Design of a Lagrangian Float for Monitoring Phytoplankton Abundance in Coastal Waters

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Abstract— **This project focuses on the design of a low-cost, low energy float for sampling data across vertical profiles in the coastal waters. The float relies on ocean currents and drifts to a set target location while sampling data. The device will use GPS to obtain its position while surfaced. Via the cellular network, the device can send messages and retrieve commands. This paper will focus on the physical design, specifically the energy considerations, propulsion mechanism, and vehicle body design. A semi-passive design and an active, conventional design are being considered. The semi-passive design has a compressible volume that changes passively due hydrostatic pressure at different depths. The buoyancy difference due to the passively changing volume would allow the float to be positively buoyant at the surface and negatively buoyant near the seafloor. A thruster was used to move the between the float between these two points. The conventional system on the other hand, actively changes its buoyancy using a pump that would increase its volume. Energy calculations for the work done to ascend and descend different depths using the two designs were done. The results showed that the semi-passive system's energy usage grows exponentially with depth, while the conventional system's energy usage grows linearly. At shallow depths, the semi-passive system is more energy efficient, while at deeper depths the conventional system out performs the passive system. The semi-passive system is also cheaper than the conventional system. Because there are possible energy savings and costs savings with using the semi-passive system, this design was built out and tested. Two prototypes were built. In a series of tests, the float demonstrated that it was able to maintain its position at the surface and seafloor, move between these two positions autonomously, and hold depth using a proportional controller. The calculations for the theoretical equilibrium depth, mass, and compressible volume were validated by the results of the test. Although more work is required to develop and test its full functionality, this is a promising start in the design of this coastal float.**

I. INTRODUCTION

The monitoring of phytoplankton abundance is of great interest in coastal areas where algae blooms often occur. Monitoring of phytoplankton can be done using satellite ocean color techniques. This allows for proxy measurements of phytoplankton abundance on a large spatial scale. While satellite data provides good spatial coverage, it has its limitations. *In situ* measurements are more precise and accurate compared to satellite measurements. Satellite measurements get single data points that represent areas that cover up to 81 km^2, meaning that these measurements have low resolution[3]. Remote sensing also has problems due to spotty coverage caused by cloud interference. Due to it having infrequent repeat passes over a single ocean surface, there is also poor a temporal resolution. *In situ* chlorophyll fluorometry can be used in addition to remote sensing technology to study and understand phytoplankton and monitor harmful algal blooms (HABs). This method provides better temporal and spatial resolution, but doesn't have the wide spatial coverage of satellite remote sensing. Its effective in collecting measurements in a targeted area. Because of the attenuation of EM waves in water, satellite data only measures data on the ocean surface, losing the third dimension of depth. Satellite data wouldn't be able to capture the full picture of what is going on because of differences present in the water depths, such as nutrients, light and temperature, which impact on phytoplankton.

The monitoring of HABs is important for communities because these blooms can produce harmful toxins and affect drinking water. Many organizations sample waters to monitor phytoplankton and toxins via techniques such as remote sensing, manual sampling, citizen reports, and robotic sampling[4]. The option to use *in situ* measurements of chlorophyll-a concentrations for HAB monitoring can be expanded to be used by more organizations by making the technology cheaper and more accessible. There is a need for the design of a low-cost system for bloom detection. The design of a coastal monitoring system poses an interesting set of challenges.

The float should be able to make a minimum of 2 profiles a day, but around 5 a day would be more appropriate in order for the float to obtain more data from vertical profiles. The deployment length would be around 3 months. This time period is long enough to study phytoplankton over the course of the summer for example. With 5 profiles a day over the course of 3 months, this means that the float will make around 450 profiles. With Lipo batteries having a energy density of 200 Watt hrs/ kg, 1 kg of Lipo batteries can provide 720 kJ of energy. With 300 profiles, each profile must be around 2400 kJ. The power consumption of the rest of the electronics, including the microcontroller and the sensors will add to the required energy storage.

Lagrangian floats follow all three components of oceanic velocity on all time scales[1]. Other Lagrangian floats have been developed in the past that are neutrally buoyant at most depths, allowing it to better follow the trajectory of water. D'Asaro (2002) mentioned that previous Lagrangian floats have tried to match the density and compressibility of water[1]. The Mixed Layer Lagrangian Float(MLLF) that was developed to operate up to 250 db or around 250 meter depths changes its volume by extruding a piston. The instrument volume is 50000 ml and uses a 750 ml active control volume. MLLF sends and receives data using the Orbcomm satellite system and determines its position using GPS.

There are some differences in the use case of previous floats and our float. While previous Lagrangian floats were designed to drift with the current, our float selectively drifts depending on current velocity. The float will have a programmed trajectory. The concept is to use bang bang control, where the float rides the currents if the current velocity points towards the end destination and anchor itself otherwise. Because of this, the float being designed will have some Lagrangian properties to it, without being truly Lagrangian. This refers to its ability to drift with surface currents. To selectively ride the currents, the float needs some way to anchor and de-anchor itself. One design to consider is to use a compressible volume to vary the buoyancy force to allow the float to be negatively buoyant on the seafloor and positively buoyant near the surface. This way the float will have a net downward force near the seafloor that keeps it "virtually anchored" to the bottom. To de-anchor itself and return to the surface, a thruster can be used to propel itself through the water column. This would be a semi-passive design because it varies its buoyancy passively but also requires a thruster. An alternative design is to use a conventional buoyancy engine that changes its buoyancy using a piston.

An appropriate navigation system is essential in this application. This device will not have a horizontal propulsion system, instead it will solely rely on the power of the currents. The device will be able to ascend and descend vertically across the depth of the water. This allows it to take advantage of the differences in current speeds across varying depths. Current speeds at greater depths are much smaller than those at shallow depths. The device can selectively choose when to rise to the surface to allow the surface currents to move it. The vehicle can take advantage of periodic tidal patterns present in coastal areas. Buzzards Bay is a good example of a coastal area where tide patterns are well understood. During high tide, current velocity will be flowing northeast into Buzzards Bay, while during low tide, current velocity will point southwest out of Buzzards Bay. When the velocity of the current points away from the target destination, the device will spend time in a inactive state, where it lies on the sea floor, experiencing relatively little current. These tidal patterns cause the current velocity to oscillate between opposite directions. If the velocity is pointing the opposite direction to the final destination, the float can wait for the tide to change. The velocity vector will reverse and point towards the final destination after some time (tidal period is around 12.5 hours). The semi-passive design is relatively unique because its buoyancy system differs from most of that of previous floats. Energy calculations for the work done by the thruster for the semi-passive design and the for the work done by the piston in the conventional design shows that there is motivation to explore the use of the semi-passive design for shallow water applications in an energy perspective. For a proof of concept, prototypes for the semi-passive design were built and tested. The qualitative and quantitative data from these tests validated both the concept of the semi-passive design and the volume and mass calculations that customized the float to operate in specific conditions. Although further testing, development of its navigation system, integration of scientific senors, and development of a communications system is required, the results of this study show a promising start for the semi-passive design.

