Triton

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Abstract— **A remotely operated underwater vehicle (ROV) is a tele-robotic submarine commonly used for ocean exploration and inspection work on offshore oil rigs. The goal of the Triton project is to modify an existing open source underwater drone to allow ecologists from the Department of Environmental Conservation at University of Massachusetts Amherst to conduct research on the declining river herring population within the Massachusetts and greater New England region. In addition, two new components were implemented; a buoy that enables wireless connection and a piston ballast to provide a more efficient means of depth control. The purpose of these new modifications was to improve the overall performance of the underwater drone in addition to reducing research costs at the Gloucester Marine Research Station.**

I. Introduction

THE current market for remote operated vehicles does not provide an economical solution for unwater monitoring in freshwater bodies. A low cost model such as the VideoRay Scout Unwater ROV cost $3,895.00. According to research from the Duke University Center, in 2010 the total net worth of ROV sales was approximately $850 million with nearly 50% of the those ROVs employed by the offshore oil and gas industry and 25% for defense & security and scientific research respectively [1]. The drive for advancements in ROV technology is made largely in part by commercial firms within the offshore oil and gas industry to support field operations in platform and pipeline inspections, construction support, and subsea installations [2]. Consequently, a majority of current ROV models in the market are specifically purposed for ocean water deployment.

River herring are anadromous fish that spend the majority of their adult lives in the ocean and return to freshwater bodies to reproduce. Since the 1960s, the population of river herring in New England has dramatically decreased from a population of millions in 1990 to between 5,000 and 8,000 in 2010 [3] as shown in **Fig. 1**. The decline in the river herring population has been attributed to increased predation by striped bass and other animals, loss and degradation of inhabitant from population, and overfishing. The river herring plays a key role in maintaining biodiversity within the marine ecosystems. Commercially fished cod and flounder feed on river herring as a primary food source. Furthermore, without the river herring to use as bait for groundfish, the commercially fishery industry faced a significant decline in profit.

In 2005, the Commonwealth of Massachusetts approved a harvest moratorium for river herring in addition to increased stocking efforts to maintain and enhance existing populations and establish new populations. Despite these efforts, river herring populations have remained stagnant, experiencing little growth since the regulations were passed. Scientists from University of Massachusetts Amherst are currently studying the reproductive behavior of river herring since little is known on the topic. Spawning populations of river herring can be found in rivers and freshwater lakes, however, researchers do not know the precise location of the fish eggs. Knowing this information will enable researchers to better understand the environmental and ecological significance of the spawning sites in order to enhance existing river herring populations.

Currently, researchers are monitoring river herring population through traditional scuba diving methods. This current means of study is expensive as training, equipment, and manpower are required. A more economical approach to this problem would be to deploy an underwater drone that would assist researchers in monitoring the river herring population without requiring a diver. In addition, ROVs mitigate the cost regarding of diving, which ultimately reduces human risk and enables study at greater depths than previously capable without hazardous physical limitations.

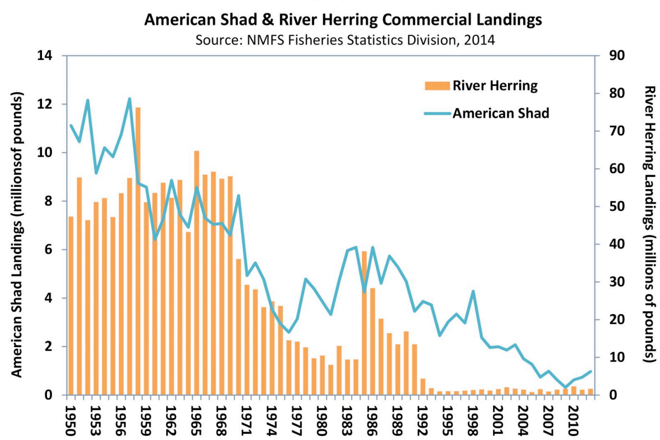

Fig. 1. Plot showing the population of the river herring from 1950 to 2010. The river herring population faced a significant drop in 1971 and 1987.

II. Design

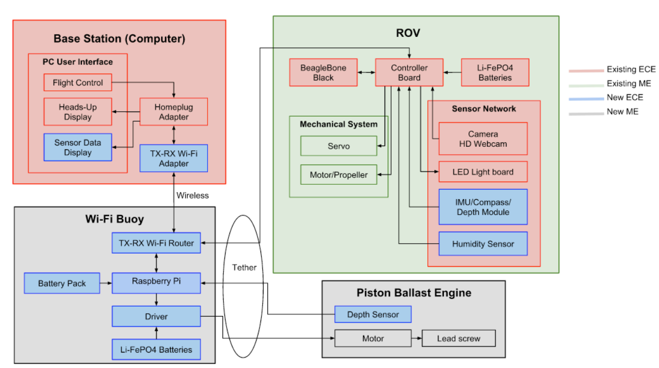

Fig. 2. System block diagram consisting of four major subsystems; base station, Wi-Fi boat, ROV, and piston ballast engine.

