Active Stabilization of a Floating Wind Turbine Platform

A Technical Report submitted to the Department of Mechanical and Aerospace Engineering

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

MAE 4610/4620, ME Design I & II
Fall, 2021

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Introduction

As time progresses, humans have become more and more reliant on electricity to power their everyday lives. Fossil fuels, currently our primary source of energy, only exist in finite quantities, and clean sources of energy are now required to provide the power needed for society to thrive in an environmentally friendly and reliable manner. Wind energy is one source of this clean energy, although current wind energy has its drawbacks. Turbines are often placed on land in large wind farms, and these farms take up vast quantities of valuable land and cause annoying visual and audio pollution. Other turbines are placed in shallow water but these turbines can be extremely expensive to install and maintain the submerged concrete bases, while not solving many of the issues with land-based wind farms.

The goal of our project was to design a scale-model of a floating wind turbine base which used active methods for maintaining its stability. Initially, we were given a passively damped design completed by a previous year's project group for use in this process. Introducing active stabilization to their design provides the unique ability to reliably counteract forces acting upon the structure from wind, waves, and currents. The active stabilization method had to be designed considering constraints of codes, constructability, cost, functionality, maintainability, sustainability, standards, and more. Following a meticulous design process, we were able to assemble a physical prototype of an active stabilization method and test its effectiveness in water.

Background

Research

As the offshore wind project pipeline grows, the motivation for transitioning from fixed-bottom to floating offshore wind turbines is fueled by a number of factors including more opportunities for power generation in deeper waters and higher wind speeds. According to the National Renewable Energy Lab (NREL) and as seen in Figure 1, 80% of wind resources are in waters deeper than 60 meters, and at that depth, fixed-bottom structures become exponentially more expensive. Floating wind platforms, which currently only account for 0.3% of offshore projects, would allow turbines to be placed further offshore and generate considerably more power (Musial, 2020). Furthermore, floating platforms can be inspired by existing oil rig technologies which could allow for a transition of knowledge and jobs between industries. As the renewable energy industry grows, it is also important for carbon-emitting businesses to find other focuses, and the design of floating platforms could aid that transition.

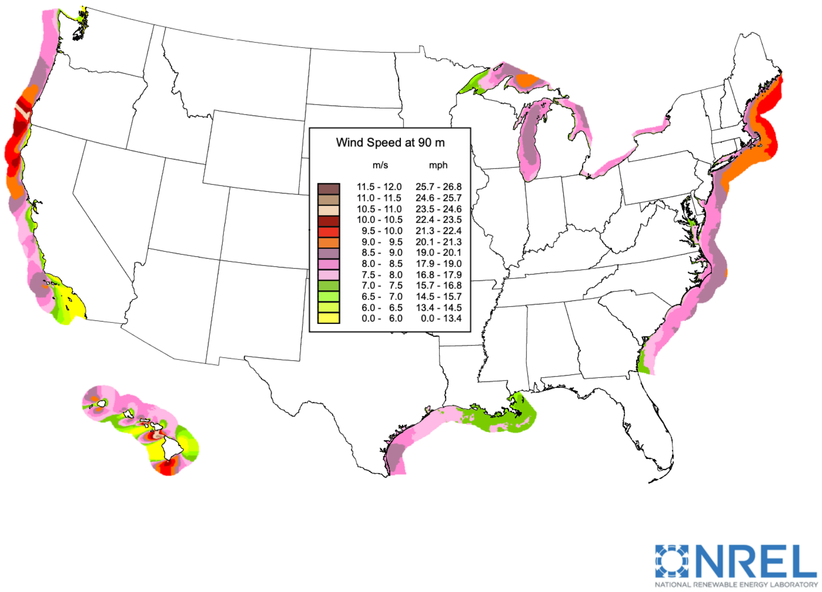


Figure 1. United States offshore wind resource at 90 m above the surface
Note. Image retrieved from NREL technical report: Assessment of Offshore Wind Energy Resources for the United States. (Schwartz et al., 2010)

Although the benefits of floating wind seem clear, there are still a number of technical challenges that exist and prevent the construction of utility-scale projects. To counteract high installation and mooring costs, floating turbines must be made as efficient as possible, and power efficiency is highly dependent on platform stability, especially in shallower water. For example, large pitch motions of the turbine caused by impacting waves could impact the pitch control system of the blades and lead to efficiency problems or even sinking (Yang et al., 2019).

Passive Control

To solve these problems, the vast majority of current approaches use passive stability to design the geometry of the substructure in a way that creates a righting force and minimizes the impacts of the waves. The three primary designs of passive floating platforms can be seen in Figure 2 and include the tension-leg platform, spar-buoy, and semi-submersible designs. The techniques and drawbacks of each current passive design are summarized in Table 1.

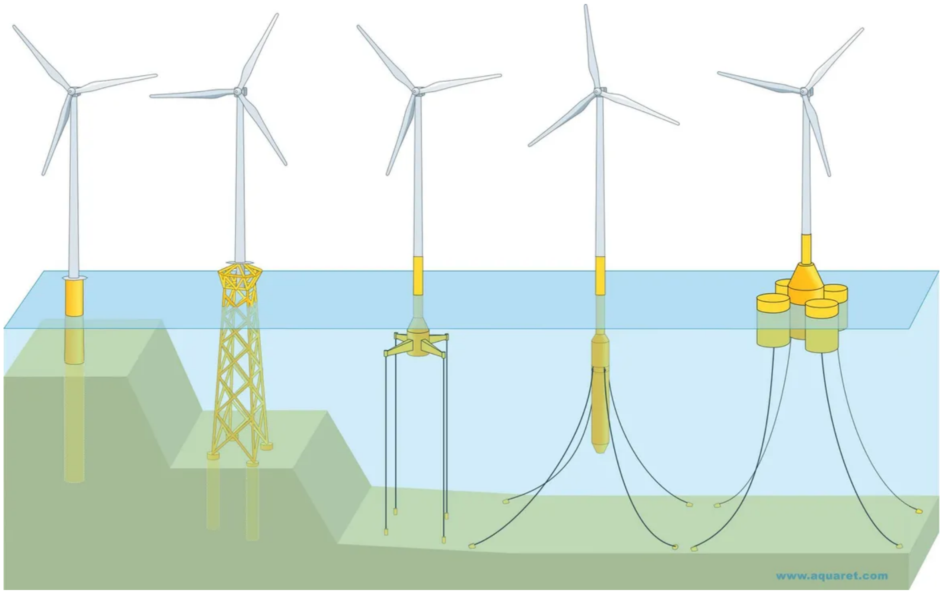
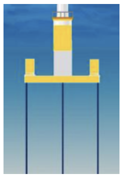
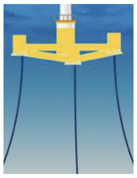


Figure 2. Offshore wind turbine designs. From left to right: two fixed-bottom structures, tension-leg platform, spar-buoy, and semi-submersible platform.

Note. Image retrieved from Aquaret.com (Aquaret, 2012).

Table 1. Summary of Current Passive Floating Platform Designs.

Design	Image	Technique	Benefits	Drawbacks
Tension-Leg Platform		High tension and buoyancy forces	- Excellent stability - No horizontal movement	- High anchoring and installation costs
Spar-buoy		Lowers center of gravity to provide a higher righting force	- Good passive stability - Cheaper installation	- Can only be placed in deeper waters
Semi-submersible		Maximizes buoyancy by spreading out the weight	- More buoyant - Easier port side maintenance	- Higher surface area and more sensitivity to waves

Note. Images retrieved from Greenbarrel website (Singer, 2020).

The tension-leg platform, which typically features four anchor ropes taut with the ocean bed, achieves excellent stability through high buoyant and tension forces, but it is the most expensive of the three, requiring high anchoring costs and complex installation in deep waters. The spar-buoy, on the other hand, maximizes passive stability by lowering the center of gravity through a deep underwater monopile shape (Salic et al., 2019). As the center of gravity is lowered, the distance to the center of buoyancy increases, and therefore there is a higher righting torque when the platform tilts. Although the spar-buoy tends to provide sufficient passive stability, it has very little depth independence and can typically only be placed in waters deeper than 50 meters (Yang et al., 2019). This provides even further limitations on the site design process, which is already considerably restricted due to protected waters and government regulations. Finally, the semi-submersible platform maintains flotation by maximizing its buoyancy and spreading out its weight into four large columns. Although this does lead to higher buoyancy forces, it also increases the surface area of the substructure which leads to more wave sensitivity and unreliability during high wave conditions (Salic et al., 2019). Semi-submersible structures must also incorporate some sort of active control to overcome their wave instability; similarly, our design will be placed on a semi-submersible structure and use both passive and active control.

Active Control

One of the most notable current uses of active control in floating wind stabilization is WindFloat, a design concept which distributes water throughout the columns of a semi-submersible platform to account for wind thrust and wave instabilities. The system uses closed-loop feedback, actively sensing the platform's tilt and adjusting the distribution of water to minimize the error between tilt and desired stability (Principal Power, 2019).

