Redesign of the WPI Rotary Kite-Powered Water Pump

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ABSTRACT

This project continued to optimize the design of the WPI Rotary Kite Powered Water Pump. This system is intended to provide cheap and reliable access to clean drinking water for developing nations. The main results of the project include producing a desired flow rate of about 600 L/hour, implementing a kite pump frame that lowered the center of gravity and reduced height below seven feet, producing an improved kite control box with remote control capabilities, implementing a rotary spring for kite retraction, and demonstrating intended control of the kite.

ACKNOWLEDGMENTS

The design, testing and production of this report would not have been possible without the guidance and expertise of several key individuals who must be recognized. Professor David Olinger provided extensive feedback on design, testing and the report. Without his expertise and passion for wind energy and kite power the project would not have been possible. We would also like to thank Don McCasland from the Blue Hills Weather Observatory for his kite expertise and assistance. Without his knowledge and guidance, the project would not have been possible.

AUTHORSHIP

The execution of this project was split into four subgroups. Each subgroup also wrote the sections of this paper directly related to their part of the project. The remaining sections of the paper were evenly distributed throughout the project team.

The subgroups consisted of the following members:

- Motorized control of the kite – Jonathan Van Blarcum and Hanqing Zhao
- Retraction forces and gear ratios – Christopher Beauchemin
- Redesigning of the frame – Alexander Draper and Obadiah Munene
- Surface pumping system – Andrew Bauer

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CHAPTER 1: INTRODUCTION

Access to clean drinking water is a basic necessity that all humans need in order to survive. As the world becomes more industrialized and third world countries continue to develop, more people will also need access to energy. However, based on a 2012 study conducted by Millennium Development, 783 million people in the world remain without access to acceptable drinking water and 1.2 billion people do not have access to a reliable source of energy. That is about 11% of the total population that does not have access to clean water and 17% without access to reliable energy. In addition, Africa is home to large regions where over 40% of people do not have access to drinking water. As the population grows in regions without reliable energy and safe drinking water, renewable energy generation methods must be considered.

Renewable Energy will become a more viable source of energy production in the future as people continue to try to make the world a cleaner place. Solar, wind and hydro power have become cheaper and more efficient as research has intensified over the years. Wind energy has emerged as one of the most popular sources of renewable energy. Research teams, companies and universities have developed various stationary and airborne methods for harnessing wind energy.

The WPI Kite Power Project has been to develop a low cost, kite powered water pump system for use in under developed nations. It has been redesigned and optimized by students at the university since 2007 and has consisted of fourteen different project teams. Each team helped to implement design changes that have drastically improved the performance, safety and efficiency since the beginning of the project. The two main designs throughout the years are the rocking arm design and the rotary power pump design. Figure 1 compares the two designs below.

Figure 1: Comparison of Rocking Arm and Rotary Pump Frame Design

The rocking arm design (on left) consisted of a long arm that rocked up and down due to a change in kite altitude. This horizontal motion was converted to linear motion and electricity was produced through a generator. More recent designs replaced the generator with a water pump. The current design (on right) uses a rotary power pump converting the circular motion of the unraveling string into the linear motion of the piston pump. Past iterations of the design were extremely important for the group to understand to move forward with the project.

The goals of our project were to make large design changes as well as small iterations to the system to improve performance, ease of maintenance and reliability. The first goal of the project was to redesign and build the A frame of the system. A smaller frame with a lower center of gravity was necessary because the rocking arm was no longer in use. The next goal of the project was to introduce a rotary spring to retract the kite string once the kite reached a specified altitude. This was intended to automatically help switch the kite between the power and stall phase. The third goal of the project was to design and build a surface pumping system that would allow the assembly to pump from a standing water source from a specified distance. The final goal of the project was to create a kite communication system and reduce the weight of the current servo assembly. This would automatically alter the length of the upper tethers to induce power or stall phase. There were various other small changes made to the current design to improve the performance that were not originally set as goals.

The team achieved these set goals by producing and altering countless design variations. Final designs for each goal were reached through extensive edits and collaboration with all team members. The students assigned to each goal began to build the systems. Once the fabrication process was finished, students conducted a variety of tests in the laboratory to ensure proper operation. Lastly, the test results obtained in lab were verified with field testing.

CHAPTER 2: BACKGROUND

2.1 Water Need in Africa

Water is one of the basic needs of humanity and is a necessity to support life. People in different geographical regions have varying access to water and in certain areas it can be very difficult to obtain. People in developing nations and in areas of Africa in particular struggle every day to access clean drinking water and often spend significant portions of their day locating it [1]. People living in these developing nations have to spend this large amount of time searching for and retrieving water because there is currently no efficient method for collecting and transporting it. Consequently, millions of people living in developing nations struggle daily to gain access to clean drinking water.

A majority of the people inhabiting rural areas in the sub-Saharan region of Africa do not have easy access to clean water. The vast majority of these people were forced to walk six to ten miles to acquire water from a natural source [1]. A large number of Africans also suffered from contaminated well or town water while droughts during the dry season make it even more difficult to access. The African people not only need access to clean water for personal needs; they also need it to sustain their agriculturally based economy. According to the World Bank [2], agriculture has provided employment for about three quarters of the population in these struggling regions of Africa while producing about a third its GDP. Due to these hardships that the African people face on a regular basis, the United Nations has increased funding to help increase the supply of water to those living sub-Saharan Africa [3].

Access to clean drinking water will not improve for many of the inhabitants of the developing nations in Africa in the future. Several countries are experiencing rapid population growth so demand will only increase in the years to come [3]. The increasing population will also create a greater water demand in the agricultural industry. It is essential to find ways to help provide water necessary for irrigation and clean drinking water for all people in developing nations. Volunteer and research groups have started helping the developing communities in Africa to obtain clean water. Various innovative methods for developing cheap ways to access clean drinking water have been tested. One of these methods is using renewable energy from the sun or the wind to help the people gain access to water.

2.2 Wind in Africa

According to the Africa Power / Water / Infra Blog, wind speeds in Africa are suitable for wind power deployment and are naturally stronger in the Northern and Southern parts of Africa. According to Meigh [4], Eastern Africa encounters winds that average between 25 and 45 miles per hour. These winds are more than sufficient to deploy kites which require winds that are about seven miles per hour to sustain their altitude. Central Africa is subject to much lower wind speeds that would not be able to sustain kite deployment. Winds in this region of the continent usually average 4-9 miles per hour [5]. Figure 2 shows wind fluctuating across the African continent.

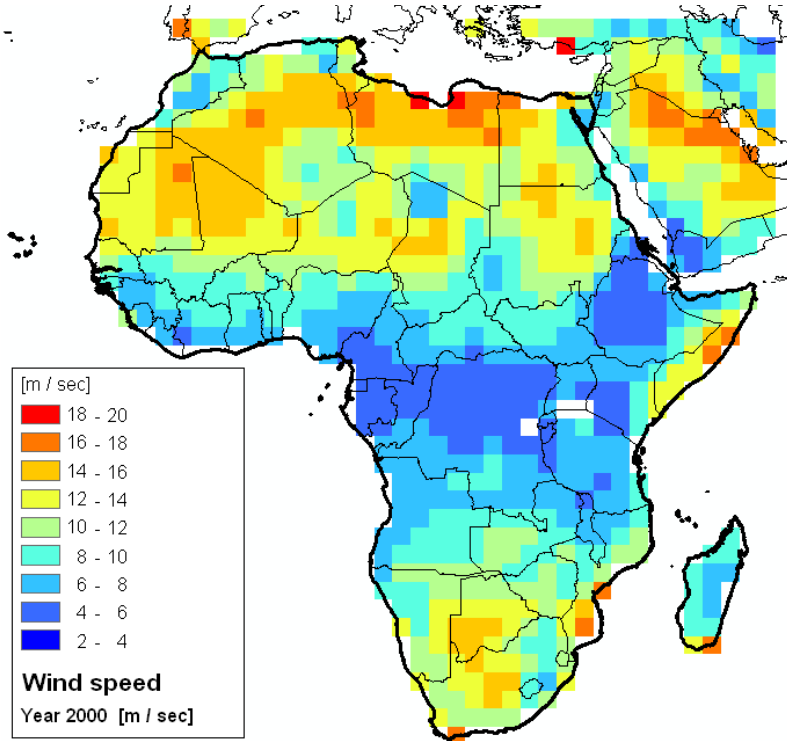

Figure 2: Fluctuations of Wind Speed in Africa [5]

There are a variety of large companies, including Google, that have begun investing in renewable energy in Africa because of its large potential supply of renewable energy [1,3,6]. Kenya, Ghana and South Africa are encouraging renewable energy projects. The largest of these projects is located in Kenya about 12 kilometers from Lake Turkana due to its favorable wind conditions. Google has invested almost $12 million on this project near Lake Turkana due to the high wind speeds [6]. Other regions, including Nigeria on the western side of the continent, have much less favorable wind conditions and would not be as suitable for wind energy projects. The average wind speeds in this region are between 4 -5MPH [7]. The following data image was recorded and analyzed to determine the feasibility of harvesting renewable energy in Nigeria.

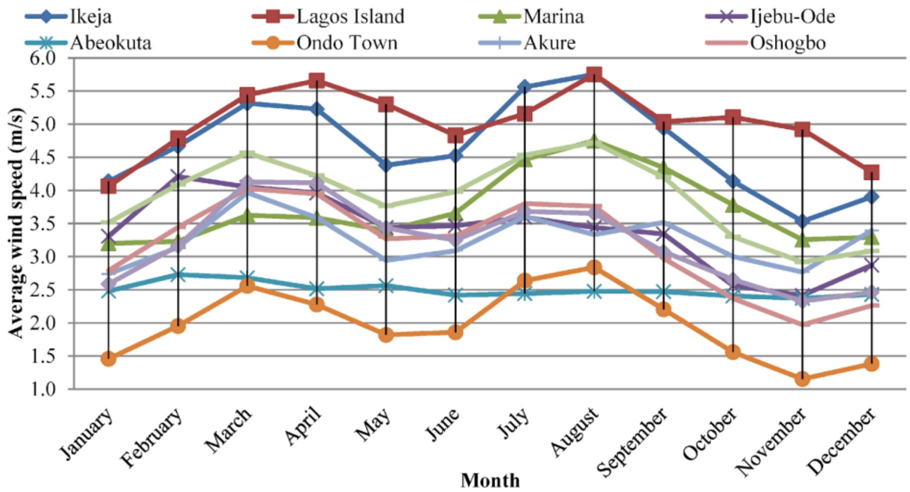

Figure 3: Average Monthly Wind Speeds in Nigeria [8]

North African countries have also been partaking in renewable energy projects and a plan to increase renewable energy production. Countries including Algeria, Libya, Tunisia and Egypt established goals to increase their renewable energy by 20% by 2020 while Morocco aims to increase by 40%. Considering that wind speeds in North Africa are often the most favorable averaging above 40 MPH, it is clear why these countries are increasing wind energy production [5]. South Africa on the other hand has been researching and increasing renewable energies for more than a decade now. In 2014, a large scale wind farm was deployed in South Africa and has increased South Africa's renewable energy by almost 35%.

Due to Africa's interests and investments in renewable energy, the continent is aiming to increase the standards of living by increasing energy power and clean water up to 20% by 2030. This is a great improvement from 5% in 2013. As a result, many projects relating to renewable energy have been, are being, and will be established in Africa.

2.3 Need for Sustainable Energy

The need for sustainable energy solutions have become continuously more and more pressing. Climate change, already tied to a number of increasingly powerful storms, is projected to cause temperatures to rise, ice caps to melt and sea levels to rise. The cause of this drastic climate change is due to the alarming amount of greenhouse gases, namely CO_2, being released into the atmosphere [9]. Most of these gases are the byproducts of combustion based mechanical systems that provide energy for humanity. Due to the technological advances of the last century, it is clear that a replacement for fossil fuels that are not detrimental to the planet need to be developed.

Fossil fuels are a finite resource and the availability of fossil fuels will continue to decline regardless of improving energy generating efficiencies. Based on Shafiee and Topal's model in Energy Policy Vol 37, "Coal reserves will be available until 2112, and will be the only fossil fuel available after 2042." While this model does suggest that coal availability will provide a significant amount of time to find an alternative fuel source it does not account for the effect on the environment the continued use of fossil fuels will have.

The solution to the inevitable decay of fossil fuels sources is to create an alternate method to power homes and businesses without harming the environment. This is the sustainable energy mission, to power the world in a way that humans are not dependent on a finite resource and in way that is not damaging to the planet.

It is predicted that there will be a total energy demand increase of about 50% by the year 2020. Many countries in the past decade have noticed the growth of total energy demand and are trying to find ways to meet it. The majority of these countries are also trying to diminish global warming and the emission of greenhouse gases by producing and investing in renewable energy [10]. Furthermore, the increase of total energy demand universally and the depletion of fossil fuels has made renewable energy far better alternatives. Hence, more technology has been developed in the last decade to help people harness this renewable energy.

2.4 Airborne Wind Energy

Airborne wind energy (AWE) is a technology that aims to harness wind energy at median to high altitudes [10]. AWE consists of a system that flies in the air freely or is bound to the ground with a chain or rope, somewhat like a kite or balloon. Fundamentally, AWE converts the unusable kinetic energy of wind to electrical or mechanical energy [11].

AWE is advantageous compared to other renewable energies because AWE is able to harness winds in high altitude that are normally stronger compared to low altitudes [10]. Moreover, AWE requires materials that are much cheaper than a conventional wind turbine and could potentially produce energy for the entire humanity [12].

