UNIVERSITY OF WASHINGTON

Lagrangian DAC Float

ME 495 Project

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TABLES AND FIGURES

1 Introduction and Background

An area of interest for marine renewable energy research lies in harnessing the power of the tides to generate electricity using underwater turbines. Potential tidal turbine locations need to be characterized to quantify energy availability from tidal currents. This will allow for the optimal placement of turbines and maximize energy production. Many of the existing devices that can measure energy density at potential sites are expensive or lack the ability to spatially resolve currents. The team will explore a solution for a low-cost underwater data acquisition device with buoyancy control. During the device’s deployment, a transponder will send signals to a network of drifting buoys that will allow for post-hoc triangulation of the floats. Localization will be supplemented by an Inertial Measurement Unit on board the floats. Typical deployments will involve a “swarm” on the order of ten floats which will be dispersed to resolve current patterns. The Lagrangian velocity measurement by the float can be used to calculate kinetic power density, a quantity of importance for current turbine siting. For the limited scope of the project, the group will focus primarily on the packaging of the float, the buoyancy control mechanism, and the controls for the sensors on the pod.

2 Design Specification

2.1 Requirements & Constraints

The project team was provided with several initial constraints on the float design in order to maintain a low cost, meet adequate performance levels, and keep the float small enough for one person to operate. The initial design specifications can be found in Table 1.

Table 1: Initial Design Specifications

Economics	
Project Total Budget	$5,000
Material cost per Float	$1000, optimally less than $500
Performance	
Deployment Time	6-12 hrs
Number of Deployments	6
Battery	Alkaline or NiMH for prototype
Size	< 20 cm any dimension
'Terminal' Vertical velocity	Up to 0.5 m/s
Settling time	< 2 seconds
Mass	< 6 kg
Depth Rating	100 m

The constraints were adjusted throughout the prototype development. The size and deployment time were the most difficult specifications to meet. The following sections outline how the final float design meets the design constraints outlined at the project's inception.

2.2 Cost

Table 2: Top Level Bill of Materials

Category	Cost	Mass (Kg)
Electronics	$460	0.716
Buoyancy Control	$440	0.923
Packaging	$60	2.674
Machining	$500	n/a
Total:	$1,460	4.314
Maximum:	$1,000	4.631
Available:	-$460	0.317

A driving goal of this project was to manufacture each float for $1000 or less. As seen in Table 2, the prototype developed has a total cost of $1460, including estimated manufacturing costs for the parts machined in house. The estimated cost of custom manufacturing will likely exceed the $500 specified. This high cost results from tight tolerances required on all sealing surfaces of one thousandths of an inch, difficulties associated with machining PVC, and multiple setups required for the bottom end cap and for the pipe housing (see Appendix 8.1 for full BOM and more details regarding cost breakdown for each part).

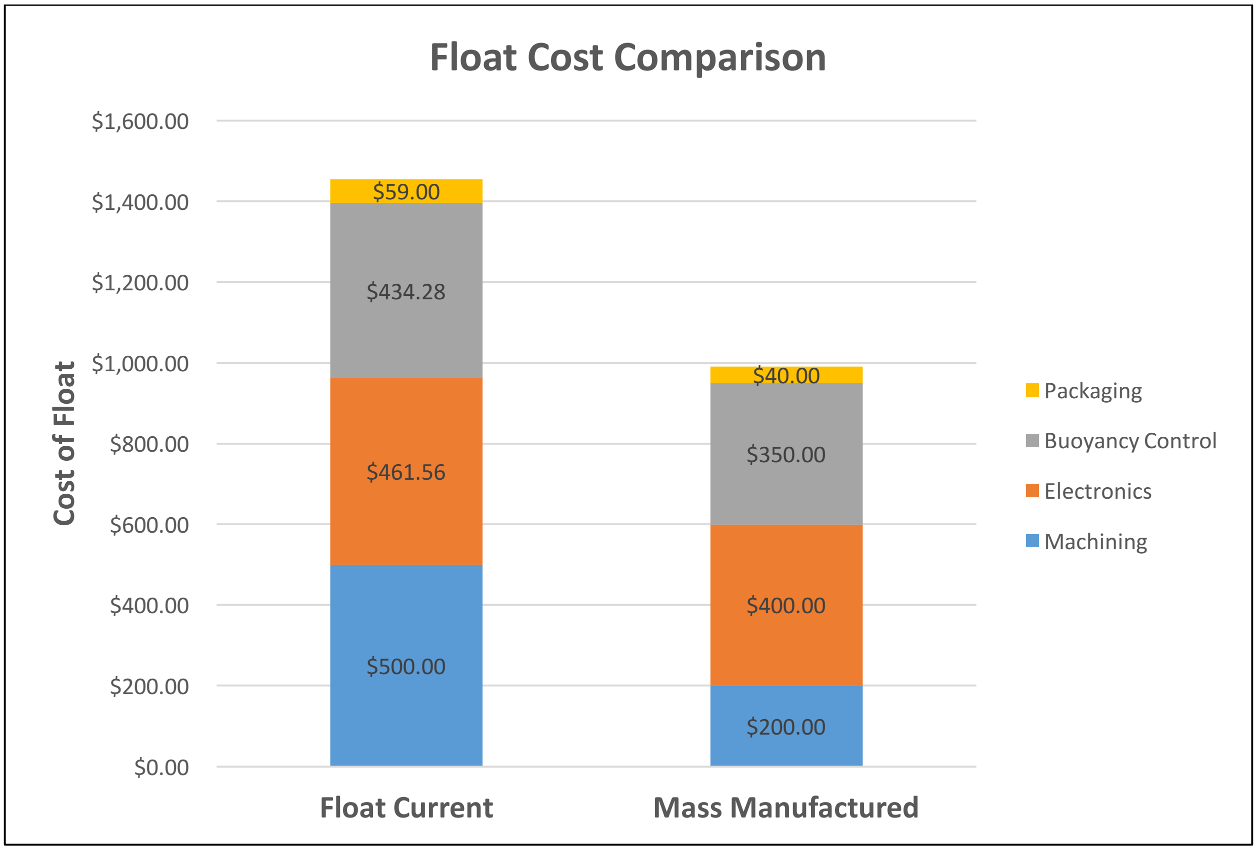

Figure 1: Reduction for Mass Manufacturing

The cost per float when producing a single prototype will be greater than manufacturing a swarm of floats. Mass manufacturing could allow for the cost per float to be below the $1000 benchmark. The most significant decrease that will result from mass manufacturing is the reduced cost of machining and custom manufacturing. Reusing machining setups and tooling will allow for the 60% decrease shown in Figure 1. Packaging and housing costs are predicted to decrease 33% due to bulk purchasing of the required materials. Like the housing, the buoyancy control system is predicted to decrease 20% due to bulk purchasing of mechanisms like the motor and lead screw. In addition, in future prototypes using a brushless DC motor and an encoder instead of a stepper motor could reduce cost. Finally, the price of the electronics package are predicted to decrease by 15% through a combination of bulk purchasing and less expensive components.

2.3 Opportunities & Assumptions

All systems on the float were designed to be as modular as possible to allow for flexibility in the future. The packaging for batteries and printed circuit boards are 3-D printed allowing for custom mounting arrangements and configurations. Excess space in the float provides plenty of space for new and altered components in redesign phases if current components do not perform as expected.

Design of the float was performed under the assumption of seawater being the primary medium for testing and experimentation. It is assumed that the experimenter(s) will have a general knowledge of the local water region including the depth of the seabed as the float will not have the means to ensure operation when dragged along the ocean floor. Additionally, it is assumed that the water will be fairly clear of debris along the path of the float.

