Design of a Two-Kite, Rotary Power Cycle for the WPI Kite-Powered Water Pump

A Major Qualifying Project Report submitted to the faculty of WORCESTER POLYTECHNIC INSTITUTE in partial fulfillment of the requirements for the Degree of Bachelor of Science by:

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Abstract

This project continued the development of the WPI Rotary Kite Powered Water Pump to be used in developing regions. The water pump operates with Rokkaku kites that extend/retract two tether lines to spin a bike wheel, gear mechanism, and water pump axle. Improvements to the water pump include: design, fabrication, and testing of an on-board Arduino-based system to vary the angle of attack of the kite, implementing a dual kite system for non-manual tether line retraction, and allowing for easier mechanical disassembly of the pump. Field testing was conducted on the new system for the first time, and water pumping rates of 1000 liters/hour were achieved. These pumping rates were much higher than those achieved by a previous WPI kite-powered water pump based on a rocking arm concept.

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Authorship

All sections were written by each team member to a certain degree, while Justin Marsh and Daniel Long acted as overall document editors. This table describes the primary author only.

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</tr>
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Introduction

In the modern age, it has become increasingly apparent that continued reliance on non-renewable energy resources is both ecologically and economically reckless. It is with this mindset that renewable energy markets have begun to see more rapid growth within the past decade. Wind Power has seen the second largest amount of overall growth during this time period, behind Hydropower, with an extremely marked growth in developed countries. Several teams of WPI Students have worked to create a low-cost design to harness airborne wind energy in order to pump water. In particular, this Major Qualifying Project (MQP) is intended for use in developing areas of the world where access to clean and potable water is scarce and in many cases non-existent. Since water is a vital resource, it causes an extreme burden on developing societies when water is not readily available. The use of low cost airborne wind energy through kite power would make the acquisition of water possible where it was previously inaccessible, creating a positive impact on the quality of life in developing nations.

The project began as a rocking arm mechanism mounted on a wooden A-frame [1]. This design and its iterations were extensively field tested. A picture of this setup can be seen in the Figure 1. In this rocking arm set-up, a kite was tethered to one end of a beam, which was in turn attached to a wooden A-frame. This beam was fastened in a way so that it could rock up and down based upon the kite’s motion. Accordingly, when the kite was in the power phase it would ascend and provide the force to rock the arm upward. In the stall phase it would descend, allowing the tether line to go slack and the beam to fall. This produced a rocking motion that was used to mechanically create electricity.
Starting in 2015, this design was radically altered to a rotary power-cycle system [2]. Some immediate benefits that resulted from this design change were increases in efficiency as well as the ability for all required parts to be housed within the A-frame. Additionally, the type of kite was changed from a large power sled kite (86 ft²) to a smaller area Rokkaku kite (36 ft²) because the rotary power cycle system did not require as much total force to operate. A lower required force to operate allows the system to function effectively at lower winds speeds than previous designs were capable of. When combined with the smaller size kite and lighter weight of the A-frame, this allowed the system to become usable in a wider variety of environmental conditions. The new design can be seen in Figure 2.
Looking forward, our main goal for this iteration of the kite power MQP is to continue the development of this new rotary power cycle water pump. The two main design goals were the implementation of a feasible system to stall the kite while it is in operation, and developing a method by which the kite and its lines can be automatically retracted.
1. Background

1.1 Airborne Wind Energy

Airborne Wind Energy (AWE) is a form of renewable energy that uses tethered kites, balloons, or gliders to harness the energy from the wind while aloft. This is different from Wind Energy (WE) in that the system is not static on the ground. Instead, there is a tether anchoring the system to the ground which lets the device move about in the atmosphere at height. In general this method allows for better wind speeds (and thus better power generation), since it is not rooted to one section of land but can find faster and more powerful winds in any direction. The technology behind AWE poses as many benefits as challenges.

1.1.1 Benefits of AWE

As a renewable resource, AWE is more environmentally friendly than fossil fuels. Wind is readily available and limitless as long as the weather provides conditions necessary for wind. Figure 3 is a map of average wind speeds in Africa at a height of 200m. From this figure, it is evident that the northern and southern portions of the continent are well-suited to using a WE system to generate energy.

![Figure 3: Wind Speeds in Africa, IREA© [3]](image-url)
Though it is still being developed, AWE may be a more viable option than other forms of WE for a variety of reasons, the first being that AWE systems operate at higher elevations than non-airborne WE systems. This is beneficial because wind speeds increase with elevation, thereby increasing the potential power input. Figure 4 shows a map of global wind energy density at two different elevations; the left diagram is a 400ft height typical of turbines, and the right diagram is the wind at 2000ft, a space that can be occupied by AWE [4]. The higher altitudes see an increase of between 1.5-3 times more powerful winds with respect to ground level.

Figure 4: Wind Energy Density (kW/m^2) of the World at Different Heights, Joby Energy© 2010 [4]

A second reason AWE is superior to WE is that AWE systems typically have a smaller footprint than WE systems, both from a raw materials standpoint and from an aesthetic view. Wind turbines require a huge amount of material to manufacture, ship, assemble, and operate. When set up, they can be built as high as the Eiffel Tower, easily seen from across the landscape in large wind farms. In contrast, AWE systems like Altaeros Energies’ BAT blimp can consistently float higher than the cloud ceiling [5]. The physical ground footprint is minimal, and there is virtually no landscape pollution since the AWE device is tethered via thin cables. Manufacturing AWE systems costs significantly less materials
and money for a similar or better energy output when compared to traditional turbines. The visual impact and energy output of AWE versus turbines can be seen in Figure 5.

