

# **Buoyancy Driven Underwater Glider**

Daniel Kowalyshyn

Swarthmore College Department of Engineering

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Advisor: Professor Erik Cheever



## **Abstract**

My senior design project was to design, construct, and test an underwater glider. A glider operates by changing its buoyancy to descend and ascend, and then converts this vertical motion into horizontal motion by the addition of wings. The change in buoyancy in my glider was effected by using a linear actuator to move two pistons, which were open to the environment, in and out. By moving the pistons in and out, the volume of water displaced by the glider can be controlled. Because of Archimedes' principle, the change in volume of water that is displaced changes the buoyancy of the glider. The glider was built out of pieces of 6 inch inner diameter, schedule 40, white PVC pipe, along with two end caps and a PVC coupling. The wing of my glider was made from a piece of plywood. After construction, testing showed that the glider had the ability to both descend and ascend in a water tank in the basement of the engineering building. When the glider was taken to the pool however, it failed to return to the surface after sinking, though it displayed its ability to glide forward while it sank.

## **Introduction**

In the past, oceanographic surveys have been limited by the costs of operating ships. Fuel for ships is expensive and becoming more expensive, as well as the cost of a full crew that needs supplies for their journey. Small, inexpensive, unmanned devices can cut the cost of researching the ocean immensely. These devices consist mainly of sea floats, and underwater gliders. These two are very similar in that they use a change in buoyancy to survey a range of ocean depths; however, a sea float stays in one spot, whereas a glider can use its buoyancy change to travel a predetermined path. The concept of an underwater glider goes back to a

project known as *Concept Whisper* in 1960, which was a 2-man swimmer delivery vehicle. In 1989, renowned oceanographer Henry Stommel proposed the idea to have a small fleet of gliders which would operate by using the oceans temperature gradient to power the buoyancy engines, however it was not until the late 90's that his vision became closer to reality. In the late 90's and early 2000's, 3 different gliders were developed and tested primarily for the use that Stommel once envisioned, namely as a platform for oceanographic research. These 3 gliders are the *Spray*, *Seaglider*, and *Slocum*, developed by Scripps Institute for Oceanography, the University of Washington, and the Webb Research Corporation respectively<sup>1</sup>. These underwater gliders are becoming more popular for use in oceanographic surveys due to their ability to go on long journeys, covering many miles of ocean and sampling a wide range of depths, all at a low cost. The cost is low because gliders use very little power. Unlike most oceangoing vessels that need to be constantly turning a propeller to move, an ocean glider only needs to change its buoyancy to move forward. As the glider rises and falls through the ocean, its wings allow it to glide forward, just like a glider in air. A change in buoyancy involves pumping liquid to change the volume, but after this pumping is done, the entire vessel can mostly turn off until the vessel needs to change directions again, which coming from a depth of up to 2000 meters, can be over an hour. Though these gliders move very slowly, at speeds of only about 2 to 3 miles per hour, they can cover a great distance without needing to refuel. Gliders have made journeys lasting up to seven months completely autonomously, as well as crossing the Atlantic, earning the record for furthest autonomous journey by a robot.

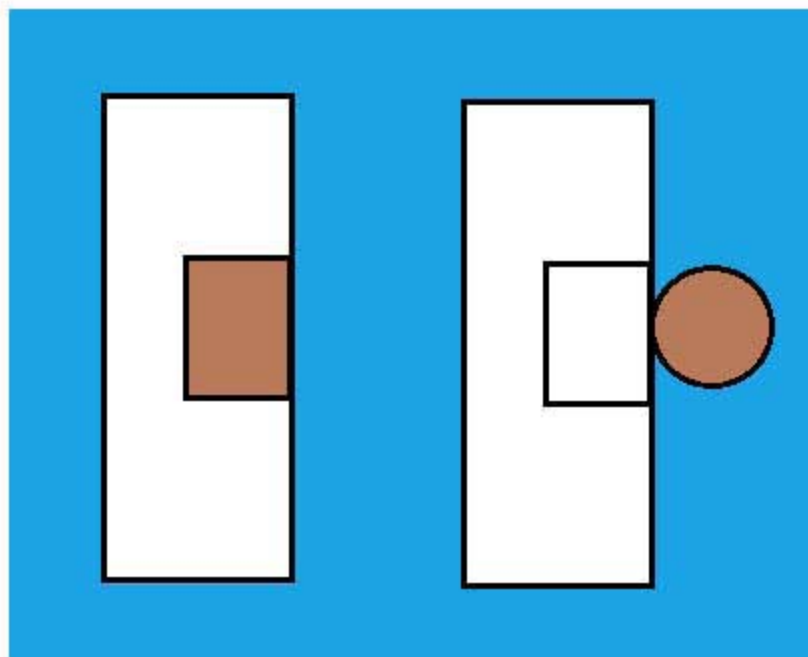
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<sup>1</sup> Jenkins, Scott A; Humphreys, Douglas E; Sherman, Jeff; Osse, Jim; Jones, Clayton; Leonard, Naomi; et al.(2003). Underwater Glider System Study. *Scripps Institution of Oceanography*. UC San Diego: Scripps Institution of Oceanography. Retrieved from: <http://escholarship.org/uc/item/1c28t6bb>

These early gliders were all quite similar in size, with a length of about 2 meters, a span of about 1 meter, and a displaced volume of nearly 50 liters, while operating with a net buoyancy of about 1-3 Newton's. Though similar in size, they differ slightly in their control systems used to control buoyancy. The *Spray* and *Seaglider* are used primarily for deep sea environments, whereas the *Slocum* is used in shallow water applications, sometimes in depths as small as 4 meters. These gliders have made voyages lasting up to 7 months, completely autonomously.