3 Product Effects

3.1 Risk and Liability

It is important to discuss potential risks and liability, ethical issues, and impacts on society and the environment when considering the deployment of a float in a marine environment. While the pod is very safe on its own, there are risks to researchers during the launch of the float. It is important that everyone stays safe while on the water by wearing life preservers and practicing safe boating. Other than falling out of the boat, there are not many risks to human life from the float. One thing that could be of concern is harm to other marine vessels during deployment, such as damaging a propeller if drifting just below the surface.

3.2 Ethical Issues

As mentioned previously, the float weighs about 4.3 kg and is about 48 cm long. While small when compared to other vessels on the water, the float could pose a risk to propellers and jets of various watercraft. If a collision did occur, the chances of damage to the pod and the vessel involved is slight however a possibility. The researchers deploying the float could be held liable for those damages and also suffer the financial loss of a float. To mitigate this risk, it is recommended that a notice to mariners is made before each deployment and that the locations of release and pickup are in low traffic areas away from major shipping lanes. Another concern is the loss of the pod due to a malfunction in the positioning system. If the float washed up on a public or private beach, it should be easily identifiable as safe, with contact information for the responsible research group. For that reason, plans are in place to paint the pod with highly visible colors and label the outside with contact information.

3.3 Impact on Society

The impact that a marine float such as this one could have on society is twofold. The data acquisition and research that can be accomplished with a float like this is invaluable to the marine research community and could help locate tidal turbines for power generation. This would have a benefit to society. Green energy could be supplied to surrounding communities and researchers would have an improved understanding of tidal flows in areas of interest. The increased understanding of tidal flows is invaluable to a number of industries, not just marine energy. For example, construction projects, environmental cleanups, and biological research could all be influenced in a positive manner.

3.4 Impact on Environment

The float prototype includes 16 AA batteries that would be harmful to the environmental if the housing were to flood and the float were to be lost at sea. Alkaline batteries contain non-negligible amounts of mercury which would add to the increasing levels of mercury in the biosphere. Another more obvious environmental impact caused by a flooded housing would be losing the float to the body of water. The PVC housing and electronics would add to the growing amount of garbage already littering the sea floor.

To mitigate these risks, significant bench testing will be performed to ensure proper sealing of the housing at the expected pressures before any deployments in the environment. As the risks are slight in environmental impact, the benefits of furthering marine research in this area far outweigh the consequences of something going wrong.

4 Conceptual Development

4.1 Housing

Housing design development went hand in hand with the buoyancy control engine (BCE) design. Many concepts for the BCE used parts of the housing as an integral piece to the control system or was directly impacted by the design. The housing development initially was split into two different float shapes, cylindrical or spherical like shapes. The elongated cylindrical type housing was chosen to decrease drag and necessary weight to achieve neutral buoyancy. The housing's shape, size and materials were developed around the BCE, cost, size limitations, strength under pressure, resistance to corrosion, accessibility to the inside of the float and sealing. Development was also dependent on the dimensional, performance and cost specifications given. The initial design consisted of a plastic housing with two end caps, a design which has been used in researched floats. To reduce costs, a pre-machined high pressure housing was also researched. The next step was to look at cost, sealing and sizing for the BCE. The cap design was dependent on the sealing mechanism. End cap development started with an off-the-shelf PVC cap but highly accurate sealing was difficult to achieve. After further development, a cap design was provided by James Joslin from the Applied Physics Lab at the University of Washington. The locking and sealing mechanisms were already specified for pressures over 1100 kPa, however this design was modified to fit the BCE configuration, electronics and sensors. Further development went into the BCE and bottom end cap interaction.

4.2 Buoyancy Control Engine

Developing a BCE to fit inside the float, control the float at a depth of 100 m and have minimal power draw was the most significant engineering challenge faced by the project team. The concept development phase lasted multiple weeks, filled with research and preliminary design development. Concepts included two types, those that changed the volume of the float and those that changed the mass. Volume displacement ideas included total float volume change due to housing walls expanding and contracting, extrusion of a linear actuated cylinder, extrusion of a bladder with lead screw and motor, and a hydraulic bladder. Concept development for mass controlled engine included using a pump, internal hydraulic bladder, syringe or dynamically sealed piston-cylinder and a motor controlled internal bladder. Each concept was analyzed for cost, size, power draw and ability initially to narrow down the concept selection and development. Most designs did not fit the criteria because they drew too much power or were too expensive. Final concept development focused on a stepper motor and lead screw either controlling a bladder or a piston-cylinder. This design was chosen because it fit the criteria best. This is an area where further concept development could be beneficial to the power efficiency and cost of the float.

4.3 ELECTRONICS

All onboard electronics were designed to attach to 3D printed packages that would allow the lead screw to run through them, as well as provide the ability to draw the entire package out with the motor. Only one end cap should need to be removed at a time. This design came to fruition and is described in more detail below.

Choosing the electronics package and control software was important to the performance of the buoyancy control engine and overall ability of the float. The Arduino platform was chosen for its simplicity, ease of programming, online resources, and ability to interface with many sensors at once. After considering multiple options, the Arduino Uno was chosen as the main microcontroller. Sensors were chosen based on their cost, size, accuracy, and ability to interface with the Arduino. The depth sensor was the highest priority as it is the main input to the buoyancy control engine. The sensor was chosen due to high accuracy allowing for precise depth measurement, a design that was easy to implement into the float housing, and a competitive cost. Other sensors included in the float design are discussed in following sections.

Another significant aspect of the electronics development was the battery pack. A restriction of alkaline battery chemistry made it difficult to reach required voltage levels for the stepper motor while maintaining enough energy for a 12-hour deployment.

Many different battery configurations were tried, but as mentioned previously, 16 AA batteries in series were chosen in the end. The final specification of the float's electronics package is discussed in following sections.

4.4 Failure Modes and Analysis

It is important to determine possible failure modes of the float before further testing and design revisions. Because the float is an underwater pressure vessel with controlled dynamic sealing, there are multiple modes of failures the float could experience while in the field. It is important to develop fail-safes to decrease failures and lost floats. Based on research, analysis, environmental conditions and concept development the following failure modes are the most likely: piston failure, pressure or other sensor failures, micro controller failure, sealing failure, loss of power or low battery, thermal runaway, motor oscillation, and environmental interference. It is important that each failure mode is addressed and a failsafe mechanism is developed to decrease the likelihood of complete failure and loss of float.

Firstly, the piston could fail by either over extending, or by instability causing loss of sealing or binding the lead screw within the motor. To avoid over-extension, the piston head location will be tracked through the microcontroller which will allow the motor a maximum step count away from the cylinder midpoint. There will also be a physical stop attached at a certain height on the lead screw to inhibit further entry into the motor. To avoid binding, testing rigidity of piston and cylinder and machining to high tolerance will decrease the likelihood of piston head instability and lead screw binding. With sensory failure, it is important that the microcontroller code contains failsafes that if pressure sensor is unrealistically stable, produces obviously inaccurate data, or stops transmitting data, that the float automatically extends the piston and travels to the surface for recovery. With microcontroller failure, whether it be software or hardware failure, the failure could cause loss of control of the BCE and could result in complete failure and loss of that float. It is possible that a seal could go bad or be dysfunctional due to incorrect machining and could allow for leakage. If the leak flow rate is small enough, a humidity sensor within the float could detect a leak and extend the piston to return the float to the surface before the leak becomes catastrophic. This controlled reaction would be the same reaction if thermal runaway occurred or if battery power were low.