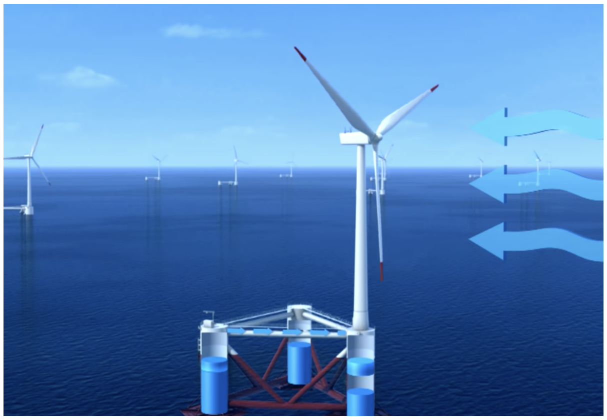


Figure 3. WindFloat Active Ballast System.
Note. Image captured from WindFloat concept animation (Principal Power, 2011).

In Figure 3, for example, the wind thrust provides a counter-clockwise tipping moment, but by pumping water through the gangways in the opposite direction, a righting moment is produced which stabilizes the tipping of the platform. One of the biggest drawbacks of this design, however, is the speed of response as water can only be pumped slowly and the system can only respond to lower frequencies of waves and winds (*Inc. - Globalizing Floating Wind*, n.d.).

Another experimental method of active platform stabilization is achieved through the pitch control system of the blades. By actively adjusting the pitch of the turbine blades, the thrust force on the turbine can be varied in response to the incoming waves and create a stabilizing moment (Yang et al., 2019). As the pitch changes, the angle of attack of wind on the airfoil also changes, and the thrust can be increased or decreased as desired (Anderson, 2020, 39-42). This solution uses the Supervisory Control and Data Acquisition (SCADA) system of the turbine, but because the SCADA system runs at a slower frequency than that of the waves, active thrust control cannot respond to instantaneous changes of the waves (Yang et al., 2019). Furthermore, using blade pitch control to adjust platform stability means that the control system cannot simultaneously focus on power efficiency, which is necessary to maintain an appropriate coefficient of performance for ideal power generation at various wind speeds.

In order to account for the fallbacks of these common active and passive solutions, our design will focus on reliability, durability, and speed of response, as well as adhere to a number of constraints and specifications which were outlined at the beginning of the project.

Constraints

The primary constraints that were placed upon the design of our stabilization system included scheduling, cost, safety, and environmental considerations. Perhaps one of the most impactful constraints was scheduling, as our team had only one semester to ideate, design, assemble, and test a functioning stabilization concept. In order to establish and follow task deadlines, a Gantt chart was created at the beginning of the project which listed expected durations of various tasks and ideal completion dates. This chart can be seen in Appendix G. Examples of tasks included ordering motors and circuitry, designing water resistant casing, and testing the assembled design. Additionally, changes often needed to be made to the Gantt chart, as there were unexpected shipping complications during the planning process. Next, our budget was $667, and therefore our design needed to be cost-friendly and durable so that parts didn’t need to be replaced often. Although this project’s design is just a model of a turbine base, considering cost will also be important when implementing the concept on a real turbine, as offshore floating wind currently is unable to be constructed at utility-scale due to high costs. Furthermore, the electrical safety of our design was paramount, and it was important that the electronic components of our model did not become wet during testing. Failure to adhere to this constraint could lead to damaged parts or a safety risk to the students operating the model. Finally, it was important that our design had limited or no moving parts underwater so as to pose minimal risk to the environment and marine wildlife.

Specifications

The original specifications addressed the main constraints put on the project: cost, safety, and the environmental effect. Addressing these constraints in the active design could not backpedal any progress made in the development of last semester’s wind turbine base. The addition of an active solution should not make the device worse at floating passively. Furthermore, any mechanical and electrical systems had to be above the water in order to keep the solution safe for the environment and to keep the parts in good condition for repeated use. These parts had to be protected by a physical barrier in some way in case of waves that could crash up against the floating platform. The tension-leg platform design combined with the semi-submersible base was an ideal solution to keep the active parts out of the water on the base platform whilst also maximizing on the passive damping from the base. The final solution cost $133.99, and the project cost $157.75 including an extra motor and other components such as tape and delivery fees, which was well below the $667 limit.

Overall, these additions would raise the center of gravity, which is in direct conflict to the earlier specification of keeping the device floatable. They also add weight to cause the entire system to float lower in the water, so some level of passive floatation had to be improved. When the original design for the motorbox and electronics were printed and collected, the device was tested on its floatability. The device had an overall raised center of gravity and a lowered center of buoyancy, so a weighted chain was added below the surface of the water to keep the center of gravity low and foam rectangles were added to the corners with tape of the base to raise the center of buoyancy. After these adjustments, the platform floated about an inch above the water, so the electronics were safe and the motors would not disturb the water.

Design Process

Concept Selection

The first step to the design process occurred with the ideation phase. During this phase at the start of the project, all team members separately brainstormed ideas of how the project was going to move forward. Each member of the team had to come up with three concepts and how they would each work. After mild deliberation, we concluded that we would discuss seven of the 15 designs further due to repetition as well as effectiveness of the designs.

The first design was centered around mounting pumps to the platform and distributing water to different areas through pumps, thus changing the center of gravity whenever a wave affected the stability of the platform. This idea can be seen in Figure 4.

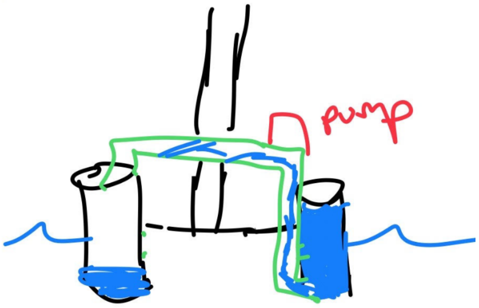


Figure 4. Pumps Ideation Design Concept

The second design considered was similar to the pump design through distribution of weight, but instead of using water it would use masses sliding on the platform. Two weights were to move linearly and parallel to each other making the platform heavier on the location where the wave would meet the platform (Figure 5).

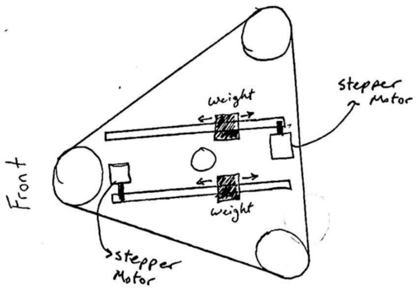


Figure 5. Horizontal Sliding Masses Concept

The third idea dealt with the redistribution of weight in the vertical direction. The weight would move through the main column of the wind turbine attached to a string on a low friction track. The mass would be released downward or pulled upward in order to keep the turbine from rocking in the water (Figure 6).

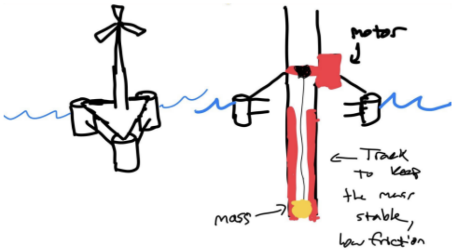


Figure 6. Vertical Sliding Mass Concept

The fourth concept was called swinging arms. These arms would be located in the cavity below the platform between the columns and supporting structure (Figure 7). The "arms" would have weights attached to them and swing underneath the platform creating a restoring force to tilt the platform back to a level position. A central motor on top of the platform would allow for quick movements, creating a simple design.

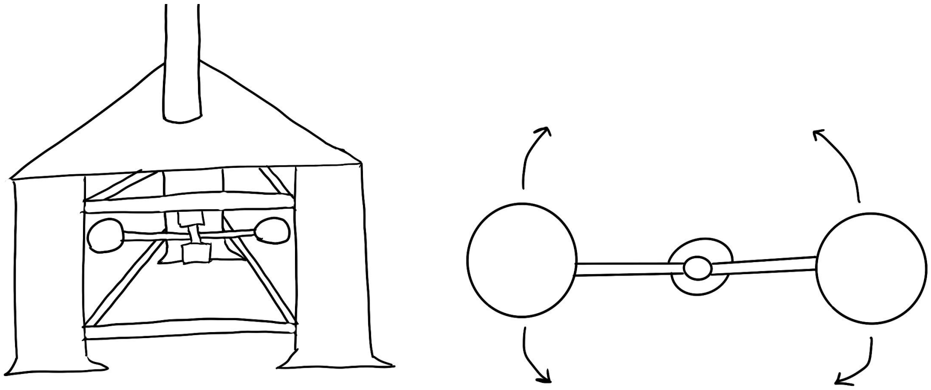


Figure 7. Swinging Arms Design Concept

The next design is the base propeller. Three individual propellers would be attached to each of the main columns underwater and either spin up or spin down to pull/push the platform, stabilizing it to the motion of waves (Figure 8).