This report covers the design, construction, and successful testing of my own underwater glider. The gliders mentioned above operate at depths of up to 2000 meters. My glider will likely operate up to a depth of 10 feet. Though the concepts used will be very similar, in practice my glider will not much resemble the gliders of which I have already spoken. Because of the shallow depths at which the *Slocum* operates, it is the model that is most comparable to my own glider. Whereas the *Spray* and *Seaglider* use hydraulics to pump a liquid from an internal reservoir to an external reservoir for buoyancy control, the *Slocum* uses electrical pumps to control the buoyancy. At the depths at which the *Spray* and *Seaglider* operate, the pressure is too great for a lightweight electrical pump to overcome. In the shallow water at which both my glider and the *Slocum* operate, electrical pumps are sufficient for the buoyancy change. The *Slocum* uses these electrical pumps much as the other aforementioned gliders, pumping a liquid from an internal reservoir to an external reservoir, and in the process changing the volume of the vessel. For this process to work, the interior of the glider needs to be a vacuum, such that the water pressure outside the glider can push the liquid from the

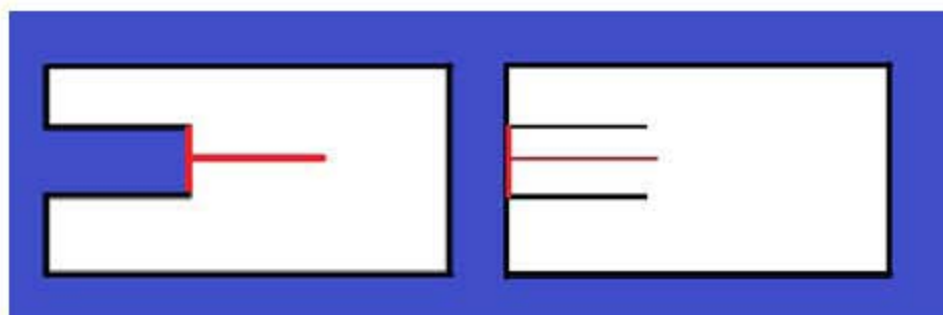
external reservoir back into the internal reservoir. To illustrate this idea, I have included the image below.



*Figure 1. Internal External Reservoir Buoyancy Control*

In Figure 1, the left picture shows the vessel in its least buoyant state, when all the liquid is in the internal reservoir, the brown rectangle. The image on the right shows the vessel in its most buoyant state, when all the liquid has been pumped into an external reservoir, the brown circle. If the total volume of the vessel is all of the white volume plus all of the brown volume, you can see that by pumping the brown liquid into the external reservoir, the volume of the vessel is increased. Due to the complications of using the internal external reservoir technique, such as needing a vacuum inside the glider as well as pumping some sort of oil through the glider, I decided to adapt this technique by using pistons instead of reservoirs. The pistons are left open to the environment, allowing water to flood them. As the pistons move in and out, the volume

of the glider will change in much the same way as shown in Figure 1. A similar depiction of the piston technique is shown below in Figure 2.



*Figure 2. Piston Buoyancy Control*

The leftmost picture depicts the vessel in its least buoyant state, whereas the rightmost picture depicts the vessel in its most buoyant state. The red colored T shape shows the piston, as it moves from its fully retracted position in the left image to its fully extended position in the right image the volume of the vessel is increased.

When designing an underwater glider there are three main components that need to be dealt with. The first and most important of these is the buoyancy control. The vessel must be able to change its buoyancy so that it can descend and ascend. The next component that is necessary is a way to control the pitch of the glider. Pitch is the angle at which the nose of the glider is in reference to the horizontal. This is important because without some sort of angle, the glider will not move forward as it sinks. Also, if the pitch angle is the wrong way, the glider could move backwards instead of forwards. The third component is a way to sense the depth of the glider. The glider needs to know how deep it is so that it knows when to return to the surface, or doesn't go deeper than the glider is rated for. For my glider, as I have already discussed, pistons open to the environment will be used to control the buoyancy of the glider.

These pistons will also serve to fulfill the second necessary component, pitch control. By placing the pistons at the front of my submarine, and balancing the weight so that it floats flat, I can assure that the vessel will sink nose down and rise nose up. For the final component, depth sensing, a simple pressure sensor can be used to determine what depth the glider is at.

### **Technical Discussion:**

When designing an underwater glider there are three main components that need to be dealt with. The first and most important of these is the buoyancy control. The vessel must be able to change its buoyancy so that it can descend and ascend. The next component that is necessary is a way to control the pitch of the glider. Pitch is the angle at which the nose of the glider is in reference to the horizontal. This is important because without some sort of angle, the glider will not move forward as it sinks. Also, if the pitch angle is the wrong way, the glider could move backwards instead of forwards. The third component is a way to sense the depth of the glider. The glider needs to know how deep it is so that it knows when to return to the surface, or doesn't go deeper than the glider is rated for.

The concept of an underwater glider is analogous to that of gliding in air, however in an underwater glider, ascending glides are also possible. Gliding is a buoyancy driven form of motion in which the power necessary to overcome the drag on the vehicle at a given velocity is supplied by gravity in the form of a net buoyancy. Horizontal translation using the vertical force of gravity is made possible by the lift produced by the gliders wings. Buoyancy is defined as an upward force exerted by a fluid that opposes the weight of an object immersed in that fluid.