2.4.1 Benefits of Airborne Wind Energy

Airborne wind energy is significantly cleaner than burning fossil fuels because it does not produce greenhouse gases. Unlike fossil fuels, wind energy is an unlimited resource as long as the sun is heating the atmosphere. Wind energy is also one of the most cost-effective renewable energies, costing about 40 to 60 cents per kilowatt hour [13].

Airborne Wind Energy generates energy from the wind but does not require a static structure on land. It has several additional benefits when compared to stationary wind energy generation. These benefits are highlighted by the energy density of the wind at higher elevations. AWE devices are able to harness winds at higher altitudes than conventional wind turbines and produce a smaller carbon footprint. Wind turbines require vast amount of material to build, transport and operate while AWE devices such as Altaeros Energies' BAT blimp (shown in Figure 4) requires much less material to build. Conventional wind turbines require large amounts of land, however, airborne wind energy devices require the land to attach a tether or grounding device increasing the value per unit of energy. There are various startup companies have developed designs to harness high altitude wind energy through AWE which has resulted in different types of airborne wind energy.

2.4.2 Types of Airborne Wind Energy

Airborne Wind Energy (AWE) generation is a clean and renewable source of power generation that involves systems suspended in the sky and those attached by a tether to the ground. There are three types of AWE but this section will only discuss two of them. The two types of airborne wind energy that will be discussed are on board and ground power generation.

On Board Power Generation

On board power generation is a type of AWE that generates electricity from the kite or device in the air. The electrical generator or turbine is part of the system and the energy is transported down the tether to the ground. On board power generation systems can reach much higher altitudes than conventional wind turbines, therefore, can operate at higher rotational speeds. The higher winds eliminate the need for a heavy gearbox making the system relatively light weight.

One example of a current design for the on board power generation system is called the BAT and was created by Altaeros Energies. The BAT [14](Buoyant Airborne Turbine) consists of a turbine located inside an aerostat (an industrial blimp with an envelope) that is used to produce current through an electromagnet. The current is transported down the conductive tether to the ground. The system stays aloft by placing gases that are less dense than air in the envelope. Figure 4 shows this company's current design.

Figure 4: Altaeros Energies Design

Ground Power Generation

Ground power generation has become the preferred option by most companies that are researching and designing airborne wind energy systems. This type of AWE uses an electric generator on the ground to produce electricity. Ground power generation is a more viable option than on board power generation because it reduces the weight of the system when the electric generator is on the ground. This design also does not require the transport of energy down the tether of the kite. Instead, the tether is unraveled from a drum that creates the rotational motion required to turn the generator. This process is done in cycles that involve unraveling and then retracting the tether once it has reached maximum altitude. This is accomplished by increasing the angle of the kite to produce power phase and then decreasing the angle of attack to produce stall phase, thus, retracting the kite using less force. There are several companies that are currently testing various ground power generation designs that differ in weight and number of kites.

Teams across the world are researching and developing ground power generation that possesses a variety of features. These features include the number of tethers used, weight, rigidity of the kites and method for steering the kite. The Swiss Kite Power team, the Kite Power team at TU Delft and SkySails Power are among those that are producing systems with a single main kite. Aboard the kite is a control pod with electric drives or motors that change the length of the tethers and the altitude of the system. The altitude is changed to switch the kite between power and stall phase. Figure 5 pictured below, shows SkySails's design that incorporates one main tether.

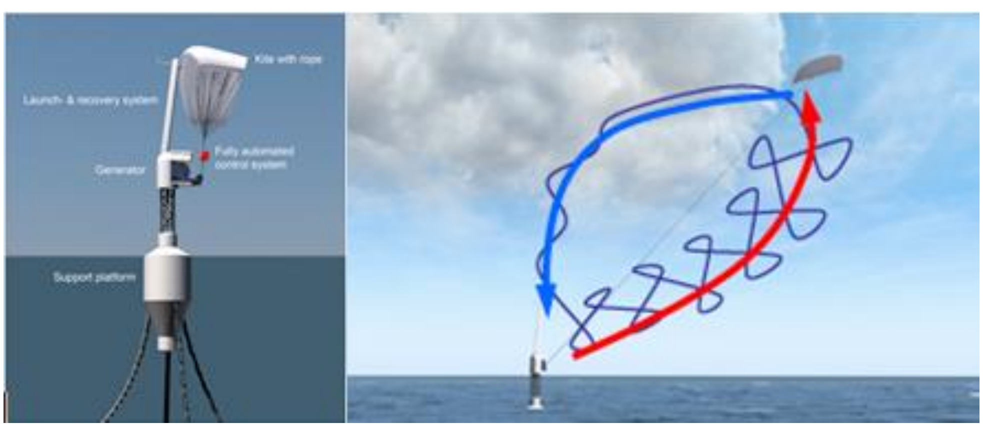

Figure 5: SkySails Design

Other research teams such as KiteGen and Enerkite have incorporated more than one kite into their power generation designs. These companies use two or three main tethers to induce stall and power phase with the changing lengths of the kites. When one kite is rising in power phase, it causes the other kite to fall and induce stall phase. Although these companies are incorporating flexible wings in their designs, many research teams are using rigid wings for a variety of reasons.

This project chose to use ground power generation; however, the system has been consistently changing ever since the preliminary design in 2007. Research, calculations and field testing led the teams to choose ground power generation. The next section will explain testing methods and design iterations throughout the years.

2.5 Testing Locations and Conditions

2.5.1 Field Testing

Field testing is an essential part of the MQP and validates assumptions, calculations and trial experiments in the lab. Testing at one of the field sites provides conditions with varying parameters such as wind speed and direction that cannot be simulated in the lab environment. Conducting testing in these conditions are comparable to those that people will be experiencing in third world countries and help the group to understand any issues that they may encounter with the system.

The field testing occurred at Brookwood Farm in Milton, MA, Pope John Paul Park located in Boston, MA and Moore State Park in Paxton, MA. These locations provided ample space as well as consistent wind conditions. Brookwood farm is situated at an elevation of 435 feet, which usually provided consistent wind testing conditions. Favorable wind conditions were also encountered at Moore State Park due to the high elevation. Pope John Paul Park is located just two miles west of the Boston Harbor and typically offered the best wind conditions of the sites. The strong wind conditions at coastal locations are due to the sea and land breeze effects. A permit was obtained to test the trailer and kites at the Brookwood Farm, however, the trailer and A-frame of the system were not approved for testing at Pope John Paul Park and therefore testing at this site was limited to only the kite. The group had to be careful to keep the kite and equipment at a safe distance from physical obstructions such as trees, buildings and people at each location. Accurately evaluating the wind speed and direction is paramount to avoid these obstructions. The trailer is stored at another location located in Milton, MA known as Blue Hills Weather Observatory. The observatory is located within minutes of Brookwood Farm. This location does not provide optimal wind conditions or ample space so testing could not be conducted there.

2.5.2 Setup

The trailer must be positioned in the field properly based on wind conditions, direction of the wind, and obstructions. The trailer gate is set down and the kite is attached to the kite string that is wrapped around the bicycle wheel. The kite is walked out to the proper launch distance based on the wind magnitude. The team members holding the kite let go with a gust of wind and a person holding the middle of the line helps to guide it in the direction of the trailer while achieving stability. Once the kite is stable, the team tested the retraction method, adjusted the angle of attack using the RC motor and observed the pump functionality. Figure 6 shows the setup with the kite out toward the left of the photo while the pumping assembly, retraction spring and bike wheels are on the right.

Figure 6: Kite setup

2.5.3 Testing Conditions

Sufficient wind conditions are essential for successful testing in the field. Wind conditions were monitored each day prior to a field test. The weather also needed to be watched closely as rainy or stormy days could result in potentially dangerous conditions. The wind speed required to fly the kite is about seven or eight miles per hour while ten to fifteen is ideal. The kite can be very difficult to control in wind speeds higher than fifteen miles per hour and there is a higher chance of damaged equipment. All testing equipment was inspected for damage before and after each testing session.

2.6 Previous MQPs

Design iterations that date back to the beginning of the Kite Power MQP projects are outlined in the table below.

Year	IQP/ MQP Title	Main Accomplishments	Author(s)	Reference Citation
2007	Wind Power From Kites MQP	Designed and constructed the basic A - frame structure and rocking arm. Selected kite for use in power generation based on testing and mathematical analysis. Ran simulations based on steady state and dynamic theory of the tested kites.	Michael Blouin Benjamin Isabella Joshua Rodden	Blouin et al. 2007
2008	Kite Power for Heifer International's Overlook Farm IQP	Developed educational exhibits on kite power for use at the Heifer International's Overlook Farm site.	Gabriel Baldwin Peter Bertoli Taylor Lalonde Michael Sangermano Nicholas Urko	Baldwin et al. 2008
2008	Design of a One Kilowatt Scale Kite Power System MQP	Completed and tested the demonstrator which was able to generate power as well as autonomously keep the kite aloft for a short period of time. Performed stress analysis in Cosmosworks and ran power generation simulations in MATLAB.	Ryan Buckley Christopher Colschen Michael DeCuir Max Hurgin Erik Lovejoy Nicholas Simone	Buckley et al. 2008
2009	Development of a Wind Monitoring System and Grain Grinder IQP	Designed a balloon mounted wind monitoring system using an anemometer. Implemented a small grain grinder to be attached to the power converter on the kite power system.	Deepa Krishnaswamy Travis Perullo Joseph Phaneuf	Krishnaswa my et al. 2008
2009	Design of a Data Acquisition System for a Kite Power Demonstrator MQP	Designed data collection system for physical attributes of the system as well as for power generation. Designed secondary power generation and oscillation control subcomponents. Further optimized rocking arm and A frame as well as tested each system and subcomponent.	Lauren Alex Eric Restefano, Luke Fekete Scott Gary	Alex et al. 2009
2010	Design of a Dynamometer For The WPI	Designed and built a dynamometer used to measure torque and power.	Kuthan Toydemir	Toydemir, 2009

	Kite Power System MQP			
2010	Re-Design and Testing of the WPI Kite Power System MQP	Modified system: Used a more stable and larger sled kite. Upgraded gear shaft. Built mechanism to change angle of attack of kite. Measured tension of kite tether during testing.	Adam Cartier Eric Murphy Travis Perullo Matthew Tomasko Kimberly White	Cartier et al. 2010
2011	Design of a Remote Controlled Tether System for the WPI Kite Power System MQP	Developed wireless system to remotely control trailing edge lines of kite to alter angle of attack and side-to-side motion. Designed a control box with two motors, gear boxes, transmitters, and two spools to control the length of trailing tethers.	Michael Frewin Emanuel Jimenez Michael Roth	Frewin et al. 2011
2012	Design of a Kite Powered Water Pump and Airborne Wind Turbine MQP	Redesigned system to add a mechanical water pump and head simulation valve. Initial design and testing of Airborne Wind Turbine.	Kyle Bartosik Jennifer Gill Andrew Lybarger Daniel Nyren John W Wilder	Bartosik et al. 2012
2013	Re- Design of the WPI Kite Powered Water Pump and Wind Turbine Systems	Altered transfer arm. Modified sliding weight mechanism. Added adjustable weight to rocking arm. Added a ground tether. Redesigned lightweight, airborne wind turbine.	Valerie Butler Jeffrey Corado Kimberly Joback Bryan Karsky Matthew Melia Robert Monteith Brandy A Warner	Butler et al. 2013
2014	Optimization of the WPI Kite Powered Water Pump	Performed extensive field testing on the kite system. Created a functioning VI in LabVIEW for data acquisition. Created a simulation using Matlab to model random wind speeds. Design a portable trailer system.	Aaron Durkee Christopher Ettis Dong Kim David Levien	Durkee et al. 2014

2015	Design and Testing of Kite-Powered Water Pump Concepts	Designed a new mechanism to transfer the energy from the kite to the pump using a bike wheel.	Caitlin Chase Lindsey DeLuca Aaron Marshall Ronald Mazurkiewicz	Chase et al. 2015
2016	Design of a Two-Kite, Rotary Power Cycle for the WPI Kite-Powered Water Pump	Designed, fabricated and tested an on-board Arduino-based system to vary attack angle of the kite. Implemented a dual kite system for non-manual retraction.	Michael Gagliano Justin Marsh Daniel Long	Gagliano et al. 2016

2.6.1 Previous Designs

The WPI Kite Power Project has consisted of various design iterations since the beginning of the project in 2007. The changes in the system during each project help to improve the performance and ease of use. It is essential to understand the improvements and considerations that have been made in the past in order to make critical decisions on changes that need to be made during the current projects. Reasons for changes and findings in previous projects are important to recognize to maximize the results of the current project. The rocking arm design and the rotary wheel pump design are the two main iterations of the design since 2007.

Rocking Arm Design

The original design of the WPI Kite Power MQP frame consisted of an A-frame, rocking arm, PowerSled 81 kite, generator and trailer. The generator was replaced with a water pump from an old wind mill by an MQP team in 2012 because they determined it to be a more practical use of the energy for underdeveloped nations. The pump chosen was a linear motion piston pump used to extract water from wells. The piston was forced in an upward motion as the kite gained altitude pulling the rocking arm up. The opposite occurred when the kite lost altitude. The upward and downward motion of the kite resulted in the pumping of water. The rocking arm typically would complete a full motion every five to ten seconds on days with strong winds. A picture of the rocking arm design can be seen in Figure 7.