With motor oscillations, it is possible for the float to continually oscillate as it tries to reach its set depth, however this would use too much power and could cause future failure due to low battery. Therefore, the controller must have a time limit for the BCE to be on when deploying and resurfacing. Finally, there is the possibility that the float could interact with environment, whether it be plants, sea floor, or animals If these interactions were to occur, the float could be damaged or lose its buoyancy control. These failures are irregular and hard to develop failsafe mechanisms for. However, testing could be useful to test impacts and muddy seafloor interactions to find the best failsafe mechanism for post impact of the float. Overall, due to the fact that the float is within water and controls its own buoyancy, there are many different failure modes that could occur during deployment. To minimize these, the above failsafes will be installed to decrease number of failures in a float fleet.

5 FINAL SPECIFICATION

The final float design was broken down into 6 sub-groups of the housing, BCE, battery pack and electronics packaging, microcontroller, sensors and PID controller. The PVC and Delrin housing was designed to withstand operational pressures and resist corrosion from seawater conditions. The bottom housing cap has a dual purpose, acting as a cap as well as a cylinder for the driven BCE piston. As the pod moves, an Arduino Uno microcontroller controls the stepper motor based on the external pressure. The Arduino Uno also records all data from sensors to a micro SD card. The battery pack is made up of 16 AA alkaline batteries which are used for preliminary testing, however lithium ion batteries provide a promising alternative after initial testing. These are not proposed for initial testing due to the hazard posed by lithium-water reactions in a pressure vessel that develops a leak.

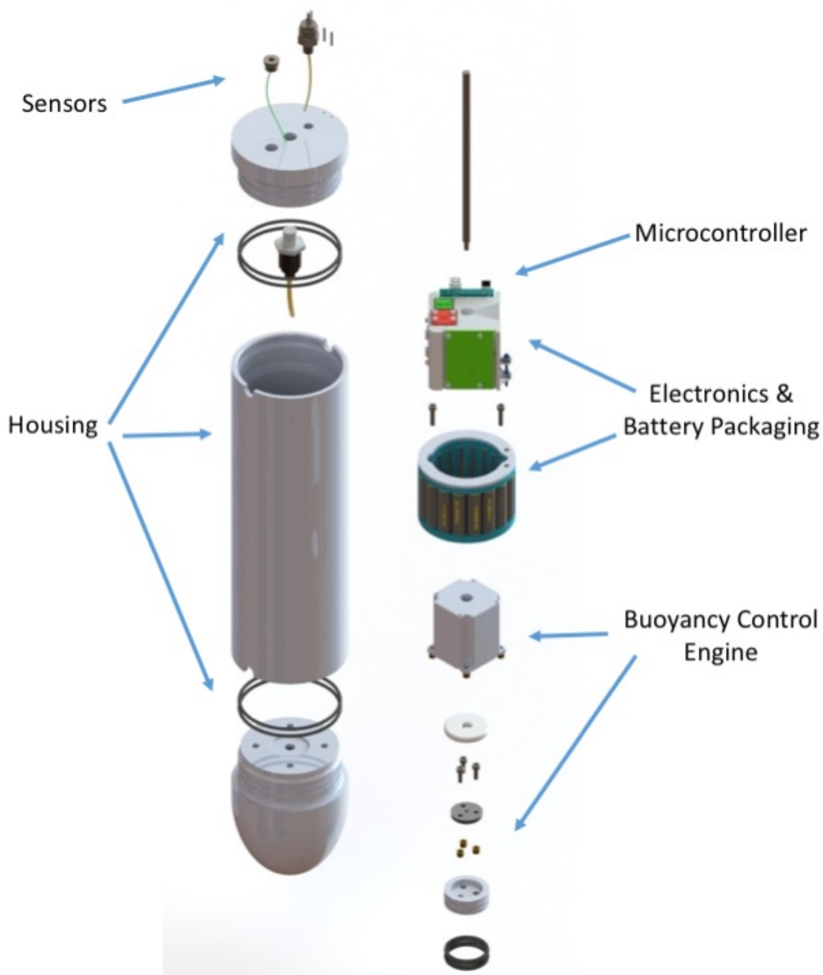

Figure 2: Float Exploded View

5.1 HOUSING

The housing is a three-part piece. The main body cylinder was made of schedule 80 high pressure PVC pipe, and the two end caps were made of Delrin. The body's height is dependent on the cylinder height of the BCE, which determines the lead screw retraction height. The diameter of the cylinder was chosen to house all electronics, batteries and motor while maintaining a small profile to reduce drag when traveling through the water column. The material, schedule 80 PVC, was chosen due to its high pressure capacity of 2500 kPa and low cost. Post machining allowed for high tolerance sealing surfaces at each end, with O-ring grooves and a filament groove used as a locking mechanism. The caps were designed to seal to the body while maintaining high rigidity. Both end caps and the PVC body needed precision machining to achieve high tolerance sealing surfaces on both sides. The top cap sits partially inside the body and two O-rings sit against the body wall. The connector, pressure sensor and pressure release valve are all located on the top cap. The bottom cap houses the buoyancy cylinder and piston and acts as a locating feature for the engine. This is done so that the entire BCE is aligned on a single end cap. The end cap extrudes much further from the body and has a cone like shape to decrease drag. Again, two O-ring seals are used between the bottom cap and body. The housing was an integral part of the BCE design, structurally supporting the stepper motor as well as precisely aligning the cylinder and the motor to avoid any binding or misalignment with the lead screw or piston.

The float prototype is significantly under the weight requirement at 4.31 kg and requires a total internal volume of 0.0043 m^3 to have a factor of safety of 1.1 for the condition of being too heavy. This additional weight will likely be filled by wires, epoxy and any additional equipment included inside the housing. To achieve this internal volume, the float failed to meet the initial dimensional specification of being less than 20 cm in any direction. The float is 48 cm long with a diameter of 11.4 cm.

Serviceability was a significant design intention for the float housing. By removing the filament retention device, both end caps are able to be pulled out of the main body of the float without the need of any tools. All motor components, battery packs, boards and sensors will be removed simultaneously when the bottom cap is pulled from the float. This will have one pigtail connector to the top cap to disconnect from the external pressure sensor and the external bulkhead connector.