Net buoyancy then is given by the difference in the buoyancy force and the weight of the object, thus net buoyancy can be either positive or negative in a standard gravitational reference frame. Buoyancy is created by the change in hydrostatic pressure over a vertical displacement. Hydrostatic pressure increases with depth, thus there is a greater force due to pressure at the bottom of an immersed object than at the top, creating a net upwards force. Archimedes' Principle tells us that this net upwards force is also equivalent to the weight of liquid which is displaced by the object. The force balance in the vertical direction is then given by Equation 1 below, where  $f_z$  is the net force acting on the object,  $\rho$  is the density of the liquid in which the object is immersed,  $V$  is the volume of displaced liquid,  $m$  is the mass of the object, and  $g$  is the acceleration due to gravity.

$$\text{Eq. 1} \quad f_z = \rho V g - m g$$

In the case of a glider which wants to be able to ascend as well as descend, we need to be able to create both a positive net force and a negative net force. A glider accomplishes this by changing the volume of water that is displaced by the vehicle. If we say that a glider can change its volume by an amount  $\Delta V$  in the positive or negative direction, then in order to have the ability to create both a positive and negative net buoyancy force, at the unchanged volume  $V$ , the submarine must be neutrally buoyant. This means that there is no net force acting on the submarine, so it will neither ascend nor descend. This is shown in Equation 2 below.

$$\text{Eq. 2} \quad 0 = \rho V g - m g$$

Then by changing the volume by  $\Delta V$ , the submarine can achieve a buoyant force as shown in Equation 3 below.



$$\text{Eq. 3} \quad B = \rho(V + \Delta V)g - mg$$

Combining with Equation 2, we get that the net buoyant force,  $B$ , is given by Equation 4.

$$\text{Eq. 4} \quad B = \rho \Delta V g$$

The force balance diagram below shows all of the forces acting on the submarine.

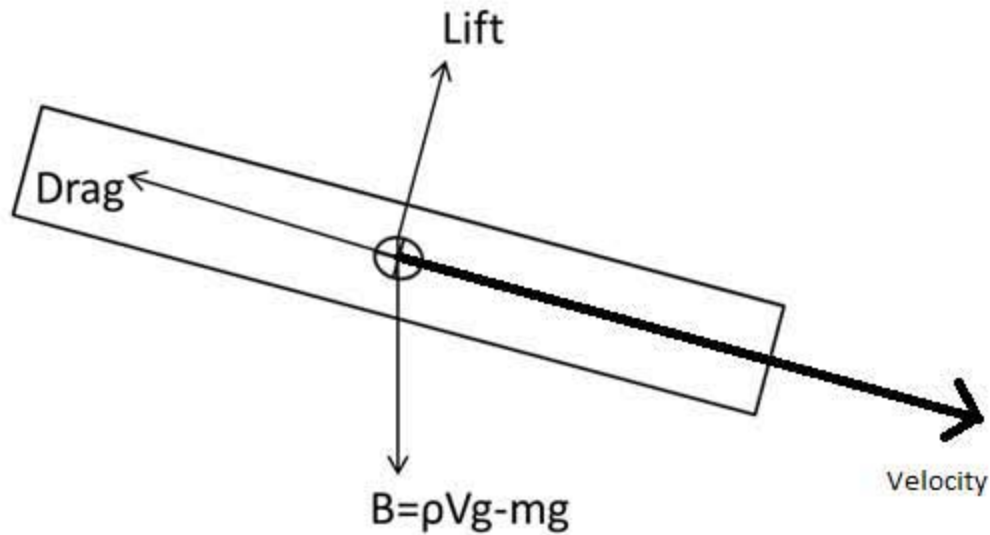


Figure 3. Free-Body Diagram

The force of drag,  $F_D$ , is caused by a combination of viscous friction and form drag, and so it is proportional to the speed of the submarine,  $v$ , and the frontal area of the submarine,  $A$ . The drag equation is shown below.

$$\text{Eq. 5} \quad F_D = \frac{1}{2} \rho v^2 c_d A$$

In this equation above,  $c_d$  is a dimensionless quantity called the coefficient of friction. In most cases, the force of drag for a ship or submarine is found experimentally in a towing tank by dragging it through the water at various speeds and measuring the resistance force.

The lift force in the diagram above is caused by a pressure differential between the top and bottom of the hydrofoils attached to the submarine. Lift is always in the direction normal to the wing. Because of the angle,  $\theta$ , at which the submarine ascends or descends, this lift force has both a vertical and horizontal component, allowing it to counteract and overcome the drag force and create horizontal motion. A commonly used equation for lift is shown below.

$$\text{Eq. 6} \quad F_L = \frac{1}{2} \rho v^2 c_L A$$

You will notice that this equation is very similar to the above equation for the Drag force. However, in this equation, the coefficient of lift,  $c_L$ , is a dimensionless quantity that describes the airfoils shape and also the angle of attack, or the angle at which the fluid is approaching the foil. In most cases, the force of lift is very difficult to calculate analytically, and so the coefficient of lift, much like that of drag, is often found experimentally in a wind tunnel.