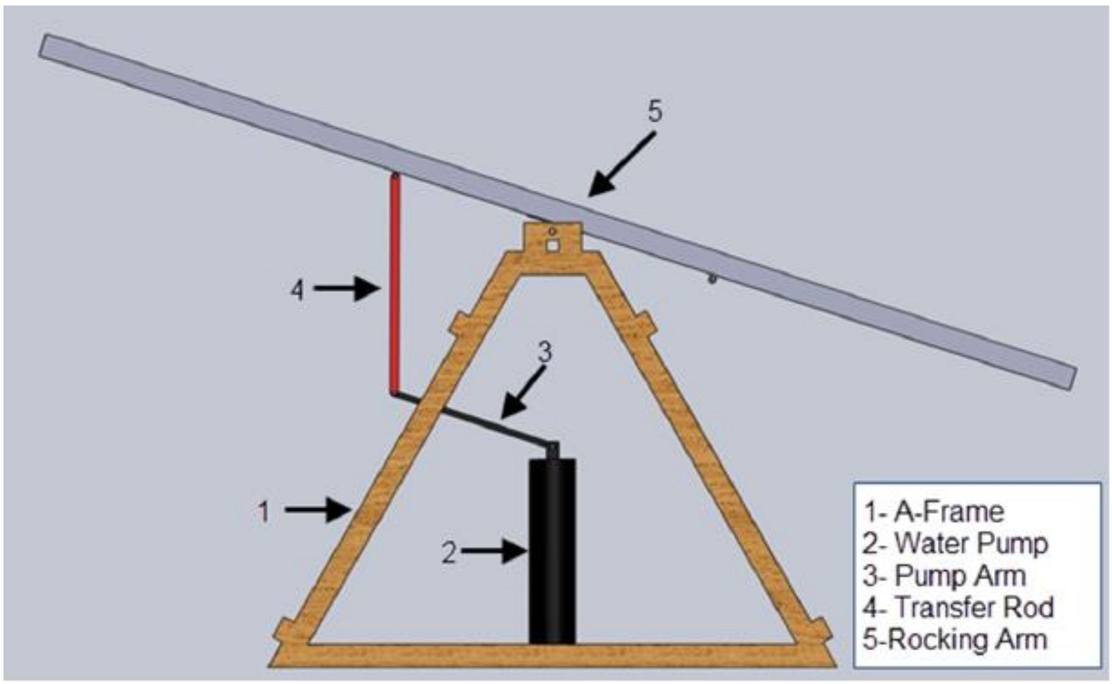

Figure 7: SolidWorks Model of Rocking Arm Design (Bartosik et al. 2012)

Rotary Power Pump Design

The current design of the system is comprised of a rokkaku kite, bike wheel spool and piston pump. This design produces the linear pumping motion by converting the rotational motion of the bike wheel to the linear motion using a pump cam mechanism. The kite line is wrapped around the bike wheel and the release of the kite unravels the bike string creating the rotational motion. A bicycle chain attaches the bike wheel to the horizontal shaft of the pump. The kite is retracted by changing the angle of attack of the kite and reducing the altitude allowing the kite string to be wrapped around the bike wheel again. The rotary power pump design is shown in Figure 8.

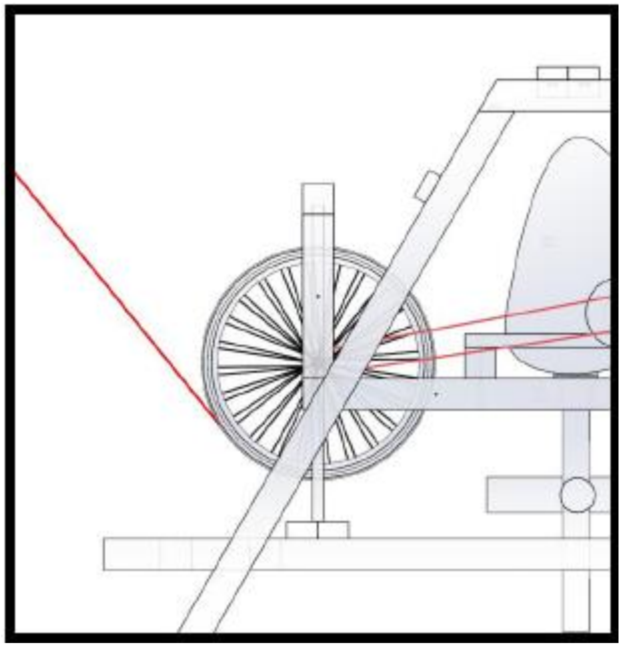

Figure 8: Rotary Power Pump Design (Ciulla et al. 2015)

2.7 Summer 2016 Project Goals

2.7.1 General Goals

This project aims to produce a functioning rotary pump system using power generated from a pumping kite. Specifically, for this year's project the team set out to improve the various components that made up the system, make the system easier to use, and test the system in the lab and in the field. The team split up so that smaller groups could lead the different improvement for each subsystem. The specific aims of each subgroup are listed below.

2.7.2 Kite Motor Control

Previous MQP's utilized a motor box secured directly to the kite pulling on the bridle string to readjust the kite. The system consisted of an Arduino controller a stepper motor and battery. The goals of the kite motor control system include decreasing the weight and size of the motor box while increasing the power, determining the optimal position for the motor system to maximize kite stability and adding a long range wireless system for motor control.

2.7.3 Retraction Forces

The previous kite retraction system design used a two kite system in which one kite in power phase pulls back the second kite which is in stall phase and then the kites switch back and forth to create a power cycle. This system proved to be too difficult to operate in realistic wind conditions. The goals for the kite retraction system is to retract the kite while in stall mode, simplify the operation of the system and the ability to operate the system under a variety of wind conditions.

2.7.4 Frame Design

The past teams created a frame for the system that was tall enough to have the biggest rocking arm on top, and be able to fit in the bed of a pick-up truck. In 2015 when the rocking arm design was changed to the bike wheel design, the old frame was taller than it needed to be with the heavy pump creating a top-heavy structure and had a lot of unnecessary components fixed to the top. The goals for the redesign of the frame are to lower the center of gravity, reduce the overall height to below seven feet, eliminate the rocking arm components and improve the stability of the design during transportation.

2.7.5 Surface Pumping

Previous kite powered water pump designs at WPI pumped water from a simulated underground well. An overall goal of this year's project was to develop a piping system that allows for pumping from a standing water source. Additional goals of the surface pumping system include achieving a consistent flow rate that can produce enough water for a small village in a day, pump the water from a distance of at least thirty feet, and allow the system to be disconnected and stored for travel easily.

2.7.6 Pump-Kite Gear Train

The previous design of the pump-kite gear train replaced a single gear hub on the kite wheel to a multi-gear hub. This improved the flow rate for the pump flow rate over a variety of wind conditions due to the adjustable gear ratio. However, this gear ratio was limited to a top end of a 1:3 kite-pump cycle ratio, which limited the performance of the pump during high wind conditions. The goal for the pump-kite gear train is to improve the top end gear ratio range of a gear train and to remove slack from the chain used in the gear train.

CHAPTER 3: METHODOLOGY

3.1 Initial Testing

It is essential to understand the previous project iterations and utilize these improvements while working on an ongoing project. The first few testing sessions involved minor modifications and basic functioning of the kite pump system developed by prior project teams. The previous system included the original kite pump frame design made for a rocking arm water pump, a retrofitted windmill water pump assembly, a bike wheel assembly that would convert rotational motion to linear motion in the windmill pump, and a rokkaku kite with a programmed servo to adjust its angle of attack during flight.

The goal of the initial testing sessions was focused on understanding the current system and how it could be improved. The main focus was on the suggested areas for improvement specified by the previous project team. The system was brought to an open field with ideal wind conditions and the team watched the kite pump water while altering the angle of attack. The project was separated in subsystems based on the results from the initial testing. Once the subsystems were tested several times, the team began working on improving the servo functionality, kite retraction, frame redesign, and ability to pump water from nearby sources.

3.2 Motor Box Development

3.2.1 Needed Improvements

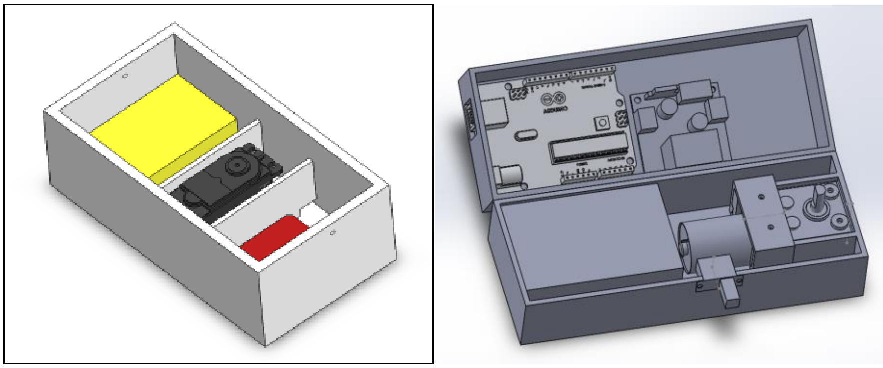

Figure 9: Comparison between previous Servo box design (left) and new design (right)

The previous motor box housed a bulky motor and battery on the spine of the kite as shown in Figure 9, operating on time delays to readjust the kite. Early testing made it clear that housing the system on the spine of the kite destabilized the kite drastically. Furthermore, it was nearly impossible to determine if the motor was truly affecting the orientation of the kite, or if variable winds were simply pushing the kite around. Another problem with the previous design is that it did not have a remote method of controlling the motor once the kite is in the air. The motor run time was predetermined but this proved troublesome because the timing between power phase and stall phase depended on the wind condition. To address these problems, the team needed to develop a more stable configuration for the kite system with the ability to remote control the system from the ground.

3.2.2 Wireless Communication

Wireless transmission allowed the team to adjust the kite's orientation and observe the effects on the kite's flight. The wireless transmission had to be able to reach over 300 ft., the max distance of the kite spool. Furthermore, it needed to input to an Arduino Uno Board, which in turn controlled the motor.

The initial transmission attempt used the UCEC XY-MK-5V / XY-FST 433Mhz RF Transmitter and Receiver Link Kit (Figure 10). This small Tx/Rx system was listed to work up to 400 feet, was easily compatible with Arduino, and was inexpensive. A third party library called Virtual Library provided the software infrastructure to send wireless data through the 433 MHz Tx/Rx system. The library was created by Mike McCauley and is freely available at https://www.pjrc.com/teensy/td_libs_VirtualWire.html .

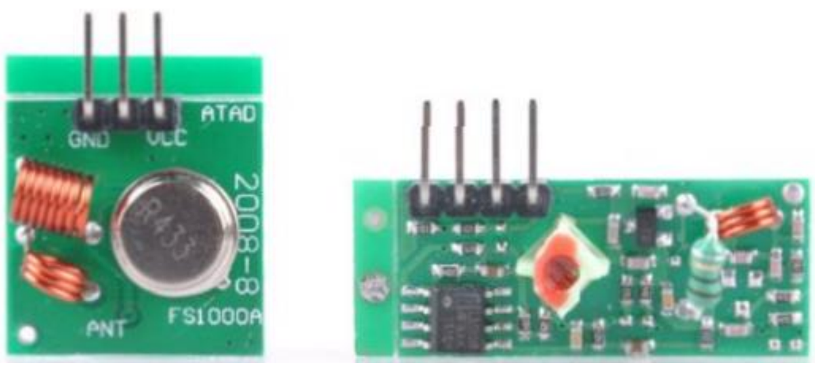

Figure 10: UCEC XY-MK-5V / XY-FST 433Mhz RF Transmitter and Receiver Link Kit

A program was successfully implemented using virtual library that enabled the transmission of simple data. We chose to transmit simple integers, which corresponded with motor commands. Initially this command was used to turn the motor on and off and developed into switching the motor's direction between forward and backward for a set time. This code can is available in the team OneDrive under the code directory.

Unfortunately, this configuration proved to be unsuccessful. Despite the use of spiral antennas and increasing the voltage to the maximum setting, the range was determined to be only 65 feet in an outdoors environment.

The FlySky® Controller is a wireless controller and receiver module used to control planes and drones and had a range of over 1000 feet (Figure 11). The receiver had 6 channels that were associated with the various controls on the transmitter. Typically, these channels were directly connected to a servo, or servo controller. To suit our purposes channels 1, 2, and 5 were instead wired to Arduino inputs. The inputs range from 900 – 2000 which are the typical input controls of a servo motor, which the receive was intended to control. Rather in this case, these commands were associated with commands for the kite. The controls implemented in the current software are described in the table below.

Figure 11: FlySky® Controller and Receiver Modules

Channel	Remote Action	Command
2	Right joystick up and down	Motor forward and backwards respectfully
4	Right joystick right left	Motor forward and backwards respectfully for set time
5	Left knob twist	Turns autonomous mode on/off

As shown in the table above, moving the joystick up and down turned the motor on in the forward or reverse direction until it was disengaged. Moving the joystick left or right turned the motor forward or backwards for a specified time (at the time a drastic 25 seconds). The autonomous mode was the intended end goal of the system. In the autonomous mode the kite would be able to change the angle of attack automatically creating the desired pumping motion. This was originally accomplished by programming the motor to wind and unwind the bridle for set times. The unwinding process took less time because the tension force in the string helped the process.

The FlySky® had been tested at the required distance and the controls were operational but due to wind restrictions, it was not tested at altitude. The success of the remote enabled the group to observe the motor box's effect on the flight of the kite.