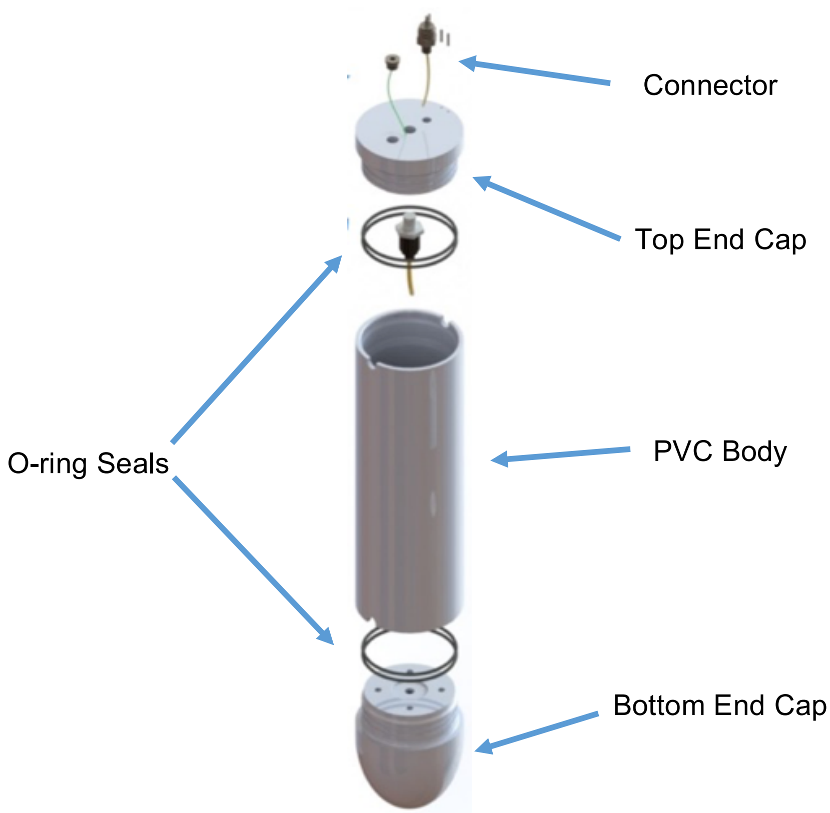

Figure 3: Housing Exploded View

5.2 Buoyancy Control Engine

The BCE consists of a NEMA 23 rotating nut stepper motor which drives a lead screw in a vertical linear motion, driving a dynamically sealed piston in the cylinder within the bottom cap. The motor is mounted to the bottom cap as well to keep concentricity with the cylinder and piston to avoid binding and to stay within loading deflection tolerances.

The piston displaces a total volume of 167 cc. The piston head sits at the midpoint of the cylinder when the float is neutrally buoyant in nominal salt water with a density of 1027 kg/m^3. Weight adjustments will be necessary to keep neutral buoyancy at the midpoint due to varying salt water densities. This will allow for driving forces in either direction, whether the float needs to return to the surface or sink to a desired depth. The 83 cc adjustment to displacement suggests a terminal velocity of 0.33 m/s. The cylinder is a turned Delrin cylinder with a diameter of 4.45 cm. The lead screw will attach to an aluminum plate that will be fastened to the top of the piston head to distribute load and make sure there is a strong connection between the lead screw and the piston head. The piston will also have two T-seals for dynamic sealing, rated to 34.5 MPa, with nylon back up rings on each side of the seal.

The stepper motor and lead screw allow for small linear adjustments (0.00042 in) and have the capacity for large axial loading without the risk of causing motor failure or buckling. The motor is attached to the bottom cap with fasteners but has a locating feature directly above the cylinder to ensure concentricity. Calculations show that the motor will need to supply at least 175 N of force at 100 m depth. The NEMA 23 double stack configuration has the capability seen in the performance curves in Appendix 8.2 to move at a speed of 1.25 cm/s with this great of a force acting on it.

A consideration raised during the final design review for the float involved the internal pressure difference when adjusting the internal volume. Because of the heat sink in the external seawater, the thermodynamic process can be modeled as approximately isothermal. Thus, the simplified ideal gas law $P_1V_1=P_2V_2$ can be used to determine that the internal pressure of the float would increase by approximately 12.5% when the BCE moves from maximum to minimum volume. This amounts to a gauge pressure increase of 12.4 kPa, resulting in a force of 20 N on the inside of the piston, a negligible value in terms of the amount of thrust force our motor already needs to provide. However, the force on either end cap could end up being non-negligible, as through the same calculation each end cap should experience a total force of 107 N as a result of this pressure increase. For example, when the float is on the surface, moving the piston from the bottom of its throw to the top of its throw (switching from recovery to submergence) could provide enough force to pop the top end cap off if external pressure exceeds atmospheric pressure.

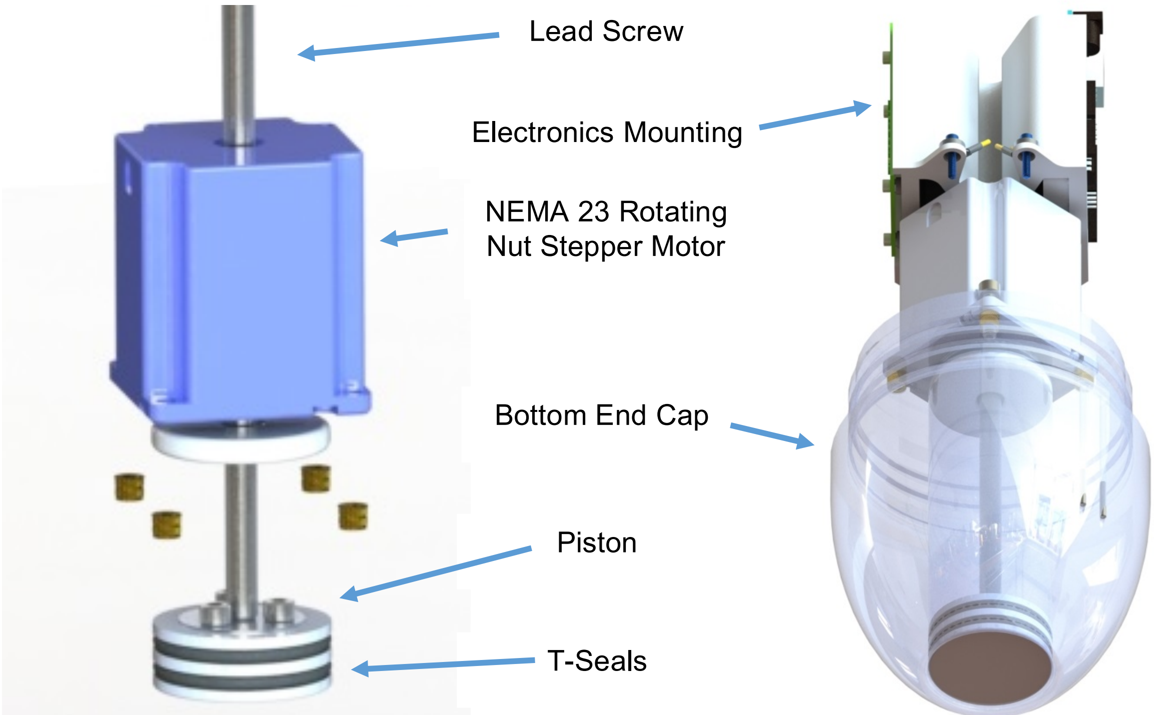

Figure 4: Buoyancy Control Engine

5.3 Battery and Electronics Packaging

The batteries are packaged within a rigid 3D Printed plastic housing which serves to constrain the batteries within a tight volume surrounding the stepper motor as well as allow for current-carrying bus bars to slip into both the top and bottom to provide a reliable method of carrying current. Through this design, a heavy bundle of wires is avoided and movement the batteries is prevented. The battery package has a retaining ring on top to provide a strong contact between the bus bars and the positive and negative terminals on the batteries. The battery package uses the same fastener holes as the motor, therefore there is no additional fastener weight. On top of the retaining ring lies the electronics package which has locations for each PCB to be mounted. This entire assembly will be able to be removed along with the bottom end cap for servicing. The main drawback of this design is the lack of space around the motors to place heat sinks or other heat conductive material.

To include materials for heat dissipation, the entire assembly would need to move upwards in the housing, or material selection would need to be altered. For example, the bottom end cap could be machined from aluminum to increase heat dissipation while maintaining high tolerances.