II. Conceptual Overview

1) Design 1: Semi-Passive System: The semi-passive design has a compressible volume and a incompressible volume. The compressible volume is filled with air that changes volume at different depths due to passive changes in hydrostatic pressure. The float moves across different depths using a thruster.

2) Design 2: Conventional Buoyancy System: The conventional design also has a compressible volume but that compressibel volume is compressed actively rather than passively. The active

III. ENERGY CALCULATIONS

We are considering a couple designs for the buoyancy mechanism of the float. A factor that has to be minimized is the energy cost. The float must be able to operate its electronics and sensors, while being able to operate the necessary pumps and thrusters. A theoretical mission would require 300 profiles over the course of 3 months. 1 kg of Lipo batteries would store 720 KJ of Energy. Assuming that electronics and sensors will continuously draw .1 Amps at 5 volts for an hour a day, these components will already consume 162 kJ over the course of 3 months. The 10 Newtons of force generated by a Blue Robotics T100 Thruster requires 58.67 Watts in one direction and 32.68 Watts in reverse. This is at a operating efficiency of 15 and 30 respectively. For estimations, we can assume that the thruster requires 45 Watts and operates at a 20 efficiency. We have to keep in mind the inefficiencies of both systems doing the energy calculations. Assuming we have 600 KJ of energy, the float operates at 45 watts, the float thrusts with a force of 10 N, the float travels at .5 m/s, and the average depth is 5 meters, the energy expenditure for a single profile is 1 KJ Joules. These rough estimates are reasonable. Given 600 KJ of energy in batteries, each profile would be allotted 2 KJ. This is a theoretical estimate for the energy costs for the semi-passive design. A more rigorous calculation will be done do compare the differences between the semi-passive and conventional design. First, we will go over the assumptions that were made and the parameters that were set, then we will go over the details of each design, then perform analysis on energy consumption and compare the results of the analysis. Note that the below energy calculations don't account for the inefficiencies present in the thrusters or pistons (or pumps).

A. Assumptions and Parameters

Here we define some parameters that are important for understanding the energy consumption and vehicle states. There is an anchor force F_{anchor}, which keeps the device on the seafloor and a float force F_{float} that keeps the device afloat. Both designs will have a fixed float force at the surface, and the way the systems behave across different depths of the water column would be different.

- gravitational acceleration

$$g = 9.8\ m/s^2$$

- salt water density:

$$\rho = 1025\ kg/m^3$$

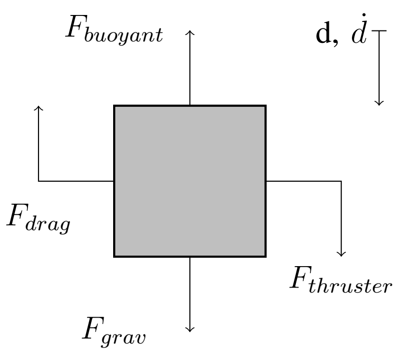
- coordinate system: depth below water and rate of change of depth is given by d and $\dot{d}$ respectively.
- Size and Shape: The shape of the device can be approximated as a cylinder. The total $Volume$ is the sum of the in-compressible part and compressible part. The radius R of the cylinder determines the area A of the circular faces. The height h is determined by volume and area. The compressible volume $V_C = V_C(d)$ differs with each design and at each depth. The compressible volume refers to a volume that changes with depth, which allows for buoyancy changes. The compressible volume would be filled by a compressible fluid such as air. The incompressible volume refers to the stiff parts of the vehicle, usually including the pressure vessel, nose cap, thrusters, and fins.

- Forces: The forces that may act on the device include a buoyant force F_b, drag force F_d, force of gravity F_g and applied thrust force F_T.

B. Design 1: Semi-Passive Buoyancy System

This design attempts to harness the pressure differences across water depths to move the device vertically through the water column. During certain parts of the decent and ascent, the device can move without power, while during other parts, some mechanism is required to provide thrust.

The Passive Buoyancy System comprises of an incompressible volume (V_{IC}) that houses the electronics, batteries, sensors, and other components and a compressible volume ($V_C(d)$ that changes size due to the pressure changes across depths of water. At the surface of the water where $Pressure = P_{atm}, V_C(d=0) = V_{C,atm}$.



The buoyant force changes as volume changes with depth. There is a certain depth where the buoyant force equals the force of gravity, for which we will call the equilibrium depth d_{eq}. The buoyant force at depth d is given by:

$$F_b(d) = \rho \cdot (V_{IC} + \frac{P_{atm} \cdot V_{C,atm}}{P_{atm} + \rho \cdot g \cdot d}) \cdot g$$

When the device is moving at a non-zero velocity $\dot{d}$, it feels a drag force given by:

$$F_d = C_d \cdot \rho \cdot A \cdot \dot{d}^2 = Z_{d|d|} \cdot \dot{d}^2$$

At d_{eq}, the buoyant force equals the force of gravity ($F_b = F_g$). For velocity $\dot{d}$ equals 0, the device is at equilibrium and the summation of forces equal 0. Solving for d_{eq} gives us:

$$d_{eq} = [\ \frac{P_{atm} \cdot V_{C,atm}}{\frac{m}{\rho} - V_{IC}} - P_{atm}\ ] \cdot (\frac{1}{\rho \cdot g})$$

where:

$$F_b > F_g \ for \ d > d_{eq}$$
$$F_b < F_g \ for \ d > d_{eq}$$

d_{eq} is important because it is the equilibrium point of this unstable system. Because of the relationship between F_b and d, device tends to accelerate away from d_{eq}. We take advantage of this fact to reduce the amount of work required to make vertical profiles. If we have the device start on the surface and move towards d_{eq}, a thrust force F_T needs to be applied. Once the device descends past depth d_{eq}, the system will passively move towards the seafloor and away from d_{eq}. A similar case is true on the ascent, where work is needed to ascend the device from the seafloor to d_{eq}, but after that the device can passively ascend.

Once the float reaches the surface or the seafloor, the net forces at those points will maintain the float's depth without extra energy input as long as the depth is greater than d_{eq} and external forces are weaker than the float force and anchor force.