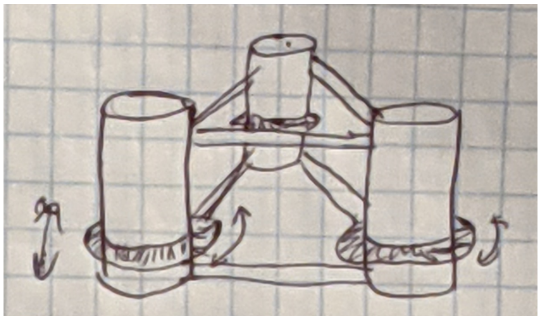


Figure 8. Base Propeller Design Concept

The sixth design was the underwater wing. This design consisted of a large underwater wing that would move linearly along the supporting structure of the platform on one axis. As the wing moves, a lift force is created between the water and the wing which applies a force to one side of the platform (Figure 9). The wing would be able to rotate and change its angle to accommodate stabilizing waves from different sides.

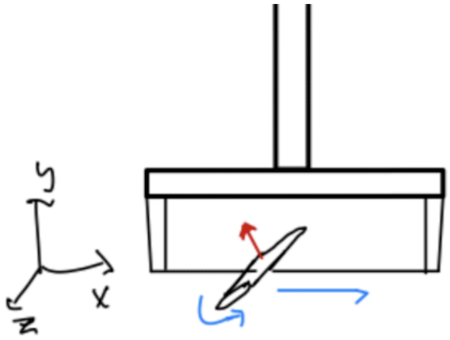


Figure 9. Underwater Wing Design Concept

The final concept that was considered was used as the reference point for the ideation because it is already being developed by large corporations. The Tightening of Anchor Ropes concept was made up of motors attached to the top of the platform that would pull or release rope tied to the ocean floor (Figure 10). When one corner of the structure was too high, the corresponding motor wheels in the anchor rope and applied a tensive force to restore stability.

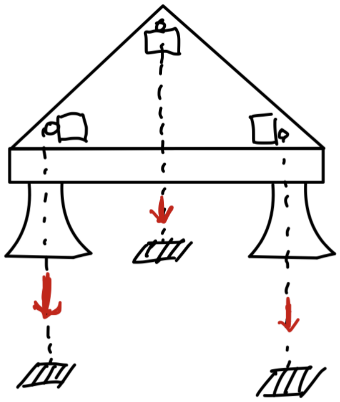


Figure 10. Tightening Anchor Ropes Design Concept

The next step in the process was to screen each idea and compare them to each other. We completed this on a table, and ranked each design against the reference (Tightening anchor ropes) on criteria that were important to the design including floatability, water resistance, and response time to name a few. This chart can be seen in Appendix C, where the reference was set to 0, and if a design was better in a certain aspect shown, we would assign it a positive one. If the other concept was worse on a criteria, we would assign it a negative one. From there, we tallied the total for each design and continued with the designs that scored a positive number, as well as with the reference.

At this stage, we wanted to redesign the concepts and combine ones that were similar to more viable options. The horizontal sliding mass and swinging arms were combined to create a concept with sliding masses along the support structure of the platform, underwater. This is shown in Figure 11. The second concept updated was the reference, where the motors and ropes were moved to the center of all three sides, instead of the corners, to prevent water damage to the electric machines and still have the platform be able to float.

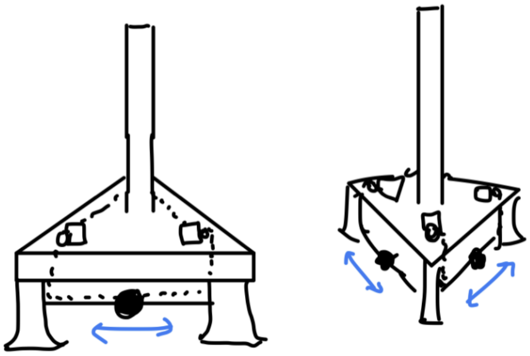


Figure 11. Updated Sliding Mass Concept

Lastly, we worked on a more in depth scoring system where each criteria was broken down into components and given percentage weights to its importance. For example, we thought that fast response time to a wave impact was important so we gave it 16%, one of the highest percentages. The scoring for the tightening anchor ropes design can be seen in Appendix D under scoring summary. Each member of the team evaluated each of the four concepts left and scored on a level from 1-5 of how well the system would operate in each criteria. The averages of the teams scores were taken, and we decided through discussion to proceed with the reference concept, the tightening of anchor ropes. We believed that this was the best design because of its relatively low weight on the platform as well as its fast response time to a wave impact. Many of the other designs, such as sliding masses, would be slower and not be able to counter the force of the wave in time, so we believed that motors pulling and releasing tension would be our best choice.

Decision Making

When making a decision on which design we were going to proceed with, we needed to consider the following factors; Maximum displacement, continuous displacement, and horizontal and vertical motion. Some of the designs allowed only a definitive maximum resistive force to the impact of the waves such as moving weights or using pumps to move water on the platform. The maximum resistive force in these scenarios would be the mass of the weighted objects and of the quantity of water. With the tensioning of anchored ropes design, the maximum force we could apply was limited by the amount of torque the three servo motors could handle, which is around 0.15 N-m in our model (Seeed Studio, 2021). Since waves move through the water and platform relatively fast, we needed a system that had continuous motion to be able to adapt to the changing conditions. Some of the designs only allowed displacement in waves or acted harmonically. The servo motors were selected specifically so they could be programmed to act in a continuous motion as well as switch directions quickly to either pull or release the line attached to them. The last consideration is horizontal and vertical motion. The goal of the project is to stabilize the platform in the vertical axis, or z-axis. The tensioned anchoring of ropes was the only design able to stay fixed in the XY, or horizontal plane, without extra weight being added. With most of the other designs, chains would have been added to the bottom of the platform anchored at the sea floor. This would add unnecessary weight to the platform and affect its floatability. The design we went with uses the tethers to stabilize itself in the vertical axis as well as stay stationary in the horizontal plane.

The maximum force that can be applied to the system using the torque from the servo motor specifications and the radial distance on the rope spool attached to the motors is 7.5N per motor. This would come to a total of 22.5N of force applied to the platform from the three motors combined.

Standards

When considering the standards in place to build an offshore wind turbine platform, we looked into an offshore wind turbine as well as standards to offshore oil rigs since those standards have been in place for a longer period of time and are more developed. The Bureau of Ocean Energy Management is the government entity responsible for granting leases, easements, and rights-of-way for orderly, safe, and environmentally responsible renewable energy developments (Sirnivas & Musial, 2014). The most important standards that need to be considered for a project like this are IEC 61400-3, Wind Turbines - Part 3: Design requirements for offshore wind turbines, ISO 19900, General requirements for offshore structures, and ISO 19904-2, Floating offshore structures-tension leg platforms (Sirnivas & Musial, 2014). Those three are the up to date requirements for offshore wind turbines specifically.

For safe offshore operations according to the American Petroleum Institute, there are many standards to consider. The first is RP 2A-WSD: Planning, Designing, and constructing fixed offshore platforms-working stress design. This standard deals with guidance for hurricane, earthquake loading, soil and foundation considerations, as well as structural damage for above and below water structures (API, 2014). Because we are using a tension-leg platform design, standards for the tensioned lines also must be considered. This standard is RP 2T: Planning, Designing and Constructing Tension Leg Platforms (API, 2019).

Risk Analysis

Through the ideation and screening processes, risk was a large factor considered for our model. In our design, the largest level of risk is seen with electronics being mounted on the platform itself. We were worried about water getting into the platform and damaging the electronics and making the components unusable. This could be caused by the platform not being buoyant enough or having a fault in our programming that would pull the platform into the water and not release the ropes. This could be applied to the real world scenario. If the platform was pulled down too far due to programming or equipment error, then the electronics could be damaged, and the platform could sink. This would put the workers on the platform at the time in danger, so there would need to be extensive checks of the physical equipment, of the electronic programming, and of course include safety measures for the staff in case of an emergency. The seriousness of a situation as this one would put the company/organization in financial danger as well as have liabilities for their employees. Through something as complicated as a offshore platform with the standards of not only wind turbine platforms but oil rig platforms, I don't foresee the platform sinking accidentally likely to occur if properly programmed and maintained. Another aspect that needs to be considered in these designs is the weather and hurricane conditions. The platform would need to be designed to survive not only regular waves, but also extreme circumstances such as the winds and wave impacts of a hurricane at sea. To prevent catastrophes to the platform, I believe adding more tensioned tethers would decrease the likelihood of tipping or swaying during these extreme circumstances. This would in turn put more weight on the platform, so it would need to be able to float better.