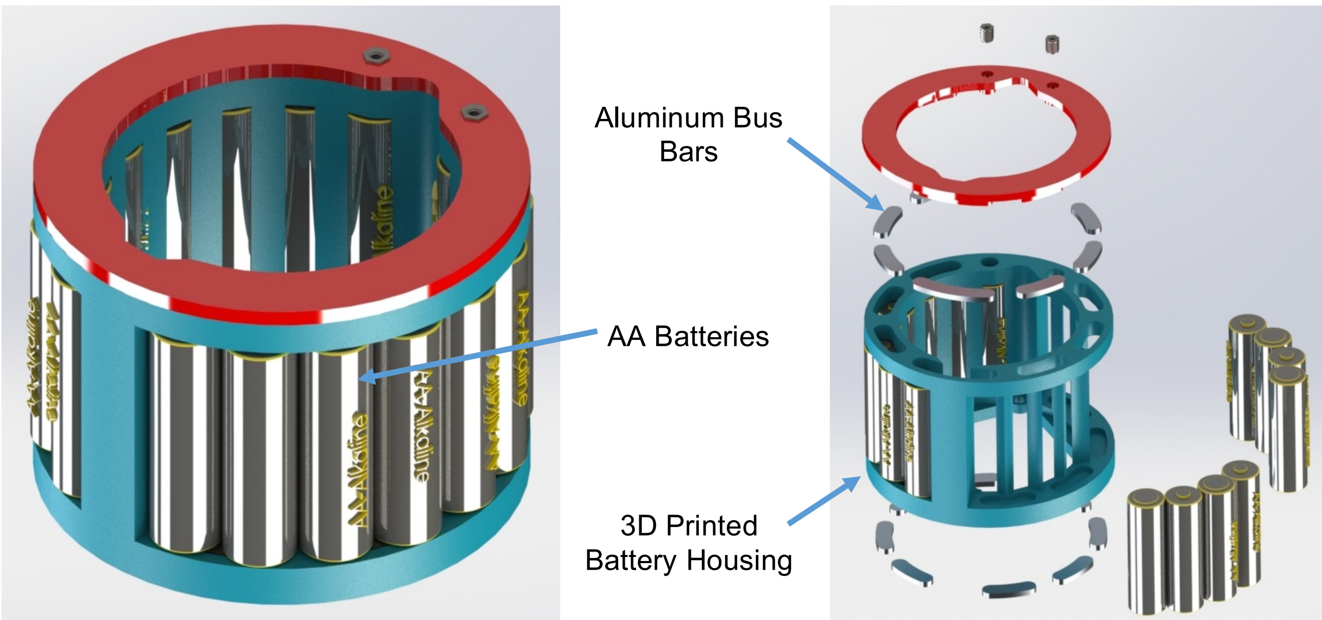

Figure 5: Battery Packaging

The float is designed for 6, 6-12 hour deployments corresponding to 1-2 tidal cycles before recharging. This specification was a driving factor for the amount of power housed within the float. To meet this specification, the prototype contains 16 AA batteries oriented in series with a nominal energy storage of 2700 mAh per cell and a nominal voltage of 24 V for the entire pack. This results in a total battery pack energy capacity of 64.8 Wh. The energy capacity was calculated based upon specifications given by *Energizer*, the manufacturer, for their AA batteries with a constant draw of 50 mA. The calculated energy draw of 6 deployments is approximately 60 Wh. This gives our system a factor of safety for energy consumption of 1.1. Unfortunately, it was challenging to accurately predict the capacity needed based on the varying power draw from the electronics in the float. Through bench testing the motor, which receives 24V +/- 10%, the needed energy capacity can be determined and the battery pack can be altered accordingly.

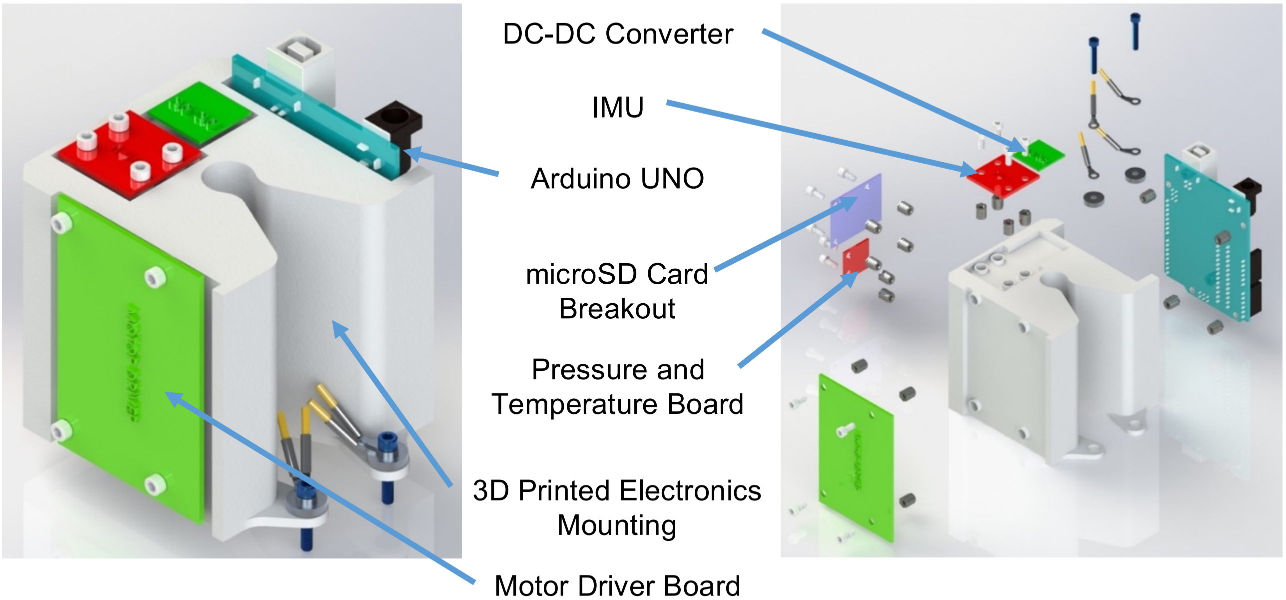

Figure 6: Electronics Assembly

Additionally, the float will have a 3D printed housing for mounting electronics inside the float. This housing has two mounting screws with access to the screws used to mount the motor and battery housing. Altered designs and board changes will be easily adjusted with the 3D printed design to incorporate upgrades of the float. Figure 6 shows the mounting system and exploded views of it.

Based on analytical calculations our design possesses a factor of safety of 1.1 against running out of energy. The power budget can be seen in Table 3. The motor requires about 5 times the power of any other electronic; the next highest power draw is from the microcontroller. This power calculation for the motor is relatively rudimentary however because detailed information about the power requirement is unfortunately challenging to find from Thomson (the manufacturer). The most significant obstacles to increased accuracy is currently not knowing how long we will need to run the motor at full power and what our best options are for reducing the power draw. The Oriental motor driver module includes a sleep mode to use less energy, however it is uncertain what the power draw is in that mode. It is important that the control scheme is accurate and precise, allowing the float to reach the desired depth with little to no oscillation. Achieving this will require testing and tuning.

Table 3: Power Budget

	Voltage	Estimated Amperage (mA)	Wattage (mW)	mWh (12hrs)
Microcontroller	12	50	600	7200
IMU	3.3	0.6	2.0	23.8
Depth Sensor	5	1	5	60
Internal Pressure/Temp	5	0.01	0.05	0.6
Shield Board - SD	5	100	500	6000
External Pressure Sensor	5	4	20	240

	Sink Work (J)	Rise Work (J)	Total Work (6 drops & rises in J)	mWh
Motor (6 cycles)	14040	14040	168480	46800

	mWh
Total mWh	60084
Energy F.S	1.08

The 24 V pack voltage will be reduced to 9 V using a DC-DC converter. The high voltage system is for the motor driver board while the low voltage system includes the microcontroller, sensors, and all other electronics within the float.