To calculate the work W done by F_T, we need to integrate F_T from intervals of d in the range [0, d_{eq}] for the descent and [d_{sf}, d_{eq}] for the ascent, where d_{sf} is the depth to the seafloor and $Z_{\dot{d}|\dot{d}}$ is a constant for drag.

$$F_T(d, \dot{d}) =$$
$$Z_{\dot{d}|\dot{d}|}\ \dot{d}\ |\dot{d}| + \rho \cdot (V_{IC} + \frac{P_{atm} \cdot V_{C,atm}}{P_{atm} + \rho \cdot g \cdot d}) \cdot g - m\ g$$

$$W = W_{descent} + W_{ascent}$$

$$W = \int_0^{d_{eq}} [F_T(d, \dot{d} > 0)]\ dd + \int_{d_{sf}}^{d_{eq}} [F_T(d, \dot{d} < 0)]\ dd$$

This gives us:

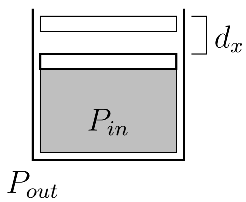
$$W = w(0, d_{eq}, \dot{d} > 0) + w(d_{sf}, d_{eq}, \dot{d} < 0) \quad (1)$$

where w is the work done to move between initial depth d_0 to final depth d_f at velocity $\dot{(d)}$

$$w(d_0, d_f, \dot{(d)}) = [Z_{\dot{d}|\dot{d}|}\dot{d}|\dot{d}| + \rho g V_{IC} - mg][d_f - d_0] + [P_{atm}V_{atm}]\ln(\frac{P_{atm} + \rho g d_f}{P_{atm} + \rho g d_0}) \quad (2)$$

C. Design 2: Conventional Buoyancy System

The Conventional Buoyancy System actively changes its volume to change its buoyant force F_b. It comprises of an incompressible Volume (V_{IC}) that houses the electronics, batteries, sensors, and other components and a compressible volume. The compressible volume is changed using some type of actuator or pump. It expands its volume and in doing so, pushes away a certain volume of water. This increased water displacement causes a increased buoyant force. At the surface of the water, pressure equals P_{atm}, and $V_C(d = 0) = V_{C,atm}$.



The buoyancy system can be modeled as a piston that has a internal pressure P_{in} and compressible volume V_C. It feels a pressure from its environment P_{out}. When the piston moves a distance dx, there is a volume change of d_V. V_0 is the initial volume and V_f is the final volume. The work W done to change the volume by pushing out water is given by:

$$W = \int_{V_0}^{V_f} [P_{out} - P_{in}] \cdot dV$$

The device will push out water and expand to ascend from the seafloor and will pull in water and contract when it descends. We can assume that P_{out} is constant and equals P_{atm} at the surface and P_{sf} at the seafloor. $V_{C,atm}$ is the required compressible volume at the surface, $V_{C,sf}$ is the required compressible volume on the seafloor, and V_{IC} is the incompressible volume. For simplification, the compressible volume in this design can be actively compressed via a pump, but not passively compressed by hydrostatic pressure.

This gives us:

$$W_{ascent} = \int_{V_{C,sf}}^{V_{C,atm}} (\frac{P_{atm} V_{atm}}{V} - P_{sf}) dV$$

$$W_{descent} = \int_{V_{C,atm}}^{V_{C,sf}} (\frac{P_{atm} V_{atm}}{V} - P_{atm}) dV$$

D. COMPARISONS 1

For the first method of comparisons, we will hold the anchor and float forces constant. Both designs will have the same anchor and float force. The energy consumption would be through the thrust energy with the passive design and volume displacement energy with the conventional design to ascend and descend. The V_{IC}, $V_{C,atm}$, and $V_{C,sf}$ depends on the d_{eq}, F_{float}, and F_{anchor}. Note that d_{eq} is only relevant for the semi-passive design. At a given depth d, the equilibrium equations at the surface and the seafloor are given by:

Surface:

$$\rho \cdot V_{surface}\ g = F_{float} + m \cdot g$$

$$V_{IC} + V_{C,atm} = \frac{F_{float} + m \cdot g}{\rho \cdot g}$$

Seafloor:

$$\rho \cdot V_{sf} \cdot g + F_{anchor} = m \cdot g$$

$$V_{IC} + \frac{P_{atm} \cdot V_{C,atm}}{P_{sf}} = \frac{m \cdot g - F_{anchor}}{\rho \cdot g}$$

Solving for V_{IC} and $V_{C,atm}$, we get:

$$V_{C,atm} = (\frac{F_{float} + F_{anchor}}{\rho \cdot g}) \cdot (\frac{P_{sf}}{P_{sf} - P_{atm}})$$

$$V_{IC} = \frac{m \cdot g + F_{float}}{\rho \cdot g} - V_{C,atm}$$

To achieve the desired seafloor and sea surface force constraints for passive design, either V_{IC} and $V_{C,atm}$ have to be changed or $V_{C,atm}$ and m have to be changed according to each depth. The vertical speed $|\dot{d}|$ used for the calculation is 1 m/s.

The results show that the passive design is more efficient. The V_{IC} and V_C that were chosen at each depth may not be reasonable for lower depths, where V_{IC} is nearly 0. This device would have an operating range, which changes as a function of mass.

E. COMPARISONS 2

Another way to compare this system is to have the same V_{IC} and same $V_{C,atm}$ and have the F_{anchor} vary. The calculations for the passive design will give us the resulting F_{anchor} at that depth. This will be used to calculate the work done by the conventional Buoyancy Engine. The operating range will

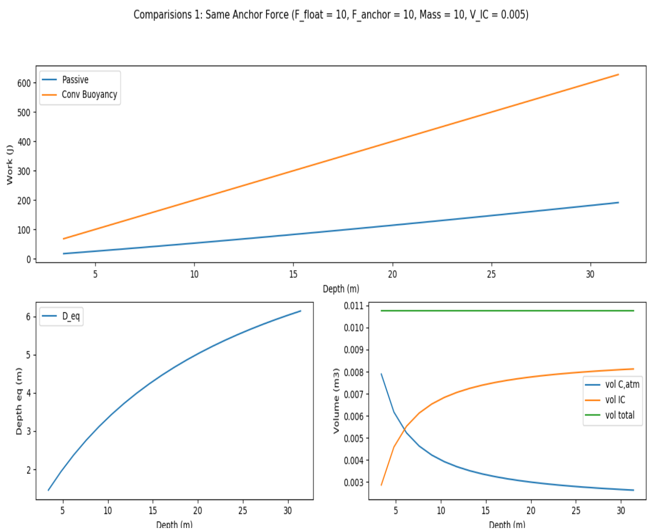


Fig. 1. X axis for all 3 plots is the depth of the sea floor. Plot 1 shows energy consumption in Joules. Plot 2 shows the equilibrium depth D_{eq} in meters. Plot 3 shows the compressible volume at atmospheric pressure and incompressible volume as a function of depth. The radius of the cylindrical incompressible volume is set to 0.05 m. Mass is set to 10 kg. Both anchor and float forces are set to 10 N.