![Figure 5: Heights of Various WE Systems vs Energy Output, Altaeros Energies© [5]](image)

1.2 Different types or classifications of AWE Systems, incl. companies doing these

There are multiple types of AWE systems, varying by how they collect energy and how they send or use the energy. On-board AWE generates electricity on the airborne system itself, while ground AWE uses the airborne system to generate electricity on the ground.

1.2.1 On-Board Power Generation

The first form of AWE generation is on-board energy generation. Systems in this category convert the wind’s energy into useable energy onboard the aloft system itself. A high-profile example is the BAT designed by Altaeros Energies [5]. The BAT (Buoyant Airborne Turbine) in Figure 6 consists of a small turbine inside the chassis of a blimp. The turbine spins and creates a current using an electromagnet. The energy is then sent to the ground via an insulated conducting tether and processed further.
The Makani Kite, currently being experimented with at Google’s labs, is the second big on-board generation AWE system [6]. It resembles a plane but has eight DC motors with props to harness the wind. As seen in Figure 7, the rigid kite-plane moves in a roughly circular path similar to the motion of a wind turbine. The energy created by the motors is sent along the tether line like the BAT blimp above. On an average day in steady winds the Makani kite can produce around 600 kW of energy, enough to power 200 households.
1.2.2 Ground Power Generation

Though on-board power generation is a viable option, more companies and organizations are pursuing the track of generating the power on the ground. This option is usually more feasible because it eliminates the weight of a generation system in the air with the kite, as well as not having to worry about transporting energy hundreds of feet down a tether line to the ground. Most systems in this category pull on a generator in a base station, moving with the force of the wind. After rising in the power phase, the kites stall (decrease their angle of attack) in one manner or another and are retracted towards base using a minimal amount of energy. TwingTec and KiteGen have analogous designs in this category, with kites that produce 100 kW of energy. Figure 8 below shows the retraction and power phases in a ground generation AWE system.

Figure 8: Kite Phases of Flight, TwingTec AG© [7]

1.3 Previous WPI AWE Projects

The first kite-powered water pump was built in 2012 and consisted of the rocking arm design, modified to run a pump instead of generate electricity [8]. The rotary concept came about in 2015 with the team Chase et al. [9]. Over the summer of 2015, another WPI group was able to finalize the design and integration of the new two-wheeled line setup onto the A-frame structure [2]. This design and
integration also included the adaptation of the windmill pump that is being used. The adaptations implemented on the windmill water pump were an addition of a gear and bike chain attaching the pump’s rotational axle to the axle of the two bike wheels, as well as a reduction in length of the actual pump shaft or column.

With the completion of the summer 2015 group’s project a set of recommendations was compiled for use by future project groups. This list of recommendations included the idea of a gearing system, a redesign of the braking system, a redesign of the A-frame structure, a new pump as well as a new head pressure gauge for testing purposes. In addition to these recommendations the advisor of the project, Professor David Olinger, also had a set of recommendations for the team to take into account. Prof. Olinger’s recommendations included the design of a new stalling angle of attack system and a retraction system that would retract the power line of the kite while in stall mode. These two recommendations quickly became the focus of the project for the 2015-2016 academic year.
1.4 Project Goals

Our team was able to develop and define project goals that would ultimately result in the continued development of the WPI Rotary Kite Powered Water Pump. Our project was carried out to:

a. Develop Low-cost Airborne Wind Energy Water Pump for use in developing countries

b. Continued development of the WPI rotary kite-powered water pump.

The individual project goals were created and constantly revised throughout the course of the project in order to ensure the proper focus and scope for the project was maintained. Our team set the following three goals for the project:

1. Design a stall mechanism to change the Rokkaku kite’s angle of attack to create successive kite power and retraction phases

2. Design and implement a subsystem to retract the kite line during the retraction phase. After considering both a two-kite and rotary spring system, a two kite system was chosen for implementation

3. Create an improved multi-gear train system between the bike wheels and windmill pump axle with the capability for varying gear ratios

Figure 9: Updated Rotary Design Model
2. Methodology
2.1 Preliminary Design Choices and Field Testing

Shortly after testing began, the team experienced some difficulties with the PowerSled kites during a field testing day in late September 2015. Given these difficulties and the expertise from Blue Hills Observatory director, Don McCasland, the team made the decision to try a new, different design of kite that would better fit the new specifications of the kite powered water pump. Because of the integration of the new power cycle concept that replaced the rocking arm concept, less force from the kite was needed. The need for less force allowed the team to consider a kite design that previously would not have been considered. This new design, shown in Figure 10, is called a Rokkaku kite which is a much simpler and smaller kite design than the PowerSleds. The Rokkaku kite is much easier to fly at lower wind speeds and has increased stability during flight compared to the PowerSled.

![Diagram of Rokkaku Kite](public_domain)

Figure 10: Diagram of Rokkaku Kite (public domain)

With the adaptation of the new Rokkaku kite design came a new idea for the subsystem that would be responsible for the retraction of the power line of the kite during its stall phase. This new idea involved the introduction of a second kite that would enter its power phase while the first kite entered its stall phase. The power line of the second kite would be wrapped around the second bike wheel on the A-frame structure and would be attached to the first bike wheel. This attachment of wheels would
allow the line of the first kite to be retracted or reeled in while the second kite’s power line is drawn out during its power phase. This idea of retraction was weighed and compared against the previous idea of line retraction using a mechanical spring-loaded reel. This comparison can be seen in the table below:

<table>
<thead>
<tr>
<th>Two Kite System</th>
<th>Spring-loaded Reel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implement immediately</td>
<td>Help with slack control</td>
</tr>
<tr>
<td>Minimal modifications to current setup</td>
<td>Less complicated</td>
</tr>
<tr>
<td>Lines could tangle</td>
<td>Higher initial cost</td>
</tr>
<tr>
<td>Difficult to launch 2 kites</td>
<td>Can retract less total line (max ~125 ft)</td>
</tr>
<tr>
<td>Difficult to manually control</td>
<td></td>
</tr>
</tbody>
</table>

This initial comparison seemed to favor the spring-loaded reel line retraction subsystem. However, after future field-testing, the comparison between the two methods would be revisited.