Solution

Final Design

Our design solution chosen was an active tension leg system on a semi-submersible base. The principle of the tension leg design relies on three physical lines running from the floating base and anchored to the ocean floor. These lines are wound around spools that protrude from the long sides of the floating base and hold extra slack that can be released or retracted depending on the need. Using a line on each side allows the base to be pulled up and down against the rocking of the base from any direction. The three spools are each attached to motors which are controlled by a processing unit. The processing unit is also connected to a 3-axis gyroscope/3-axis accelerometer sensor which provides angular tilt values of the structure. Figure 12 shows the CAD design with these positioned within a protective motor box.

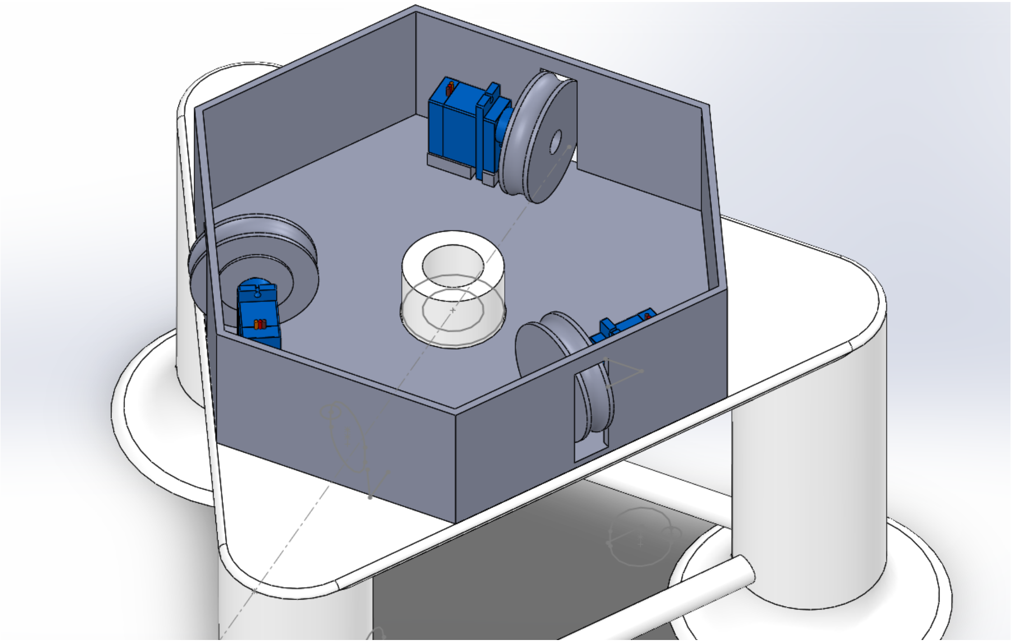


Figure 12: CAD Drawing with Motorbox and Motors

In our case, we developed a scale prototype of this system. Our base was a 3D printed semi-submersible design built by a prior year's capstone group at the University of Virginia. For our structure, we 3D printed the spools and a large mount and casing for the motors and the sensor. Our processing unit was an ELEGOO Mega 2560 microcontroller running the Arduino IDE which was externally mounted off the base with wires connected to the motors and sensors on the base. The sensor we chose to use was an MPU 6050 3-axis gyro/3-axis accelerometer. The three motors we chose were 360-degree continuous servos, one per spool, in order to pull and release the lines. The cables in our model were thin nylon twine, and each line was tied to 1 kg weights, for the purpose of securing the platform to the bottom of a tub. The initial base design we inherited was not built to hold the weight of our additions, however, and it was necessary to add more foam and weight for the purpose of restabilizing the passive system by lowering the center of gravity and raising the center of buoyancy.

The Arduino code for the microcontroller had four major purposes. First, it had to initialize the 3-axis gyroscope/3-axis accelerometer sensor and use it to determine the angle of tilt about the X and Y axes (θ and ϕ, respectively). Second, using these angles of tilt, the program had to determine the output rate of each of the three servo motors. For our servo motors, the rate could vary from 0 (full speed CCW) to 180 (full speed CW), with a stop-code being sent for a value of 90. The first step was to map the 2-axis angular displacement inputs to the triangular array of three servos, shown in Figure 13, and use these angles to determine the vertical displacement of the base at each of the three motors (Eqs. 1,4, and 7). Second, these vertical displacements were used to calculate the servo rotation rates (Eqs. 2, 5, and 8). Due to time constraints, a proper proportional-integral- derivative control, the best control system option for solutions like these, was not used, instead opting for a more direct approach. For the purpose of this report, the equations and figures below show a range of servo rates from -90 to 90, with a stop at 0, though one can easily imagine how this would be mapped to the 0 to 180 range required by the servo motors.

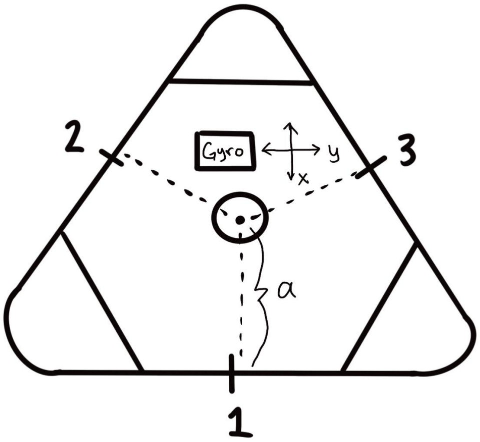


Figure 13: Diagram of motor placement and numbering, relative to X and Y axes

$$Inputs:\ \theta,\ \phi$$

$$Outputs:\ Rate_1,\ Rate_2,\ Rate_3$$

<u>Servo 1</u>

$$Z_1 = -\,a * sin(\phi) \tag{1}$$

$$Rate_1 = \frac{Z_1}{|Z_1|}(Z_1K_1)^{K_2} \tag{2}$$

$$Rate_1 = \frac{-a*sin(\phi)}{|-a*sin(\phi)|}(-\,a * sin(\phi)K_1)^{K_2} \tag{3}$$

<u>Servo 2</u>

$$Z_2 = -\,\frac{a}{2}(sin(\theta)\sqrt{3} - sin(\phi)) \tag{4}$$

$$Rate_2 = \frac{Z_2}{|Z_2|}(Z_2K_1)^{K_2} \tag{5}$$

$$Rate_2 = \frac{-\frac{a}{2}(sin(\theta)\sqrt{3}-sin(\phi))}{\left|-\frac{a}{2}(sin(\theta)\sqrt{3}-sin(\phi))\right|}(-\,\frac{a}{2}(sin(\theta)\sqrt{3} - sin(\phi))K_1)^{K_2} \tag{6}$$

<u>Servo 3</u>

$$Z_3 = -\,\frac{a}{2}(sin(-\,\phi) - sin(\theta_1)\sqrt{3}) \tag{7}$$

$$Rate_3 = \frac{Z_3}{|Z_3|}(Z_2K_1)^{K_2} \tag{8}$$

$$Rate_3 = \frac{-\frac{a}{2}(sin(-\phi)-sin(\theta)\sqrt{3})}{\left|-\frac{a}{2}(sin(-\phi)-sin(\theta)\sqrt{3})\right|}\left(-\frac{a}{2}(sin(-\phi) - sin(\theta)\sqrt{3})K_1\right)^{K_2} \qquad (9)$$

For our testing, the values of K_1 and K_2 shown in equations 2,3,5,6,8, and 9 were set using initial guesses with plans to modify as needed. Unfortunately, these values were unable to be tuned for more optimal operation. Therefore, the initial values of $K_1 = 24$ and $K_2 = 2$ were left as-is. The value of 24 was chosen as it would maximize the servo rotation rate at a tilt of 7.5 degrees. The value of K_2 was chosen to create a power function relationship with degree of two between the rate of rotation of the servos and the angle of tilt of the platform, as shown in figure 14. One should also notice that the absolute value terms will always return a value of negative or positive one. This is due to K_2 being a positive, even integer, and allows the rate to maintain its positive or negative state based on the value of the vertical displacement.

Figure 14: Power function relationship between angle of tilt (horizontal axis) and servo rate (vertical axis). Maximum rate of 90 is reached at 7.5 degrees.

For the next major function of the program, the code attempted to track how far the servos had rotated from their initial position. This was done by multiplying the servo rotation rate by a time factor (the time between servo write commands) each instance that a servo write command was executed, and totaling a sum of each of these calculations (Eq. 10). This could have been done much better using encoders or tracking the amount of tension in the cables, but unfortunately this design did not have those capabilities. Using this value, a rough maximum rotation limit was able to be set, to prevent the structure from pulling itself down into the water.

$$total \mathrel{+}= rate * K_t \tag{10}$$

The last major function of the program was the reset to initial conditions. When the platform was no longer tilting away from a particular motor's side, that motor would unwind however much cable it had wound according to the total calculated above. This was an extremely rough solution, as it would be better to unwind the cables together in a slow, controlled fashion to return the tension in the cables to their initial values and not induce more rocking. This release of the cables is another aspect of the program that could be tuned much further in the future. The full code is shown in Appendix B.

