, we decided on ordering ¼” thick black acrylic plastic to construct the control box. The box was designed as an assembly of 6 pieces of the acrylic plastic. Each piece was cut using a laser cutter and then assembled. The box dimensions are 9” by 9” by 6” as seen in Figure 12. The sides and bottom of the box are glued together while the top of the box is attached using a screw on each corner. This makes the top of the box removable and gives accessibility to the instrumentation inside the box. Next, a center hole was cut in the bottom and top of the box. The center hole is 1” in diameter. The center hole was laser cut for the top and a drill press was used to cut the hole in the bottom. This center hole allows for the main tether of the kite to run through the center of the box.

Finally, carbon fiber tube attachments were added to the top and bottom of the control box to address the concern of the motion of the control box itself. The motion of the motor may cause unwanted movement of the control box which may cause unwanted movement in the kite. To help stabilize the control box, carbon fiber tubes were attached to the top and bottom of the control box, the idea being that the rigidity of the tubes will prevent the control box from moving. These plastic attachments acted as holders for the carbon fiber tubes that were added to the control box as seen in Figure 14 below.

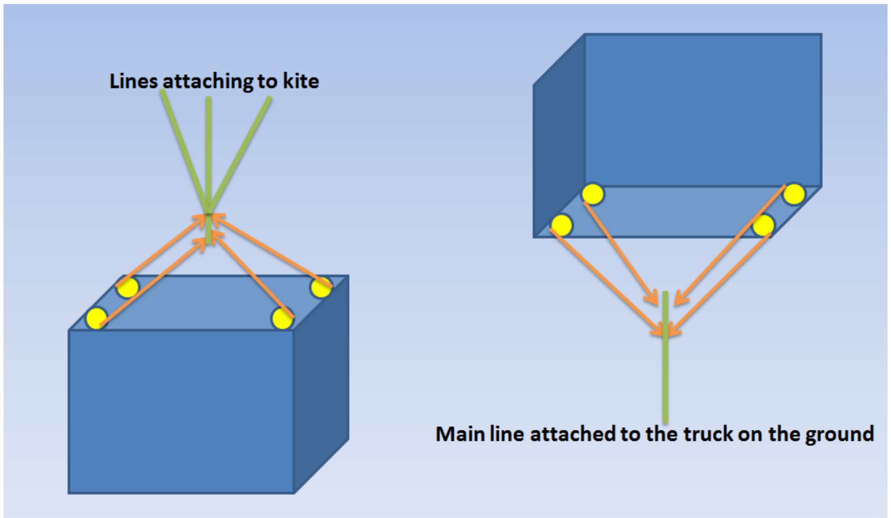


Figure 14: Carbon Fiber Tube Attachments

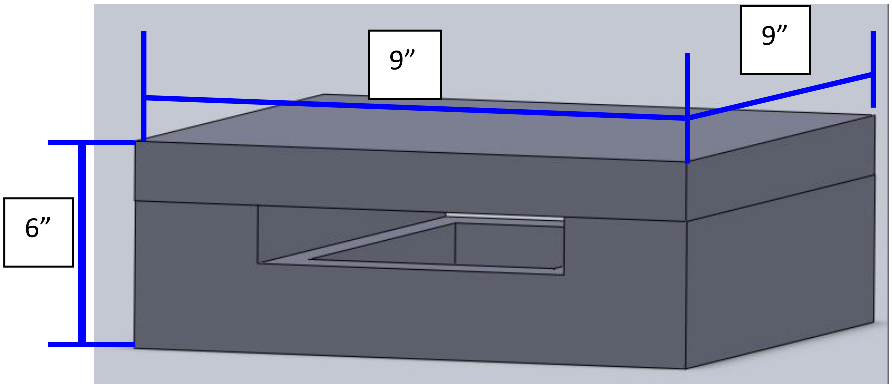


Figure 15: Control Box

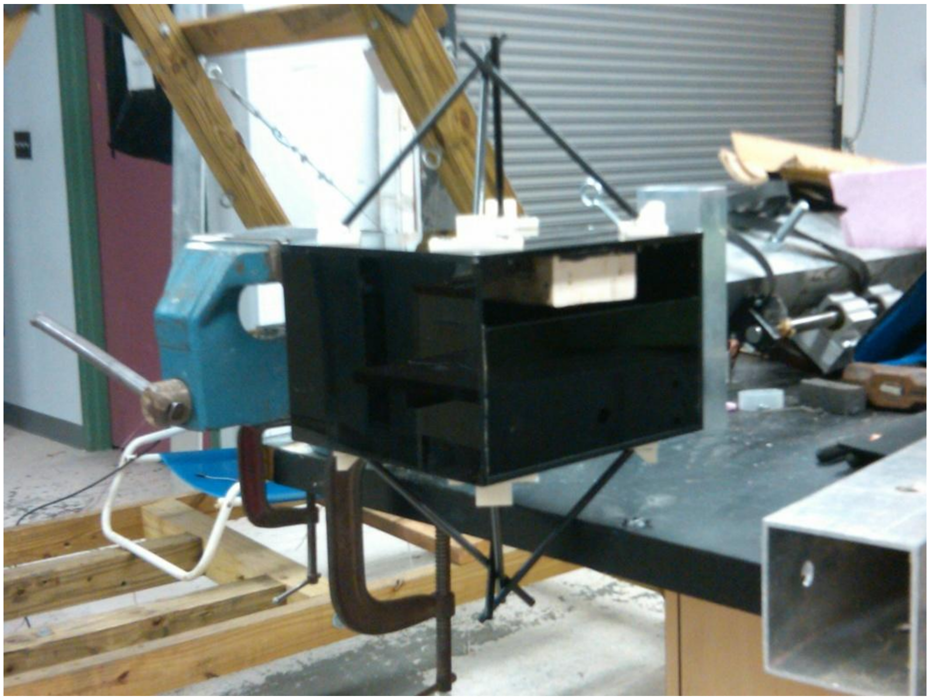


Figure 16: Finished Control Box

The next components of the control box obtained were the motors needed to pull on the trailing edge lines of the kite. After field testing it was determined that the amount of torque required to match the maximum force exerted by the kite was 162 in*lbf. Taking this data into account, a small, lightweight motor that could provide the necessary torque was searched for. After considering several options, the Dewalt 12V New Style Drill Motor was ordered from Robot Marketplace. The motor has a weight of 1.14 lbs and comes with a gearbox that weighs in at 0.85 lbs, the maximum torque it provides is 350 in*lbf and its maximum revolutions per minute is 1800. The gearboxes of the motors will each be attached to a spindle that will change the trailing edge line length of the kite.

In order to actually pull in the trailing edge lines of the kite, a spool is necessary to wind and unwind the string. For our purposes, the spool had to attach to the gearbox so that it can be directly powered by the motor. Since a spool that could directly attach to our gearbox could not be found, it had to be manufactured. The spool was manufactured in the Manufacturing Lab of the Mechanical Engineering Department at WPI using rods of 6061 Aluminum. The motor, gearbox, and spool can be seen in Figure 17 below.

Figure 17: Motor, Gearbox and Spool

2.2 Aerodynamic Box Covering