A. Overview

Faculty members from the Department of Environmental Conservation at University of Massachusetts Amherst purchased the underwater drone called OpenROV [4] as both a research and learning tool for students. However, the ROV suffered damaged from a past underwater operation that short circuited a significant portion of the electronics onboard. As a result, part of this project was to first diagnose issues and make repairs on the underwater drone as necessary. This process took approximately one semester to complete as there were multiple issues with both the electronic hardware and mechanical components. A series of tests were performed in a pool environment to ensure that the ROV could maintain water tightness for extended periods of time.

Once the underwater drone was confirmed operational and watertight, it was determined that additional features could be added to improve system performance and reduce power consumption. The first improvement was done on the base station, which consists of a personal laptop connected to the ROV through Wi-Fi. Several scripts were modified on the Google Chrome web based user interface "Cockpit" [5] to enable additional telemetry sensor data display. In addition, a sub-system was implemented so that the user would be able to save video footage from onboard the ROV to a local hard drive. The Wi-Fi buoy helps improve tether management and increases operational distance by enabling a wireless connection between the ROV and the base station. A wireless access point was set up on the buoy to allow the user to control and receive live video feed from the ROV camera The underwater drone is still tethered, however, it is connected to the Wi-Fi buoy. This significantly reduced the tether required to the operate the device from 300 feet to 22 feet. After repairing the ROV, additional sensors were added to monitor the system's orientation and the humidity level within the electronics compartment. This is intended to aid the user in pinpointing the position of the underwater drone and monitoring humidity levels in the ROV, which might occur due to water leakage. The final major component of this project is the piston ballast system that allows the user to manually control the depth of the ROV without inputs from the vertical motor. This significantly improves power consumption of the overall system and prolonging the single-charge run time of the system.

TABLE I
SPECIFICATIONS

Specification	Value
Battery Life	<3h
Wi-Fi Range	<300ft
Depth	<20ft
Video Quality	=1080p Full HD at 30fps

A list of the system specifications is shown in **Table 1**. To support the researchers in studying the river herring eggs, the underwater drone must be able to reach a depth of 20 feet to gather video footages with a desired operational run time of approximately three hours. In addition, the user must be able to operate the ROV wirelessly up to 300 feet as a means of demonstrating initial system functionality with the upgrades installed. Lastly, the video quality from the camera should provide sufficiently high quality footage to help researchers identify objects underwater. **Fig. 2** is system block diagram of all the four subsystems. The red and green blocks are existing electrical and mechanical engineering components, while the blue and grey are new electrical and mechanical engineering components that were implemented in this project.

B. Base Station

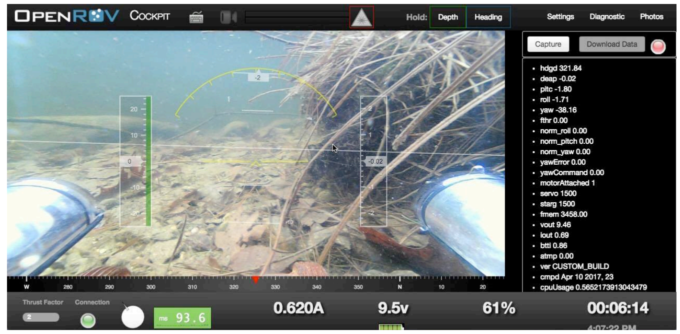

Fig. 3. Cockpit is a user interface that the user access through a personal computer to stream live video footage from the onboard camera and control the ROV.

The underwater drone is controlled through a user interface as shown in **Fig. 3**, which is accessed by either a personal computer or mobile device. The user connects to the ROV through connecting to an IP address through the URL bar in an internet browser. This provides the user with access to the video feed and motor controls of the ROV, and displays the battery life, current draw of the electrical system, depth of this ROV, board temperature read outs, and additional instrumentation. The original setup was the computer, which was connected to the HomePlug adapter [6] through an Ethernet cable. The HomePlug device itself is connected to the underwater drone using a 300 feet long tether. Connection is made through the HomePlug adapter that allows a device such as a computer to connect to other devices using an electrical wire. However, this presents an issue as a 300 feet long tether greatly increases the possibility of entanglement around rocks or tree branches. If such an event does occur, the user will have to physically enter the water to untangle the wire by hand or cut the wire.