Overall the greatest concern from this aspect of the system is heat. Based on analytical calculations the steady state temperature assuming constant operation of the motor will be 305 K, but this is dependent on the ratings of the batteries and motor. The current plan is to operate the stepper at low speed with high torque which will produce a significant amount of heat. This will be examined in depth during testing, and if a more effective method of heat transfer is needed to move dissipative energy from the battery package area to the surrounding seawater, it will be implemented in the second revision.

5.4 MICROCONTROLLER

The microcontroller that is being used is the Arduino Uno. This board's main advantage is that it allows for simple interfacing with the sensors and provided a large supply of online resources for code. The simplicity of the Arduino system made it possible to create a prototype quickly and set a baseline to be improved on later. Power consumption of the Arduino Uno still needs to be measured during prolonged runs of the system because power consumption is approximate. Complete float testing is needed for reliable information on the contribution to the power consumption of the entire system with all control systems and sensors writing. When using this microcontroller to read and write the sensor information, about 85% of the dynamic RAM was used causing the controller to skip some readings. Potential microcontroller replacements are discussed in the Future Work and Recommendations section.

Arduino Uno includes 14 Digital pins 2 compatible with I2C communication, and 6 analog pins. This pin layout is more than sufficient for the number of sensors that will be in the float prototype. Final pin mapping of the microcontroller can be seen in Figure 7 with the sensors discussed below.

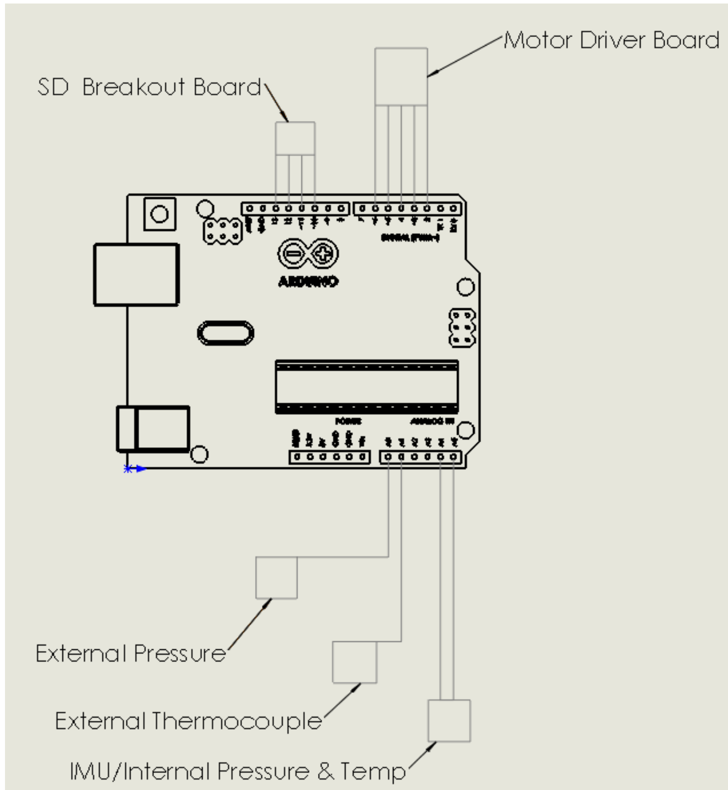

Figure 7: Pin Mapping of Microcontroller

5.5 SENSORS

There are a variety of sensors included in the final float design. These include an external pressure sensor used for depth measurement, an internal temperature and pressure sensor for health monitoring, and a 9-axis inertial measurement unit (IMU) for inertial navigation. All of the sensors in the float will be logging to a microSD card breakout board built by Adafruit. The ability to view all of the sensor data post-deployment will provide a detailed description of the events that occurred during the test. Each log will include a timestamp in order to match the sensor data to the position data.

The external pressure sensor is a Honeywell MLH series and has a range of 0-1380 kPa (0-200 psig). The error present in the sensor is about 7 kPa (1 psi) across the full range and could have an effect on our depth measurements. Preliminary testing has revealed a stable reading from the sensor at atmospheric pressure, but more in depth testing is necessary.

The internal temperature and pressure sensor is a breakout board for the Bosch BMP180 produced by Sparkfun Electronics. This board will be used to monitor internal temperature and pressure and will help to implement code to return the float to the surface if we have a thermal runaway event. The IMU is included to track the acceleration and axial tilt of the pod during deployment. The IMU will also allow for greater locational accuracy between GPS pings. The IMU used in the prototype is a STMicroelectronics LSM9DS1 on a Sparkfun breakout board.

Other sensors that will be included in the future are an external thermocouple to measure water temperature, a GPS location device to find the float after it has resurfaced from a deployment, the transducer for localization, an onboard hydrophone, and a humidity sensor.

5.6 PI CONTROL

In order to control the depth of the float, a PI controller will be implemented. It will be a single input single output system where the input is the external pressure and the output is number of steps the motor should take to compensate for any pressure difference. The PI controller will stabilize the system as it approaches the desired depth and should eliminate most oscillation that could occur with the delayed feedback loop of pressure to number of steps from the motor.

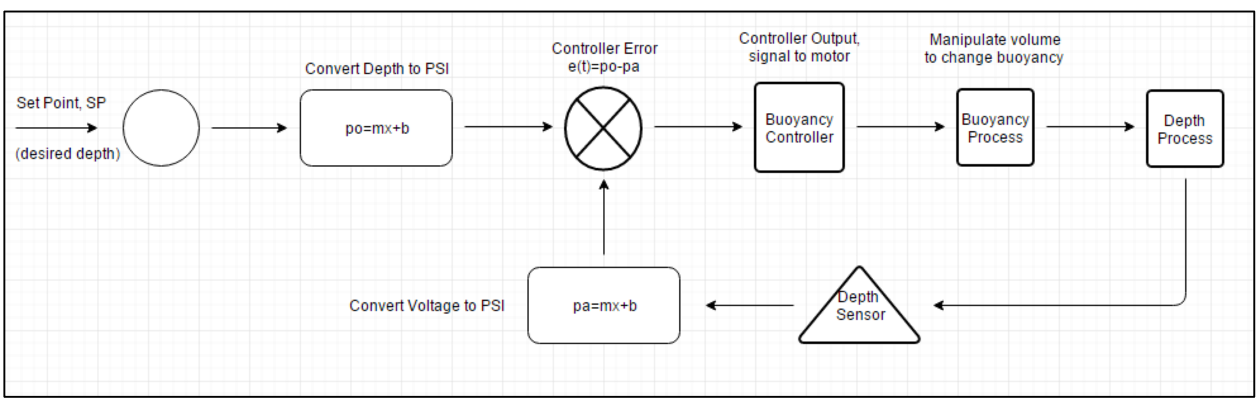

Figure 8: Block Diagram of Controls

A block diagram for the controls is shown in Figure 8. Here it can be seen that the input variable is a given depth which will then be converted to a pressure in psi and fed into the controller error. This will be compared to the measured value for pressure from the feedback loop that has also been converted from a voltage to a psi pressure from the depth sensor.

This error will then be fed into the buoyancy controller through a transfer function that will then output a command for number of steps that the stepper motor should then take. This change in motor position will then move the piston displacing some volume of water creating a buoyancy force on the floater to make it rise or sink accordingly.

In this control loop, the output variable does not directly control the input variable. The output of the stepper motor controls the buoyancy force seen on the pod which then controls the acceleration of the system and the pressure is directly related to the position of the float in the water. Since the input variable is not able to be directly controlled, two variables must be monitored and used in the control loop to fully define the system. The variables that will be used will be the pressure and the derivative of the output which will be indicative of the derivative of the pressure. Below explains more in detail the reasoning behind this as well as illustrates when each of the control regimes will be used.