Since the control box has flat sides, there was concern that when the box is lifted with the kite, the force of the wind on its blunt side would create significant drag on the system, severely affecting its ability to stay airborne. To help reduce these effects, an aerodynamic covering was designed that would attach to the front and rear sides of the box. The attachments would give the box an airfoil-like shape, which would both reduce drag and produce a lift force to counteract some of the weight of the box. A conceptual CAD drawing of the covering is shown below:

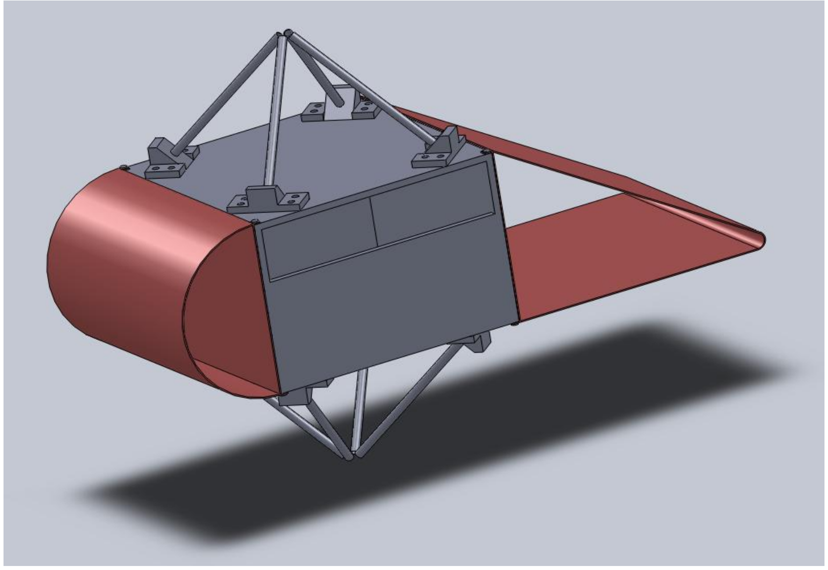


Figure 18: Aerodynamic Covering Concept

In the model, the covering is in read and is mounted to the control box (in black). In selecting materials for the covering, light-weight materials such as cardboard and sheet aluminum were considered. The original idea was to make the covering a frame (as shown in the CAD drawing) and to attach the pieces to the box via screws on the top and bottom. However, the team decided to use insulating foam to make the covering out of two solid pieces, one for the front and one for the back. Using the foam would make the covering much easier to manufacture, and much lighter weight than the other materials considered.

Both pieces were built by cutting multiple pieces of the same shape out of a large piece of the foam material. Then the pieces were glued side-by-side, and sanded down to make a smooth, uniform shape. Any major spots of unevenness were covered using spackel, making an even overall shape for both pieces; important for reducing drag as much as possible. The pieces were attached to the box and each other using Velcro straps. Slits were cut on the top and bottom of both members near the side that interfaces with the box, and straps were threaded through the slits and adhered in place. On both parts, the top strap was designed to loop through the openings on the sides of the box, directly connecting the foam and the box. A single strap looped through the bottom slits, which connected the two pieces to each other as well as pressed the pieces securely to their respective sides of the box. The finalized covering is shown mounted to the box in the figure below:

Figure 19: Finalized Aerodynamic Covering Mounted to Box

2.3 Attaching the Box to the Main Tether

With the main tether running through the center of the box and the tips of the carbon fiber tubes on its top and bottom, a method of securely attaching the box to the tether was developed. It was determined that the most effective way to make this attachment was to secure the line to the box at a single point; namely, the point where the tubes intersect at the top of the box. Fastening the main tether to this point prevents the box or tubes from bearing any of the tension in the line, and causes the top carbon fiber tubes to bear the weight of the box. The absence of a second rigid connection allows the tubes to stabilize the box without sustaining the tesion in the main tether. Also, the tips of the tubes were tied together with string to keep the main tether threaded through the tube intersection points.