3.2.3 Motor Configuration

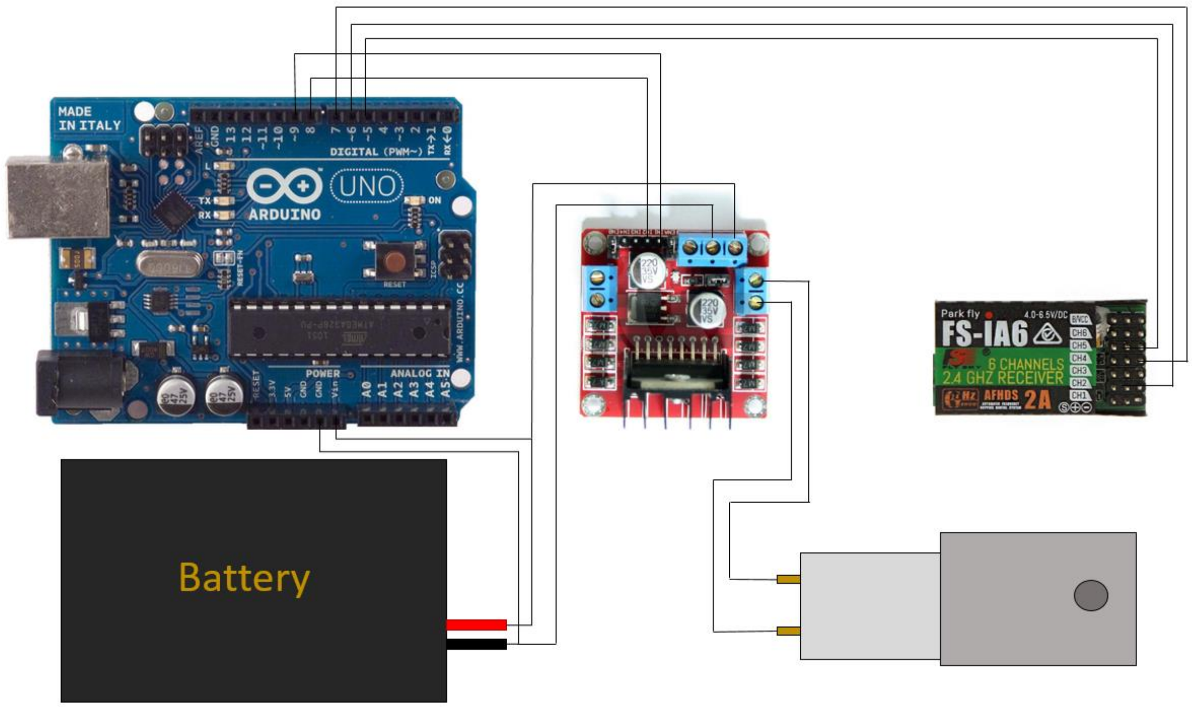

Figure 12: Circuit Diagram of Motor Configuration

The Circuit above outlines the motor configuration implemented. This Section will outline the specific function of each component and reasons for the configuration.

Battery

The System required 12 Volts and 1.4 Amps to run optimally. The large 12V Nickel Metal Hydride battery rechargeable battery that is shown above was the battery used by the previous team. The team first considered a lighter Lithium Polymer battery to cut the weight of the system. The second battery considered was light weight, 12V but it was non-rechargeable. The last option was to use a combination a 9V battery and AA batteries. By connecting them in series the required 12V was achieved using batteries that were both lightweight and cheap. The motor required 12 volts and sufficient current was required.

The team needed to find a balance between weight and size because an increase in weight destabilized the kite while a smaller battery would not provide the required voltage.

Motor

The previous group compared the servo motor and stepper motor and were able to justify the servo as the better option for this project due to its lightweight and sufficient torque. However, we found that the servo motor had several downsides. The servo was not able to hold its position under a tremendous amount of torque. Instead, the servo needed to jiggle back and forth to hold the position. The team recognized that the kite line slipped under this torque. This created issues when the team was attempting the keep the kite in power or stall phase. The servo also consumed a great deal of battery. The servo drained the battery quickly because it was always drawing current during and between phase changes.

Due to these two disadvantages of the servo, the team decided to choose a different motor. The motor chosen was a simple DC motor with attached gear box and rated to 12kg.cm with built in worm gear. The gearing system prevented slipping even when the motor was not running. This enabled the system to hold the kite in position without expending much energy. The shaft was 6mm in diameter and was fitted with a pulley mechanism to pull on the kite bridle.

Arduino Uno

The Arduino Uno was the controller of the system. It took in data from the receiver and related the appropriate command to the motor through the L298 module. The team made sure the Arduino was connected directly to battery power supply and not the regulated 5V from the L298 module. The motor could short the Arduino circuit when drawing power rendering the motor non-functional.

L298 Module

This module was the step in the circuit between the Arduino and the motor. When the Arduino sent out low voltage AC pulses, the L298 module directed voltage from the power source to the motor depending on the two inputs from the Arduino. Therefore, the direction of rotation of the DC motor could be reversed by changing the voltage input on the L298 module which was controlled by the Arduino signal.

L298 input 1	L298 input 2	Motor
1	0	Forward
0	1	Back
0	0	Stop

3.2.4 Casing

Casing was very important because the weight has a huge impact on kite operation and strength of the casing was prioritized to protect the circuit inside. Therefore, the balance of the weight and strength was the top priority for the case design. The configuration of the case was determined first by the team. The previous group tried several positions on the kite and determined the best place for the case was located near the top bridal. However, this time, the team considered locating the case on the kite line and off the kite itself. Tests were conducted by hanging weights comparable to the case to the kite line. The kite was more stable in the air and lift off was an easier task with this configuration.

Once the optimal location of the case was determined, several bridle pulling mechanisms were considered. Eventually the fishing rail mechanism was chosen due to its simplicity and effectiveness. The fishing rail was a pulley fixed on the motor shaft. A string was tied to the pulley, threaded through a small hole in the case and connected to the kite line near the bridle on the other end. While the motor shaft rotated, it pulled in or let out line by pulling on the bridle to successfully induce power and stall phase.

The team designed the case using SolidWorks with the goal of keeping circuit secure and allowing for easy maintenance. The case was configured as a cylinder and opened as shown in Figure 13. Each half consisted circuit components mounted on the plate board that could be removed. The case and the pulley was 3D printed by Dimension SST 1200es which provided a layer thickness of 0.2 mm resulting in a good strength to weight ratio.

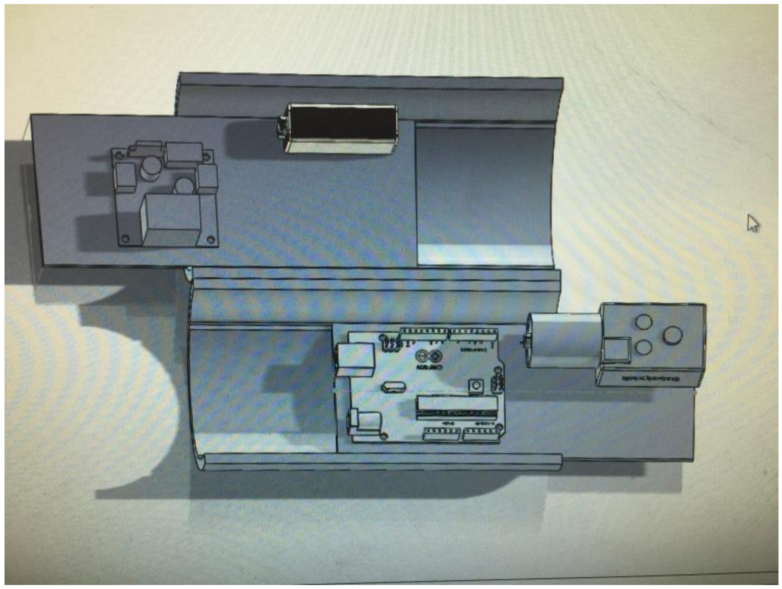

Figure 13: Initial CAD of circuit organization in casing

The mounting method of the case on the kite line used three metals rings tied to the body of the case. Kite line was threaded through the rings and wrapped around three times. The configuration was time consuming to attach, however, it proved the most effective

While testing with the cylindrical case the two sliding acrylic plates snapped distorting the motor configuration. In an effort to make a more stable casing solution, another case was designed without acrylic plates. It was reconfigured as a rectangular box which is pictured below. It was slightly smaller in volume and provided a more rigid housing for the motor. This configuration was the final casing to be tested.

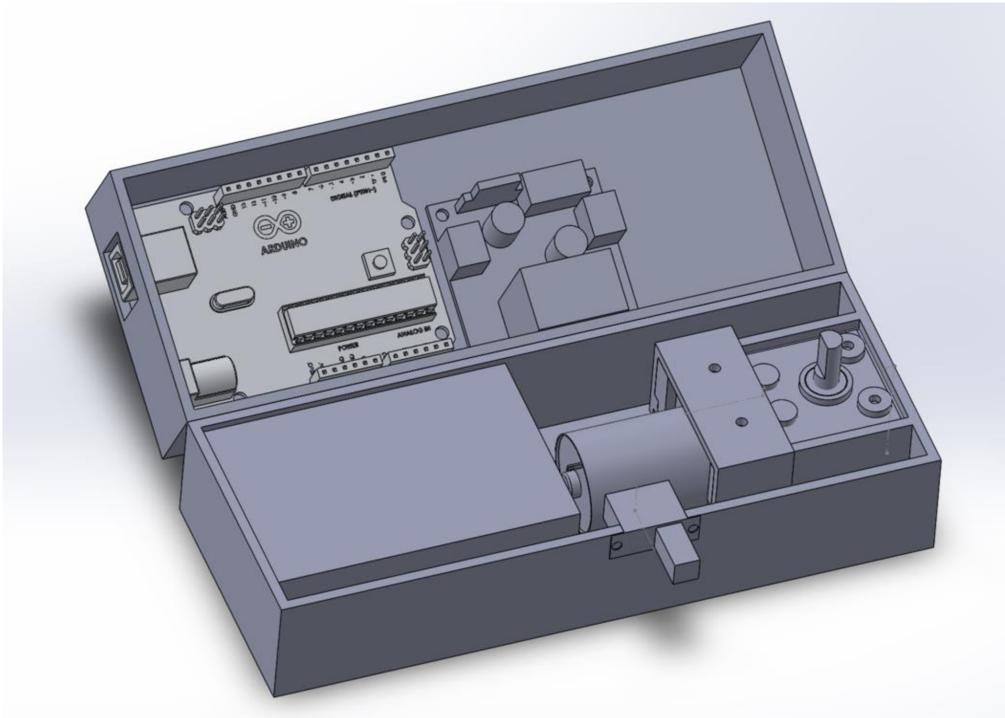

Figure 14: Initial CAD of circuit organization in casing

3.3 Retraction Forces

The previous team tested a two kite system that operated by retracting one kite while extending another, however, this proved difficult to control due to the variability of the crosswinds and other imposing factors resulting in tangled kites. In light of these previous findings as well as the higher costs that are associated with a second kite and servo system, a reel spring was chosen to provide a retraction force to pull the kite in during its stall phase. The general idea of these two systems are shown in Figure 15.

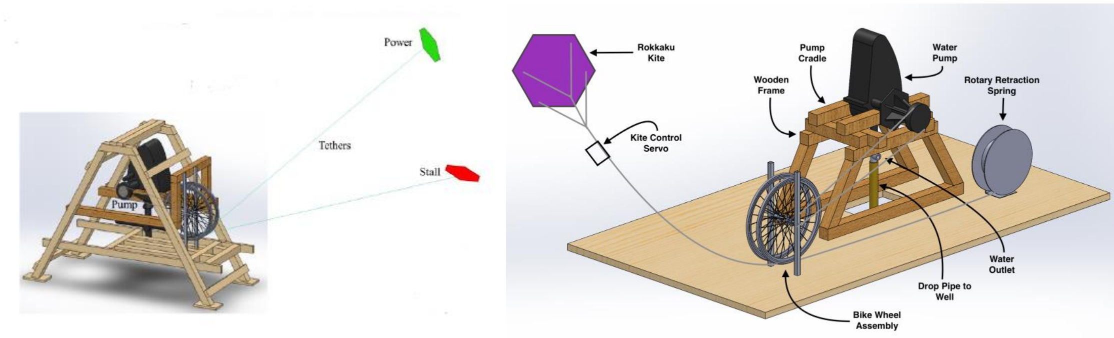

Figure 15: Two-Kite Retraction System vs Rotary Spring Retraction System

3.3.1 General Mechanics

In order for the retraction system to produce a work cycle for the water pump, the forces on the kite tether by the reel spring must be able to produce a force that is greater than the force produced by the kite in stall mode. It also needs to provide a smaller force than the force created by kite in its power phase as seen in the free body diagrams in Figure 16 and Figure 17. In our initial testing, it was found that the kite produced around 4-10 lb_f in wind conditions of 10mph at 5 meters without the motor attached. Thus the spring reel had to be able to produce a force within that range in order to provide a power cycle to the water pump.

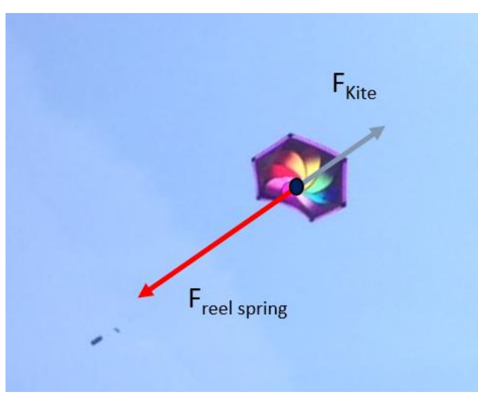

Figure 16: Kite Stall FBD

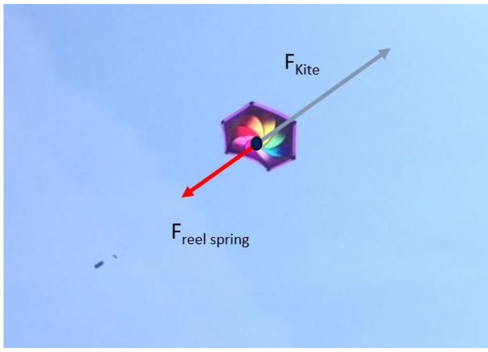

Figure 17: Kite Power Mode FBD

3.3.2 Spring Constant

In order to understand how the retraction system will respond in the field, an initial lab test is needed to measure the spring constant of the linear real spring by itself to understand the forces it will produce on to the kite. Since the our reel spring is linear such as the one seen in Figure 18, the forces produced by the spring can be modeled as $F_{Spring} = K * \Delta x$. The first lab test of the kite retraction system was to measure the force of the linear reel spring, F_{Spring}, with respect to linear displacement of the reel , Δx , in order to calculate the spring constant, K, of the system.