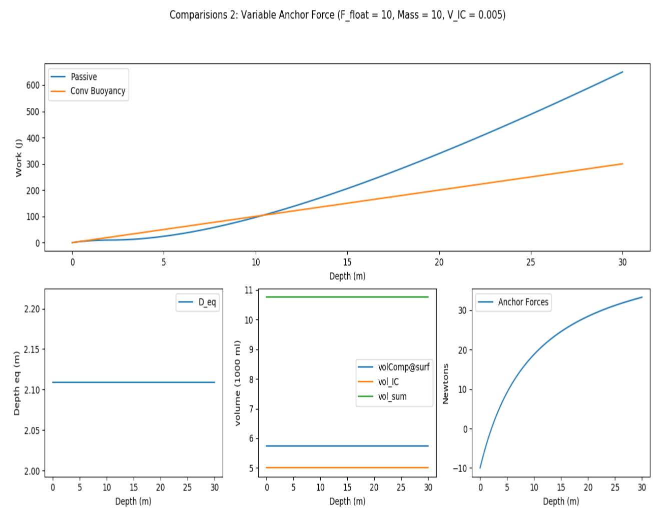


Fig. 2. Plot 1 shows the energy use for ascent and descent for both designs as the depth varies. At shallow depths, the passive system uses less energy. As the seafloor gets deeper, the passive system becomes comparably more energy intensive because the energy expenditure grows exponentially with depth while the conventional design is linear. The mass is 10 kg, V_{IC} is .005 m3 and F_{float} is set to 10 N

be determined by the resulting F_{anchor}. If F_{anchor} is negative at the seafloor depth, the float will be outside its operating range.

The calculations for work done by the conventional design is different for this method of comparison. The bounds of the integral will be between the compressible volume to match the same anchoring force at seafloor depth as the passive design $V_{C,sf}$ and compressible volume at the atmospheric pressure $V_{C,atm}$.

$$W_{descent} = \int_{V_{C,atm}}^{V_{C,sf}} \left(\frac{P_{atm}V_{atm}}{V} - P_{atm}\right)dV$$

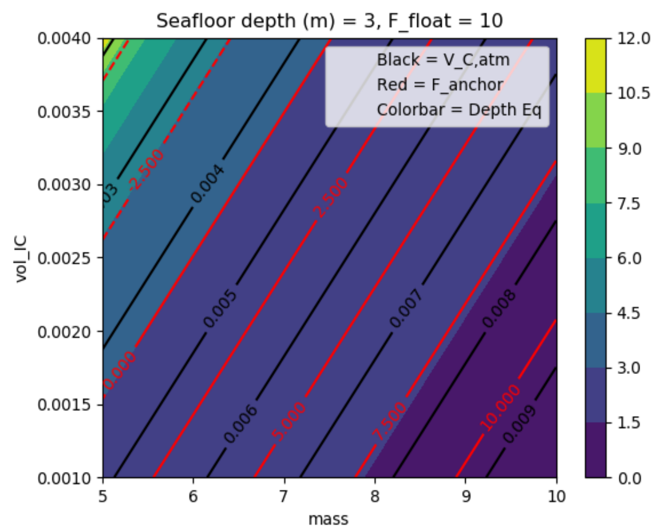
$$W_{ascent} = \int_{V_{C,sf}}^{V_{C,atm}} \left(\frac{P_{atm}V_{atm}}{V} - P_{sf}\right)dV$$

$$W_{total} = P_{atm}[V_{C,atm} - V_{C,sf}] + P_{sf}[V_{C,sf} - V_{C,atm}]$$

The results of the energy calculations show that the passive design offers energy savings for low depths. So we decided to test it.

F. Mass and Volume Considerations

The V_{IC} and $mass$ are closely related to functionality of the semi-passive design. In order to help choose the parameters to make the device act as desired, the below figure was created.



IV. Design

A. Center of Mass, Buoyancy, and Pressure

To keep the vehicle in a constant vertical orientation, F_b should be acting on the head of the device, while the force of gravity is on the tail. This causes the device to resist rotations because the F_g and F_b act as restoring forces that return the device back to a vertical position.

The center of pressure is usually considered in rocket design, but in this case the restoring forces from F_b and F_g should be significant enough that the placement of the center of pressure can be ignored.

V. PROTOTYPE 1

A. Float Test

1) Goals: The first prototype was tested for the conditions that it (1) stays at surface when it is near the surface, (2) stays on the bottom when the device is near the bottom, and (3) is ballasted in the middle of the water column.

2) Methods: The V_{IC} was measured to be 3500 ml or .0035 cubic meters and mass was measured to be 3.390 kg. This was done by finding the displacement of water using a graduated cylinder. The way this was measured likely introduced some error into the measurement.

Tank height was about 1.5 meters.

The ballasting was done by adding weight to a positively buoyant device (without the compressible volume) until the added weight causes it to sink.

After this was done, the bubble wrap was added to act as a compressible volume. Bubble wrap made ballasting easy because decreasing the compressible volume can be done by simply popping the bubbles. Based on the measured volume and mass, the calculated compressible volume is going to be 50 ml. When ballasting, the actually compressible volume of the bubble wrap was adjusted and measured to be 20 ml. This difference is likely due to the inaccurate measurement of the incompresssible volume.

When the float was near the surface, it stayed near the surface. The float would rise back to the surface even if it is pushed down slightly. As the float rises, we can also see that it is accelerating. When the float is near the bottom, it stays at the bottom. The float sinks when it is near the bottom. The float is ballasted so the equilibrium point is within the range of the tank depth. To test this, we held the float at different depths and released it. We can see that the float goes from accelerating to the surface to accelerating to the bottom as that initial depth increases. The float test was shown to be successful because all three of the stated conditions were met.

3) Problems: Leak: A leakage was found during the float test was that the float started leaking. After debugging, the source was found to be the depth sensor. The O-ring was mounted on a poorly faced surface and didn't make good contact. This was fixed by doing a face cut over the surface.