In order to make the secure connection, metal stops were obtained from the Higgins Laboratories Machine Shop. These stops were attached to the tether on either side of the tube intersection point by threading the line through the holes drilled into the stops. The line was threaded through the holes in the stops multiple times so that the metal pieces would not slip down the line when tension in the line was lost. To prevent the metal stops from damaging the carbon fiber tubes, disks were made out of insulating foam to provide a barrier of padding between the stops and the tubes. This attachment method is shown in the following figure:

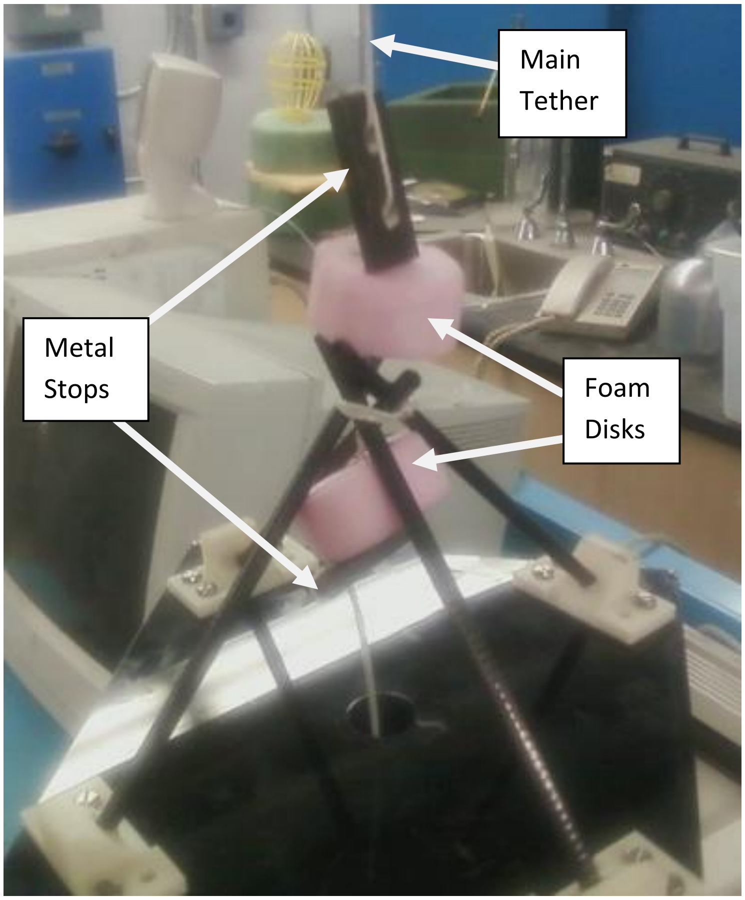


Figure 20: Main Tether Attachment Method

3. Instrumentation

In order to acquire reliable measurements, certain devices and software were used to aid the design and testing of the control box. Much of the instrumentation used in the 2009-10 Kite Power MQP, including a load cell, data acquisition (DAQ) system, and LabVIEW virtual instrument (VI), was used to measure the tension in the kite's tether line and trailing edge lines. The measurements gathered from these devices guided the selection of motors for the control box, and established other parameters for the components of the kite control system.

3.1 Load Cell

The load cell apparatus was designed by the 2009-10 MQP group with the purpose of accurately measuring the tension in the kite's tether. The load cell itself was a model THB-1K from Transducer Techniques with the capacity to measure compression up to 1000 pounds[13]. This load cell was first used by the 2008-09 Kite Power group, and was reconfigured the following year. The 2009-10 group placed the load cell within an aluminum block, shown in Figure 15, which could be connected by means of two eyebolts to the end of the kite tether on one side and to a static object on the other. The load cell was connected to one of the eyebolts in such a way that when a force was applied by the kite, the cell would be compressed between a washer and a nut. The compression force would be equal to the tensile force of the kite tether, allowing the cell to report accurate readings of the tension in the tether[5].

Before each use, the load cell was calibrated by hanging a known weight from one of the eyebolts, and adjusting the balance potentiometer on the load cell signal conditioner until the reading reported on the LabVIEW VI was accurate. Figure 21 shows the calibration of the load cell as it is attached between a static bar and a known weight. In field testing the load cell was used to measure tension in the main tether and trailing edge lines. In the case of the trailing edge lines, the load cell was attached between the end of one trailing edge line and the handle bar used to vary the kite's angle of attack. The tension readings gathered from pulling on the trailing edge lines to stall the kite revealed the force needed from the motors in the control box in order to reel in these lines under strong wind conditions.