There are two different commanded motions for the piston (up and down) and there are two instances that this piston motion would be needed when controlling the float. Using the error as well as the derivative of the output is how the float electronics will determine what direction to drive the piston.

Increasing Buoyancy: There are two scenarios that increasing buoyancy is a command that will need to be sent to the motor from the controller.

The first is a situation when the float is sinking and approaching the desired depth. In this situation the commanded pressure is more than the measured pressure on the outside of the float. This provides a negative error and indicates that the float is at a higher depth than desired. Additionally, the float is approaching the desired depth so the PI controller is providing a decreasing output and therefore the derivative of the output is negative. In this case the pod should begin to increase buoyancy and start the deceleration of the float as it approaches the desired depth. This inequality relation can be described as $P_{ref} < P_{meas}$ where P_{ref} is the target pressure and P_{meas} is the pressure recorded by the external pressure sensor.

The second scenario that increasing the buoyancy of the float is desired is when it is under the desired depth and continuing to accelerate downward. This will indicate that the reference pressure is greater than the measured pressure and provide a positive error. Additionally, the slope of the output will still be negative as the float is still accelerating downward so it should continue to increase its buoyancy. This inequality can still be described as $P_{ref} < P_{meas}$, however the derivative of the output with respect to time will be positive.

Decreasing Buoyancy: Similar to increasing the buoyancy of the float, there are two more scenarios where decreasing buoyancy will be the desired command

The first decreasing buoyancy scenario is when the pod is accelerating upward and is approaching its desired depth. In this situation the reference pressure is greater than the measured pressure leading to a positive error. The derivative of the output is positive because the float is accelerating upward towards the desired depth. The piston should begin making the float less buoyant as to decelerate the pod as it approaches the set point. The inequality can now be described as $P_{ref} > P_{meas}$.

The final scenario is when the float over shoots the desired depth while traveling upward. In this situation, $P_{ref} > P_{meas}$, and as a result the error is negative. In this case the pod will still be accelerating upward and the output derivative will be positive. To counter the continued acceleration upward, the controller should make the float decrease the buoyancy.

6 Future Work and Recommendations

6.1 Testing Plans

With the components for a working prototype coming in there are several things that still need to be tested. Several forms of testing will be implemented with the float including bench testing, tank testing, and field testing.

To ensure all components of the system work well together, several forms of bench testing will be conducted before the float goes to water. Testing will include cycle testing with the buoyancy control system to ensure reliability and proper piston motion. This will also include failure tests of piston over extension and response to several emergency situations.

Tests will also include long period power consumption, temperature monitoring and prolonged data recording to see how the system will respond after hours of operation. Actually putting the motor through its paces should provide information for prototype revision. Fully loaded tests of the motor and piston system will be performed using weights or an arbor press to simulated pressure at depth.

After the float has displayed adequate performance for controls and mechanism performance, several tests will be performed in the water tank in the UW Oceanography Department. The first tests will be pressurized tank testing to ensure the float will seal properly at depth for extended periods of time. After the float proves adequate sealing design, a fully functional float will be tested in a large seawater tank. The float will be given a designated depth to go to and a time to remain at the depth. During this the motion of the pod as well, as the accuracy of the depth will be observed and measured.

Depending on how the bench and tank testing goes, it may be necessary to revise the prototype ahead of field testing. Initially, fishing line will be connected to the float in shallow benign waters to ensure the device can be recovered if any problems arise After at least five successful launches and recoveries of the float, there will be a final full test of the pod including a release and recover of the system over the length of a tidal series.

6.2 RECOMMENDATIONS

Even though the initial prototype is not yet complete, several recommendations have already been developed for a next version that improve the design, ease of manufacturing, and price of the pod. First, several improvements can be made to the housing to remove weight from the end caps, especially through further stress analysis. The benefits of material removal will be somewhat balanced out by the cost addition of increasing the amount of machining necessary. However, pockets in the end caps could be a good solution to decrease overall size because the end caps currently constitute 40% of the total float weight. Through initial exploration into the concept via ANSYS Static Structural, the pockets were not included in this prototype because although the bottom end cap had an acceptable factor of safety against yielding, it experienced a deflection inside the piston bore that raised concerns about the sealing.

Therefore, the dynamic seals should be validated through testing before this modification is explored.

Through further stress analysis, perhaps a different plastic or material altogether could be used that would decrease weight. For example, composites are used commonly in boat building and might be worth exploring. However, composites are expensive and would also likely increase the processing cost of the project. Sticking with the same materials, a nominal inner diameter for the PVC housing would be a great improvement to reduce the amount of machine time needed for these parts though the manufacturer tolerances for PVC pipe are likely not nearly up to the standard needed by the float's sealing mechanisms, something that would need to be addressed.

The motor we used may be able to be replaced by one with reduced specifications which would further reduce the cost of the float. Currently, the stepper motor we use is quite expensive and switching to a DC brushless motor and encoder might decrease cost; the main obstacle to this is the specific setup being used on the lead screw. The Kollmorgen motor in the current design uses two lead nuts within the housing to translate the lead screw axially. Finding a different motor that would be able to work in the same way would likely require a custom solution of some sort, or at least would greatly increase the packaging requirement and weight of the system as a whole. That being said, we have a significant amount of unused volume in this design that could potentially be filled with a linear actuator of a different sort.

In addition, changing to a Beaglebone Black microcontroller could help with some of the dynamic RAM issues that are occurring because of the increase in processing power. The trade-off here is greater power draw, however it would likely still be significantly lower than the power draw of the motor.

Finally, to reduce drag and enable the float to be seen clearly when retrieving the pod, a fairing would be an excellent addition, though this is more mass and makes surfacing a bit more complicated. This would also serve as some protection to the pressure sensor and connector on the top cap of the float.

Another important modification that should be made once the seals are validated through testing is a change of battery chemistry. For the purposes of this prototype, alkaline batteries were used because of their lack of reactivity with water. Lithium chemistry batteries however will provide significantly higher voltage, allowing for a battery configuration within the same battery package that will still power the 24 V motor but store more energy. Also, currently all the batteries are oriented in series where having a series-parallel configuration would reduce the current draw on each battery, prolonging their life, significantly increasing safety, and dissipating less heat. Finally, switching to a lithium chemistry will allow for recharge ability, a desirable characteristic for long deployment periods.

7 REFERENCES AND ACKNOWLEDGMENTS

Without the help of Dr. Brian Polagye, Trevor Harrison, and other members of the Northwest National Marine Renewable Energy Center, this project could not have been possible. The team sends our sincerest thanks for the guidance and support.

The team would like to thank James Joslin and his lab for help with the end cap seals and O-ring specifications. The team would also like to thank Eric D'Asaro (Applied Physics Lab) for helping to determine the use of T-seals in the dynamic sealing application. The BCE depends heavily on this sealing.

The Thomson catalog was used for specifying the lead screw and motor and power curve diagrams were sourced from there.