Fig. 4. Float Test (Float) : The float was able to stay at the surface of the water without energy input. The float would accelerate back to the surface given small displacements away form the surface

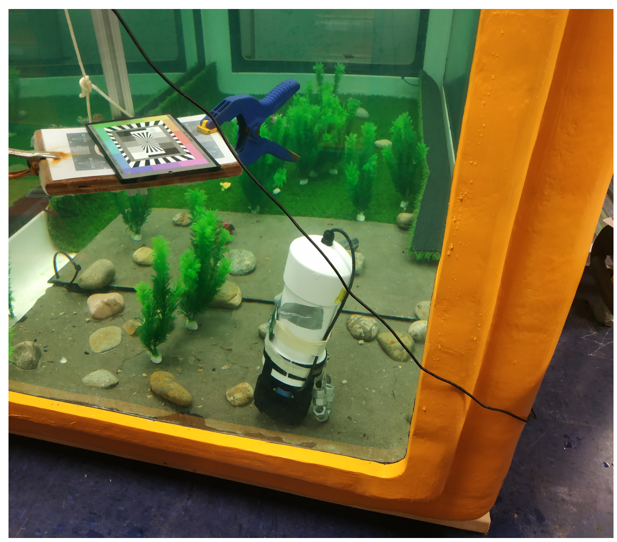


Fig. 5. Float Test (Sink): The same float, with the same ballasting was able to stay at the tank floor and return to the tank floor given small displacements away from the floor

Inconvenience: Having to take the electronics in and out of the float every time the code needed to be changed was a hassle. The electronics would sometimes short or unplug during handling, a better way of packaging the electronics could help deal with both of these problems.

B. Thruster Test

1) Goals: The prototype must be able to (1) ascend to the surface of the water and stay there and (2) descend to the bottom and stay there. The descent and ascent must be done efficiently, meaning that (3) energy isn't lost due to unnecessary motion and (4) drag isn't a problem. Experimental setup is shown in Figure 6, 7 and 8.

2) Methods: Qualitative Assessment: The thruster test included a qualitative assessment of its performance and a quantitative measurement of the thruster force.

During the qualitative test, the float was programmed to ascend at its max ascending speed for 3 seconds and then set to idle for 10 seconds. Then it descends at the max descend speed and was set to idle for 10 seconds. This process was done repeatedly and the behavior of the float was observed.

3) Results: Qualitative Assessment: The float was observed to successfully accelerate to the surface. Once it reached the surface it wouldn't be able to keep ascending so it turns on its side and it thrusts horizontally across the surface of the water. During the idle period the float ended up floating back to the bottom of the tank. This was because the float wasn't ballasted correctly before the test. However, the test was still informative on the performance of the ascending thrust component. While ascending seems to have no problem, descending does. During Descent, the thruster pushes water up, but it hits against a flat face of the float body, causing a lot of drag. The drag seemingly negates all the downward acceleration the thruster generates. The float stays at the same depth while the thruster is trying to descend. This is problematic because the thruster is incapable of accelerating the device downward. The float was also seen rotating on a nearly vertical axis. The thrusting force caused to tail of the float to spin around a vertical axis that cut through the center of the vehicle. The vehicle itself was tilted at around a 15 to 30 degree angle from the vertical as it spun.

4) Methods: Quantitative Assessment: The float was attached from the bottom with a negatively buoyant weight and attached from the top to a scale that measured the weight. The weight was negatively buoyant enough to keep the rope (neutrally buoyant cotton twine) that attached everything taught. The scale was zeroed before running the thruster. The thruster was set to run near its max forward and reverse settings and we measured the changes in the net forces in the system by reading the weight reading on the scale. The Ascending PWN signal was set to 2000 μs and Descending PWN signal set to 1000 μs. The rest state was set to 1500 μs. The float was ballasted again before this test for neutral buoyancy in the middle of the water, to an air weight of 3465 grams. Compressible volume was 20 ml Incompressible volume was 3523ml

5) Results: Quantitative Assessment: To supplement the Qualitative assessment of thruster performance, the thruster forces were measured. This will also be used to access the performance difference between this prototype and a future iteration.

The digital weight scale was zeroed before initialization of thruster. When the Thruster was initialized, the readings on the scale would change depending on whether it feels a greater force downward (positive weight measurement) or would the system be for positively buoyant (negative weight measurement). The Ascend PWN signal was expected to make the system feel more negatively buoyant, thus expecting a negative reading. The measurement we received centered around -800 grams, with a maximum reading of -1100 grams. The Descend PWN signal was expected to pull the system down, causing it to feel negatively buoyant and thus a positive reading on the scale. However, the scale actually had a negative reading that was centered around 60 grams. The reason that this may have happened was that the water was thrusted towards a flat face on the prototype, then deflected in the opposite direction. During the qualitative thruster test, the float was seen spinning around more than it was moving vertically. The thrust force might have caused some type of fluid flow or was directed in a way that actually caused the forcing to the surface. The descend measurements show that the thruster can't operate as required.

	Avg Measured Weight (g)	Force
Ascend	-800	7.84 N
Descend	-60	.59 N

Fig. 6. The float was attached from the bottom to a weight that keep the rope taught during the experiment. A rope connected the top of the float to a scale

Fig. 7. A scale was set up to measure the net forces of the system

VI. Stress

For a thin walled cylinder:

Circumferential Stress is $\sigma_c = \frac{p*R}{t}$

Axial stress is $\sigma_a = \frac{p*R}{2*t}$

Maximum Shear stress is given by $\tau_{max} = \frac{p*R}{4*t}$

PVC has a tensile yield stress of 52 MPa. Wall thickness is .00832m and radius is .1016m.

Yield Pressure due to circumferential stress is given by:

$$P_Y = (.00832m) \cdot (52 \cdot 10^6 Pa)/.1016m$$

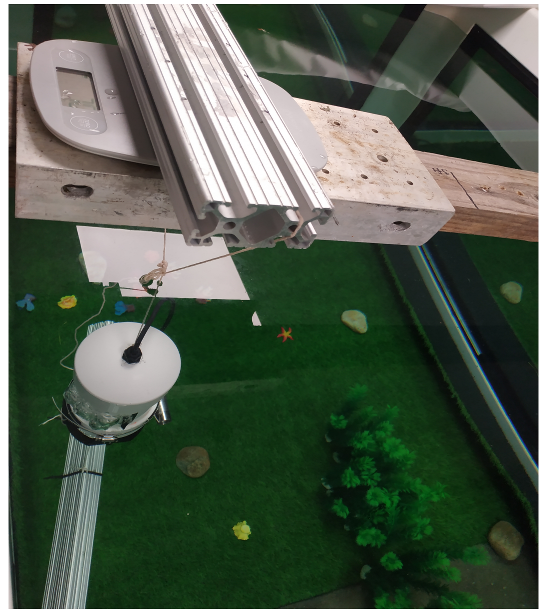


Fig. 8. Top view of the experiment setup.