Throughout the duration of A-term and B-term (October-December 2015) several field-testing sessions were conducted with the focus on understanding the performance and behavior of the Rokkaku kite design. The first testing session with the Rokkaku took place on October 10, 2015 at Brookwood Community Farm in Canton, MA. This testing session involved not only the Rokkaku kite, but also the entire A-frame and pump configuration. The team was able to achieve one successful, sustained launch of the kite with the power line attached directly to the spool (bike wheel) on the A-frame structure. With the kite flying stably in the air, the entirety of the tension was received by the spool and A-frame, which caused the kite to climb in altitude while the spool spun the axle of the water pump, thus pumping water. Due to the inconsistency of the wind, the kite did not remain in the air long enough for any measurements to be taken. However, some other critical notes on the systems performance were taken during the flight. Two major problems were noticed during the initiated “power” phase of the kite: the first that slack in the kite power line would develop with abrupt changes in wind velocity, and...
second that the slack line would come off of the spool and become entangled in the chain and gears. These problems would prove to be very easy to address with a simple realignment of the power spool gear to the water pump gear and the eye hook responsible for feeding line to the power spool with the spool itself.

![Figure 11: Bicycle Chain Connecting Power Spool and Pump](image)

The next testing session that the team had was held on November 8, 2015 and proved to be a very successful testing day for the team due to pristine wind conditions at Brookwood Farm. The wind conditions that day were recorded by the team to be steady at around 5-10 mph from a constant direction with gusts of up to about 20mph. Multiple launches were successfully carried out, providing the team with a total of six recorded trials with monitored parameters for each. The first parameter was a control set by the team that became labeled as the bridle setting, which was the length of the top bridle line vs. the bottom bridle line, with a total of three different bridle settings used. Bridle setting ‘0’ was the initial factory setting that the kite came with, setting ‘1’ was a shorter top bridle, and ‘2’ was longer. The bridle setting along with the rest of the recorded parameters for each trial were recorded in Table 2 below. One parameter not in the table was the average force or kite line tension; this was recorded at 6.86 pounds for the ‘0’ factory setting and 4.44 pounds for the modified ‘2’ bridle setting.
A third field testing day was held on November 15, 2015 at the same location. This field testing session was also proved to be a very successful day of testing for the team as a total of nine trial launches and flights were recorded. The team recorded similar parameters for these runs as in the previous testing session with the addition of the load or pressure on the pump as well as the angle of the kite power line. In order to simulate the load on the pump the team attached a simple hose spigot valve to the pump and would count the number of turns on the valve (four complete turns shut the valve entirely). Although there was no way to precisely measure the pressure put on the pump by the valve, the team is confident the valve was successful due to the result of trial 5, where the valve was completely closed and caused a backward flow of the pump, thus proving an induced pressure at the pump exit.

In addition to simulation of head pressure on the pump, the team was also able to hit a huge milestone when two kites were successfully launched at the same time with each one attached to their respective spool. This was done by first launching the Rokkaku and allowing it to ascend until stable. At the same time, a delta kite was attached to the second reel and walked to the end of the field, with all of its line out and on the ground. The two line spools (bike wheels) were then connected to each other so that they would spin in the same direction. The Rokkaku line was then released and thus ‘reeled in’ and

<table>
<thead>
<tr>
<th>Bridle Setting</th>
<th>Time Elapsed (s)</th>
<th>Volume (L)</th>
<th>Flow Rate (L/s)</th>
<th>Flow Rate (L/hr)</th>
<th>Rotation (#)</th>
<th>Rotation (per sec)</th>
<th>Rotation (per min)</th>
<th>String Length (ft)</th>
<th>VRel (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15</td>
<td>4</td>
<td>0.23</td>
<td>840</td>
<td>25</td>
<td>1.67</td>
<td>100</td>
<td>150</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>29</td>
<td>4</td>
<td>0.14</td>
<td>497</td>
<td>29</td>
<td>1.00</td>
<td>60</td>
<td>174</td>
<td>6</td>
</tr>
<tr>
<td>0</td>
<td>49</td>
<td>4</td>
<td>0.09</td>
<td>309</td>
<td>29</td>
<td>0.59</td>
<td>35.51</td>
<td>174</td>
<td>3.55</td>
</tr>
<tr>
<td>1</td>
<td>27</td>
<td>4</td>
<td>0.16</td>
<td>560</td>
<td>35</td>
<td>1.30</td>
<td>77.78</td>
<td>210</td>
<td>7.78</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>3</td>
<td>0.32</td>
<td>1160</td>
<td>21</td>
<td>2.33</td>
<td>140</td>
<td>126</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>4</td>
<td>.12</td>
<td>420</td>
<td>29</td>
<td>0.97</td>
<td>58</td>
<td>174</td>
<td>5.80</td>
</tr>
</tbody>
</table>
launched the delta kite while ascending further into the sky. This trial turned out to work much better than expected despite some difficulties flying the less stable delta kite, and the team was able to reconsider the two kite line retraction system due to the trials' success. The data from this test session day can be seen in Table 3 below:

Table 3: Field Testing Data 11Nov2015

<table>
<thead>
<tr>
<th>Run #</th>
<th>Load</th>
<th>Wind Velocity (mph)</th>
<th>Time (s)</th>
<th># of Spool Rotations</th>
<th>Tether Angle (degrees)</th>
<th>Volume Pumped (Liters)</th>
<th>Pump Rate (L/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
<td>3.1</td>
<td>42</td>
<td>N/A</td>
<td>No mes.</td>
<td>3</td>
<td>257</td>
</tr>
<tr>
<td>2</td>
<td>None</td>
<td>3.1 w/ 5.0 gust</td>
<td>27</td>
<td>31</td>
<td>No mes.</td>
<td>3</td>
<td>396</td>
</tr>
<tr>
<td>3</td>
<td>None</td>
<td>0.9 w/ 3.4 gust</td>
<td>52</td>
<td>36</td>
<td>23-30</td>
<td>4</td>
<td>276</td>
</tr>
<tr>
<td>4</td>
<td>2.5 turns</td>
<td>1.4 w/ 3.0 gust</td>
<td>70</td>
<td>37</td>
<td>No mes.</td>
<td>4</td>
<td>205</td>
</tr>
<tr>
<td>5</td>
<td>4 turns</td>
<td>Aborted run</td>
<td>too much</td>
<td>pressure</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>6</td>
<td>2.5 turns</td>
<td>3.6 w/ 6.5 gust</td>
<td>35</td>
<td>37</td>
<td>32-37</td>
<td>4</td>
<td>411</td>
</tr>
<tr>
<td>7</td>
<td>2.5 turns</td>
<td>3.9 w/ 4.1 gust</td>
<td>46</td>
<td>37</td>
<td>No mes.</td>
<td>4</td>
<td>313</td>
</tr>
<tr>
<td>8</td>
<td>2.5 turns</td>
<td>3.8</td>
<td>32</td>
<td>36</td>
<td>25-35</td>
<td>4</td>
<td>450</td>
</tr>
<tr>
<td>9 (2 Kites)</td>
<td>None</td>
<td>4.3</td>
<td>68</td>
<td>N/A</td>
<td>No mes.</td>
<td>4</td>
<td>158</td>
</tr>
</tbody>
</table>

Lastly, tests were conducted to determine how much additional weight could be added to the kite's spars without inhibiting the kite’s ability to fly successfully. The purpose of this testing was to help inform the teams decisions about how heavy an on-board servo or motor setup could be and where on the kite it can/should be placed. The method by which this was tested was to tie 1-2lb chains to the kite at various locations and attempt to fly the kite. The figure shows the weight testing set-up with two chains in use, one located at the upper intersection and the other at the lower intersection.
The initial results that were yielded from these tests showed that even with a single pound of weight added onto the kite its flight was noticeably affected, producing a fishtailing motion. Even with this motion present, the kite was generally still able to maintain flight and remain airborne. This was not the case when 2+ pounds of weight were added to the kite. Not only did the fishtailing motion still occur, it became much more pronounced and the kite effectively could not maintain flight for more than roughly ten seconds. When the weight was added to the intersection of the bridle lines with the main tether, the kite was nearly impossible to fly. The most stable location was on the top spar, and the second most stable was on the bottom spar. However, the bottom spar location still had pronounced fishtailing and tended to dive-bomb the ground. From the testing it became apparent that any on-board housing as well as any motor set-up would need to be as lightweight as possible in order to affect the kite's flight as minimally as possible.
2.2 Further Design Choices and Implementation

Creating a reliable yet lightweight method of stalling the Rokkaku kite was imperative and would be a large part of the design aspect of the project. Through research, the team arrived at two potential methods by which a motor could be used to stall the kites: a servo based method and a stepper motor based method. From that point the team decided to move forward with developing both of these methods into functioning systems that could retract kite line in a laboratory setting.

To begin the design of the stalling method systems, an understanding of the forces the kite would be experiencing during its flight was necessary. In order to understand this, a flat plate aerodynamic assumption was made and the team was able to calculate suspected coefficients of lift and drag for the kite at the anticipated angle of attack. The anticipated angle of attack was 30 degrees these calculations were performed. Using these coefficients and a simple aerodynamic force equation, theoretical lift and drag forces were calculated. These forces were vital in the design of the stalling systems because the torque ratings of each motor would have to be great enough to overcome the total force on the kite. The third equation used for this calculation can be seen below and was taken from page 15 in reference [10].

![Figure 13: Flat Plate Coefficient Curves](image)
Table 4: Variables for Torque Calculations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>Air Density</td>
<td>( 1.22 \frac{kg}{m^3} )</td>
</tr>
<tr>
<td>( A )</td>
<td>Kite Area</td>
<td>( 3.3445 \text{ m}^2 )</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Wind Velocity</td>
<td>( 3.38 \frac{m}{s} )</td>
</tr>
<tr>
<td>( T )</td>
<td>Servo Torque</td>
<td>( 1.08 \text{ N} \cdot \text{m} )</td>
</tr>
<tr>
<td>( C_L )</td>
<td>Lift Coeff.</td>
<td>( 0.86 )</td>
</tr>
<tr>
<td>( C_D )</td>
<td>Drag Coeff.</td>
<td>( 1.5 )</td>
</tr>
<tr>
<td>( F_L )</td>
<td>Lift Force</td>
<td>( 15.79 \text{ N} )</td>
</tr>
<tr>
<td>( F_D )</td>
<td>Drag Force</td>
<td>( 27.54 \text{ N} )</td>
</tr>
<tr>
<td>( F_T )</td>
<td>Total Force</td>
<td>( 72.57 \text{ N} )</td>
</tr>
<tr>
<td>( L )</td>
<td>Lever Arm Length</td>
<td>( 1.49 \text{ cm} )</td>
</tr>
</tbody>
</table>

\[ F_L = \frac{1}{2} \cdot \rho \cdot A \cdot \nu^2 \cdot C_L \]  
[1]

\[ F_D = \frac{1}{2} \cdot \rho \cdot A \cdot \nu^2 \cdot C_D \]  
[2]

\[ F_T = \frac{1}{2} \cdot \rho \cdot A \cdot \nu^2 \cdot \sqrt{C_L^2 + (C_D + C_D,power)^2} \]  
[3]

\[ L = \left( \frac{T}{F_T} \right) \cdot 100 \]  
[4]