Summing the forces acting on the submarine in the X and Z directions (horizontal and vertical respectively), we get the two force equations below.

$$\text{Eq. 7} \quad F_x = F_L \sin \theta - F_D \cos \theta$$

$$\text{Eq. 8} \quad F_z = B - (F_L \cos \theta + F_D \sin \theta)$$

My project was completed by using an Arduino microcontroller to control all the electrical systems on the glider. This included a pressure sensor used to sense depth, and a linear actuator used to move the pistons used for buoyancy control. The Arduino microcontroller can be programmed using the C coding language. Arduino's can take both analog and digital inputs as well as analog and digital outputs. Further, the Arduino can output

pulse width modulation signals, or PWM, which is useful as that is how the linear actuator was controlled. The linear actuator ran off of a 12 volt power source, which meant that I needed to connect a separate power source. The Arduino can only output up to 5 volts. To do this, I used an Arduino motor shield, which allows for the control of up to 2 DC brush motors, or 1 DC stepper motor. The linear Actuator was a DC brush motor. A 12 volt power source was connected to the motor shield along with the positive and negative lead wires of the motor. The motor could then be controlled through the Arduino. A sample piece of code is shown below, and the entire code can be found in the appendix.

```
int motorBack() {
    digitalWrite(4,HIGH); //sets motor direction
    digitalWrite(9,LOW); //turns off brake
    analogWrite(3,255); //sets power
}

int motorForward() {
    digitalWrite(4,LOW); //sets motor direction
    digitalWrite(9,LOW); //turns off brake
    analogWrite(3,255); //sets power
}

int motorStop() {
    digitalWrite(9,HIGH); //turns on brake
}
```

*Figure 4. Sample Linear Actuator Code*

The three functions shown in Figure 4 do what their names imply. The `motorForward()` function moves the motor forward at full speed, whereas the `motorBack()` function moves the motor backwards at full speed. The `motorStop()` function simply turns on the brake built into the actuator to stop the motor. In the code, you may notice that the power setting is written as going to analog pin 3 with a value of 255. This is a PWM signal, where the value 255 is the width of the pulses sent and is the maximum possible. The linear actuator that I used also has a built in potentiometer to give displacement feedback. This

sensor is a variable resistance device which outputs a voltage from 0 to 5 volts. This signal can be read by the analog pins on the Arduino, allowing the Arduino to know the current position of the actuator.

The Arduino code for the potentiometer is shown below.

```
float ReadPot() {
    float v; //initialize float v
    v = analogRead(potPin); //read analog signal
    v = (v - 362)*(11.625/305); //calibrate from analog to position
    Serial.print("\nPot Reading:");
    Serial.print(v);
    return v; //return position in inches
}
```

*Figure 5. Arduino Code for Potentiometer*

In the code above, the analog value read from the sensor is converted to a position in inches. This was done by taking data points at various positions and curve fitting the data. By applying this curve fit, the analog value is converted to position in inches. A similar process had to be used to convert the analog signal read from the pressure sensor into a depth reading in feet. The code for this is shown below.

```
float ReadDepth() {
    float d;
    d = analogRead(pressPin); //read analog signal from sensor
    Serial.print("\n");
    Serial.print(d);
    d = .01380074*d-2.58820446; //convert to depth in feet
    Serial.print("\nDepth:");
    Serial.print(d);
    return d;
}
```

*Figure 6. Arduino Code for Pressure Sensor*

For calibrating the potentiometer, data points were taken at different positions. For calibrating the pressure sensor, data points were taken at varying depths. Both calibration curves turned out to be linear.

### **Hull Description:**

My submarine is made from a schedule 40, 6 inch diameter PVC pipe, along with a 6 inch PVC coupling and two PVC end caps. The submarine is 4 feet in length, and with the full ballast on board weighs approximately 66 pounds. The displaced volume of the hull is about 1 cubic foot. The wings of the glider are made from ply wood, and have a wing span of about 3 feet from tip to tip.

The interior of the submarine is taken up mostly by the linear actuator and the two water pistons, which together make up the buoyancy engine. The two pistons are mounted through the bow end cap with the ends of the pistons open to the environment, allowing water to move in and out of the pistons. The pistons are mounted evenly spaced through the center of the end cap.



*Figure 7. Pistons Mounted through End Cap*

The linear actuator is mounted to the hull by two wooden mounts which I designed and built in the machine shop with a piece of 2x4. One of the mounts attaches to the linear actuator with a



small steel pin. The other mount is simply a support which the actuator rests upon. The linear actuator is shown below, along with an end view showing the actuator mounted in the glider.

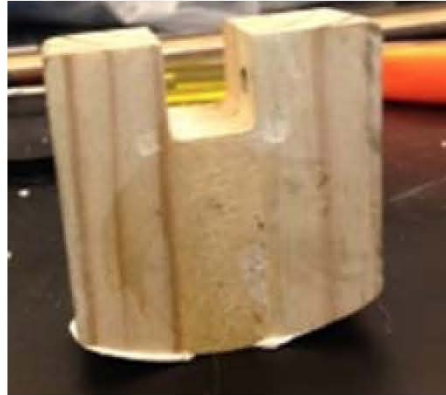


*Figure 8. (Top) Linear Actuator (Bottom) Linear Actuator Mounted End View*

The next few images show how the actuator sits in the mounts inside the glider, as well as individual images showing the details of the mounts.