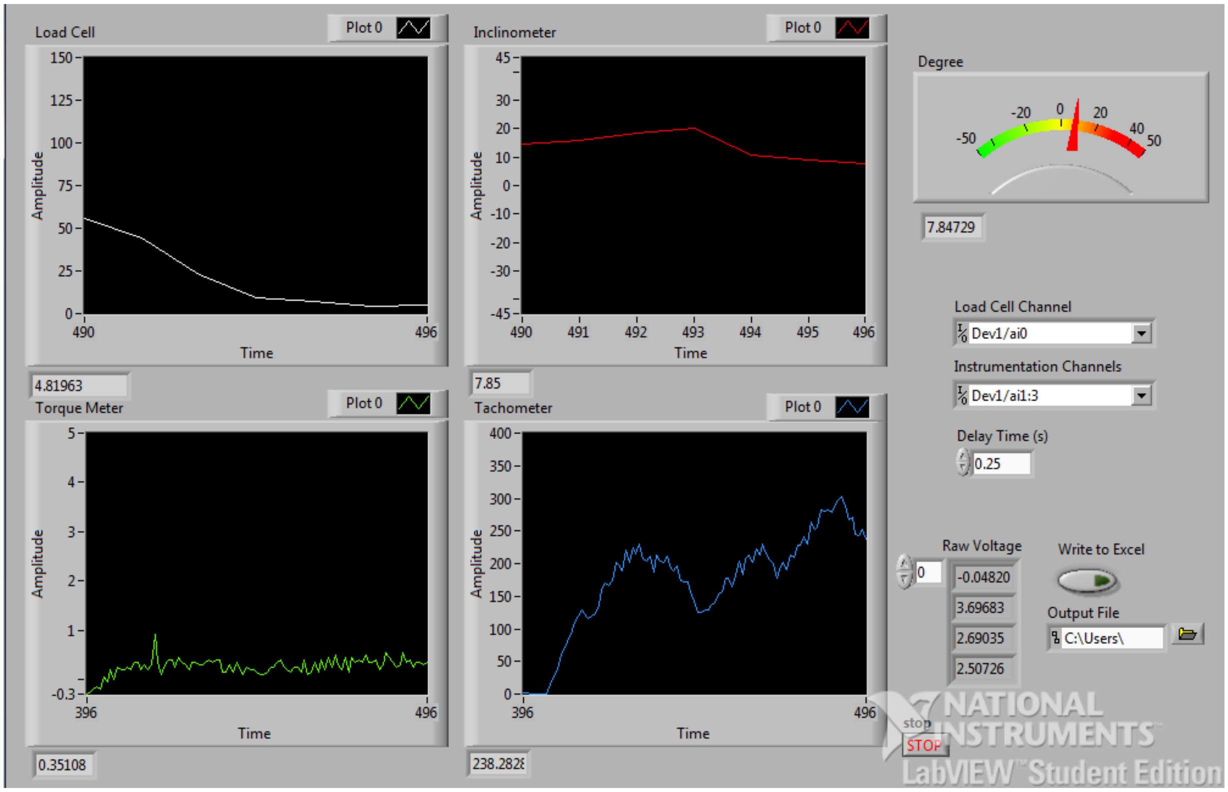
Figure 21: Load Cell Calibration [5]

3.2 DAQ System

The data acquisition unit was originally developed by the 2008-09 MQP team, which included a 12 bit DAQ board and a model TMO-1 load cell signal conditioner, which was wired and attached to the DAQ board to amplify the signal from the load cell[13]. The following year, a new power source was developed based on two USB cables. This system transmitted 10 watts of power to the DAQ system, as opposed to 15 watts from the original system. Since the entire unit only required 9 watts, the new power setup was more economical, and made the unit independent of an AC power source, which can be hard to obtain in field testing. The two USB cables plug into the laptop, and exchange both power and data[5]. During calibration and testing, the load cell was connected to the signal conditioner through two wires and the DAQ system was connected to the laptop through the USB cables. To calibrate the load cell, the balance potentiometer was adjusted while a know weight was hung from the load cell until the output reading on the LabVIEW VI reported the correct load value.

3.3 LabVIEW

The data collected from the load cell was recorded through a LabVIEW virtual instrument developed by the 2008-09 MQP team. This VI (see Figure 22) numerically manipulated the load cell voltage signals, after being amplified through the signal conditioner, into units of pound force. The VI was originally designed to collect data from the load cell, an inclinometer, a torque meter, and a tachometer, which were all used to take measurements on the original kite power apparatus. It was also designed to automatically write the collected data to an Excel spreadsheet[5]. For the current project, only the load cell readings were considered, which were plotted in the top-left corner of the VI front panel. During field testing, the load cell readings on the trailing edge lines were recorded on an Excel spreadsheet, which was later used to determine the force required from the motors in the control box in order to successfully vary the kite's angle of attack.



Load Cell: 4.81963

Inclinometer: 7.85

Degree: 7.84729

Torque Meter: 0.35108

Tachometer: 238.2828

Load Cell Channel: Dev1/ai0

Instrumentation Channels: Dev1/ai1:3

Delay Time (s): 0.25

Raw Voltage: 0

-0.04820
3.69683
2.69035
2.50726

Output File: C:\Users\

Figure 22: LabVIEW VI Front Panel [13]

4. Testing Methodology

As the remote control system was developed, testing was done in the laboratory as well as out in the field, on the beach in Seabrook, New Hampshire.

4.1 Lab Testing

In order to test the functionality of our new control box system, experiments were performed involving the control box and its components. The first of these experiments involved testing the assembly of the motor, gearbox and spool by trying to have it pull up weight. The weight would be pulled up by attaching string from the spool to a weight and trying to wind the string up using the motor to power the spindle. The purpose of this experiment was to simulate the force that the assembly would need to exert to pull on the trailing edge lines of the kite while the kite is in flight.