Figure 18: Inside a Linear Reel Spring

The force produced by the spring was measured every 10ft using a line attached to the reel and a fish weight scale. The linear reel spring was under an initial displacement, which produced an initial force that corresponds to the intercept of the linear regression of the test data. Using the test results in Figure 19 and linear regression analysis, the force of the reel spring was estimated in Lb_f as $F_{Spring} = 0.262054 * \Delta x + 3.982143$ with an R^2 value of 0.9921, yielding a spring constant of $K = 0.262054 \frac{Lb_f}{Ft}$.

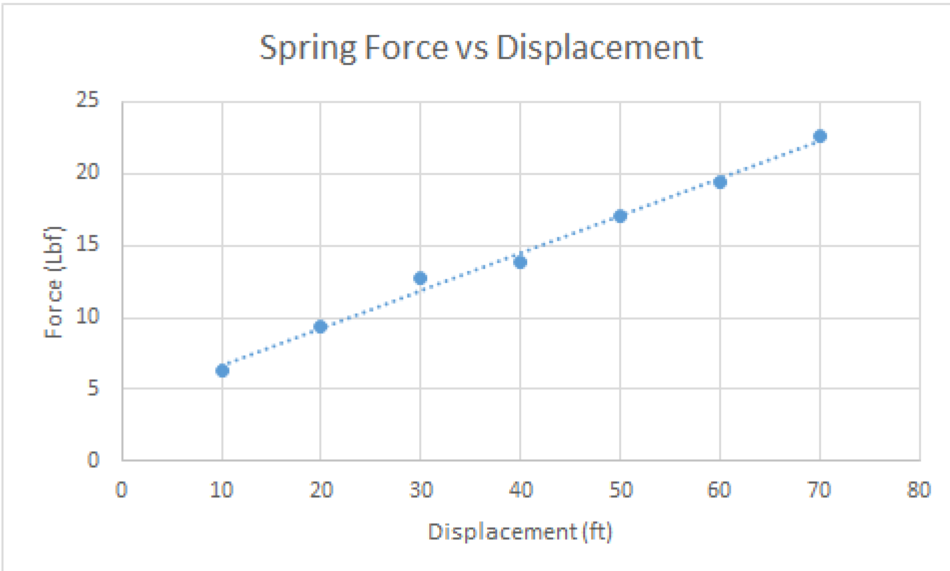

Figure 19: Spring Force Test Data

With the same data and the radius of the spring reel, the torque that the reel spring produced can be calculated in $\mathrm{Lb} * \mathrm{Ft}$ as $\tau_{Spring} = F_{Spring} * r_{rotor} = 0.14249 * \Delta x + 2.165407$ with an $r_{rotor} = 0.54375\ ft$. The torque of the reel spring could be manipulated by a torque transfer device which could optimize the force provided by the reel spring to the kite.

3.3.3 Torque Transfer

Three preliminary methods that transfer the torque from the reel spring to the kite wheel were analyzed before implementing the first iteration of the retraction system as seen in Table 1. The four criteria used that analyzed each design were the force ratio of the kite wheel to the spring reel, the max displacement of the kite line while the retention system was engaged, the complexity of operation of each subsystem and the cost.

Table 1: Preliminary Design Analysis of Torque Transfer

Torque Transfer Preliminary Analysis			
Torque Transfer Method	Kite Line	Gearing/Chains	Axial Shaft
Force Ratio (Kite:Spring)	1:1	0.503:1 to 1.563:1	0.483:1
Max Line Displacement	100ft	198 Ft to 64 Ft	207 Ft
Engagement Complexity	Simple	Complex	Complex
Cost	Low	High	Highest

From the analysis it was clear that the use of gearing and chains would provide the best design for the retraction system due to the range of retraction forces it was providing to the kite. However, due to the simplicity and cost of the torque transfer with a kite line, the kite line method was used for initial testing of the retraction system. The Kite Line method is simply attaching a kite line from the rotary spring to the kite wheel in the opposite direction of the kite as seen in Figure 20.

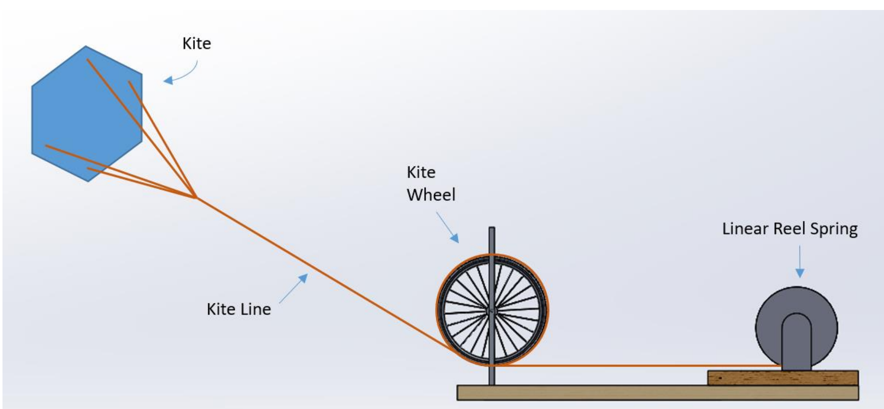

Figure 20: Kite Line Torque Transfer Method

After the kite line torque transfer method was fully tested, a gear train was developed between the rotary spring and the bike wheel. However, due to time constraints this system was not tested in the field.

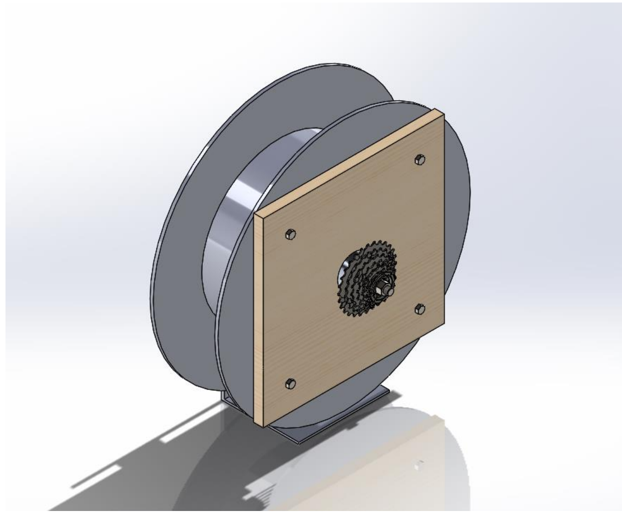

Figure 21: Rotary Spring with Gear Train

3.4 Gear Train

The team concluded that developing a gear train with a bigger gear ratio range would optimize flow rates in a variety of wind conditions. Due to the limitations of one gear on the water pump, the old system's gear ratio range was limited compared to a multi-gear system using a five speed bike gear as seen in Table 2.

Table 2 Gear and Pump Cycle Ratio of Old and New Gear Trains

	Gear Ratio Range (Kite Gear: Pump Gear)	Pump Cycle Ratio Range (Cycle of Kite Wheel : Cycle of Pump)
Old Gear Train (Single Gear)	[0.6395 : 1] to [1.2710 : 1]	[0.2131 : 1] to [0.4236 : 1]
New Gear Train (Multi Gear)	[0.5031 : 1] to [1.9874 : 1]	[0.1677 : 1] to [0.6624 : 1]

A system was developed to attach a five speed bike gear to the existing infrastructure including a ½ inch threaded rod that was attached to the pump. A gear adapter that attached the threaded rod to the gear sprocket was designed in SolidWorks, and was made on a metal lathe with 6061 Aluminum.

Figure 22: Previous Gear Train

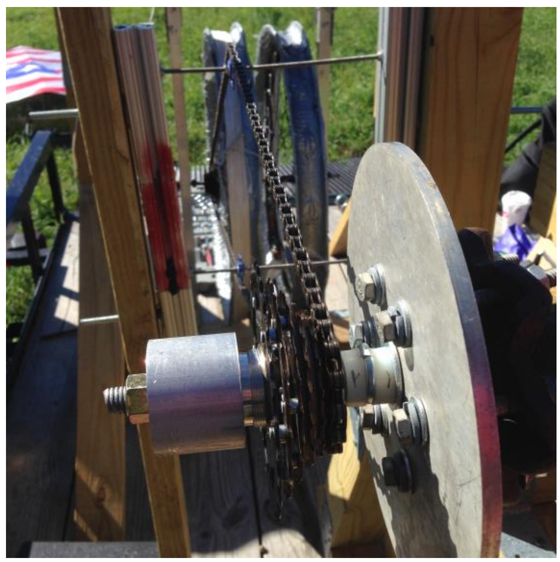

Figure 23: New Gear Train

Due to the differences in length between the different gear ratios, a chain tensioner was developed to tighten any slack in the chain as seen in Figure 23. The team decided to manually set idler gears in place instead of using springs due stability issues of the idler gears in the previous design. The team was able to develop a stable chain tensioner for the system using aluminum extrusion, threaded rods, and bike idler gears.

3.5 Frame Design

The previous A-Frame was designed for the rocking arm system that was used in previous projects. In 2015, the team that designed the rotary power design retrofitted the mechanics to the original frame. In 2016, the original frame was ready to be refreshed and fitted for the kite system's new mechanics.

Figure 24: Comparison of Old (left) and New (right) Frames

The shape of the A-Frame was chosen based on similar rocking arm systems. The rocking arm needed to be high off the surface so that the arm could have optimal room to rock. This frame also included additional wooden supports connecting the diagonal support beams and prevented the frame from collapsing on itself. Some of these features, such as the additional support for structural integrity, were important to include in the new frame. However, the height of the frame could be lowered substantially while still cradling the new system a proper distance above the surface.

3.5.1 Decreasing the Overall Height of the Pump

The water pump was the main part of this system that needed to be supported. The pump set up included unnecessary height between the pump mechanism and the water pumping cylinder. The only piece between the two parts of the system that was necessary to keep was a T-shaped pipe joint for the water to flow out of after being pumped up the cylinder. All other connections were reduced, including the male thread connections between pieces and pipe thread adapters.

The external connections were reduced simply by purchasing new piping, but the internal connections needed to be altered. The inner rod that provides the linear pumping motions needed to be reduced the same amount as the external pipes. This could only be achieved by sawing off a portion of the inner rod. Inner rods of the pump and the cylinder were of different thickness and thread size, so a new piece to link the two together was necessary. This could be achieved by welding together two female threads of the proper sizes. Shown in figure 25 and figure 26 are the CAD assemblies of the old and new design and a picture of the new design during lab testing.

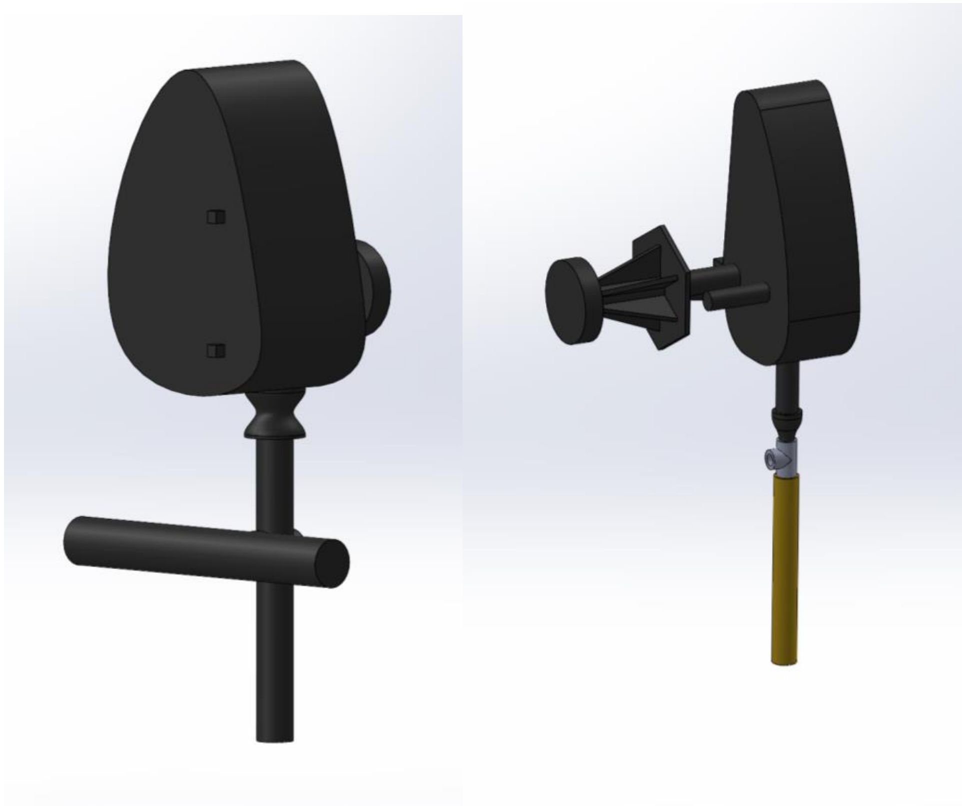

Figure 25: Reduced Pump subsystem CAD (Right)[1]

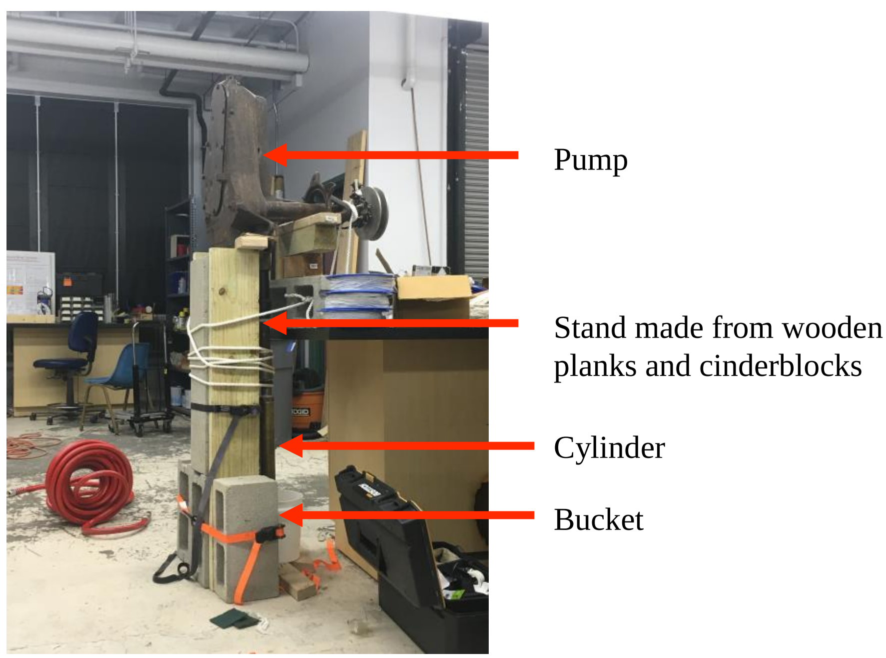

Figure 26: Reduced pump subsystem test setup

[1] Figure CAD for previous projects was never drawn to correct scale, and cylinder was not accounted for.