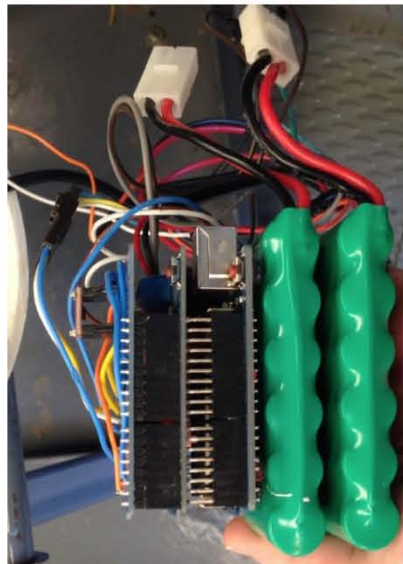


*Figure 9. Linear Actuator in Mounts*



*Figure 10. Linear Actuator Mount (front view)*

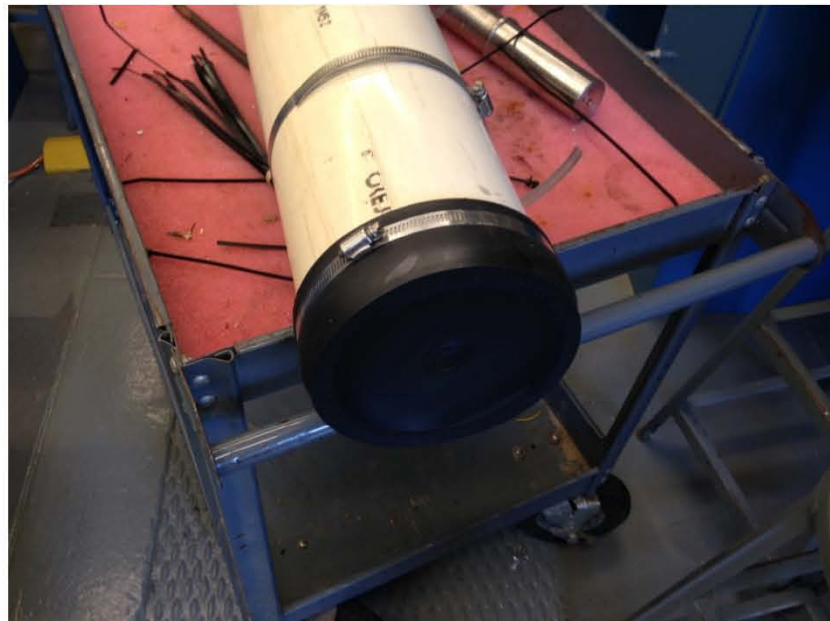
The two piston rods are attached to the actuating portion of the linear actuator such that they can be moved through their full range. The rods are connected to the actuator by a small pin which was also made in the machine shop with the help of Grant Smith. Inside is also where the electronics which control the submarine are housed. The Arduino, along with the battery packs which serve as the power source, are mounted via Velcro just inside the stern end cap, allowing for easy access for recharging and programming.



*Figure 11. Batteries and Arduino Connected with Velcro*

It also makes use of a pressure sensor, mounted through the bow end cap, to measure the depth of the submarine. To mount the pressure sensor, a hole was drilled and tapped through the bow end cap with a 1/8 NPT thread. This hole can be seen in left and right images in Figure 8.

For construction purposes, the PVC pipe was cut into two lengths and after mounting interior pieces was put back together using a PVC coupling. To make this connection, as well as the pistons and the bow end cap water tight, they were glued together using a marine adhesive sealant. The pressure sensor was made watertight by Teflon thread seal tape. The stern end cap necessarily was left removable so that the electronics inside could be programmed and the batteries charged. Because this end cap also needed to be watertight, a flexible rubber end cap with built in O-rings and worm screw clamp were used. This end cap is shown below.



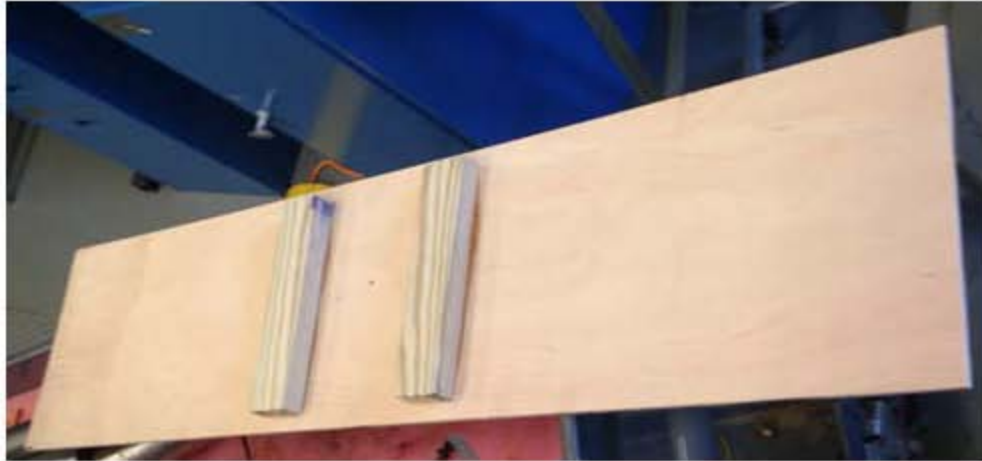
*Figure 12. Stern End Cap*



The linear actuator mounts were attached to the inside of the pipe by wood screws through clearance holes drilled in the PVC pipe. The wood screws and the holes they went through in the PVC were liberally coated in the marine adhesive sealant so that they would remain watertight.

The final element to the hull is the ballast. Due to the displaced volume of about 1 cubic foot, the submarine is required to weigh approximately 66 pounds. With the hull fully put together and all electrical and mechanical components attached, the vessel weighed approximately 22 pounds, leaving 44 pounds necessary to achieve neutral buoyancy. This additional weight was added in the form of steel rod stock which could be fit into the empty spaces inside the glider as well as being attached to the exterior of the glider via cable ties and worm clamps. This ballast serves multiple purposes in the functioning of the vessel. The ballast allows the submarine to be neutrally buoyant at its normal volume, which in turn allows for the submarine to achieve both positive and negative buoyancy. The ballast, attached at the bottom of the hull, also adds stability to the submarine. Any roll will autocorrect itself because of the low center of gravity cause by the ballast. Finally the ballast allows for some pitch control. At neutrally buoyant, the submarine needs to float parallel to the surface. By arranging the ballast correctly, this can be achieved. This will allow for the submarine to pitch downwards while descending and pitch upwards while ascending. After the ballast was attached, the first tests could be run to see if the glider could sink and then float back to the surface. After this, the wing was made from a sheet of plywood and some small wooden boards. Because of the weight of the glider as well as the size, I decided that the wing would be detachable to make

transport easier. For testing, the wing was attached with 2 bungee cords. The wing is shown below.