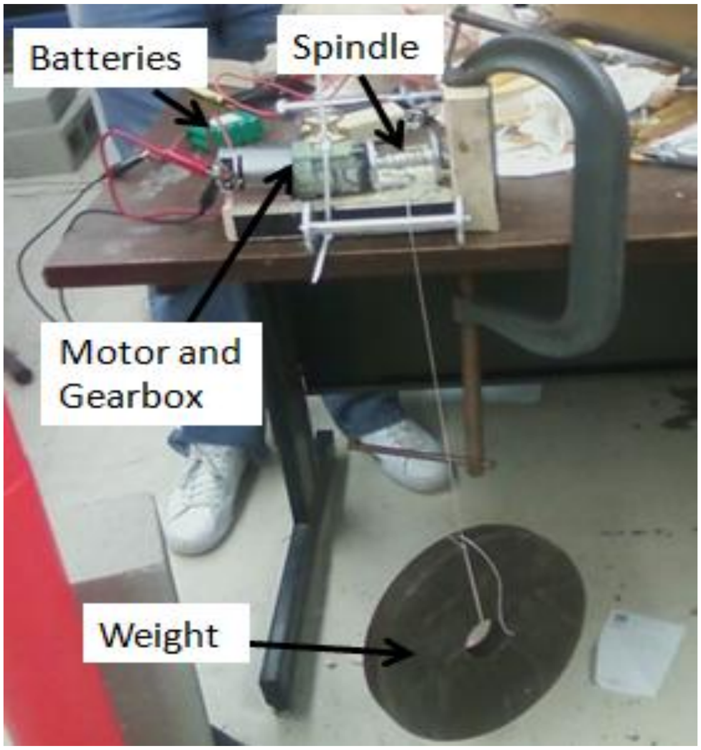


Figure 23: Lab Test 1 Setup

Another experiment that was going to be performed in the lab involved simulating the control box pulling on the trailing edges of the kite. The purpose of this experiment would be to test the ability of the control box to pull on each trailing edge of the kite without the box itself moving. This would address the concern that the control box might move upward as opposed to the trailing edge lines moving downward when each motor pulled on the trailing edge lines. Unfotunately the motor controller that was selected malfunctioned before this experiement could be peformed. An auxiliary motor controller was obtained but it could only provide a single output of control so the motors could no longer be controlled individually. Due to this unfortunate incident, the second lab test could not be performed.

Electronic readings, such as the voltage, amp-hour capacity, and battery life, were also taken for the power source. These readings were necessary to better understand the allowable time frame to correctly operate the remote controlled motors powering the spools which adjusted the trailing edge lines of the sled kite. In the field, the systems were tested to assess the capability of the remote control system. The remote control system was mounted on the main tether and used to control the length of the trailing edge lines.

4.2 Field Testing

The team traveled three times to Seabrook, New Hampshire in order to conduct field testing of the kite and control system with the strong, consistant winds found at the beach. The first field test was conducted on October 10, 2010 with the goal of measuring the maximum tension in the trailing edge lines while changing the kite’s angle of attack, and finding the maximum weight that the kite could lift while still remaining steadily airborne. The load cell and laptop were used to measure the tension in the trailing edge lines. The load cell was placed along one of the trailing edge lines, and recorded tension readings to the laptop using LabVIEW as the kite was stalled by pulling on the trailing edge lines. These tension readings were used to determine the load that the motors in the control box would have to overcome while reeling in the these lines.

Next, sandbags of known weight were attached to the main tether near the kite using tie wraps to simulate the potential weight of the control box. More sandbags were added sequentially until the kite struggled to gain altitude while lifting the bags. From this test, the maximum weight of the control box and its components was measured. This limitation, as well as the trailing edge line tension readings, guided the team's selection of box components and materials.

The next field test took place on March 20, 2011, and involved evaluating the effectiveness of the weight and orientation of the control box on the main tether. The control box was brought to the testing site without its components, but instead housed sandbags to simulate the combined weight of the motors, gear boxes, spindles, batteries, receiver, and motor controller. The box was connected to the main tether by threading the line through the middle of the box and using the metal stops to keep the box stationary on the tether. The motion of the kite was still controlled manually from the ground, but the ability of the kite to lift the box and the effectiveness of the method of attaching the control box to the main tether were evaluated, allowing the team to determine the successfulness of the design thus far as well as future work to be done. The performance and effectiveness of the aerodynamic covering was also tested during this trip, allowing the team to note improvements to be made to the box's aerodynamics.

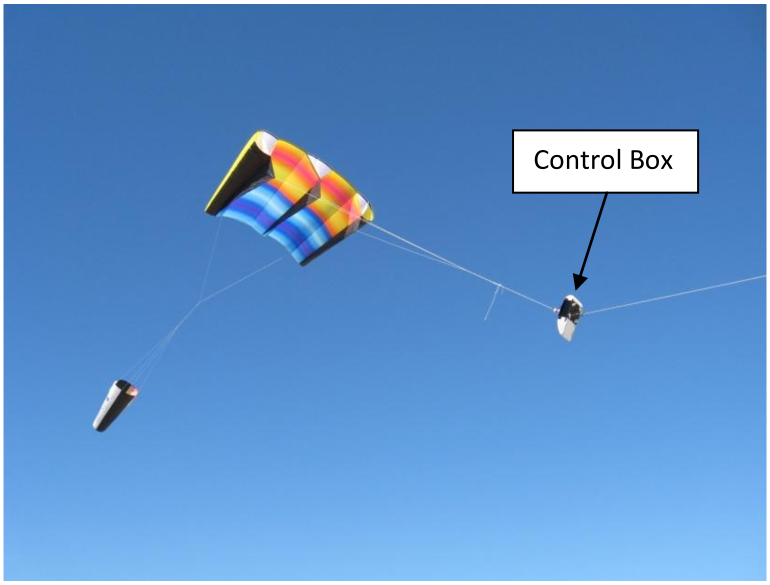


Figure 24: Kite with Empty Control Box Attached to Main Tether

The final field test took place in April 2011, and involved testing the completely assembled control box system. The trailing edge lines were attached to the spindles in the box, allowing the kite's motion to be completely controlled through remote-control. The overall success of the control box design was determined, as well as areas to be improved on by the following year's project team.

5. Results

The effectiveness of the control system and its components were analyzed using the data obtained from the laboratory experiments and field tests. This section will summarize the results of these tests chronologically, and the modifications and conclusions that followed.

5.1 Field Test 1

At the first field test, tension in the trailing edge lines was measured while adjusting the kite's angle of attack by hand. Several cycles of increasing and decreasing the kite's angle of attack in order to stall and redeploy the kite, respectively, were performed while the load cell recorded tension readings every half-second through LabVIEW. With a maximum windspeed of about 15 mph, the tension readings while increasing the angle of attack peaked around 18 lbs. A sample of the recorded data is shown in the figure below. From the data, the team concluded that each motor would have to be able to lift, with a reasonable factor of safety, 20 lbs.