Public Health and Safety

Wind turbines have minimal safety risks while providing many benefits over other forms of power generation. For instance, activities relating to the maintenance and use of wind turbines average less than one death per year, while other non-renewable sources of energy average anywhere from 3 to 25 deaths per year (Ritchie, 2021). This is due to the nature of wind energy, where turbine blades are high in the air and far from hitting anything on the ground. Due to the height, maintenance can sometimes be more challenging, but with proper precautions it is much safer than other sources of energy.

Our offshore design has been created to consider the safety and health of the public. Our design is meant to be located in deeper water, which is generally far offshore. This reduces visual and audio pollution caused by wind turbines located in near-shore shallow water or on land. These forms of pollution can cause regions to be undesirable for the residence of humans or animals, and our design will not suffer from these issues. When it comes to the more difficult task of performing maintenance on offshore wind turbines, our design excels once again. Because of our wide base design, our solution provides a large surface area and flat environment for maintenance to be performed. Therefore, we are confident that our design provides a solution for renewable energy generation that is minimally impactful to the health and safety of the public.

Global, Social, Cultural, and Environmental Factors

Clean energy is a powerful topic in societies and governments around the world. The primary mode of energy production in many countries comes from fossil fuels, a non-renewable resource with harmful by-products which contribute to climate change. These resources will likely run short in the next decade and society only demands more power as time goes on. Developing reliable forms of renewable energy is crucial to the continued growth of society (Benavente & Park, 2021). Wind energy is a primary solution being pursued worldwide, along with hydro, solar, and geothermal energy. Further development of technologies that address the issues faced by current wind turbines and improve the entire wind energy industry is crucial to the progression of clean energy and society.

Environmental factors are crucial when considering the location and installation of wind turbines. While moving turbines offshore removes them from populous areas, it can interfere with the life of ocean creatures. Running tension ropes through the water and anchoring them to the ocean floor could threaten to harm local sea wildlife; luckily, studies have found that underwater cables have no statistically significant effect on the amount of life in underwater areas (UNEP, 2009). This points toward wind turbines having little to no effect on wildlife in the area of the wind farm. While studies have been done showing the effect on underwater life, future research could include studies into the effects that wind farms could have on flying animals, such as the blades striking birds or affecting migratory patterns.

Another primary concern for all wind turbines is the degradation of blades. While our project looked exclusively at the base of the wind turbine, it is important to consider these impacts as well. Wind turbine blades have a lifespan of around 25 years, and even less if located near or on water due to the salt in the air, which is where our design would go. The blades are also often made of fiberglass or other similar materials which are largely non-recyclable. While this is a long term public safety concern, various research teams and startups are seeking to remedy this issue through recycling centers for blades, including melting them into other usable items such as car parts (Collins, 2021). This is beneficial to society and helps maintain the clean energy promise of wind turbines.

Cost Analysis

The device is broken down into the mechanics, the electronics, and the flotation. The mechanics consist of the Feetech FS90R Micro Servo motors, nylon twine, and the 3D printed spools. Electronics consist of the ELEGOO Mega 2560 Processor along with the wiring kit. This was, by far, the most expensive section of the prototype project. The added flotation is entirely done with insulation foam, which was cut into modular rectangles. The miscellaneous materials include the tape, super glue, and the 3D printed motorbox covering. The prices of all these components materials are shown in Table 1.

Table 1: Prototype vs. Real World Costs

Prototype Part/Material	Cost (USD)	Real World Part/Material	Cost (USD)
3D Printed Motorbox + Spools x3	$28.23	Steel coverings & welds	>$5,000
Feetech FS90R Micro Servo Motors x3	$28.49	Industrial Motors	>$5,000
ELEGOO Mega 2560 Processor and Wiring/Sensor Kit	$62.99	ELEGOO Mega 2560 Processor and Wiring/Sensor Kit	$62.99
Nylon Twine	$4.69	Galvanized Steel Cables	$9.05/ft. $40k - $90k
Foam Rectangles (1 Sq Ft)	$1.40	*N/A*	
Scotch Super Glue	$4.19	*N/A*	
Duct Tape (1 roll)	$4.00	*N/A*	
Labor	*N/A*	Labor	>$10,000
Total Cost	$133.99	***Total Cost***	>$110k

Also shown in the table are the real-world cost approximations of similar systems. Scaling the cost of the active device up to real-world size and price is difficult to estimate, since floating offshore wind turbines come in all shapes and sizes. General Electric is working on a model, the Haliade-X, that is 853 feet tall, capable of producing 13MW of power (General Electric, 2021). Industrial motors cost more than $5000 to be powerful enough to hold the large structures in place. Steel cables are the most expensive item, which limit how deep these wind turbines can be installed. Currently, wind turbines are not installed in water much deeper than 3000 feet (The International Bank for Reconstruction and Development, 2019). Beyond that, the depth of water creates an environment that is too difficult and costly to anchor cables. Labor is another factor to consider for real world projects, usually greater than $10,000 to hire engineers and machine workers to move and install parts of ocean structures. Waterproofing all of these parts can be done in different ways, but assuming that the design is similar to the prototype, some sort of above-water steel covering would be needed to protect the electronics and motors from damage.

Conclusion

The final device that was constructed worked fairly well. In a number of tests, the device was able to correct itself to be level. It was difficult to capture quantitative data, but videos taken during testing showed that the motors reacted quickly enough to the sensor's input to stabilize the structure. The program, although rough, was robust enough for the majority of cases. We did find that the mechanisms surrounding the cables were not ideal and they would slip when they were not fully taut. The device was also heavier than we anticipated, and brought the platform close to the water level. Also, there was a tendency for the device to spin in the water due to unbalanced tension in the cables or the wire connecting the device to the processor. This was an unanticipated event and finding a balance in tension was necessary prior to testing. Life-sized wind turbines have to be able to keep their cables taut or they won't be able to control their stability. Like our device, they also need to be able to manage spin so that the device can always be pointing in the most ideal direction, maximizing the generated power. A large portion of our effort was put into keeping the electronics and motors from getting wet. However, more advanced waterproofing techniques could keep the electronics safer, and the platform could even be fully submerged without any electronics getting damaged. Watching our platform change its depth gave us an idea. Tension-leg platforms like these might even be able to control their depth in order to keep the blades at the right height for efficiency.

This final design was far from perfect, and there were a number of areas where potential improvements were identified. Firstly, the 3D-printed spools should be printed with a deeper notch to prevent the cables from slipping off, as happened often in testing. This could also be solved by using better methods overall (in the code or tensioning mechanism) to keep the cables taut and on-track. Second, the servo motors utilized were cheap, low-grade devices, and suffered from uncalled-for pulses, twitches, and other random occurrences. Building the device with better motors would increase cost, and potentially weight, but would have great benefits. Another area of improvement comes in the form of position tracking. As mentioned earlier, a simple “total” formula was used in the program to try and guess the motor position and, consequently, the tension in each cable. This system could be improved by using encoders to read the exact rotational position of each spool, or using an ammeter to measure the current going through each motor to determine how much force each one is pulling with. Maintaining a consistent initial level position is the purpose of this system, so being able to track where that is is of major importance. Our testing also revealed issues with water resistance of the system. It was difficult to test the effect of large waves as they would have a tendency to splash over the side of the structure, threatening the electronics inside. Finding a solution to this problem would only serve to make the system more capable. Finally, the system can be improved in the program. Utilizing a proportional-integral-derivative (PID) control would make the motors react in a much more stable, efficient, and controlled manner as their reactions, overshoot, and corrections would be managed much more methodically. Additionally, further testing of the system with all of these “variables” listed above being more stable would allow for a proper final determination of formulaic constants used in the code, further maximizing efficiency and effectiveness.

Future work in this area, besides implementing these improvements above, has a few directions to go. First, the passively stabilized base prototype needs to be redesigned and rethought. In its initial state, it was unable to stay afloat and stable without the addition of duct taped foam, and when our active design was attached, it needed even more foam and passively stabilizing weights attached for the purpose of lowering the center of gravity and raising the center of buoyancy. Adding foam and random weights to the small-scale prototype makes it just that much more difficult to draw conclusions about the effectiveness of the design at full-scale. Redoing this base for holding more weight while staying afloat and fairly balanced in still water is of key importance. Future work can also be done at analyzing the energy usage per reaction to each wave, to determine the feasibility of an active method. If the purpose of the wind turbine is to generate electricity, and it is found that a significant portion of the power generated has to be used for stabilizing itself, it will not be effective in a real world application.

Overall, this newly developing field of offshore floating wind turbine stabilization is an exciting and interesting area, and this semester-long project offered a valuable, methodical analysis. Thank you to Professor Momot for his guidance and insight throughout this process.