3.5.2 Design for the Frame

Shape of the Frame

The most important consideration to work with when designing the frame was to prevent the water pump from falling over because of its large size and weight. The pump cylinder could only extend below the floor of the trailer by 4 inches so it would have enough clearance for its water source or hose (See section 3.6 Surface Pumping) without extending below the axel of the trailer wheels. The system was fixed to a trailer for transportation and the frame shape needed to hold the pump in place during any movement. The shape that satisfied these parameters most effectively was a trapezoid. Similar to the A frame, this shape had diagonal supports in the front and back to prevent the supported system from tipping over during transportation. The trapezoid was equipped with a wide horizontal top piece that the pump could be cradled in. The side supports were positioned at a 60-degree angle because this configuration worked for the previous design. Two trapezoid structures were made for either side of the pump and were connected in the front and back on the top and fastened to the trailer of the floor on the bottom, creating a trapezoidal prism. This prism is shown in the CAD assembly in figure 27.

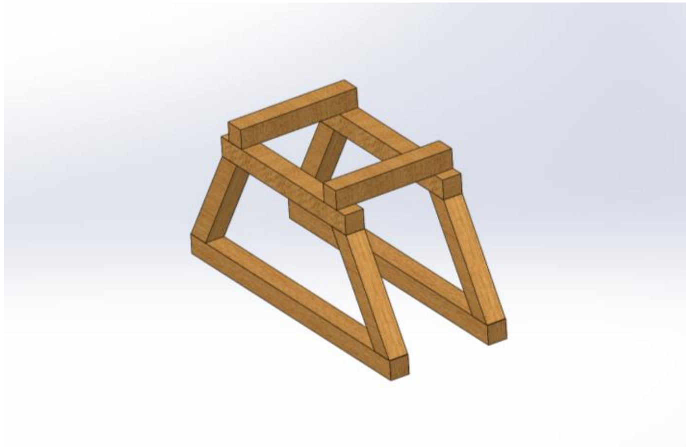

Figure 27: Initial CAD of new frame design

Cradle for the Water Pump

The pump has an egg-like shape that was hard to support with simple beams of wood. The previous team cradled the pump on the sides as it rested on horizontal beams bolted to one side of the A-Frame. After re-evaluating the shape of the pump and the cradle design, a new cradle was designed and supported the pump in the front and back, underneath the pump axles and through its one bolt hole. The beams were additionally fastened together by perpendicular beams underneath. These two beams were placed as close to each other as possible in order to provide additional support underneath the pump.

The cradle shape in the end was shaped like the pound symbol ('#'). In addition to support, it was designed to be more than just a rectangle to provide areas to hold for easy portability and removal. The trapezoidal frame was adapted to position the cradle in the same spot if the cradle was to be removed frequently. This was achieved by using 2x4 planks as the top beams connecting the two trapezoid pieces. They created a track that the cradle could be placed in without shifting during transportation.

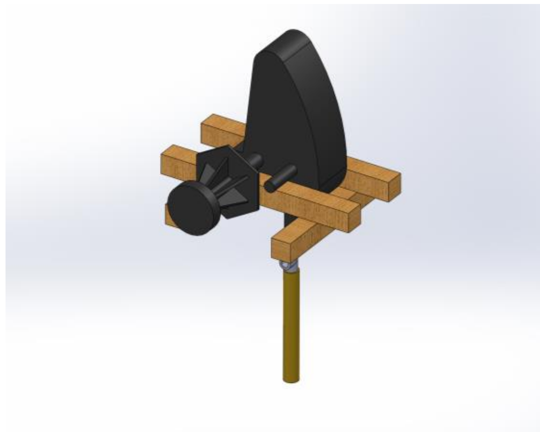

Figure 28: CAD of pump subsystem in cradle

Adapting the Trailer for Optimal Height Reduction

One of the requirements of the new frame was to lower the center of gravity. The water pump was the heaviest part of the system and it needed to be lowered significantly without protruding below the trailer axle. The cylinder was designed to extend beneath the surface of the trailer to get the pump as low as possible. A cylinder positioned below the axle could potentially contact the road during transportation and damage the system. The team decided that the pump could extend 4 inches below the surface of the trailer to maintain proper ground clearance.

3.5.3 Additional Pieces to the Frame

Additional supports were needed for the bike wheels and the chain tensioner. The kite wheel housing was supported with 45-degree angle wood supports which prevented the housing from falling over due to air drag forces during transportation. Diagonal supports were also added to the chain tension to add more stability during operation and transportation.

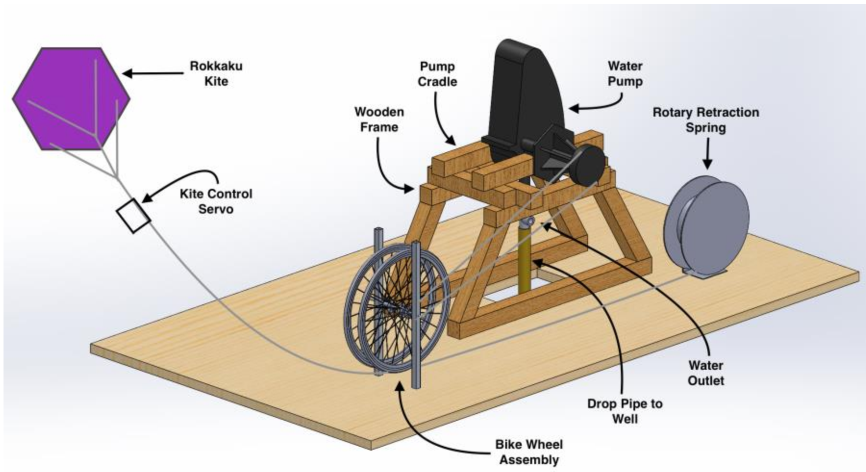

Figure 29: Complete CAD assembly of kite power system (excluding chain tensioner and kite wheel supports)

3.6 Surface Pumping

The design and fabrication of a surface pumping system was very important for the versatility of the Kite Power Project. Past project teams used a well water simulation valve to simulate pumping from a well. The system was needed to allow people in developing countries to be able to pump from standing water sources such as ponds, lakes and rivers. Previously, the system was only able to pump from a well. To create a new system, the team set design specifications, created a preliminary design, continuously optimized the design, conducted lab testing and lastly performed field testing. Figure 28 shows the old water well pressure simulator valve (left) and surface pumping system (center, right).

Figure 30: Old pressure valve (left) versus new surface pumping system (center, right).

3.6.1 System Specifications

The team determined design specifications for the system that were necessary to specify before any design work began. The specifications that needed to be determined were the operation distance from the water source, the maximum head differential between the pump and water surface, piping connections required, general ideas for priming the system and the valve and filter requirements.

The team determined that the system needed to be able to pump from a distance of thirty feet from the water source. This value was determined because rivers, ponds and lakes often have sloped banks, trees and bushes that did not allow the trailer to be parked next to the water. A thirty-foot hose gave the team plenty of distance to pump from a variety of water sources but the length of hose was not too difficult to prime or transport.

The maximum head differential between the pump and water surface was determined to be 33.9 feet. The cylinder pump used in the system was a pump designed to “pull” water from below instead of “pushing” water up. The cylinder pump creates a vacuum resulting in the pressure differential needed to drive the water up from the source to the pump. The calculation for the determination of this value is shown below using the integral of the barometric equation. This equation models the pressure change with the variation of height in a specific fluid.

$P = \rho g h + P_o$

Where P is the atmospheric pressure, ρ is the density of the fluid, g is the force of gravity, h is the height of the fluid and P_o is the initial pressure.

$P = 14.7\ lb/in^2$

The specific weight of the fluid is defined as

$\gamma = \rho g$

Thus simplifying the original expression to

$P = \gamma h + P_o$

Where γ is the specific weight of the fluid

$\gamma_{water} = 62.43\ lb/ft^3$

Converting to units of inches yields

$$\frac{62.43lb}{1ft^3}\ x\ \frac{1ft^3}{(12in)^3} = 0.03613\frac{lb}{in^3}$$

Solving for maximum pumping height of a fluid yields

$P = \gamma h$

$$(14.7\ \frac{lb}{in^2} = (0.03613\ \frac{lb}{in^3})h$$

$h = 406.88\ in = 33.9\ ft$

The surface pumping system required several connections to attach the pump, hose and valve. The pump needed to be connected to an elbow which connected to a fill point. The pump was connected to one end of the priming device while the other end of the system was connected to a reducer and thread converter. The pipe reducer connected the pipe to the smaller diameter hose and the thread converter was necessary between the pipe and garden hose threads because they had different thread lengths. The other side of the hose was connected to a thread converter and a valve.

The design of the surface pumping system needed a point to fill the system and vent air trapped within the piping and hosing. A high point was required to properly vent the air to ensure the entire system was filled with water. The pump needed to be primed separately from the system because it contained a one-way valve on the inlet of the cylinder. This is the reason why the pump would not be used as the high fill point. Priming methods were brainstormed at this point; however, they could not be verified or implemented until the testing stage.

The valve and filter were the final components to be analyzed. The system required a one-way valve and filter located at the end of the hose opposite the pump. The one-way valve opened only when the pump created vacuum pressure to "pull" the water in. However, the valve did not let water escape. The filter was place over the valve to block all debris from entering and clogging the valve. The filter would only be needed in the design if the team was eventually able to pump from a natural water source.

The team began to produce the preliminary surface pumping system design once all of the system specifications were complete. The subsequent section explains how each specification was satisfied in the design.

3.6.2 Design

The preliminary design of the surface pumping system was produced using the design specifications and then modeled using SolidWorks. The specifications described in the previous section were incorporated into the design. The parts of the system that needed to be designed or chosen were a fill point assembly, hose, piping connections, one-way valve and filter.

The fill point assembly was designed by the team considering the established specifications that included a place for water entry and the need for a high point. Figure 31 depicts the fill point system design.

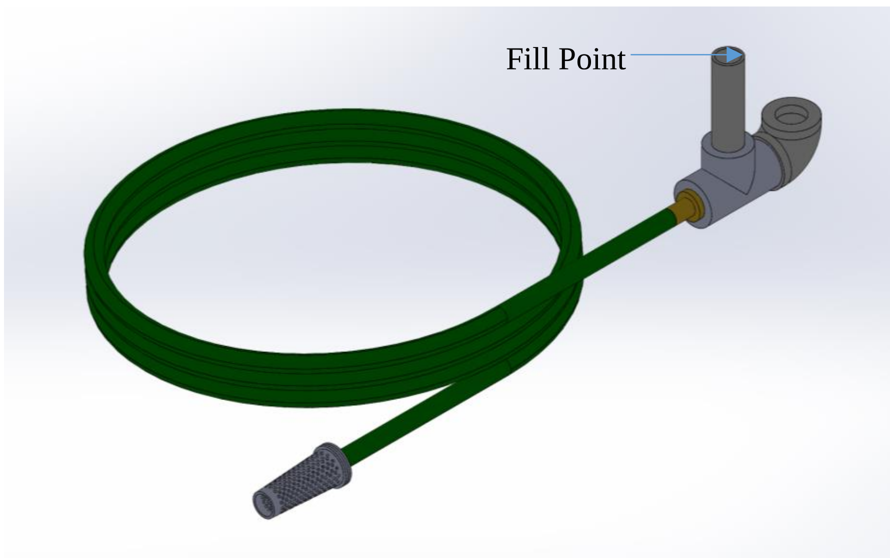

Figure 31: Surface Pump Assembly CAD with Fill Point called out

A 1-1/4” diameter elbow was connected to the bottom of the cylinder and the other end was attached to a nipple and a 1-1/4” diameter tee. The tee was connected to a 6” nipple and capped and the system was filled at this high point. The other end of the tee was connected to a reducer and thread converter to attach to the smaller diameter hose.

Hose

Hose sizes of 5/8”, ¾” and 1” were considered when the team chose the most appropriate diameter for the system. The 1” hose was eliminated quickly because it was not readily available and very expensive. The group decided to use a 5/8” diameter hose to allow for a greater flow rate and to avoid greater pressure differences throughout the system.