The housing will yield due to circumferential stress at Pressure, P = 4,258 kPa or a depth of 434 meters.

VII. Next Steps: Prototype 2

The experiments conducted using the first prototype will facilitate the design of a second prototype (Figure 12). The thruster test showed the float needs a more streamlined chasis. The design of the first prototype and second prototype coupling is shown in Figure 17 and 16. The 2nd prototype incorporates a streamlined hull to allow more streamlined movement of thruster generated water flow. This allows the inertial propulsion forces generated by the motor to be more efficient in moving the vehicle.

The second prototype will have to go through another series of tests. The next tests will be done in a larger, 3 meter water tank. The thruster test and float test will be conducted, and with a larger depth, the difference between the bouyancy forces on the surface and on the seafloor will be greater than the differences observed in the float test with the first prototype.

1) Ballasting: When ballasting the float, the incompressible volume remains constant and the mass and compressible volume can be varied to set the equilibrium depth, float force, and anchor force.

Increasing mass along with compressible volume allows for a greater proportion of the float's volume to be compressible, which amplifies the changes in buoyancy across depths.

2) Measuring the Incompressible Volume: Prototype 2 (without nose cap) of the float was first ballasted in a 1 meter freshwater tank. The incompressible volume was initially estimated via water displacement to be 4300 ml. The water weight was measured to be 415 g and air weight was measured to be 4293 g. Based on the the air weight and water weight, the incompressible volume was recalculated to be 3878 ml. The nose cap has volume 124 ml and mass of 129 g.

3) CRL testing: The float was first tested in the 3 meter saltwater tank located at the Coastal Research Lab (CRL) at WHOI. During first 2 CRL tests, lead weights were added on the outside of the float. The total volume of these weights wasn't measured, but is estimated to be around 40 ml. 30 ml of compressible volume was added to the float in the first 2 CRL tests (Figure 13). This was a very small amount of compressible volume that just met the float and sink conditions. (Figures 10 and 11)

In the CRL3 Test, the mass was increased to 5154 grams to allow for a greater compressible volume. The float should experience a larger difference in buoyancy across depths, and thus a larger float and anchor force (Figure 9).

The control of the float was done via a timer that switched the state of the float.

State 0 = INIT: Time to set up float and put it in the water

State 1 = SURFACE: Thrusters are off. Float should be at or approaching the surface of the water
State 2 = BOTTOM: The Thruster is off and float should be at or approaching the seafloor
State 3 = ASCEND: The thruster propels the float towards the surface of the water State 4 = DESCEND: The thruster propels the float towards the bottom of the water. State 5 = END: Time out. Float is ready to be recovered.
The states applies to both CRL tests and Well tests.

4) Well Testing: The float was taken out to a 14 meter deep well. The well is connected to the ocean and the float is subject to currents that can displace the float vertically. The float force and anchor force must be large enough to resist these external forces.

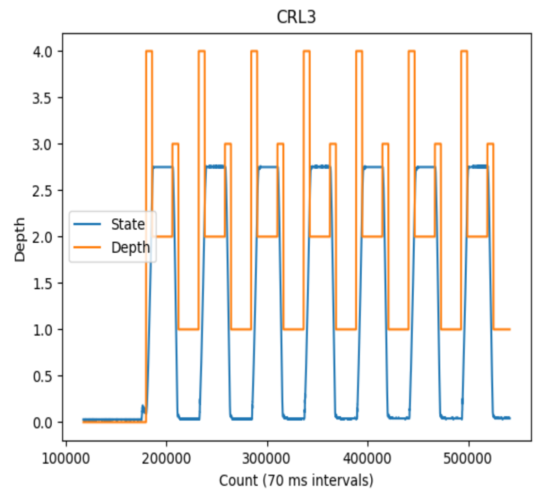


Fig. 9. Ballasted to middle of the tank. Test shows that with correctly tuned sizing parameters. The float can consistently ascend and descend while being able to remain at the surface and the bottom of the tank.

To restrict horizontal movement and constrain the float to only travel vertically across depths, the float was attached to a wire. A plastic shaft that has a near 0 water weight was used as a coupling to the vehicle. The coupling was not considered in the mass and volume measurements.

The first dive (Well Test 1) ran into some electronics issues and the device wasn't able to ascend after diving to the bottom.

The problems were resolved and a successful dive was observed.

The results of the CRL and Well test are shown in Table 1.

	CRL1	CRL2	CRL3	Well1	Well2
mass	4157	4183	5154	5168	5220
V_{IC}	NA	NA	4041	4041	4041
V_C	30	30	1310	1300	1310
d_{eq}	NA	NA	2.5	2.5	2.5

TABLE I

MASS IS GIVEN IN GRAMS, VOLUMES IN MILLILITERS, AND DEPTH IN METERS. THERE IS NO NO VALID DATA FOR SOME OF THE CRL TESTS BECAUSE THERE WAS ERROR IN THE MEASUREMENTS.

A. PID Control

A proportion controller was used to have the float hold depth. The test was done in the CRL

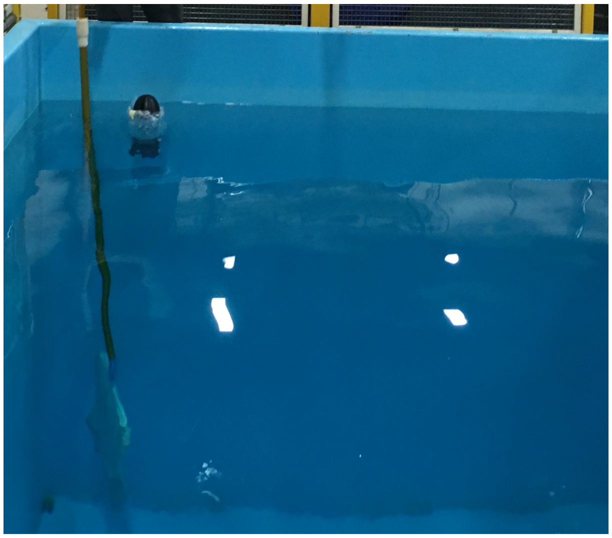


Fig. 10. Demonstration of float condition of prototype 2

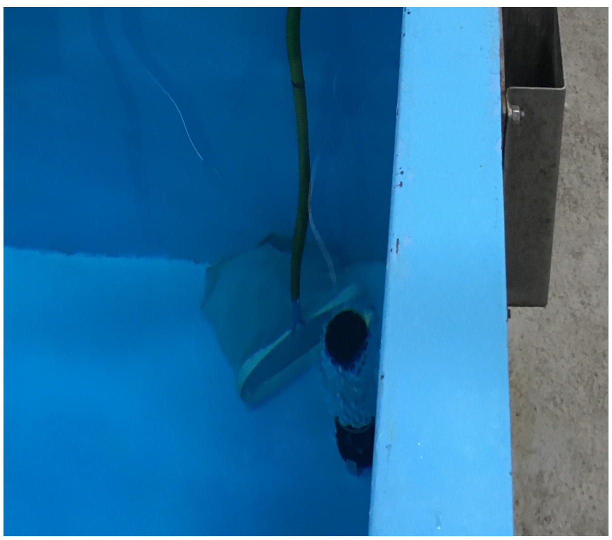


Fig. 11. Demonstration of anchoring condition of prototype 2

tank and the Set Point was set to 1.5 meters.