*Figure 13. Plywood Wing for Glider*

Below is a picture of the completed hull with the wings attached, and below that is a schematic diagram of the submarine.



*Figure 14. Completed Glider with Wings*

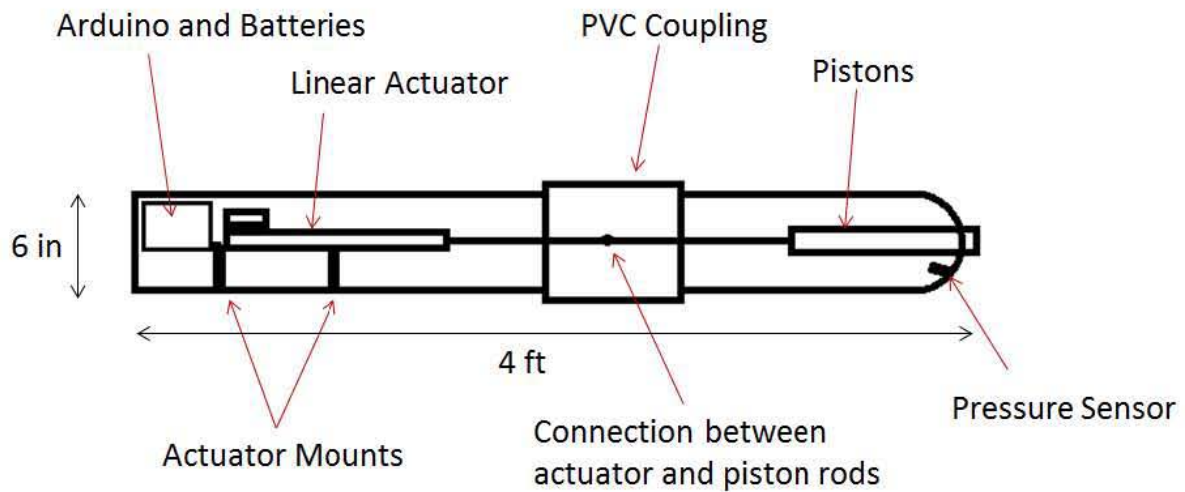


Figure 15. Glider Schematic Diagram

### **Electrical Components**

All of the electrical components are run off of two 7.2 volt rechargeable battery packs connected in series with one another to create a max of 14.4 volts. These batteries power the Arduino Uno microcontroller, the linear actuator, the pressure sensor, and the accelerometer.

The linear actuator is a 12VDC single brush motor with a built in brake and potentiometer. A schematic drawing for this part can be found in the Appendix. Using an Arduino motor shield, this motor is easily controlled, allowing for easy control of the displaced volume of the submarine. The built in potentiometer runs off a 5V input and outputs an analog signal to the Arduino. The potentiometer is a variable resistance device. The changing resistance changes the output voltage, which the Arduino reads as an analog signal. By choosing a few points and checking the potentiometer reading at those points, I was able to calibrate the signal to output the current position of the actuator.

The pressure sensor is of the SSI Technologies P51 series with a maximum pressure rating of 5 psi. The sensor operates over 12VDC and outputs a 4-20mA signal. The P51 measures gauge pressure, the reference pressure being the interior of the submarine in this case. To read the 4-20mA signal, we must transform it into a 1-5 volt signal which can be read as an analog input by the Arduino. In order to do this, we use the circuit as diagramed below.

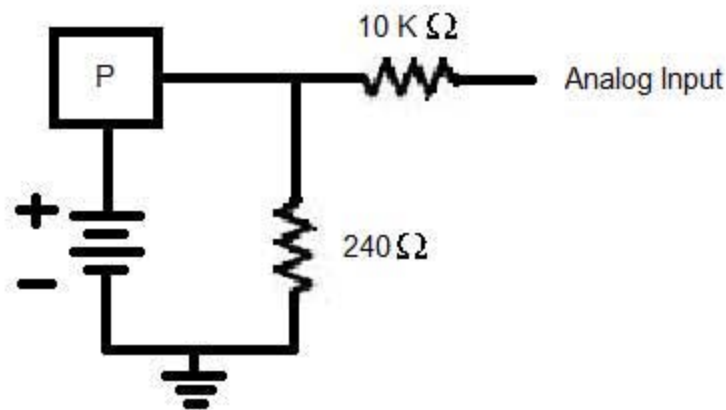


Figure 16. Pressure Sensor Circuit

The Arduino reads the voltage drop over the 240  $\Omega$  resistor as an analog value, assigning it a value between 0 and 1023. The 10k  $\Omega$  resistor serves to ensure that all of the current runs through the 240  $\Omega$  resistor and not into the Arduino. Because the 4-20mA signal will never be zero unless there is something wrong with the sensor or the wiring, the analog value will never be zero, and in fact it will never be less than about 117. If the Arduino reads a value less than this, then it knows that something is broken, and thus it can detect a malfunction. In order to make use of this sensor to find depth, the output needs to be calibrated to go from an analog value of 0 to 1023 to a depth. By finding the analog output value at various depths, I was able to calibrate the output to give me the depth at any point. It is important to note that with a

maximum pressure of 5 psi, the submarine will only be able to go down to a maximum depth of 11.53 feet.