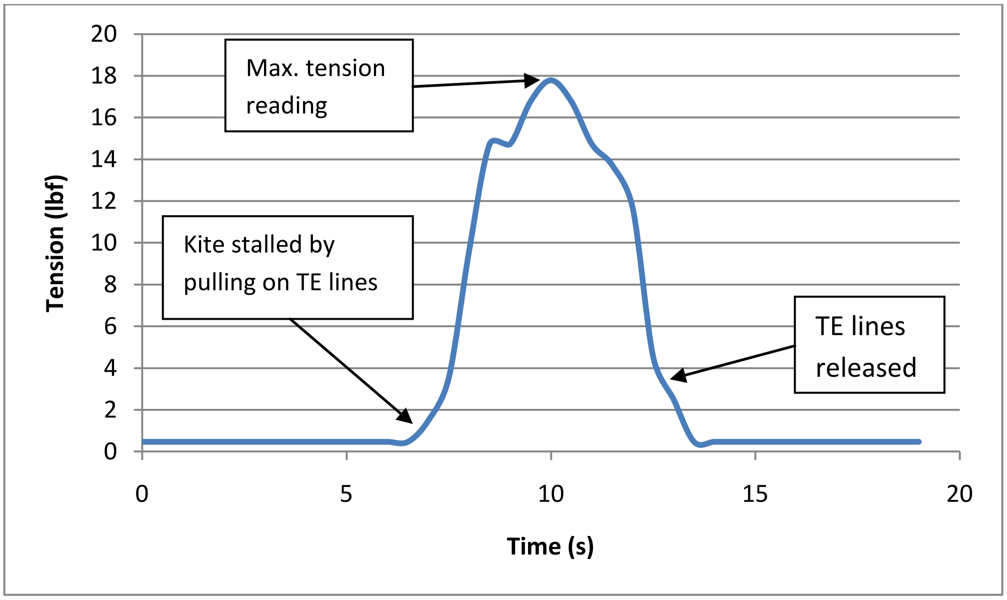


Figure 25: Sample of Tension Readings in TE Lines

As discussed in the previous chapter, sandbags were attached to the main tether where the control box would later be located in order to determine the maximum possible weight of the control box. Sandbags were added sequentially until the total weight on the main tether reached 10 lbs. At this point the kite's altitude was noticeably reduced due to the weight, but the kite could still lift off of the ground and fly sustainably with the wind speed that day. At this point, the team determined that the weight of the box must be 10 lbs or less.

5.2 Field Test 2

The second field test allowed the team to examine the performance of the control box's orientation and weight on the main tether. Before the field, the team weighed the box structure as well as the total weight of the components that would later be housed inside it. The weight of the box itself (including the aerodynamic covering) came out to 4.1 lbs, and the total weight of the components was 7.8 lbs. Although the total weight was over the 10 lb limit determined at the previous field test, the team agreed that the extra weight would not be detrimental to the kite's flight, and would be partially offset by the lift induced by the aerodynamic covering. Sandbags weighing 8 lbs total were placed in the box for this test to simulate the weight of the components.

The results of this test were heavily influenced by the low winds that day, which were inconsistent and reached a maximum speed of only 7.5 mph. The kite was unable to lift the box and sandbags, so the testing resumed after the sandbags were taken out of the box. Even though the inconsistent winds caused the kite to periodically fall to the ground, the kite and empty box were able to stay in the air long enough for the team to observe the orientation of the box. It became evident that the pitch of the box was far too high for the aerodymanic covering to be effective since the bottom of the box was facing the wind more than the front. Figure 25 shows the orientation of the box with respect to the wind direction.

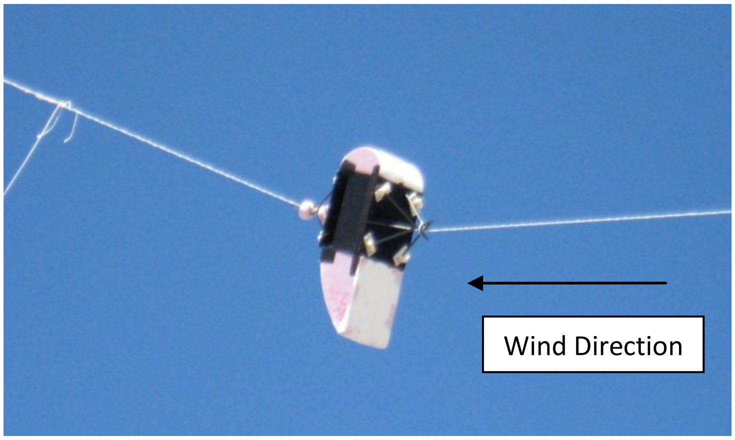


Figure 26: Orientation of Control Box During Second Field Test

The team modified the design of the box as a result of this observation. This modification included drilling new holes in the top and bottom of the box and rearranging the carbon fiber supports in such a way that the main tether would go through the box at and angle rather than straight through the center of the top and bottom. This modification would allow the box, and aerodynamic cover, to face the wind such that the front surface of the box would be nearly perpendicular to the wind direction. Figure 26 shows the control box with these modifications.

Figure 27: Modifications to Box After Second Field Test

5.3 Lab Test 1

The objective of the first lab test was to test the ability of each motor to lift the required load of 20+ lbs at a reasonable speed. When the motor assembly; consisting of a motor, gearbox, and spindle; was first tested using the test stand, a 12V, NiMH battery pack with a 2200mAh capacity was used. The team discovered after running several tests that the motor required more current than this battery pack could provide when lifting weights over 5 lbs, so sought a more durable battery pack to power the motors.

The two NiMH battery packs were replaced by a single PowerEdge 14.8V 4S Quad Cell 30C LiPo pack with a 3700mAh capacity. This pack could supply enough current and power to run the motors continuously for several minutes. This pack enabled the motor assembly to lift upwards of 25 lbs with ease, allowing lab test 1 to be completed.