The states for the control tests are different from the other tests. State 0 = INIT: Time to set up float and deploy it in the water State 1 = HOVER: Float will hold depth at set point State 5 = END: Float will stop thrusting and is ready to be recovered

Only the proportion control has been implemented. The proportional controller could be tuned to reduce oscillations.

B. Cost

The first prototype used PVC tubes and caps for the housing, which makes it cheap. The 2nd prototype is instead using material straight from Blue Robotics. While Blue Robotics has a higher material costs, the cost of fabrication with respects to time and money makes the Blue Robotics option the more cost saving option The total costs of parts from Blue Robotics is around 300 USD. The costs for the 3D printed coupling is around 150 USD from the Dunkworks lab in WHOI. The electronics costs would be around 300 USD. The total costs to fabricate the 2nd prototype is less than 1000 USD and is still a relatively affordable design. The material costs for fabricating prototype 2 are listed in Table 2.

Fig. 12. Protoype 2

VIII. Summary and Conclusion

In order to create a low cost, coastal vehicle, a semi-passive design was prototyped. The semi-passive design uses a compressible volume to change its buoyancy across depths and a thruster to enable it to move. Based on energy calculations, the semi-passive float design has shown to have some energy saving advantages when compared to a conventional buoyancy design in shallow waters. The passive design was brought to a prototype

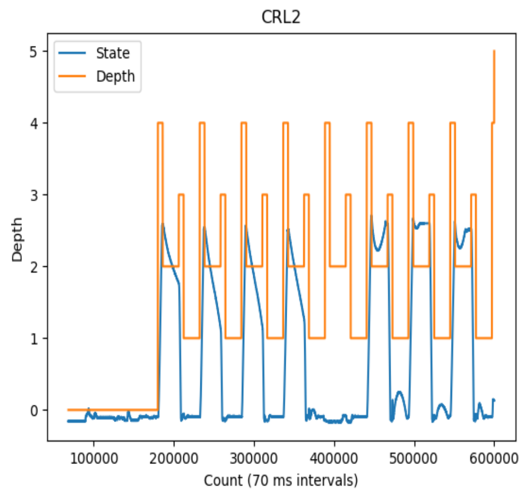


Fig. 13. CRL Test 2 data. During the first 5 profiles, the anchor force was less than zero and caused the float to rise when it should have stayed at the bottom of the tank. The compressible volume was decreased to 30 ml and the float was then able to stay on the bottom.

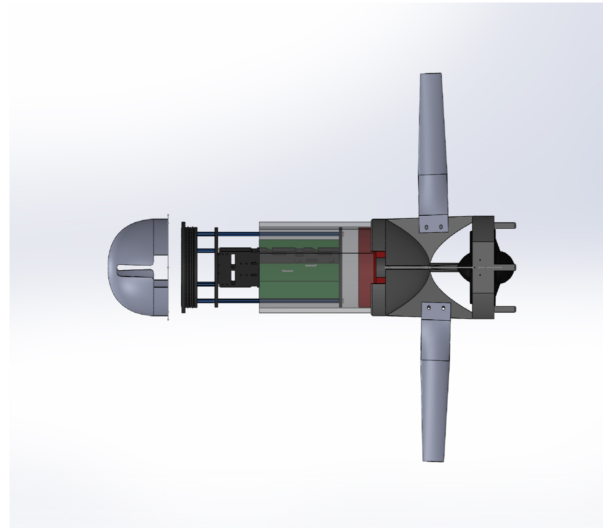


Fig. 15. Horizontal Layout of Prototype 2. Includes head end and tail end hydrodynamic hull, electronics tray, and rotation reducing fins. A single propellor could cause unwanted rotations, so fins can counter act that. However, they were never used because this hasn't been a problem.

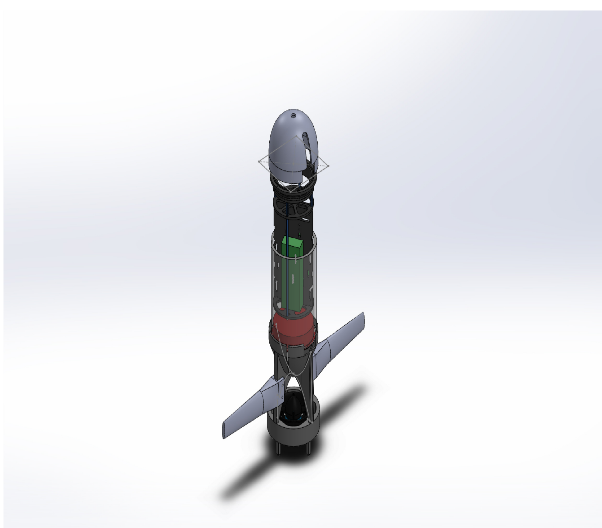


Fig. 14. Prototype 2 CAD model

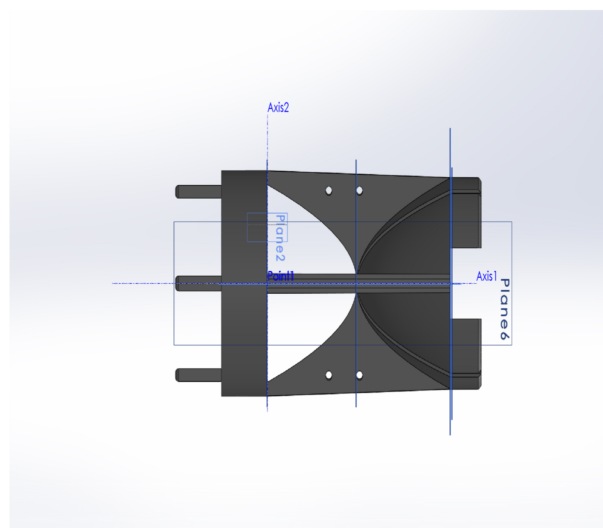


Fig. 16. 2nd Prototype Coupling: A hydrodynamic hull was added to create a low drag surface for more streamlined flow of thruster generated water flow

stage, and so far the prototype testing has shown promising results for the future of this concept. There were two prototypes, the first was built with PVC and the second was built using parts from Blue Robotics. It has been successfully deployed in the indoor tanks and the open water while being constrained horizontally. The device is stable at the surface and sea floor with an incompressible volume. With a given mass and incompressible volume, a theoretical value for the incompressible volume can be calculated. During ballasting, the actual incompressible volume used was consistent with the calculations. The calculations for float sizing was validated by actual values recorded during testing. Although progress has been made in developing this concept, more work still needs to be done.