Table 5: Components for Motor Setups

<table>
<thead>
<tr>
<th>Component</th>
<th>Servo</th>
<th>Stepper Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>HiTec HS-755HB</td>
<td>NEMA XXXX 183in*oz torque</td>
</tr>
<tr>
<td>Power</td>
<td>12V NiMH 2000mAh battery</td>
<td></td>
</tr>
<tr>
<td>Electronics Board</td>
<td>SparkFun RedBoard w/ Arduino</td>
<td></td>
</tr>
<tr>
<td>Motor Driver</td>
<td>N/A</td>
<td>DRV8825 High Current Driver</td>
</tr>
</tbody>
</table>

The team determined that the technical specifications of the HiTec HS-755HB Servo motor were sufficient, given the determined estimation of the maximum force the line of the kite would experience. To setup the system, we connected the stepper motor to a Sparkfun RedBoard with Arduino, which was in turn connect to a 12 Volt Battery pack. In order to allow full rotation of the servo, the team removed an interior 180 degree limiter from the gearing system [11]. A picture of this overall setup can be seen in Figure 14.
A stepper-motor based setup was developed in tandem with the servo. The stepper motor used the same SparkFun Redboard and 12V NiMH battery as the servo, but required a stepper motor driver in order to correctly pulse and rotate the motor. Schematics for wiring the stepper motor are provided in Appendix D. After testing, the stepper motor simply did not have enough torque to properly reel in the top bridle line of the kite. Lab tests showed it could lift a maximum of 2lb, whereas the servo could lift more than 8lb. Due to this testing, as well as the increased complexity in the circuitry, the stepper motor setup was abandoned in favor of the servo motor setup.
After determining that the servo based setup would be the most effective for this project iteration, a housing design was created that could house the servo as well as the SparkFun Redboard and 12 Volt battery pack. This housing was designed in a way that it could be easily replaceable should any portion break, and also extremely light weight based on the conclusion drawn from the previous testing of added weight on the kite during flight. Altogether, the housing along with the entirety of the servo motor setup weighed approximately 630 grams. An additional feature of this housing was the inclusion of two small holes through which lengths of string attached to the bridle lines could be fed through and then attached to the servo. Lastly, the decision was made to situate the servo and it’s housing on the top spar of the kite for the purposes of testing since that setup seemed to affect the kite’s flight the least when weight testing was conducted.

Concurrent with the creation of the motor housing, an Arduino code was developed to control the servo’s motion. First, it was necessary to determine how much line must be reeled in to sufficiently change the angle of attack and begin the kite’s stall phase, and then program in an appropriate amount of rotations for the servo to take in that amount of line. Ultimately, it was determined that between three to six inches of line need to be taken in from the top of the bridle in order to change the angle of attack enough to induce the stall phase. It is important to note that this desired effect can also be achieved by letting out that same amount of line, should the servo be attached to the bottom spar of the kite. With this knowledge in mind, a code was created that would take in the appropriate amount of line, hold that line for a predetermined amount of time and then release the line that it had taken in. This code can be found in Appendix A. After multiple short circuits in the lab, a switch was added to the stepper motor setup that, when turned on, would turn on the servo set up and begin the code.
2.2.1 MATLAB Simulation

The MATLAB simulation created for the Two-Kite, Rotary Power System for the WPI Kite Powered Water Pump was based off of the work of Professor David J. Olinger, Jitendra S. Goela, and Gretar Tryggvason [12]. Their work produced the original code that simulated the kite powered rocking arm design for the WPI Kite Powered Water Pump. The following development of the four main ordinary differential equations to describe kite behavior in flight also comes from their work [13].

The following table gives the nomenclature of variables is used throughout the entire simulation to successfully simulate the motion of the kite-powered system in the power or ascent phase of the kite.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_K$</td>
<td>Lifting surface of kite</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Drag coefficient of kite</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Lift coefficient of kite</td>
</tr>
<tr>
<td>$F_{DK}$</td>
<td>Drag force on kite</td>
</tr>
<tr>
<td>$F_{LK}$</td>
<td>Lift force on kite</td>
</tr>
<tr>
<td>$g$</td>
<td>acceleration due to gravity</td>
</tr>
<tr>
<td>$L_1$</td>
<td>tether length from kite to pulley</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
</tr>
<tr>
<td>$V_w$</td>
<td>wind speed</td>
</tr>
<tr>
<td>$V_K$</td>
<td>kite velocity</td>
</tr>
<tr>
<td>$V_R$</td>
<td>wind velocity relative to kite</td>
</tr>
<tr>
<td>$V_1, V_2$</td>
<td>components of $V_K$ in direction of tether and perpendicular to tether</td>
</tr>
<tr>
<td>$W_K$</td>
<td>weight of kite</td>
</tr>
<tr>
<td>$W_{La}$</td>
<td>load during ascent</td>
</tr>
<tr>
<td>$\phi$</td>
<td>angle of inclination of $V_R$ with horizon</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle of inclination of tether with horizon</td>
</tr>
<tr>
<td>$\beta$</td>
<td>angle of inclination of $V_K$ with horizontal</td>
</tr>
</tbody>
</table>

The figure below shows the forces that are involved with the flying of a kite in order to power a water pump. In part (a) of the figure the velocity triangle in the rest frame of the kite is shown. From

![Image](image.png)

*Figure 15: (a) Velocity triangle in rest frame of kite (b) Forces on the kite, velocity and angle definitions (c) Forces acting on a differential tether length [10]*
this velocity triangle we are able to relate the wind velocity relative to the kite. This relationship can be seen in Equation 1. Equation 2 shows how $\phi$, the angle of inclination that VR has with the horizon.