Piping Connections

Several piping connections were needed to convert the different sizes of pipe and the one-way valve to the hose. The system used two reducers to decrease the diameter of the pipe from 1-1/4” to ¾”. The size of the hose connection was ¾” regardless of the hose diameter making it convenient in the future if a diameter change was deemed necessary. On the other end of the hose, a reducer was required to increase the diameter from ¾” to 1” due to the size of the one-way valve. Figure 32 shows the full assembly including all of the reductions in pipe diameters.

Figure 32: Full pump assembly including surface pumping

The appropriate valve and filter were chosen to allow flow only in one direction and to keep debris out of the system. A foot valve was incorporated into the design because it allowed only one directional flow and was commonly used in other surface pumping designs. A filter sock was determined to be an effective and inexpensive way to ensure debris did not enter the system. It was designed to be placed around the foot valve and a draw string was pulled to hold it in place. The filter would only be necessary when pumping directly from a natural water source and if a permit was not approved to pump from the pond at the testing session, the filter sock would not be needed in the design.

3.6.3 Priming Methods

The team decided that there needed to be two separate priming methods, one for the lab and the other for field testing. The pumping system in the lab relied on a sink to fill the hose and the system. The system needed to be primed during the field testing by submerging the hose in the water. The high point fill assembly was then filled separately once the hose was attached. The details for each process were determined during lab and field testing and continuously improved. These procedures are discussed in greater detail in the results section of the report.

3.6.4 Determination of Desired Flow Rate

The final step before the testing could be conducted was to determine a value for the desired flow rate. This was determined through a series of calculations that are shown below.

$P_{village} = 100\ people$

$U_{water} = 20 \frac{L}{person} / day$, (van der Lingen, 2010)

Where $P_{village}$ is the number of people living in an average small sized village in a developing nation and U_{water} is the water usage per person per day in a developing nation for all water needs.

Calculating the total amount of water needed per day to supply the village yields

$$U_{total} = \frac{100\ People}{Village}\ x\ \frac{20\ L}{person\ per\ day} = 2000L/day$$

The team would like this total amount of water to be produced within an 8-hour period because it is the typical length of a work day. This calculation yields

$$\dot{m} = U_{total}\ x\ \frac{day}{8\ hr}$$

$$\dot{m} = \frac{2000\ L}{day}\ x\ \frac{day}{8\ hr} = \frac{250\ L}{hr}$$

This was the desired flow rate to be able to produce enough water for an entire village over a period of eight hours.

CHAPTER 4: RESULTS

4.1 Motor Box

4.1.1 Final Configuration

The final configuration of the Motor box is pictured below in Figure 33 and 34. The circuit remained effectively the same throughout the project. The components included the battery, Arduino, motor, L298 module, receiver module, and on and off switch. The most important decision with the setup was the selection of the battery and wireless receiver. The FlySky® controller was effective at a long range. Ultimately, the battery chosen for the final configuration was the Lithium Polymer battery because of its great working capacity for the motor and low weight.

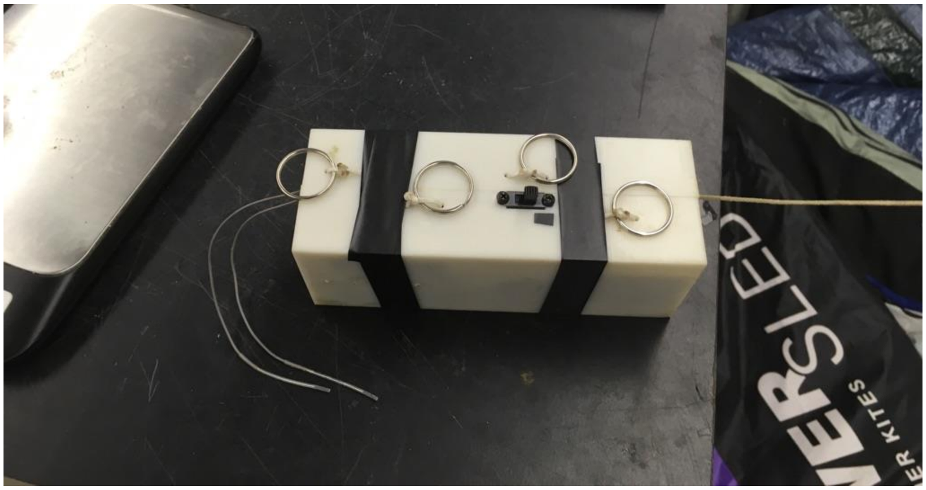

Figure 33: Final Motor Box Module

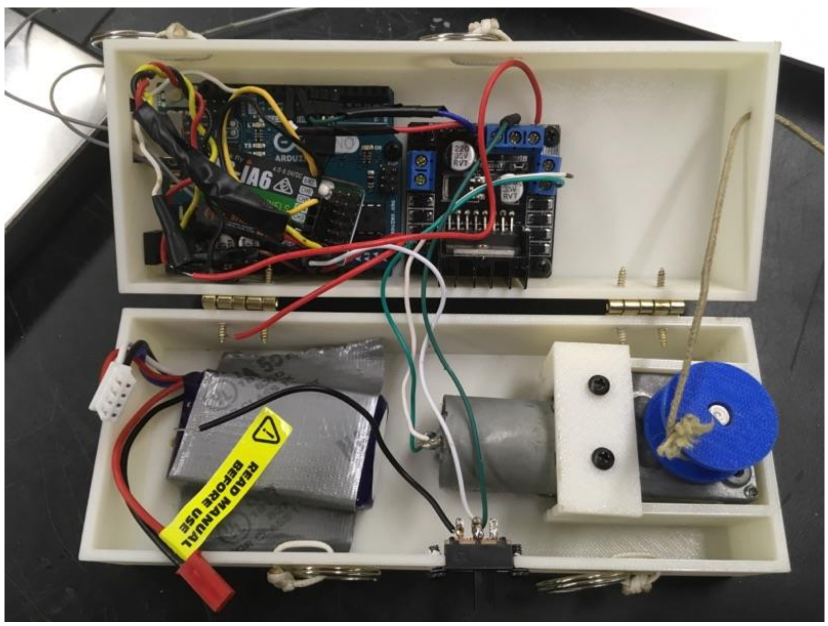

Figure 34: Inside of Final Motor Box

4.1.2 Force capacity

In the lab, the motor box was able to lift a maximum weight of 10 lbs. and was achieved with the heavy Nickel Hydride battery. The maximum weight lifted with the A23 batteries (four in parallel) was 5 lbs. These two batteries did not provide the necessary current for a larger lift capacity. The Lithium Polymer battery was not tested in the lab but proved more than adequate in all wind conditions.

Testing in the lab found that the weight of the load on the motor was linearly related to the rate of retraction of the motors string. This was important information during attempts to make the flight control autonomous because variable winds affected the force on the box and the time needed to adjust the kite. The data shown in the graph below was taken with the old Nickel Hydride battery. Although the graph does not provide data for the current setup, it serves to demonstrate the linear capacity of force on the kite and the use of this process for future autonomous control.

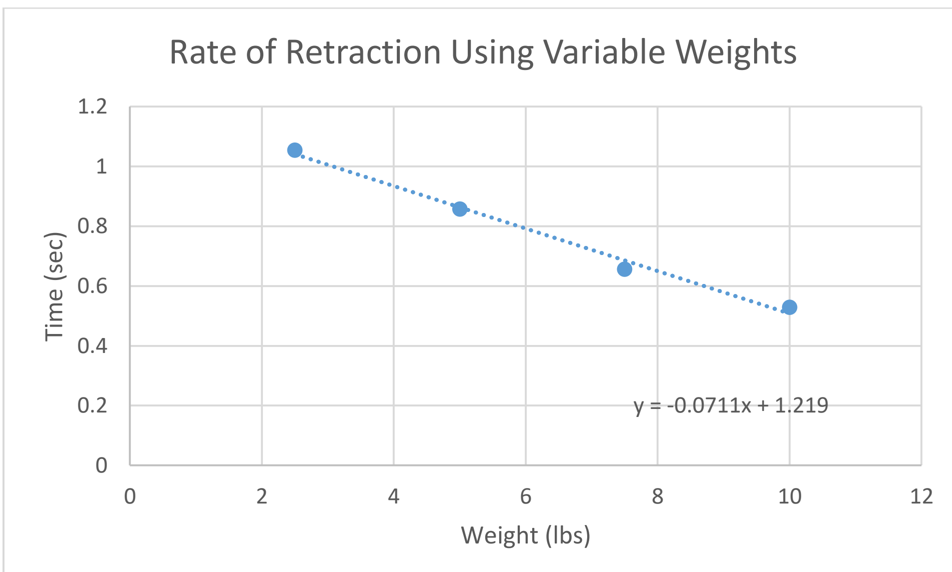

Table 3: Motor Box Rate of Retraction

4.1.3 Box Weight

Box weight and stress on the kite proved to be directly proportional and very large weight destabilized a typical flight. The team was successfully able to reduce the weight of the motor box. This was primarily accomplished by changing the motor used, downsizing the casing, and implementing lighter batteries. The table below summarizes the weight of the motor box throughout the process.

Table 4: Weight Summary

Component	**Previous MQP**	**Cylindrical Case**	**Rectangular Case**
Case	200 g	210 g	200 g
Battery	300 g	300 g	45 g
Motor	100 g	145 g	145 g
Total	600 g	655 g	390 g

4.1.4 Wireless Capability

The wireless FlySky® controller was listed to operate across a 1000-meter distance and this proved to be enough to span the length of the field and the height of the kite. Most importantly, the team needed to observe obvious flight alterations when the motor box was engaged.

4.1.5 Field Testing

The motor box was found to successfully induce changes in the kite's flight pattern. Inducing a power phase reduced the kite's angle of attack, thus, inducing a near vertical position. The expected result was that the position perpendicular to wind would increase the pull on the kite and pull on the string, overpowering the spring. However, testing proved that stall phase allowed the kite to return to a near horizontal position, producing greater lift and higher kite forces. These phases were induced on the kite repeatedly, creating the desired power cycle with the kite. The team captured videos of the induced power cycles and observed the kite changing its angle of attack in accordance with the phase.

The motor box testing was most successful during light wind situations (less than 10 mph gusts). The kite was controlled easily under these conditions, however, the forces of the spring retraction system and the pump were more difficult to overcome. It was unclear if the motor box was unable to retract the kite bridles on high wind speed days and this was experienced during testing at wind speeds of over 18 mph. However, on this particular testing day, the casing was damaged and the effectiveness of the pulley mechanism was in question.

Low wind speeds also cause issues for the kite while in flight. Lower speeds were not sufficient to maintain tension in the bridle strings creating a dynamic instability that did not produce any usable power. Future teams should look into a more exact range of wind speeds that are sufficient and which speeds will cause problems. They should also investigate strategies to overcome these high wind speeds. The team determined that the motor box assembly can still be improved and tested in a variety of wind conditions.

4.2 Retraction System

4.2.1 Kite Retraction and Extension Initial Testing

A successful field test in July showed that a simple line retraction system had the ability to retract and extend the kite line with varying wind forces. The test was conducted in wind conditions of 10 mph at 5 meters by connecting the kite line directly to the retraction spring.

4.2.2 Kite Retraction and Extension Variable Gust Testing

Using the kite line to transfer the torque of the spring reel to the kite wheel, the kite was able to produce a small power cycle by extending the kite line during wind gusts and retracting between gusts. However, the flow rate provided by this power cycle was almost negligible when compared to full kite release without the retraction spring.

4.2.3 Kite Retraction and Extension Full System Testing

Similar flow rate results were achieved without the motor box when the retraction system was used in concurrence with the kite motor box. This could have been due to a variety of factors. These include the kite failing to provide a sufficient increase in force when changed from stall to power phase, mechanical friction losses created by the line hook, or the rotary spring's force was not overcome by the kite with the weight of the motor.

4.2.4 Issues with Current Retraction System

There were a few issues with kite line torque transfer method that could be solved by implementing the newly developed gear train between retraction spring and kite wheel. During the last field testing, the tension produced by the retraction spring was enough to break the knot tied between the kite and retraction spring line. The existing bike wheel configuration also handled the force produced by the retention spring poorly because the outside of the wheel was made out rubber and duct tape. With the force of the retention spring being directed towards the gears of the bike wheel, these issues would be resolved.

4.3 Gear Train

4.3.1 Flow Rate Performance Improvement

The new gear ratio range drastically improved the flow rate provided by the system during wind conditions above 9 MPH. The team was able to drastically increase the maximum flow rate of the system because of the increase in the top gear ratio of the new gear train compared to the old one. The previous gear train design outputted a max flow rate of 480 liters per hour, while the new gear train was able to achieve a maximum flow rate of 637 liters per hour in less favorable wind conditions. This was due to the increase in pump cycles to displacement of the kite provided by the new gear train.

4.3.2 Chain Stability Improvement

The new chain tensioner provided a more stable operation of the gear train due to the ability to adjust the tension of the bike chain by manually setting the idler gears in place. This was a huge improvement over the old chain tensioner system, which was quite unstable during high wind conditions due to the instability produced by the chain.

4.4 Surface Pumping

4.4.1 Early Design Changes

The design of the surface pumping system changed throughout the constructing and early testing processes. Both large changes and small alterations were made during this time. The two most significant changes made to the design during testing were the incorporation of a ball valve at the fill point and a bucket at the end of the hose.