IX. Future Direction

The navigation system of the float needs to be built out. GPS and IMU need to be integrated and an algorithm needs to be built so the float

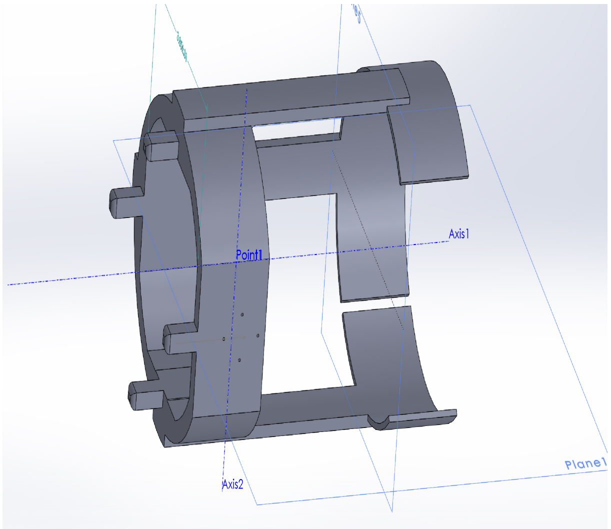


Fig. 17. 1st Prototype Coupling: No streamlined hull. Thruster generated water flow would interact with the surface of the chasis, which may not be streamlined

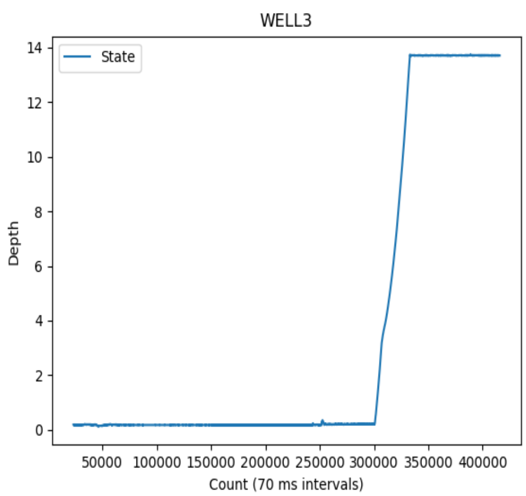


Fig. 18. The float turned off its thruster during the descent and passively sank to the bottom. The shut down of the thruster occurs at the point where the slope of the depth versus count curve changes during descent. The float doesn't require thrusting to descend after going past the equilibrium depth.

can use that data to navigate to a set location. A way to measure current velocity needs to be implemented. Some options are to implement a differential approach to find velocity using position and time, or a tilt meter approach to approximate current velocity with IMU attitude data[5].

Communication needs to be developed as well. Coastal communication can be done via cellular. The arduino board being used is the MKR GSM 1400 and is capable of cellular communication.

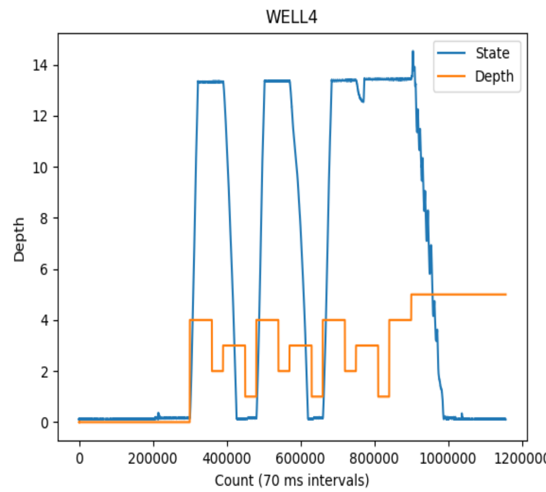


Fig. 19. Well Test 2. Float was able to successfully descend and ascend, while constrained horizontally. The mission ended during the 3rd dive and the data points past count 900,000 showed the manual lifting of the vehicle out of the water.

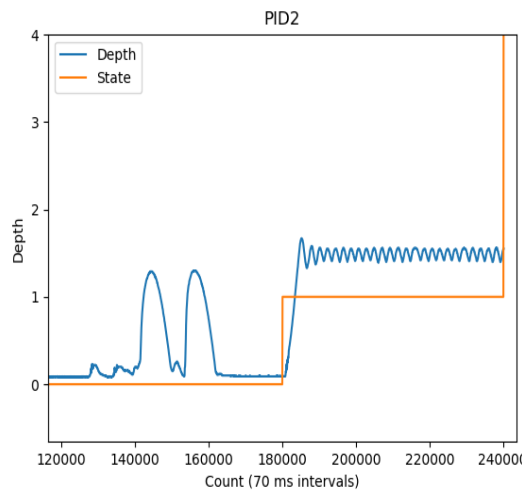


Fig. 20. Proportional controller with a set point at depth of 1.5 meters. The float is shown oscillating around 1.5 meters. The 2 curves in the beginning are from manually pushing the vehicle down to test the floating force

To further drive down the cost of the float, the float needs to be redesigned so it is made out of cheaper material and doesn't require the more expensive, off the shelf materials from Blue Robotics. The housing should be able to house the enough batteries for month long deployments. Actual energy consumption of the device needs to be measured or predicted.

Parts	Cost
Blue Robotics(BR) T100 Thruster	119.00
Arduino MKR GSM 1400	70.89
Hose Clamps	7.84
SD Card + Adapter	9.88
MicroSD Card Breakout Board	9.04
Blue Robotics Depth Sensor	68.00
IMU	4.29
Lipo Batteries 7.4V 5200mAh X 2	53.99
Blue Robotics ESC	25.00
NEO-6M GPS Module	15.66
Blue Robotics O-Ring Flange X 2 (4")	58.00
Blue Robotics Electronics Tray (4")	49.00
Blue Robotics Enclosure Vent Plugs	8.00
Blue Robotics Aluminum End Cap	20.00
Blue Robotics M10 cable Penetrator X 4	3.40
WetLink Potting Compound	19.00
3D printed parts	150.00
Total	690.99

TABLE II

COSTS OF PARTS FOR PROTOTYPE 2

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