The first change made to the ROV subsystem was to replace the 300 feet long tether with a wireless setup. Connection is no longer made through a tether between the computer and the underwater drone. This greatly improves tether management by reducing the overall length necessary to operate the underwater drone and minimize risk associated with wires getting entangled around rocks or tree branches. With the new wireless setup, no changes were made to the cockpit. In addition, several scripts were modified to incorporate data outputs from the depth and humidity sensors. The additional data can be viewed on the right side of the control program. A dead man's switch was installed in case of loss of connection within the cockpit, and in the event signal is lost the ROV lights will flash and the vertical motor will propel the underwater drone to the surface. This is a crucial feature as it minimizes potential damages to the ROV from water leakage. Researchers can now save video footages from the camera up to 10-minutes at a time on a local hard drive. Video saving is done by opening up a network stream through application called VLC or using a screen capture software.

C. Wi-Fi Buoy

This subsystem allows the user to connect to the ROV without a direct tether connection. However, the buoy is tethered to the underwater drone because wireless signals are greatly attenuated through water. As a result, it is impossible to make the ROV completely wireless without suffering from signal loss. A wireless access point was established on the buoy using a Raspberry Pi 3 Model B [7] with a Wi-Fi USB

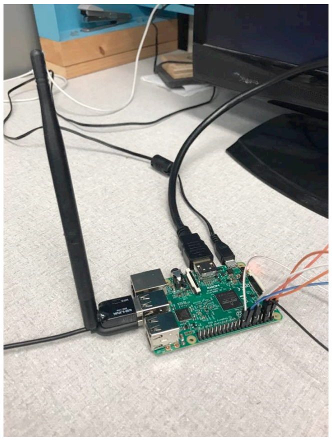

Fig. 4. The Raspberry Pi 3 Model B is equipped with a USB wireless antenna to allow it to emit a wireless signal. This allows the user to control the ROV wireless

adapter [8] powered by a rechargeable battery pack as shown in **Fig. 4**. The Raspberry Pi was connected through an Ethernet cable to the HomePlug adapter which is now exists on the buoy instead beside the base station. When the Raspberry Pi receives IPv4 packets from the computer, it transfers those packets to the ROV through the tether cable.

The BeagleBone Black [9] is a microcontroller/microprocessor that is located on the ROV. The firmware image on the device allows it to interface with the onboard camera and several other components. The signal travels through the Ethernet cable to the microprocessor, which is programmed to control the ROV based on inputs it receives from the computer. The wireless access point was set up by programming the Raspberry Pi to route incoming and outgoing IPv4 packets between the computer and ROV. The Raspberry Pi was also programmed to run scripts that control the piston ballast mounted on the ROV. Scripts to control the piston ballast gather inputs from the depth sensor and determine modulation dynamically through a programmed PID software. The custom PCB board was installed onboard the buoy and its purpose was to regulate the supplied voltage necessary to power the piston ballast from a separate battery pack.

The buoy was designed as a watertight enclosure for the Wi-Fi setup and driver for the piston and to prevent water from reaching the electronics. All of the electronics on the buoy are stored in an ABS grey box with access ports drilled out for the USB antenna and cables. The buoy itself is constructed out of a very light material and is sturdy enough to withstand repeated use in the water. The dimensions of the buoy were decided using Archimedes' principle of buoyancy:

$$F = \rho * g * V \quad (1)$$

F is the total weight of the buoy, ρ is the density of water (1,000 kg cm^-3), g is the acceleration due to gravity (9.81m s^-2), and V is the total volume of water displaced by the buoy. For the buoy to stay afloat, the buoyant force generated from the total volume of water the buoy displaces must exceed its weight. The buoy will sink if its weight is greater than the force of buoyancy. To determine the total weight of the buoy with all the electronics onboard, the buoy was measured on a scale with accuracy up to three decimal places. Once the total weight was determined, the height of which the buoy is displaced underwater is minimized to reduce drag caused by water. The height was kept at 0.5 inches to support a weight of five pounds. The radius of the bottom plate of the buoy was calculated using the height. The effects due to water drag was calculated using the drag equation below:

$$D = Cd * (\rho * V^2)/2 * A \quad (2)$$

D is the drag caused by water. Cd is the drag coefficient of a circular plate, ρ is the density of water, V is the velocity at which the ROV is travelling 1.03 m/s, and A is the surface area. Based on calculations, the effects due to water drag does not significantly impact the performance of the underwater drone compared to the water drag that the ROV experience underwater. In addition, four pairs of floats made out of foam insulation were installed on the 22 feet long tether as an indicator of depth. This helps the user determine when the ROV will begin pulling onto the buoy causing it to sink. The addition of the floats also helps prevent the tether from getting entangled around a rock or tree branch.