$$V_R^2 = V^2 + V_K^2 - 2V * V_K \cos \beta$$  \[5\]

$$\tan \phi = \frac{V_K \sin \beta}{V - V_K \cos \beta}$$  \[6\]

After the relative wind velocity and its angle of inclination are known, the lift and drag forces acting on the kite can be calculated. In part (b) of the figure these two forces and their orientation can be seen in relation to the kite itself. The forces are described by the two following equations:

$$F_{LK} = 0.5 \rho * V_R^2 * C_L * A_K$$  \[7\]

$$F_{DK} = 0.5 \rho * V_R^2 * C_D * A_K$$  \[8\]

Now with these forces, we will define two directions. Direction 1 will be the direction along or parallel to the tether and Direction 2 will be the direction normal or perpendicular to Direction 1. In order to simplify the system for the purpose of simulation, a few assumptions can be made.

1. Due to the small magnitude of tether weight compared to kite weight, the weight of the tether can be neglected.

2. With the weight of the tether being neglected, we can also neglect the lift and drag forces on the tether because of their small magnitude compared to the lift force of the kite.

3. A centripetal acceleration term appears when carrying out a force balance of the kite, however, this term is small in comparison to the load force on the kite and can also be neglected.

With these assumptions made, the force balance of the kite can be simplified down to two equations which are the first two first-order equations that describe the motion of the system will in the power phase. These two equations are as follows.
\[
\frac{dV_1}{dt} = \frac{(F_{LK} \sin(\theta+\phi) + F_{DK} \cos(\theta+\phi) - W_{La} - W_K \sin \theta) \cdot g}{(W_K + W_{La})} \tag{9}
\]

\[
\frac{dV_2}{dt} = \frac{(F_{DK} \sin(\theta+\phi) + W_K \cos(\theta+\phi) - F_{LK} \cos(\theta+\phi) + 2W_K V_1 V_2) \cdot g}{W_K} \tag{10}
\]

With these two first-order equations, we need two more in order to fully describe the motion of the system during its power phase.

\[
\frac{dL}{dt} = V_1 \tag{11}
\]

\[
\frac{d\theta}{dt} = -\frac{V_2}{L_1} \tag{12}
\]

These four first-order equations are the governing equations within the MATLAB simulation that was provided by Prof. Olinger and his colleagues Goela and Tryggvason. With this simulation accurate predictions of the results that should be seen when testing the entire system’s operation in the field. The original MATLAB script received was slightly adapted in order to better fit the simulation of the current rotary kite powered water pump design’s operation.

The additions to the MATLAB code included a better representation of the lift and drag coefficients for the kite at higher angle of attacks nearing 45-60 degrees. Previously, the MATLAB code had a lift and drag coefficients model that was only valid for low angles of attack below stall conditions. In order to make this addition, the flat plate aerodynamic assumption was made again for the kite. The graphs of both the lift and drag coefficients for a flat plate can be seen in Figure 16 and Figure 17, respectively. In both of these graphs, a best fit curve was created and these best fit equations are what were entered into the MATLAB simulation code and can be seen in the graphs themselves and below.

\[
C_l = -1.6211 \alpha_{eff}^2 + 2.5465 \alpha_{eff} + 2 \times 10^{-15} \tag{13}
\]

\[
C_d = -1.1917 \alpha_{eff}^3 + 2.8079 \alpha_{eff}^2 - 0.197 \alpha + 2 \times 10^{-15} \tag{14}
\]
Additionally, the team was able to produce more output plots from the MATLAB simulation code that are helpful in understanding the theoretical behavior of the system and will be useful in the future when comparing field test results to expected, theoretical values from the simulation.
3. Results
3.1 Lab Testing

In an effort to test that the servo could hold the line in place when tether forces were acting upon the kite, a laboratory experiment was conducted. For this experiment, a five-pound weight was attached to the bridle lines of the kite, and the kite itself was hung from the ceiling by lines attached to the corners of the top and bottom spars. This setup is displayed in Figure 18. It was found during this testing that the servo was both capable of pulling the five-pound weight upward as well as keeping that weight in place when it was meant to.

Figure 18: Hanging Weight Test

A similar lab test was conducted, essentially turning the first setup upside-down; the kite was reversed, the weight hung from lines attached to the corners of the spars, and the kite was hung by the bridle lines. The team hoped that during this test the kite would show a more apparent change in the angle of attack, instead of just lifting the weight. During this testing it became apparent that the servo
had trouble when attempting to change the angle of attack. It is possible that the increased difficulty is due to increased friction or the trouble of lifting itself along with the weight. Regardless, the team was confident in the servo’s abilities due to the success of the first test and the theory that the sideways orientation of the kite in flight—as opposed to flat to the ground—would be easier for the servo to affect.

3.2 MATLAB Simulation Outputs

Although the MATLAB simulation is still under optimization and improvements, the output returned by the current program has been useful in understanding how the system should operate when in the field. The simulation represents the system fairly accurately and can produce data useful for comparison to the data recorded during the preliminary testing during the fall of 2015 and the final testing in the spring of 2016.

The MATLAB simulation as is right now, currently outputs data for 20 seconds of simulation time and is only capable of simulating the power phase of the system. This length of time can be extended in order to obtain a better understanding of the power phase of the two-kite rotary water pump system fairly easily through simple adjustments of the code. The initial, baseline wind condition that was used was a wind velocity of seven miles per hour.