The motor lifted 5 lb, 10 lb, and 25 lb weights in numerous trials, and the rate at which the spindle wound the line from which the weights were suspended was calculated for each trial. At the end of the testing, the spindle speeds were averaged for each amount of weight. For 5 lbs the average rate was 11.108 in/s, for 10 lbs the average was 10.695 in/s, and for 25 lbs the average rate was 8.077 in/s. These results are shown graphically in Figure 27, and the full results are shown in Appendix A. The spindle speed for 25 lbs was an acceptable rate, and proved that the motor assembly and LiPo battery pack were capable of controlling the tension in the kite’s trailing edge lines.

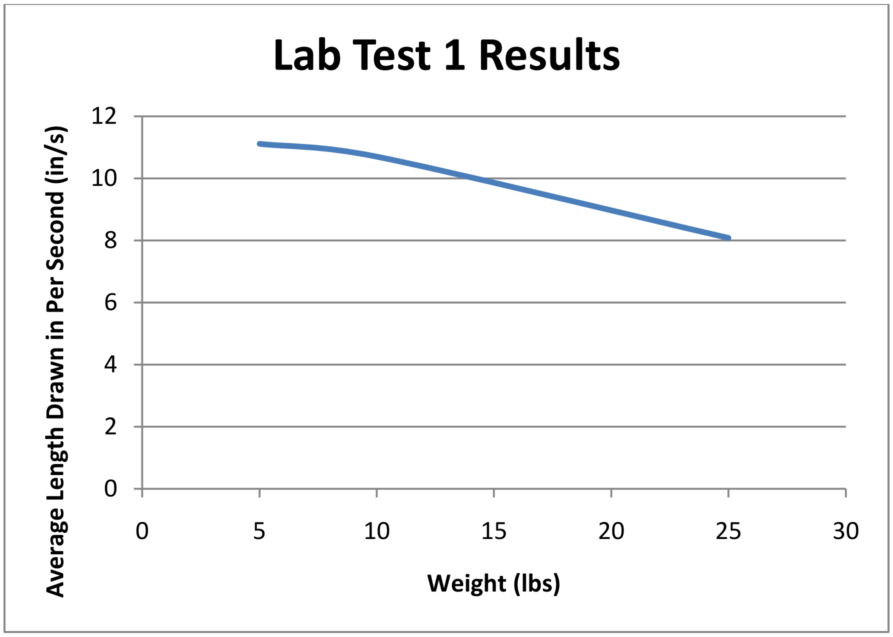


Figure 28: Spindle Speed Results

5.4 Field Test 3

For our third and final field test we went to the beach in Seabrook, NH to test the ability of the control box to pull in the trailing edge lines of the kite while the kite was in flight. To perform this test the kite was once again tethered to a truckwith the tether running through the control box. All of the components of the control system were securely inserted into control box, and additional string was attached to the trailing edge lines leading to each spindle. The tether was run through the box at an angle of forty-five degrees after modifications that resulted from the previous test were made.

During this test, conditions were much more optimal for our test with winds of about 15 mph. Due to the stronger winds, the kite was able to lift the full weight of the control box. Once the kite and control box were airborn, an attempt to stall the kite was made using the control box. This attempt was successful, so the kite and control box began to approach the ground. Before the control box hit the ground, the trailing edge lines were pulled in and the angle of attack of the kite was increased causing the kite to rise high into the air. The kite remained aloft for several moments, proving that our control box could indeed control the vertical motion of the kite.

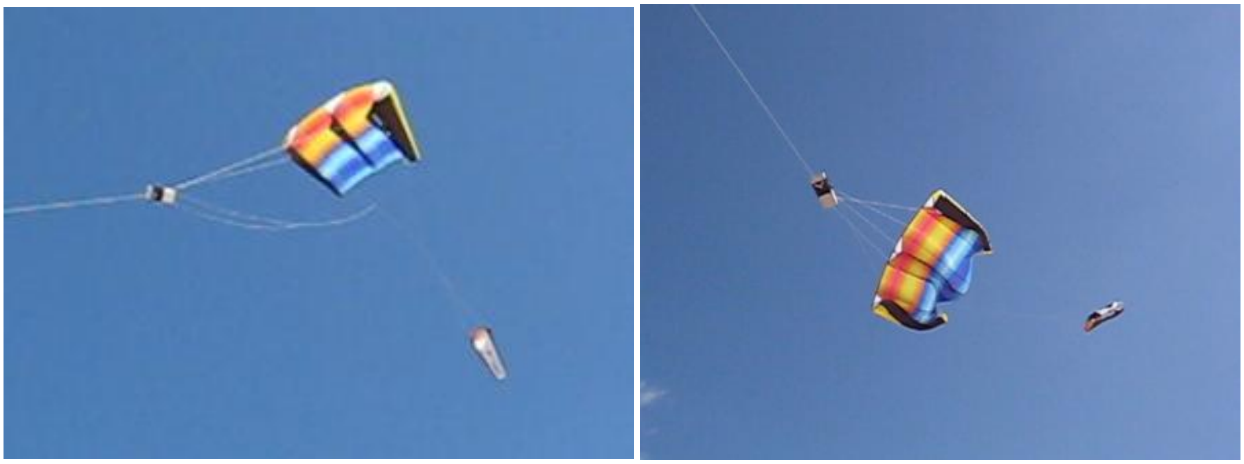


Figure 29: Lifting Kite with Loose TE Lines (Left), and Stalled Kite with Tight TE Lines (Right)

However, before the test was concluded there was an unfortunate incident. The force of the wind on the kite caused the main tether leading up to the kite to snap, which led to the kite and control box crashing into the nearby ocean. After the crash, the kite was recovered, but the control box was completely destroyed. The only parts of the control box that were recovered were the bottom piece of the box, a motor, a portion of a gearbox, and both spindles. Despite this incident, the main goal of the field test was accomplished, making it a success.