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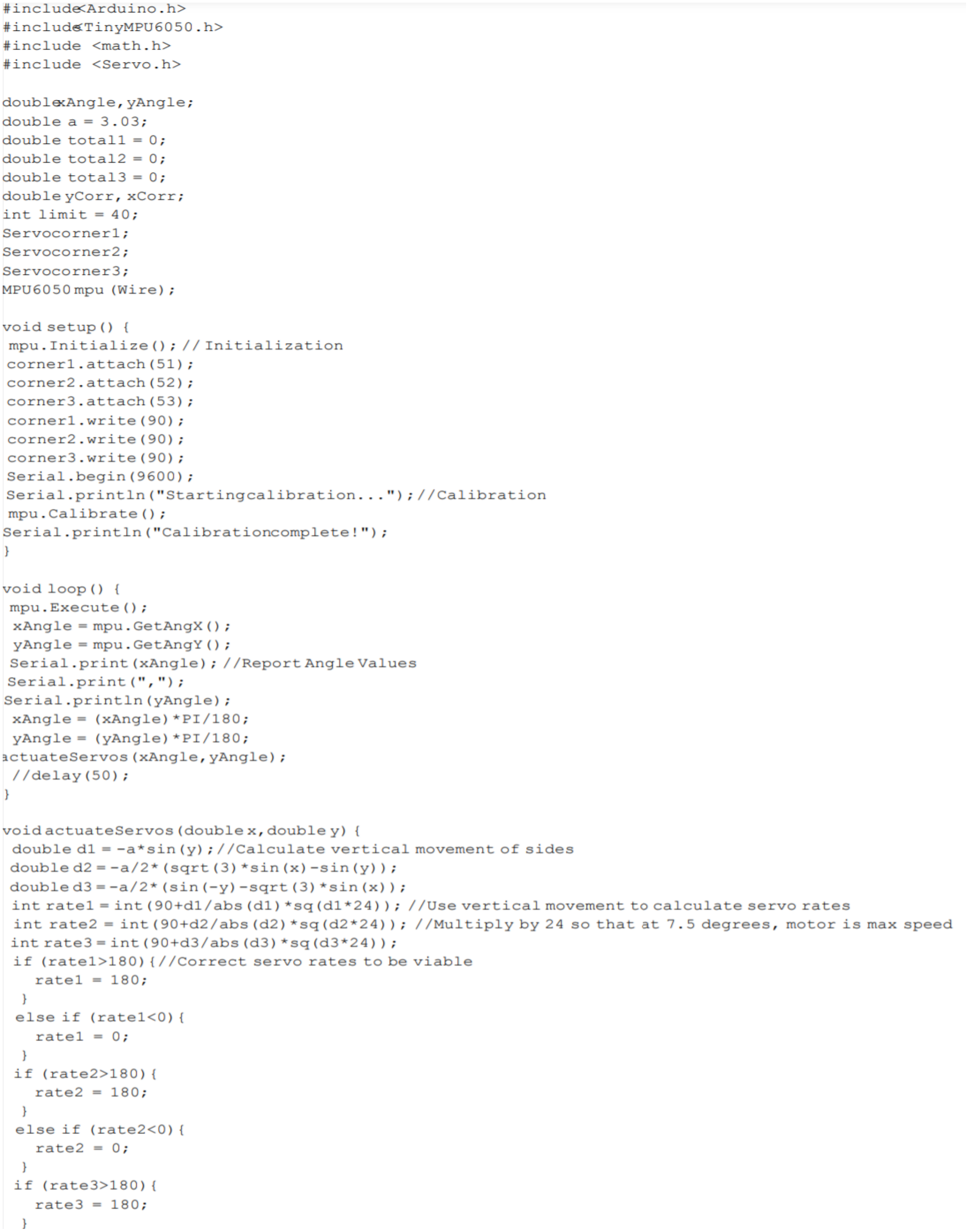
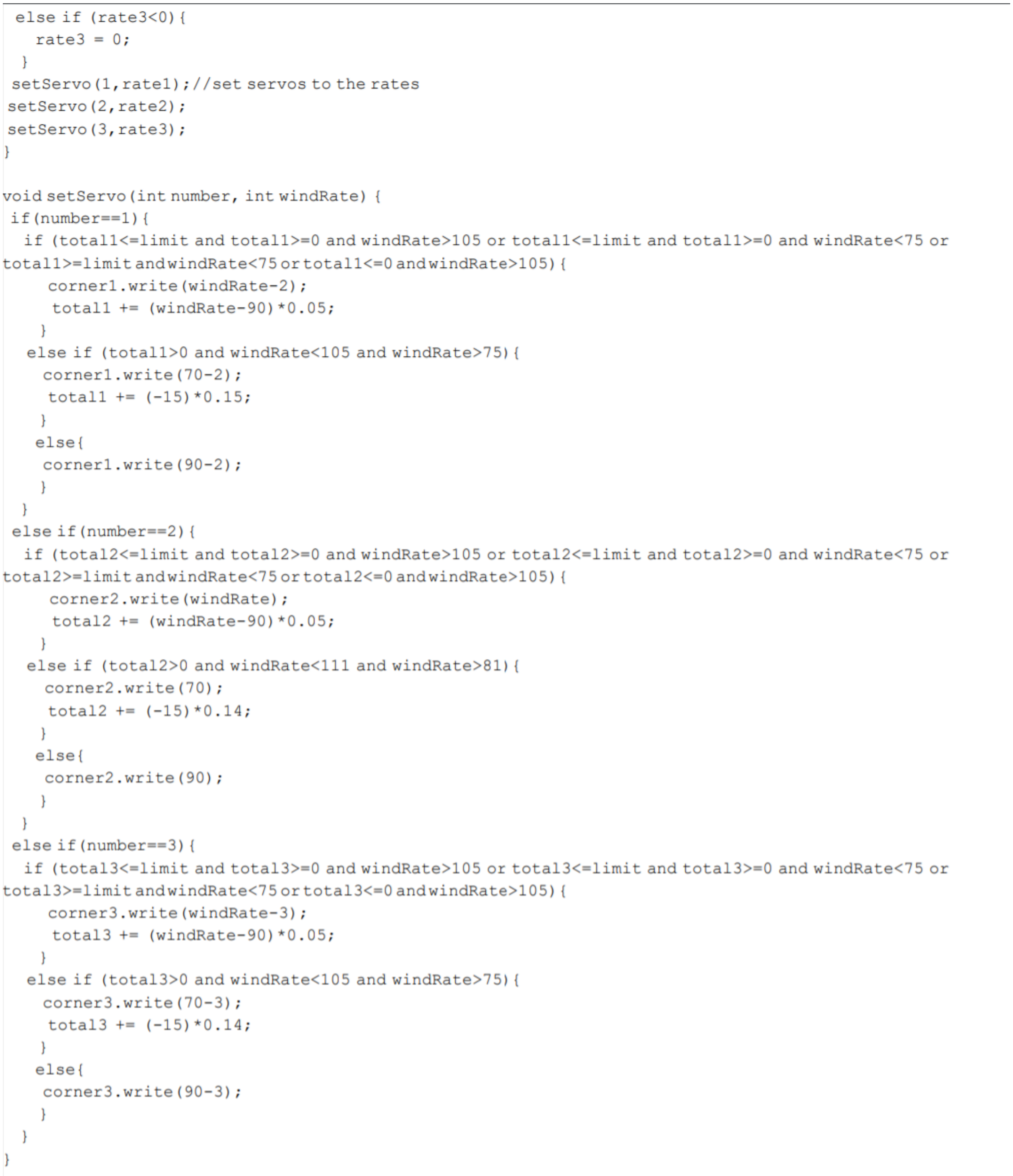
Appendix A

Contributions to the Project in the Final Weeks	
Name	**Contributions**
Ryan Anderson	● Significant work on poster ● Help with Arduino code ● Construction of final design ● Testing of base in water ● Background (research and constraints) in Technical Report
Daniel Dereberry	● Significant work on poster ● Most of the Arduino code ● Wiring of electronics and program editing for testing ● Construction of final design ● Testing of base in water ● Solution (programming section) and Conclusion in Technical Report
Matthew Metcalf	● Significant work on poster ● 3D printing of parts ● Construction of final design ● Testing of base in water ● Background (Specifications), Solution (Cost Analysis), and Conclusion in Technical Report
Christopher Murdock (COVID)	● Significant work on poster ● 3D Design of motor Spindles ● Analysis of the testing stage ● Design Process (Concept Selection, Decision Making, Standards, Risk Analysis) section of Technical Report
Conner Steenrod (COVID)	● Significant work on poster ● Analysis of the testing stage ● Introduction and Solution (Final Design, Public Health and Safety, and GSCE) in Technical Report ● Final review and editing of Technical Report