![Figure 19: MATLAB Output Graph](image)
Figure 19 is an output graph from the MATLAB simulation and it represents the resulting coefficients of lift and drag from the kite throughout the simulation versus the effective angle of attack. This output is skewed due to the fact that the focus of the graph is on higher angles of attack from around 40-60 degrees. The reason the image is distorted and looks linear is because of the fact that the MATLAB code is graphing a data point for each curve at (0, 0). This should not be the case and when resolved the relationships should represent that of the flat plate assumptions for lift and drag coefficients versus angle of attack in the given angle of attack range.

Figure 20 consists of two more plots that are outputs of the MATLAB simulation code. The first plot shows the relationships of both the lift and drag forces that are acting on the kite during its power phase in the given baseline wind conditions of seven miles per hour. These forces are slightly higher than the team had originally calculated when choosing the servo motor for the angle of attack controller. The second graph in Figure 20 represents the effective angle of attack of the kite as it ascends.
in altitude during the power phase. This graph can be helpful to understand the problems that may or may not be occurring in the current code.

![Kite and Tether Velocities](image1.png)

![Kite Position](image2.png)

![Cumulative Water Pumped](image3.png)

![Lift and Drag Coeff.](image4.png)

Figure 21: MATLAB Output Graphs

In Figure 21 there are four graphs that can be seen. Each of these graphs describe what the actual field tests should look like, theoretically. In the first graph on the top right, the kite and tether velocities can be seen how they change over time. A key thing to note from this graph is how the two velocities have different accelerations in the beginning where the kite is first being launched in the simulation. After a time of about five to six seconds, the two velocities reach the same value which is expected as the kite is now in the power phase and gaining altitude after the launch. The graph in the upper right hand corner shows the expected position of the kite on the x and y axes. The X-axis represents the kite’s horizontal distance from the pump and frame while the Y-axis represents the kite’s altitude above the pump and frame. This is useful data for field testing so that accurate estimations of the kite’s position can be made for different reasons including object avoidance and safety factors. In the bottom left hand graph, the cumulative water pumped over the time of simulation is shown. This is
important for comparison to results that are recorded in field tests to see if the system is operating at the efficiency that it should be.

Additional output from the MATLAB simulation can be seen in Figure 22. This additional output was a simulation that ran for a total time of two minutes. The point of this simulation output was to show how the system would function and how much water would be pumped at a longer time of operation than just 20 seconds. These were only a couple graphs produced with different settings and input than the baseline and can be found in the appendices.

Further improvements of the code would include refinement of the kite characteristics that are required by the code and vital to the output results. In addition to this, the code needs the addition of...
the stall phase of system and a possible alteration that would include the oscillation of each kite between the two phases.

3.3 General System Improvements

In addition to developing the motor setup for the kite, it became readily apparent that there was a need to make various improvements upon the actual infrastructure of the A-frame in order to ensure an overall smoother operation of the pump system. These modifications, as well as the reasoning behind each, are detailed in the table below. For reference a picture of the chain tensioners is included in Figure 23. Overall, these improvements were found to help the functionality of the system as chain tensioning and multi-gear system is not fully developed yet, so we did have problems testing with this in the field.

<table>
<thead>
<tr>
<th>Modification:</th>
<th>Reason:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bike Chain Tensioning System (attachment of chain wheels and springs)</td>
<td>Used to address the issue of the bike chain slipping off the gears. Can effectively slow down the rate at which the bike wheels can spin</td>
</tr>
<tr>
<td>Use of a non-threaded rod to place the bike wheels on</td>
<td>Allowed for a sturdy fastening of the wheels in place that was less likely to slip laterally</td>
</tr>
<tr>
<td>Multi-gear cassette attached to initial power line kite wheel</td>
<td>Allows for use of gears of various size to either speed up or slow down the speed at which the bike wheels can turn</td>
</tr>
<tr>
<td>Removal of nuts as a securing method of both bike wheels</td>
<td>Better combat lateral displacement of bike wheels along rod</td>
</tr>
<tr>
<td>Removal of links of bike chain</td>
<td>Increased chain tension, reducing the likelihood of the chain slipping off gears during high velocities</td>
</tr>
<tr>
<td>Removal of rocking arm from A-frame</td>
<td>No longer necessary and made for more difficult transport of the entire system</td>
</tr>
</tbody>
</table>
3.4 Spring testing

In order to test the full modified system, with all of the various improvements and additions, two D-term (April 2016) testing dates were scheduled at Brookwood Farm. The tests were conducted in the same field in which autumn testing was conducted, both for the required space and easy comparisons between tests. On the first test date, the main objective was to test whether or not the servo system would operate properly once airborne. The servo was programmed to wait five minutes from being powered on before trying to reel in line and engage the stall phase. It then was to maintain the stall phase for a short amount of time before re-releasing the bridle line and engaging the power phase once more.

Throughout various trials it was difficult to launch the kite into the air. For a majority of the attempted trials the kite would briefly remain airborne, but would fall to the ground before the servo had a chance to attempt to engage the stall phase. However, there was one trial during which the kite successfully launched and the team was able to assess the operation of the servo. During this trial, it was
found that the servo successfully changed the angle of attack, therefore initiating the stall phase. Furthermore, the servo was able to maintain the kite’s stall phase and then re-initiate the power phase. More attempts were made to replicate this outcome, but the team could not subsequently launch the kite. In addition, both kites suffered damage to their main spars from failed trials, which the team determined to be great enough to prevent further attempts at testing on that date.

Additional testing was conducted at Brookwood Farm a week later. The kite spars were repaired before this by reinforcing the interior with a fiberglass rod and 3M multipurpose glue. On this testing day the wind conditions were not as favorable as the team would have liked. Despite the low wind conditions, the kite was able to be successfully launched. However, flight was not sustained long enough in order to see the effects of the servo stall system. The team experimented with multiple bridal settings on the kite in order to adjust for the low wind conditions and the weight of the servo system. These changes in the various settings did not help the kite sustain flight in the low wind conditions, but provided a great learning opportunity for the team.