The final electrical component is an accelerometer. The accelerometer is the ADXL 362, made by Sparkfun. It operates through the SPI Digital interface which makes use of the Slave Select pins of the Arduino. Because the Arduino motor shield makes use of some of the same pins, it was necessary to change the pins on the Arduino by cutting the connections to them and reconnecting them to other pins. It turned out that I did not use the accelerometer, because the pitch was simply controlled by the movement of the pistons.

### **Testing/Results:**

In the first test, the submarine was programmed to simply descend to a depth of 4 feet and then return to the surface. Upon entering the water, it was found that the submarine was too positively buoyant to sink, and more ballast would need to be added. Also, a few small leaks were detected and taken care of. After the first test, I decided to switch from the hard plastic end cap, which was difficult to seal, to a flexible rubber end cap, which has built in o-rings for sealing purposes. The total weight of the submarine during this first test was 65.2 pounds. This is more than was estimated prior to this initial test likely due to the fact that the ballast was added to the exterior of the vessel, thus any ballast that is added increases the displaced volume of the vessel and increases that total amount of ballast necessary. To combat this problem, as much weight as possible will be added to the interior of the submarine. This is difficult due to the limited space to work with inside as well as the difficulty of getting anything past the actuator mounts; however it will be greatly beneficial to do so, as that will reduce the

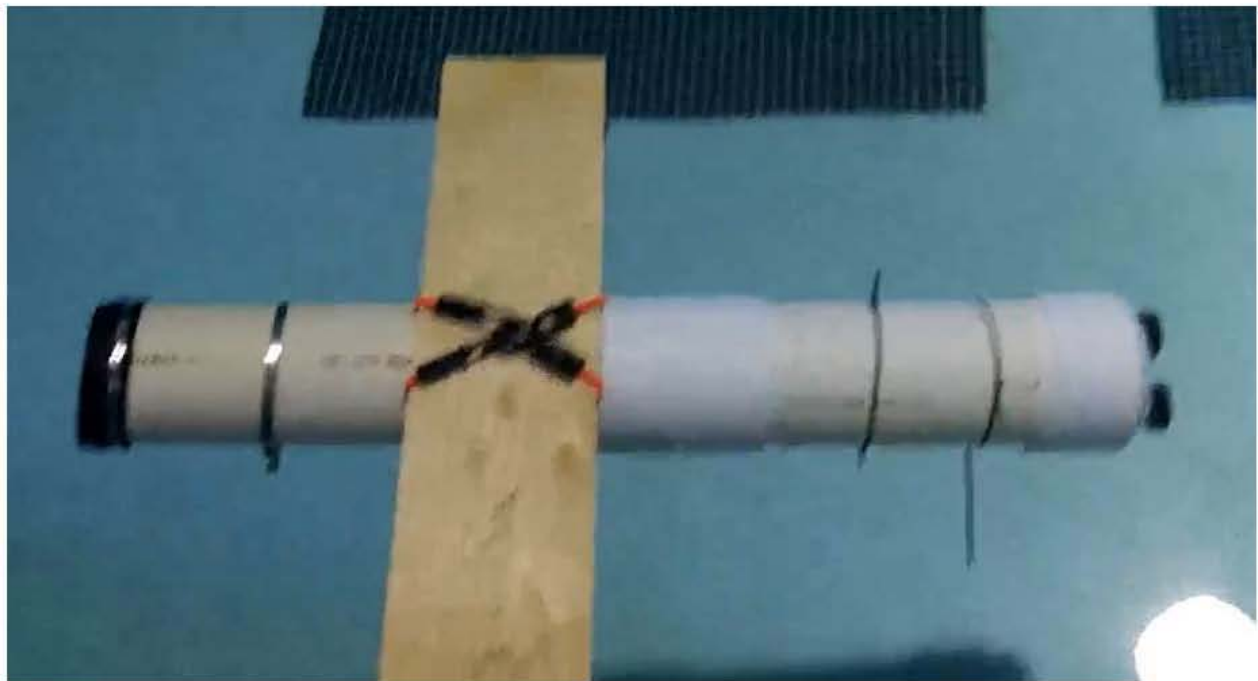
amount of extra volume being added to the outside. Also considered was the feasibility of adding gravel or sand to the interior of the submarine, however sand would be quite messy and possibly ruin the linear actuator. The gravel would be much better than the sand, however the gravel would move around inside the vessel and shift the weight balance. A third idea for reducing the volume of the added ballast is to have long thin rods of steel inside the PVC, reducing the amount of ballast needed on the exterior.

Though this initial test was a failure, there were some positive aspects to take away from the test. Though the submarine leaked, all leaks were small and quite fixable. Also, the linear actuator worked as designed, causing the submarine to sink slightly further into the water, however this was not enough to overcome its positive buoyancy. Because the change in volume of my submarine is so small, the weight of the submarine needs to be just right to enable positive and negative buoyancy.