8 APPENDICES

8.1 BOM

Table 4: Bill of Materials

Number	Item	Description	Category	Price	Quantity	Cost	Mass (kg/ea)	Total Mass (kg)	Vendor
1	Microcontroller	Arduino Uno - R3	Electronics	$24.95	1	$24.95	0.025	0.025	Sparkfun
2	Internal Pressure/Temp	SparkFun BMP180	Electronics	$9.95	1	$9.95	0.001	0.001	Sparkfun
3	IMU	SparkFun LSM9DS1	Electronics	$24.95	1	$24.95	0.001	0.001	Sparkfun
4	External Pressure	Honeywell	Electronics	$123.73	1	$123.73	0.084	0.084	Digikey
5	Motor Driver Board	Oriental Motor CVD242BR-K	Buoyancy Control	$129.00	1	$129.00	0.030	0.030	Sparkfun
6	Batteries	AA Batteries	Electronics		16	$14.00	0.384	6.144	-
7	Stepper Motor	Thomson 23B390	Buoyancy Control	$293.66	1	$293.66	0.770	0.770	Thomson
8	Lead Screw	0.083" Lead, 0.313" OD	Buoyancy Control	$0.00	1	$0.00	0.082	0.082	Thomson
9	Bottom Cap	Delrin	Packaging	$23.00	1	$23.00	1.247	1.247	Custom
10	Electronics Housing	PLA Custom	Electronics	-	1	$0.00	0.157	0.157	Custom
11	PVC Pipe	McMaster high pressure 4" diameter pipe	Packaging	$9.40	1	$9.40	0.881	0.881	McMaster
12	Top Cap	Delrin	Packaging	$23.00	1	$23.00	0.473	0.473	Custom
13	Battery housing	PLA Custom 3d Printed	Packaging		1	$0.00	0.052	0.052	Custom
14	SD Board	Micro SD Breakout Board	Electronics	$14.95	1	$14.95	0.006	0.006	Adafruit

15	Vent Plug	50925k433	Packaging	$1.22	1	$1.22	0.013	0.013	McMaster Carr
16	Main O-Rings	9452k191	Packaging	$0.22	4	$0.89	0.004	0.015	McMaster Carr
17	Wire-locking pins	97395a432	Packaging	$0.60	4	$2.41	0.001	0.002	McMaster Carr
18	Absorption Material	Microfiber Cloth	Packaging	-	-	-	-	-	-
19	Nylon #4=40 x .25" SHCS	95868A106	Electronic s	$0.06	18	$1.00	0.000	0.002	McMaster Carr
20	Battery Bus Bars	6061 Al Conductors, waterjet	Electronic s	-	16	$15.7 7	0.001	0.012	Online Metals, custom cut
21	#4-40 Press Fit Anti-Rotation Nuts	92398A112	Electronic s	$0.37	20	$7.35	0.001	0.013	McMaster Carr
22	Battery Pack Cover	PLA Custom	Electronic s	-	1	$10.0 0	0.014	0.014	custom
23	DC-DC Converter	MP1584EN	Electronic s	$12.99	1	$12.9 9	0.009	0.009	Amazon (Atomic Market)
24	Connector	IE55-1206-BCR	Electronic s	$102.0 0	1	$102. 00	0.032	0.032	Teledyne Impulse
25	Connector Dummy Plug	IE55-1206-SCP	Electronic s	$96.25	1	$96.2 5	0.000	0.000	Teledyne Impulse
26	10-24 Stainless Steel SHCS .75"lg	96006a649	Packaging	$0.25	5	$1.24	0.004	0.018	McMaster Carr
27	Brass Heat Set Insert, 10-24	93365a150	Electronic s	$0.24	7	$1.71	0.001	0.008	McMaster Carr
28	Piston Head	Delrin	Buoyancy Control	$0.00	1	$0.00	0.027	0.027	Custom Machine
29	Piston Load Plate	Machined Aluminum 6061-t6	Buoyancy Control	-	1	$5.00	0.010	0.010	Custom Machine
30	#4-40 Aluminum SHCS .625"lg	98511a253	Electronic s	$0.19	2	$0.37	0.000	0.001	McMaster Carr
31	T-Seals, Dynamic	TP-022 Hydraulic Piston T-Seal Buna-N	Buoyancy Control	$5.53	2	$11.0 6	0.002	0.004	The O-Ring Store
32	#4 Ring Terminals	For wiring	Electronic s	$0.39	4	$1.58	0.000	0.001	McMaster Carr

33	Al Spacer, Washer	Custom Machine	Electronic s	-	2	$1.00	0.000	0.001	Custom Machine
34	10-24 x .5"lg SHCS	96006a646	Buoyancy Control	$0.19	3	$0.56	0.003	0.009	McMaster Carr

8.2 MANUFACTURER DATA SHEETS

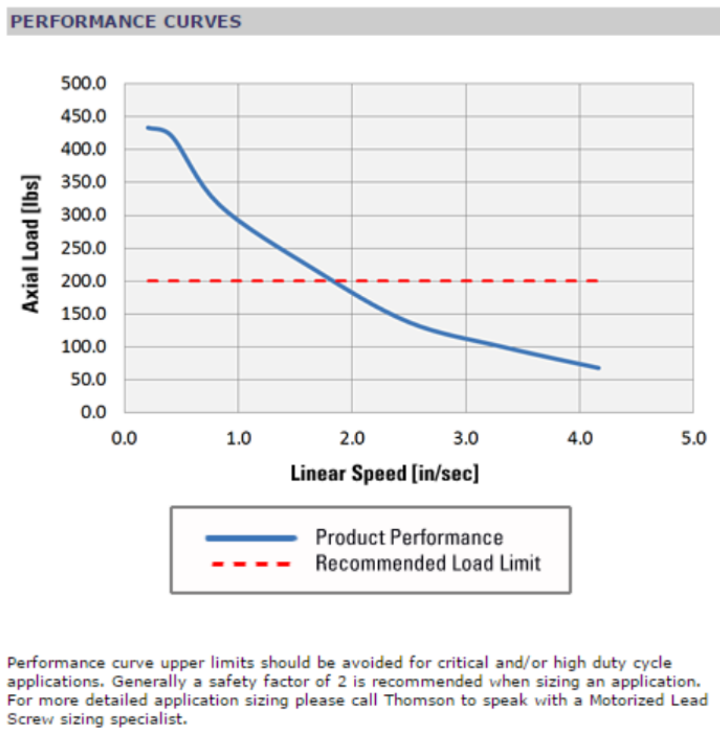

Figure 9: Motor Linear Speed vs. Axial Load

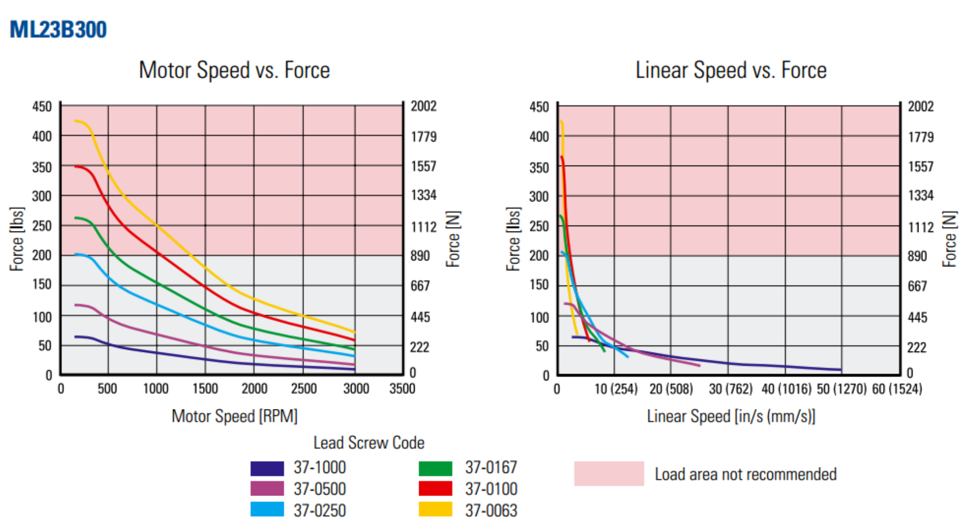

Figure 10: Motor Speed vs. Force