Appendix B



```
#include<Arduino.h>
#include<TinyMPU6050.h>
#include <math.h>
#include <Servo.h>

doublexAngle,yAngle;
double a = 3.03;
double total1 = 0;
double total2 = 0;
double total3 = 0;
double yCorr, xCorr;
int limit = 40;
Servocorner1;
Servocorner2;
Servocorner3;
MPU6050 mpu (Wire);

void setup() {
 mpu.Initialize(); // Initialization
 corner1.attach(51);
 corner2.attach(52);
 corner3.attach(53);
 corner1.write(90);
 corner2.write(90);
 corner3.write(90);
 Serial.begin(9600);
 Serial.println("Startingcalibration...");//Calibration
 mpu.Calibrate();
Serial.println("Calibrationcomplete!");
}

void loop() {
 mpu.Execute();
  xAngle = mpu.GetAngX();
  yAngle = mpu.GetAngY();
 Serial.print(xAngle); //Report Angle Values
 Serial.print(",");
Serial.println(yAngle);
  xAngle = (xAngle)*PI/180;
  yAngle = (yAngle)*PI/180;
actuateServos(xAngle,yAngle);
  //delay(50);
}

void actuateServos(double x,double y) {
  double d1 = -a*sin(y);//Calculate vertical movement of sides
  double d2 = -a/2*(sqrt(3)*sin(x)-sin(y));
  double d3 = -a/2*(sin(-y)-sqrt(3)*sin(x));
  int rate1 = int(90+d1/abs(d1)*sq(d1*24)); //Use vertical movement to calculate servo rates
  int rate2 = int(90+d2/abs(d2)*sq(d2*24)); //Multiply by 24 so that at 7.5 degrees, motor is max speed
  int rate3 = int(90+d3/abs(d3)*sq(d3*24));
  if (rate1>180){//Correct servo rates to be viable
    rate1 = 180;
  }
  else if (rate1<0){
    rate1 = 0;
  }
  if (rate2>180){
    rate2 = 180;
  }
  else if (rate2<0){
    rate2 = 0;
  }
  if (rate3>180){
    rate3 = 180;
  }
```



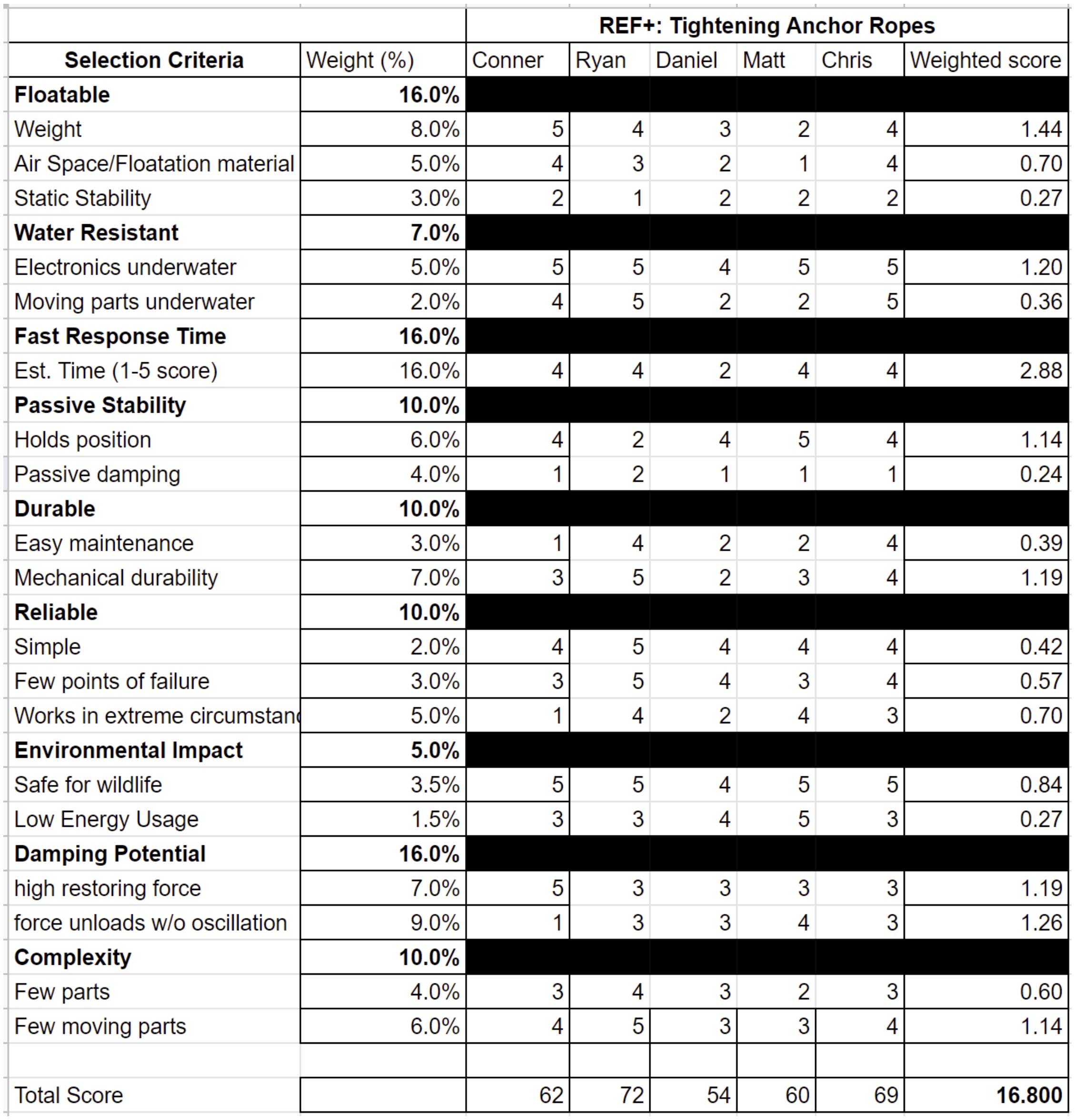
```
 else if (rate3<0){
   rate3 = 0;
  }
 setServo(1,rate1);//set servos to the rates
setServo(2,rate2);
setServo(3,rate3);
}

void setServo(int number, int windRate) {
 if(number==1){
   if (total1<=limit and total1>=0 and windRate>105 or total1<=limit and total1>=0 and windRate<75 or
total1>=limit and windRate<75 or total1<=0 and windRate>105){
      corner1.write(windRate-2);
      total1 += (windRate-90)*0.05;
     }
   else if (total1>0 and windRate<105 and windRate>75){
     corner1.write(70-2);
      total1 += (-15)*0.15;
     }
    else{
     corner1.write(90-2);
     }
  }
 else if(number==2){
   if (total2<=limit and total2>=0 and windRate>105 or total2<=limit and total2>=0 and windRate<75 or
total2>=limit and windRate<75 or total2<=0 and windRate>105){
      corner2.write(windRate);
      total2 += (windRate-90)*0.05;
     }
   else if (total2>0 and windRate<111 and windRate>81){
     corner2.write(70);
      total2 += (-15)*0.14;
     }
    else{
     corner2.write(90);
     }
  }
 else if(number==3){
   if (total3<=limit and total3>=0 and windRate>105 or total3<=limit and total3>=0 and windRate<75 or
total3>=limit and windRate<75 or total3<=0 and windRate>105){
      corner3.write(windRate-3);
      total3 += (windRate-90)*0.05;
     }
   else if (total3>0 and windRate<105 and windRate>75){
     corner3.write(70-3);
      total3 += (-15)*0.14;
     }
    else{
     corner3.write(90-3);
     }
  }
}
```

Appendix C

	Screening							
Selection Criteria	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**REF**
	Pumps	Horizontal Sliding Mass	Vertical Sliding Mass	Swinging Arms	Base Propellor	Underwater Wing	Jellyfish	Tightening Anchor Ropes
Floatable	-1	-1	-1	-1	0	-1	0	0
Water resistant	0	0	1	0	1	0	0	0
Fast response time	-1	1	0	1	1	-1	1	0
Passive stability	0	1	1	1	0	0	1	0
Durable	0	0	0	0	-1	-1	-1	0
Reliable	-1	0	1	0	0	0	1	0
Environmental impact	1	1	1	1	-1	-1	-1	0
Damping potential	-1	0	0	0	1	1	1	0
Complexity	-1	0	1	0	0	-1	-1	0
Sum	-4	2	4	2	1	-4	1	0
Rank	7	3	1	3	5	7	5	
Continue?	no	yes	yes	yes	yes	no	yes	yes