The ball valve was incorporated into the design after preliminary tests were conducted to simplify the priming process. Once the entire hose was filled with water and attached to the piping assembly, the rest of the system was filled with water from the fill point. The valve was shut quickly once the water reached the top of the fill point. The team found it difficult to screw the cap on and off when the system was vented or checked. The team was constantly checking if the system had leaks by observing the height of the water in the fill column. The ball valve significantly simplified this process. Figure 35 shows the use of the ball valve in the fill point assembly.

Figure 35: Fill Point Assembly

Preliminary testing proved that the foot valve and filter could not be placed directly on the bottom of the water source. The bottom of lakes and rivers are filled with thick plants and muck that could potentially disrupt the performance of the pumping system. Although the filter would keep most contaminants from clogging the foot valve, the team decided that a second defense mechanism was required. The filter was never incorporated into the final design because the team was never able to pump directly from a natural water source. The filter was not needed because the water was always pumped from tap water in a bucket.

The preliminary test period helped the team improve the surface pumping system before flow rates were collected and calculations made. The hose and priming method changed after the preliminary stages several times to optimize the system to produce the most consistent flow rate. Lab and field testing helped the team to develop priming methods and chose a hose that was primed easily and provided a consistent flow rate.

4.4.2 Priming Method Details

The priming method for lab testing was designed and continually improved in the lab. The team had set guidelines during the design stages but planned to set the details of the method during the lab testing. The team began priming the pumping system by taking apart the two hoses, fill assembly and foot valve. Each part was primed separately to ensure air bubbles were removed. The first hose was hooked up to the sink on one end and the other was placed in a plastic bucket. The sink was turned on and the operator at the sink firmly pressed the hose to the sink nozzle to limit water from escaping. The sink was run until bubbles no longer came out of the hose in the plastic bucket. This verified that all air in the hose was removed. The second hose was filled the same way and the foot valve was screwed on underwater in the bucket. The two hoses were screwed together and then attached to the fill assembly. The fill assembly was primed at the fill point and the ball valve was shut. The last step was to fill the bottom of the pump cylinder with water.

4.4.3 Field Testing

Field testing for the surface pumping assembly was conducted the same way as the testing completed in the lab and was completed to verify lab the results. The team needed to determine a revised priming method for the hoses, calculate the flow rate and compare it to the lab value.

The team needed to determine an alternate priming method to the one that was designed and implemented during lab testing. This was because the team did not have access to a sink that provided the water for the hose. The first step of the field testing priming method was to fill buckets of water and begin to funnel the water into the hose. Both ends of the hose were held at a high point next to each other and the hose was filled until the water line reached the top of both ends. Next, one end of the hose was attached to the fill point assembly and the other end was placed into the water source. Water was funneled into the fill point entry and it flowed into the water source at the other end of the hose. The group determined that all air was removed from the hose when air bubbles no longer escaped the end of the hose. This process was repeated for the second hose and the ends were attached. The foot valve was attached to the end of the hose under water and the fill point assembly was filled by opening the ball valve at the high point.

The team aimed to design the simplest priming method possible. Unfortunately, the team was not granted access to pump directly from the standing water source nearby. If access to the river had been granted, the priming method would have been different. In this case, the entire hose would be submerged in the water and the trapped air would be removed through both ends of the hose. Once the air bubbles were removed, the foot valve could be attached. The fill point assembly would need to be filled through the ball valve and then surface pumping could commence. The two field testing methods and the lab testing priming method are quite different, however, they all accomplish the same task. It is most important that air has been removed from the hose assembly while the method is not as important.

The team conducted several surface pumping tests to determine the flow rate that the kite power system was capable of pumping. As stated before in the results section of the report, the team obtained a flow rate of 180L/hour during lab testing. This number was produced using human power rather than kite power. The team realized that this flow rate would be far less than that when powered by the kite in the field. However, it was very important to set a reference value before performing field testing.

The first field testing data was obtained at Moore State Park in Worcester, MA during September. This location offered favorable wind conditions and gust often reached 20 MPH. Most of the testing was conducted at an average wind speed of 10MPH. This wind speed was taken at a reference height of 13ft from the ground. The team decided to use the forth gear to maximize the gear ratio and obtain a higher flow rate than in the lab. The kite provided a considerable amount of force and the team determined the force was great enough to use a higher gear ratio. The team obtained an average of 637L/hour during several trial runs. This flow rate was determined to be within the desired range of the pumping system.

4.5 Frame

Construction of the frame was very straight forward once the SolidWorks design was finalized. The team purchased several appropriately sized 4x4 pressure treated wooden beams to construct the frame, along with flat brackets. The first stage of construction was the cradle that the pump was fixed to. This cradle made the pump easier to grab and lift because its heavy egg shape was very awkward for two people to lift. This cradle was also made to be as square as possible so that it could fit in the parallel trapezoid structures securely. The cradle was fastened together with 4 large bolts, and the pump was fastened to the cradle with a large metal rod and scrap plank. This provided a tight bond, allowed for shifting without creating stress on the wood, and allowed for easy removal if necessary.

The trapezoid structures were carefully crafted to be parallel and level with each other, so that the pump cradle could rest on them without shifting during operation or transportation. The team screwed the beams together using flat brackets and several screws per bracket to ensure that the structure could support a heavy load for a long duration. The trapezoids were connected by beams on the top and bolted to the floor of the trailer. The cradle track modification (as mentioned in section 3.5.2) can be seen in Figure 36.

Figure 36: Modified frame with track for cradle

A second modification not represented in the SolidWorks design was the 45-degree support beams on either side of the trapezoid frame (Figure 37). These beams were initially incorporated in the design to provide additional support and preventing the pump from rocking. The 45-degree support beams were fixed to the trapezoids using L-brackets and several screws. Once assembled, the frame was well secured and did not rock in any direction. This ensured stability from all sides and supported the system during transportation.

Figure 37: Frame secured to trailer with added 45-degree supports

The team re-organized the pump system configuration once the frame assembly was completed and the A-Frame was disassembled and removed from the trailer. The trapezoid structure was bolted to the trailer equidistant from each wheel to ensure the center of gravity was in the middle and above the wheel axle of the trailer, so that the system was well supported when hitched for transportation and unhitched for storage. The trapezoids were also strategically fixed so that a trap door for the excess pump length could be created between the trailer's wheel axle and one of its supporting rods. The bike wheel assembly was placed towards the back gate of the trailer and in line with the rotary rod on the water pump. The chain tensioner was placed between the bike wheels and the water pump to allow for the adjustment of the bike wheel gears. The rotary spring was additionally placed in line with these components, but towards the front of the trailer. It could be attached to the bike wheels when it was needed for use.

Overall, the new system assembly and frame was able to survive several initial transportation sessions. The goal to lower the center of gravity was achieved. An additional goal to get the height of the entire system, including the trailer, to under 7 feet tall was also achieved and the entire system can be properly stored during off seasons. The modified pipes on the water pump were able to successfully continue to pump water through the cylinder as intended.

4.6 Summary

Figure 38: Successful field test at Moore State Park

Field testing was conducted by the group at several locations throughout the summer months as well as September and October. The team conducted these tests to verify calculations and lab testing. The team optimized any components of the system that did not provide sufficient results during the field testing. The group conducted field testing on the motor box, retraction system, gear assembly and surface pumping system.

CHAPTER 5: RECOMMENDATIONS & CONCLUSIONS

The kite power system had undergone several improvements over the summer of 2016 and had successful results, especially when testing each subsystem as separate entities. However, the project will always have room for improvement. This year, the team introduced an updated servo motor configuration with the ability to receive radio frequency controls by operators on the ground. The results from the summer of 2016 proved that the concept works but there needs to be future exploration in the configuration of the motor box and the wireless communication to achieve optimal control over the kite.

The team added two new concepts for optimizing the kite power system. The team added a rotary retraction spring and a surface pumping system. The rotary spring held the kite steady in the air, but was unable to create reliable flow rates within the pump. A deeper exploration into the theory behind the rotary retraction method will help the entire kite power system become an autonomous system. The surface pumping testing was very successful when using the setup at a clean reservoir near the kite power system. The future of the surface pumping system will need to be used in pond water, which is a fresh water source that will require filtering and a method to keep the valve off the bottom of the water source. Recommendations with this subsystem moving forward include testing the system in realistic circumstances and adding components necessary to achieve successful results.

5.1 Motor Box

5.1.1 Configuration

The present configuration seems to be near ideal for present setup. Improvements reducing weight and increasing power would continue to improve the system. Reducing battery weight and motor weight are two areas to explore. There is currently a risk of the Lithium-Polymer battery draining entirely and damaging itself. The addition of low voltage cut off program in the Arduino or a simple brushless ESC in the circuit should fix this problem by turning off the power before the Lithium-Polymer batteries drop below 2.5 volts. Placement of the motor on the kite string is also the most stable position of the system in the air. However, it could also be worthwhile to consider controlling the kite from the ground with another string to adjust the bridles. This would remove all instability concerns while potentially serving the same purpose.

5.1.2 Wireless Communication

Wireless communication with the kite enabled the team to directly test the influence of the motor box on the flight. It was a huge success and great proof of concept. However, on the ground there is no way to determine the amount the motor has rotated or the length of string being retracted. A sensor and additional transmission system could be influential in understanding how the motor box controls the kite.

5.2 Rotary Spring Improvements

The ability to change the retention force at the bike wheel should show improvement in the ability of the kite to overcome the retention forces produced by the reel spring during lighter wind conditions. By integrating the gear ratio torque transfer design into field testing, this should help produce a smaller retention force during lower wind conditions. This would also solve problems that were previously seen with the line transfer method as discussed before in the Results section.

5.3 Mechanical System Inefficiencies

5.3.1 Kite Line Eye Hook

Mechanical inefficiencies stem from the friction developed from the kite line brushing up against the eye hook. This is essential for redirecting the kite line to bike wheel during crosswinds or non-ideal wind alignment of the trailer. To reduce the friction produced in this process, the team suggests that a bearing be implemented into the design of an eye hook to reduce the friction produced by the kite line.

5.3.2 Pump-Gear Attachment

Currently the five speed bike gear is attached to the pump using a configuration that is not fully centered due to the mechanism in which the threaded rod is attached. Therefore, the slightly offset gear tightens and loosens the chain during the pump cycle and puts strain on the chain tensioner's idler gears. By developing a new way to center the threaded rod attachment or creating new pump-gear attachment, it could result in a more efficient gear train due to less friction losses in the system with a centered gear.

5.4 Surface Pumping for Realistic Conditions

The surface pumping system allowed the group to pump water from a standing water source such as a river or pond. This is essential if the technology will be used in a developing nation because most villages have access to a river but not a well. In the future, the next MQP team should incorporate a filter sock that will protect the foot valve from debris when pumping directly from a natural water source. It is essential that the team create a system to keep the filter and valve off the bottom of the water source as well. The team needs to determine a system that will not result in a high pressure differential between the water source and the water entering the hose.

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Figure Sources

Figure 2:

http://iet.jrc.ec.europa.eu/remea/sites/remea/files/reqno_jrc81645_final_report.pdf

Figure 3:

http://www.mdpi.com/energies/energies-07-

08508/article_deploy/html/images/energies-07-08508-g002.png

Figure 11: https://www.amazon.com/GoolRC-2-4GHz-Transmitter-Helicopter-Receiver

Figure 18: https://www.youtube.com/watch?v=UGoUPPmN-WA

APPENDIX A: ARDUINO CODE

Arduino C code for Motor Control with Flysky controller

This code is available to the working group for viewing and editing in: OneDrive\MQP\Code\RC controlled\reciever_Flysky. The drive should be shared with you by the previous group or professor.

```
int in1 = 9;
int in2 = 8;

//-------------------------FUNCTIONS----------------------------

void forward()
{
 //Serial.println("forward");
 digitalWrite(in1, HIGH);
 digitalWrite(in2, LOW);
}

void back()
{
 //Serial.println("back");
 digitalWrite(in1, LOW);
 digitalWrite(in2, HIGH);
}

void Mstop()
{
 //Serial.println("stop");
 digitalWrite(in1, LOW);
 digitalWrite(in2, LOW);
}


//estimating tension opposing motor

//reel in kite for a set time, measure how much it reels in, calculate the rate of reel in
float RateToPound(float T)
{
 return (T - 1.219)/(-0.0711)
}

//-----------------------------------------------------------
```

```
void setup()
{
  Serial.begin(9600);
  while(!Serial);

  pinMode(12,INPUT);
  pinMode(5,INPUT);
  pinMode(7,INPUT);

  pinMode(8,OUTPUT);
  pinMode(9,OUTPUT);


}
int value12; //right joystick leftright
int value7; // left knob
int value5; //right joystick, updown

void loop()
{

  value12 = pulseIn(12,HIGH);
  value7 = pulseIn(7,HIGH);
  value5 = pulseIn(5,HIGH);
  Serial.print("5: ");
  Serial.print(value5);
  Serial.print(", 7: ");
  Serial.print(value7);
  Serial.print(", 12: ");
  Serial.print(value12);
  Serial.print("\n");

  //autonomous control
  while(value7 > 1900 && value7 < 2000)
  {
    forward();
    delay(1000);
    value7 = pulseIn(7,HIGH);
    Mstop();
    delay(1000);
    value7 = pulseIn(7,HIGH);
    back();
    delay(1000);
    value7 = pulseIn(7,HIGH);
```

```
    Mstop();
    delay(1000);
    value7 = pulseIn(7,HIGH);
  }

  //General remote control control
  if(value5 > 1700 && value5 < 2000)
  {
    forward();
  }
  else if(value5 < 1300 && value5 > 900)
  {
    back();
  }

  //5 seconds of motion control
  else if(value12 < 1300 && value12 > 900)
  {
    back();
    delay(5000);
  }
  else if(value12 > 1700 && value12 < 2000)
  {
    forward();
    delay(5000);
  }

  else
  {
    Mstop();
  }
}
```