One important thing noted from this testing day was the fact that the weight distribution of the servo system on the kite is extremely important; even the slightest adjustments of the location of the servo system could alter the kite’s flight behavior. The team found that the best location for the servo system is just below the top spar of the kite with the weight of the servo system balanced on either side of the vertical spar. If the weight of the servo system is not balanced about the vertical spar of the kite, during launches the kite would tend to fly to the side where the weight was greater.

Another significant note from the day was that the amount of line to be taken in by the servo in order to stall the kite could possibly be much less than previously thought. According to Don Mac from The Blue Hills Observatory, given the kite’s bridals factory settings the amount of line needed to successfully cause stall of the kite could only be about a half of an inch, much less than the previous
amount of a half of a foot. It was also understood that if the servo system were to bring in too much bridal line length, it may cause the kite to nose dive due to the loss of wind force combined with the weight of the servo system.
4. Conclusions and Future Recommendations

From the various tests conducted and the corresponding results, the team was able to draw certain conclusions and formulate certain recommendations for areas of potential improvement.

First, it was very clear from both field and lab testing results that a stronger servo, or even multiple servos, would be needed for this system to be more reliable. In particular, there is a need for a higher holding torque in order to actively maintain the stall phase of the kite. Also, a higher holding torque would ultimately allow the system to properly function in a wider variety of conditions, as the current servo can only properly function in wind conditions between approximately five to ten miles per hour. This is inherently problematic when considering that the intended altitude of flight is greater than that in which our field-testing occurred. At higher altitude the wind speed will be greater, which will increase the amount of force on the kite and in turn increase the required hold torque of the servo.

Next, an important element that should become incorporated into the system at large is the ability to actively communicate to the servo and modify its behavior in real time. This could likely be achieved through either the use of a WiFi or radio network. This is a system that the team would highly recommend since this can allow for active adjustments based upon changing conditions in the field. The ability to communicate with the servo would also lead to overall increased control of the system by the operator. Communication between the kites would allow both kites to be able to sync up the transitions between the power and stall phases. After discussions with Richard Eberheim, a Robotics major at WPI, it appears that using the X-Bee communications modules on the SparkFun RedBoard would be the most viable option. Synchronization between the two kites is imperative for successful operation of the two-kite system.

Additionally, the team would encourage the consideration of a different housing for the system that does not require the current A-frame. The current frame is problematic in many ways, and is
ultimately not necessary as-is when considering the needs of the rotary-based design as opposed to the previous rocking-arm method. One particular concern with the A-frame is that it is not as easily transportable as other alternatives could be due to its large size and weight. Various parts of the frame are very badly splintered or constructed out of old wood that would need extensive reinforcing.

Lastly, but most importantly, it warrants note that this particular pump design has been much more successful than previous iterations of this project, at least when gauged by water pumping ability. While the above mentioned changes could surely improve the system greatly, it is also possible to simply continue optimizing the pump system as-is by making smaller adjustments throughout. Also, it is important that the design testing continues, including testing with the full two kite system in the air operating as a complete unit.

To conclude, the work done on this project has helped to highlight that this method of utilizing kite power to pump water is not just viable, but can also be very efficient as well. Although there are various elements that still need to be tested more completely, it is possible to state this project to be successful in its purposes.
5. References

6. Appendices

Appendix A – Arduino Code for Servo

#include <Servo.h>

Servo myservo; // create servo object to control a servo
// twelve servo objects can be created on most boards
// .write(180) is CW
// .write(0) is CCW

void setup() {
  delay(180000); //delays 10s for testing
  myservo.attach(9); // attaches the servo on pin 9 to the servo object
}

int count=0;
int del=100;
int in=2000;
int out=3500;

void loop() {  
  myservo.write(0);  //pulls top bridle in to stall kite
delay(in);
  while(count<10){
    myservo.write(87);
delay(del);
    myservo.write(86);
delay(del);
    myservo.write(87);
delay(del);
    myservo.write(86);
delay(del);
    count++;
  }
  count=0;
delay(100000); //delay to let kite stall

  myservo.write(180); //lets out string, entering back into power phase
delay(2000);
  myservo.detach();
delay(30000);
  myservo.attach(9);
}

This code is for when the servo is retracting the top bridle. When the servo is bringing in the bottom bridle the same code can be used just with different delay times.
Appendix B – Additional MATLAB Outputs

The MATLAB figures on this page represent the simulation ran with a heavier kite weight of 10 Newtons instead of the baseline kite weight of 8 Newtons.
The MATLAB outputs on this page represent the simulation ran with a heavier kite weight of 12 Newtons instead of the baseline kite weight of 8 Newtons.
The output on this page represents the simulation ran with a kite weight of 12 Newtons and a wind speed of 10 mph. It was found that the simulation tended to get temperamental as higher and higher wind speed values were entered.
Appendix C – Trailer Poster

WPI Kite-Powered Water Pump
Aerospace Engineering Program
Worcester Polytechnic Institute

GOALS
- Kite-powered water will help alleviate water shortages in underdeveloped nations
- Low-cost alternative to water pumping windmills

OPERATION
Two small (15 ft²) Rokkaku kites rise (power phase) and fall (stall phase) on tether lines, opposite of ea. other
During each kite’s power phase the tethers rotate two bike wheels locked together, which rotate the water pump axle and pump water
The kites stall via an attached motor, which changes their angle of attack and allows them to descend easily

FOR MORE INFORMATION:
www2.me.wpi.edu/wpi-kites
Appendix D – Wiring Schematics for Stepper Motor and Driver

Figure 24: Wiring for Stepper Motor to Driver and RedBoard [14]

Figure 25: Wiring for Stepper Motor Driver (public domain)