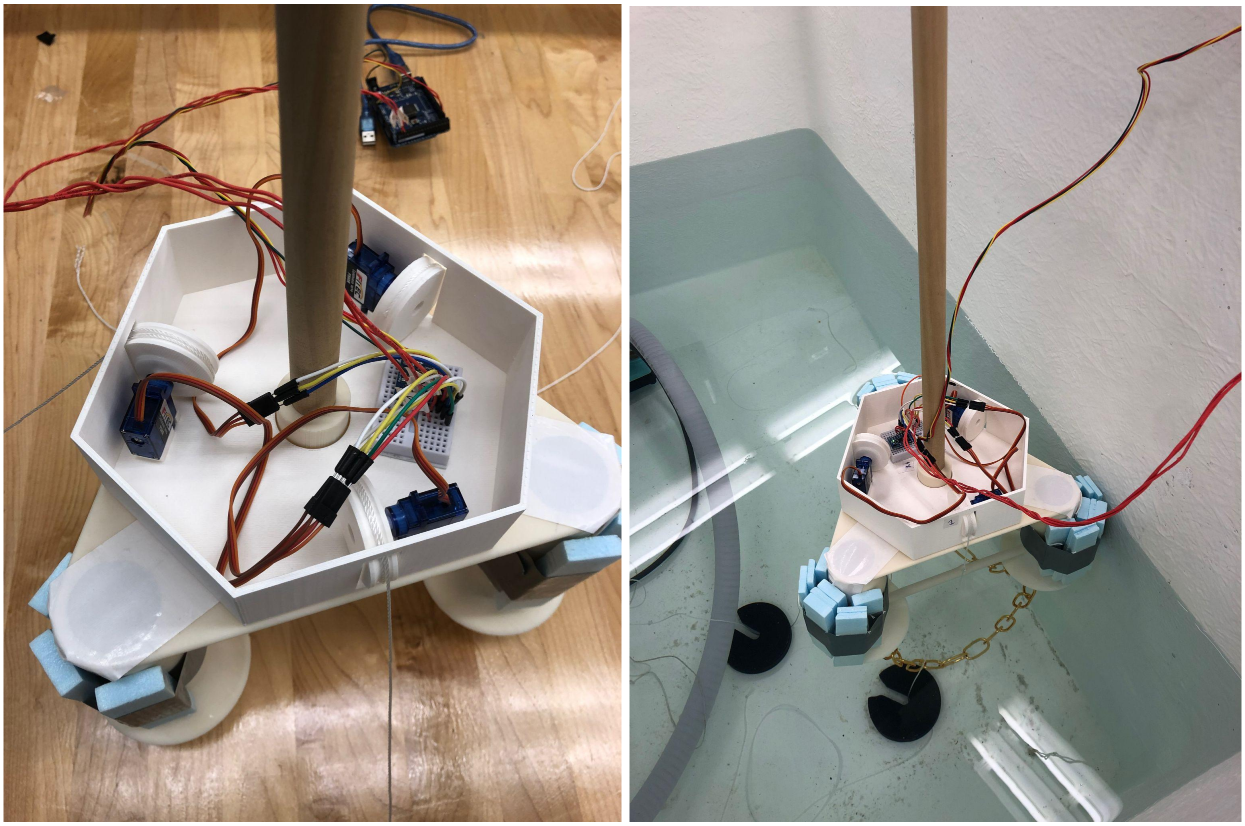
Appendix D

Scoring Summary

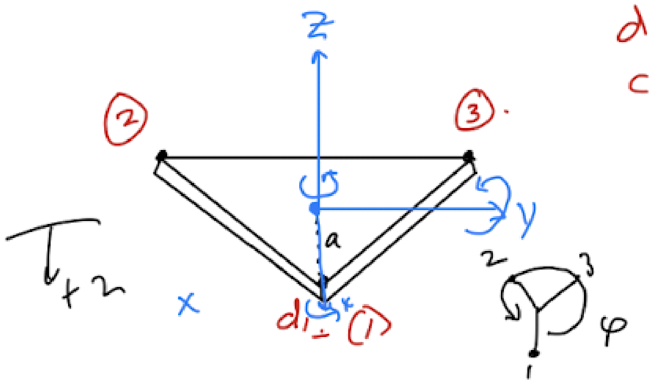


		REF+: Tightening Anchor Ropes					
Selection Criteria	Weight (%)	Conner	Ryan	Daniel	Matt	Chris	Weighted score
Floatable	**16.0%**						
Weight	8.0%	5	4	3	2	4	1.44
Air Space/Floatation material	5.0%	4	3	2	1	4	0.70
Static Stability	3.0%	2	1	2	2	2	0.27
Water Resistant	**7.0%**						
Electronics underwater	5.0%	5	5	4	5	5	1.20
Moving parts underwater	2.0%	4	5	2	2	5	0.36
Fast Response Time	**16.0%**						
Est. Time (1-5 score)	16.0%	4	4	2	4	4	2.88
Passive Stability	**10.0%**						
Holds position	6.0%	4	2	4	5	4	1.14
Passive damping	4.0%	1	2	1	1	1	0.24
Durable	**10.0%**						
Easy maintenance	3.0%	1	4	2	2	4	0.39
Mechanical durability	7.0%	3	5	2	3	4	1.19
Reliable	**10.0%**						
Simple	2.0%	4	5	4	4	4	0.42
Few points of failure	3.0%	3	5	4	3	4	0.57
Works in extreme circumstan	5.0%	1	4	2	4	3	0.70
Environmental Impact	**5.0%**						
Safe for wildlife	3.5%	5	5	4	5	5	0.84
Low Energy Usage	1.5%	3	3	4	5	3	0.27
Damping Potential	**16.0%**						
high restoring force	7.0%	5	3	3	3	3	1.19
force unloads w/o oscillation	9.0%	1	3	3	4	3	1.26
Complexity	**10.0%**						
Few parts	4.0%	3	4	3	2	3	0.60
Few moving parts	6.0%	4	5	3	3	4	1.14
Total Score		62	72	54	60	69	**16.800**

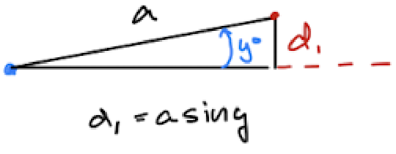
Appendix E



Appendix F



d_1 – displacement of corner 1 ✓ from datum plane



$d_1 = a\sin y$

Convert from polar → xyz

$r = a$, φ depends on corner, but is set

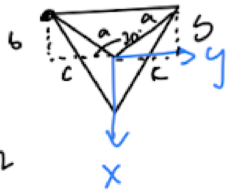
ϕ found w/ gyroscope

* Assume that there is no rotation on z

Corner 1 $\phi = y$

$r = a,\ \varphi = 0,\ \phi = y \longrightarrow d_1 = z = a\sin y$

Corner 2



$b = a/2$

$c = \sqrt{3}\,a/2$

Superposition?

$d_2 = d_{2x} + d_{2y}$

$d_{2x} = a\frac{\sqrt{3}}{2}\sin x$

$d_{2y} = -\frac{a}{2}\sin y$

$d_2 = \frac{a}{2}\left[\sqrt{3}\sin x - \sin y\right]$

Corner 3

$d_{3x} = -\frac{\sqrt{3}}{2}a\sin x$

$d_{3y} = \frac{a}{2}\sin y$

$d_3 = \frac{a}{2}\left[\sin y - \sqrt{3}\sin x\right]$

Appendix G

● Working on it

Working on it • Sep 16 - 21 • 6 days

Plan for floating platform	Sep 16 - 21	Conner Steenrod, Ryan Anderson
Accelerometer Research	Sep 16 - 21	Daniel Dereberry
Motor Integration	Sep 16 - 21	Matt Metcalf, Christopher Murdock
Gantt Chart Due	Sep 21	

● Done

Done • Sep 7 - 15 • 9 days

Ideation for Overall Design	Sep 7 - 15	Conner Steenrod, Ryan Anderson, Daniel Dereberry, Christopher Murdock, Matt Metcalf

● Empty

Empty • Sep 19 - Dec 7 • 80 days

Motor Ideation/Selection	Sep 19 - 24	Christopher Murdock, Matt Metcalf
Overall Plans/Specs Finished	Sep 19 - 30	Conner Steenrod
Test flotation in solidworks	Sep 19 - 29	Conner Steenrod, Ryan Anderson
Test Current Flotation	Sep 20 - 23	Christopher Murdock, Matt Metcalf
Fix Printing Error on platform	Sep 22 - 29	Conner Steenrod, Ryan Anderson
Make Floatation Modifications	Sep 24 - 29	Ryan Anderson, Conner Steenrod
Order Supplies	Sep 25	Daniel Dereberry
BODE Plots for System	Sep 29 - Oct 3	Ryan Anderson, Daniel Dereberry
Project Proposal	Sep 30	
Force Calculations/Diagrams	Oct 3 - 9	Ryan Anderson, Daniel Dereberry
Model 3D parts for design	Oct 3 - 12	Conner Steenrod
Design Circuits	Oct 3 - 12	Matt Metcalf
Design Water Resistant Casings	Oct 3 - 12	Christopher Murdock
Print 3D Parts	Oct 12 - 15	Conner Steenrod, Christopher Murdock
Construct Circuits	Oct 12 - 23	Matt Metcalf
Arduino Coding	Oct 12 - 31	Conner Steenrod, Matt Metcalf
Oral Report	Oct 13	
Finish Prototype	Nov 1	
Testing/Modifications of Code	Nov 1 - 19	Christopher Murdock, Matt Metcalf, Daniel Dereberry
Testing/Modifications of mechanical s...	Nov 1 - 19	Conner Steenrod, Ryan Anderson
Write Report and Poster	Nov 1 - Dec 6	Conner Steenrod, Ryan Anderson, Daniel Dereberry, Matt Metcalf, Christopher Murdock
Final Poster Due	Dec 7	