The second test of the glider took place in a small tank in the basement of the engineering department. Using the flexible end cap with the built in O-rings, and after fixing previously found leaks, the glider leaked much less than during the previous test. For this second test, many thin steel rods had been added to the interior of the glider in order to cut down on the additional volume added to the exterior of the glider. Also, the steel that was added to the outside was longer and thinner, allowing for a more dispersed weight, which made the balancing of the weight easier. For this test, the submarine was again programmed to simply descend to the bottom of the tank, about 1 foot, and come back to the surface. During the first test, the submarine sank, but failed to come back to the surface. The reason for

this was that the pressure sensor did not submerge all the way to the bottom, as there were some ridges on the side that kept it off the bottom. After changing the depth threshold to return to the surface, the submarine was tested again. This time, the submarine both descended, and ascended. After the test was over, it was found that a small amount of water entered the submarine from an unknown location, however the amount of water was very small and all electronics remained dry. After this successful test, wings were made for the final test, in the swimming pool.

For the final test in the swimming pool, the wings were attached with bungee cords to allow the submarine to glide. The glider was programmed to descend to the bottom of the shallow end of the pool, about 4 feet, and return to the surface. The picture below was taken during the test, showing how the wings were attached with bungee cords.



*Figure 17. Final Test, Glider in Pool*

The test began promising, as the submarine sank properly and glided forwards a significant amount. However, the glider did not return to the surface. For the next attempt, the battery packs were switched to a fully charged pack and the threshold for the submarine to reverse the direction of the pistons was changed to 1.5 feet instead of 4 feet. Again the glider sank as expected whilst gliding forwards, but again the glider did not return to the surface. After this test, it was found that the battery pack that had been in the glider was almost completely dead, even though it had been fully charged before the test.

### **Discussion/ Conclusion:**

Though the glider successfully descended and ascended whilst in the tank in the basement of the engineering department, it was not able to do so in the swimming pool. The major difference between these two scenarios is the depth the submarine sank to. In the tank in the basement, the total depth was about 1 foot, whereas in the pool the depth was about 4 feet. This, coupled with the evidence of the completely drained battery packs has lead me to believe that the issue in the final test stemmed from a combination of batteries and depth. At the greater depth, the linear actuator would need to provide more force to push the pistons out. This increased force would mean a larger current draw from the batteries. It is my belief that the batteries I was using were simply not strong enough to generate the current necessary for the linear actuator to overcome the water pressure at the bottom of the pool. In the future, a more powerful battery should be used to see if this theory is true.

Even though the glider did not manage to glide whilst both sinking and rising, it still demonstrated that it could both sink and rise in the tank in the engineering department. It also



demonstrated its ability to glide at least in one direction. Because of this, I believe that the project was in general a success. Given more time, there are many issues that I would like to fix, the stronger batteries being just one. I would also like to find the small leak that was allowing water into the interior. The final thing that I would have liked to implement was a method of steering the glider, whether it be through the control of the yaw, pitch, and roll, or by simply adding a rudder.

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## Appendix A: Arduino Code

### Linear Actuator Code:

```

int potPin = 2;
int g = 1;
void setup() {
  Serial.begin(9600);
  //Setup Channel A
  pinMode(4, OUTPUT); //Initiates Motor Channel A pin
  pinMode(9, OUTPUT); //Initiates Brake Channel A pin
  pinMode(potPin, INPUT);
}

float ReadPot() {
  float v; //initialize float v
  v = analogRead(potPin); //read analog signal
  v = (v - 362)*(11.625/305); //calibrate from analog to position
  Serial.print("\nPot Reading:");
  Serial.print(v);
  return v; //return position in inches
}

int motorBack() {
  digitalWrite(4, HIGH); //sets motor direction
  digitalWrite(9, LOW); //turns off brake
  analogWrite(3, 255); //sets power
}

int motorForward() {
  digitalWrite(4, LOW); //sets motor direction
  digitalWrite(9, LOW); //turns off brake
  analogWrite(3, 255); //sets power
}

int motorStop() {
  digitalWrite(9, HIGH); //turns on brake
}

void loop() {
  if (g == 1) {
    motorBack();

    float x = ReadPot();
    while (x > 0.0) {
      x = ReadPot();
    }
    motorStop();
    g = 0;
  }
}

```

Combined Linear Actuator:

```
float gotoPos(float pos){
  float x = ReadPot();
  if (x > pos){
    motorBack();
    while(x > pos){
      x = ReadPot();
    }
    motorStop();
    return 1;
  }
  if (x < pos){
    motorForward();
    while(x < pos){
      x = ReadPot();
    }
    motorStop();
    return 1;
  }

  else {
    motorStop();
    return 1;
  }
}
```

Pressure Sensor:

```
float ReadDepth() {
  float d;
  d = analogRead(pressPin); //read analog signal from sensor
  Serial.print("\n");
  Serial.print(d);
  d = .01380074*d-2.58820446; //convert to depth in feet
  Serial.print("\nDepth:");
  Serial.print(d);
  return d;
}
```

## Dive Cycle Code (setup):

```

int potPin = 2;
int g = 1;
int pressPin = 5;
void setup() {
  Serial.begin(9600);
  //Setup Channel A
  pinMode(4, OUTPUT); //Initiates Motor Channel A pin
  pinMode(9, OUTPUT); //Initiates Brake Channel A pin
  pinMode(potPin, INPUT);
  pinMode(pressPin, INPUT);
}

```

## Dive Cycle Code (loop):

```

void loop()
{
  float d;
  if (g == 1){
    gotoPos(10.9); //initialize at max buoyancy
    d = ReadDepth();

    while (d < .5) {
      d = ReadDepth(); //wait until the nose has been pushed down .5 feet before starting
    }
    g = 0;
  }
  if (g == 0){
    gotoPos(0); //sink
    d = ReadDepth();
    while (d < 1.5) { //keep sinking until reaches threshold
      d = ReadDepth();
    }
    gotoPos(10.9); //come back up
    g = 2;
  }
}

```