6. Conclusion

After extensive research and testing, the objectives of this project have been achieved. A remote control system was developed capable of adjusting the length of the trailing edge lines of the sled kite. This remote control system also endured lab testing as well as several field tests. However, throughout this project, there were several challenges that had to be overcome to complete the lab and field tests. First, knowledge of the motor, gearbox, and wiring components that were needed to assemble a safe and functioning system needed to be researched. Throughout this process, it was also necessary to keep in mind the second major challenge, designing and configuring a system which met a predetermined weight requirement while at the same time being able to handle the required load. The third and most challenging obstacle was obtaining and installing a new motor controller after the first motor controller was damaged during lab testing. Overcoming this obstacle was key in producing a functioning remote control system and completing the final field test.

Completing lab testing was essential to producing a functioning remote control system. The power and torque ability of the motor and gearbox was confirmed by lifting and reeling in weight off of the floor. Lab testing with the first and replacement motor controller were completed prior to the final field test to ensure that the remote control system would be able to withstand the required loads. As previously stated, the major obstacle during lab testing was replacing the damaged motor controller and finding a spare motor controller to complete the lab testing prior to the final field test.

Several field tests were conducted throughout the project. The first two field tests were essential in determining the weight requirement of the control box and determining the torque and power requirements for the remote control system. The final field test was critical in proving the ability and functionality of the remote control system. The remote control system was successful in controlling the kite and proved the remote control system prototype was successful.

Overall, the project was a success and the project objectives were achieved. The first step in generating wind power by kites has been achieved with minimal future work to be done. The second step to producing efficient energy through wind power by kites will be to develop a sprag clutch system to harness the power of the wind.

7. Future Work

The project team completed the goal of designing and testing a remote control system to direct the motion of the kite in preparation for developing a spool and sprag clutch system to convert the kite's motion into electrical energy. Much more work lies ahead, however, in order to optimize the control box design and develop this method of energy conversion. This section discusses the perceived future work required to complete the development of this kite power concept.

Due to the crash at the end of the final field test, the control box needs to be reconstructed, including ordering new motors, gearboxes, and electrical components. Concerning the design of the control box, the layout of the electronics inside the box needs to be redesigned. At the final field test, the project team encountered problems trying to position and secure the components in such a way that the trailing edge lines and main tether were unobstructed as they entered the box structure. The batteries, fuse, motor controller, and receiver all need to be secured in the box such that they fit logically alongside the motor assembly and do not move when the box is jarred while in flight. The components should also be intentionally positioned for easy connection and disconnection of wires before and after flight. Also, further testing of the control box design could be done to determine how long the box can control the kite on a single battery charge.

Since the main tether, consisting of two 50 lb. tension lines wound together, broke during field testing near the metal stops used to connect the box to the main tether, the material of the main tether must be changed. The project team recommends using 100+ lb. tension line for the main tether made from a material that is not easily frayed. The team suspects that a sharp edge on the metal stops may have contributed to the weakening of the tether, but a stronger material is necessary nevertheless. It is also recommended that all the edges on the metal stops are filed down to prevent them from damaging the tether when it is in tension.

Finally, the spool and sprag clutch system for generating electricity from the kite's motion needs to be designed and constructed. It is recommended that future teams look to rowing machine technology for their initial designs, and then adapt the mechanism to meet the specific needs of the kite system. A new gear system and electric generator may need to be purchased for the sprag clutch configuration and tested in the lab to find the estimated power output. Once the sprag clutch system is developed it can be tested in the field with the kite and control box attached. Most importantly, this power generation technology should continue to be developed keeping in mind the ultimate goal of implementing this system in a coastal, developing country. The construction materials, lifespan, and wind power economics of this kite power technology should all be considered so that the resulting system can potentially bring affordable and usable power to villages in a nation, such as Namibia, that has a great need for cheap and sustainable electricity.

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Appendix A: Lab Test 1 Data

5 lbs			
	Distance(in)	Time(s)	in/s
Trial 1	24.5	3.14	7.802548
Trial 2	25.5	2.86	8.916084
Trial 3	23	1.385	16.6065
avg	24.33333333	2.461667	11.10838

10 lbs			
	Distance(in)	Time(s)	in/s
Trial 1	14	1.56	8.974359
Trial 2	19	1.35	14.07407
Trial 3	15	1.66	9.036145
avg	16	1.523333	10.69486

25 lbs			
	Distance(in)	Time(s)	in/s
Trial 1	10.5	1.3	8.076923
avg	10.5	1.3	8.076923

Appendix B: Control Box Components

Part	**Part Name**	**Company**	**Model**
Motor	Dewalt 12V New Style Drill Motor	Robot Marketplace	12V New Style Drill Motor
Gearbox	Dewalt 3 Speed Gearbox	Robot Marketplace	3 Speed Gearbox
Motor Controller	Robo Claw Dual Motor Controller	Robot Marketplace	2x25A
Auxiliary Motor Controller	Stellaris Brushed DC Motor Controller	Stellaris	12-24V Brushed DC Motor Controller
Radio System	Spektrum DX5e 5-Channel 2.4Ghz Radio System	Robot Marketplace	Mode 2
Carbon Fiber Tubes	Carbon Fiber Tubes	Aerospace Composite Products	Roll Wrapped
NiMH Battery	NiMH Battery Pack	Powerizer	12 V 2200mAh
LiPo Battery	PowerEdge LiPoly Pack	Robot Marketplace	14.8V 4S Quad Cell 30C