The Wi-Fi setup was tested outdoors at a local pond. A distance test was performed to determine the strength of the wireless connection. As shown in **Fig. 5**, the maximum distance against video quality was under 250 feet with minimal or acceptable latency. Beyond 250 feet, the motors were still responsive with acceptable latency issue up to 300 feet. If there are any wireless devices were nearby, it would interfere with the wireless connection and increase latency issues of the ROV to base station connection.

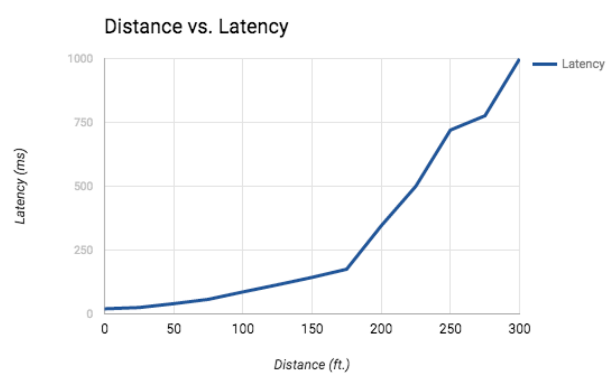

Fig. 5. Plot showing the latency of the Wi-Fi setup as the distance of the connection increases.

D. ROV

In its original state, the underwater drone enables the user to perform underwater exploration between one to two hours according to the manufacturer OpenROV. The original device came with a BeagleBone Black, controller board, camera, and three motors. The BeagleBone Black is a microprocessor and microcontroller that interfaces with a google Chrome browser based user interface called Cockpit that allows control of the motors and access to live video streaming. The microprocessor/microcontroller was pinned on top of the controller board, which enabled it to handle high-level commands. The controller board itself interfaces with the sensors, servo, motors, and LED light board through a VGA adapter located at the edge of the board. A set of three brushless DC motors with propellers were mounted on the underwater drone to produce thrust, lift, and yaw action. The propellers operate at both low and high speeds to provide a means of maneuverability. Each motor is a 3 AX-2213N 800kV brushless motors [10] with one motor mounted vertically and the additional two mounted horizontally. The horizontal motors require an output of 3.5V to maintain a top speed of two knots or 2.3 mph. The wire insulation on the motors were modified to enable operation underwater. The motors were originally intended for model RC aircrafts. Power is drawn from six rechargeable Li-FePO4 batteries [11] located in the tube chambers on the ROV. The batteries in each chamber are arranged in two pairs of three batteries connected in series to provide a voltage output of 9.6V and a current of 3.0A to the CPU module. Video footage run 1080p with sufficient lighting from the LEDS installed on-board the underwater drone to provide clear visual of the lake floor. The camera is a Genius F100 HD USB Webcam [12] and the LED light module is 2 Digitron 87lm LED light arrays [13].

Fig. 6. Topside picture of the ROV at Puffer's pond. The underwater drone was taken to a pond environment to test for leakages.

The ROV experienced a water leakage that short circuited the BeagleBone Black and the controller board. The bearings on the brushless motors were wore out because they were not sufficiently lubricated between each run. The acrylic cylinder was not properly handled, resulting in noticeable tears in the wires and cracks in the endcaps. Each endcap is sealed off using a rubber plunger to relief pressure or pressurizes the air inside the main tube. These plungers can translate freely back and forth in response to the changes in water and air pressures. All of these components were either replaced or repaired over a course of a semester. One of the biggest issues was figuring why the ROV was not able to maintain water tightness over extended periods of time. The ROV was taken to the campus pools at a maximum depth of 12.5 feet for preliminary testing before performing an actual run in a lake environment. It was concluded that the reason why the ROV leaked due to inadequate and improper lubrication of the O-rings around the endcaps and the acrylic syringes that go through the endcaps were not installed correctly. These issues were fixed by obtaining hydrophobic silicon grease for the O-rings and applying epoxy around the rims of the syringes to provide a watertight seal. This was confirmed when the ROV was tested in both a university pool and Puffer's pond for testing and demonstrated no sign of a water leakage. **Fig. 6** is a picture of the ROV functioning as intended underwater.

In addition to repairing the underwater drone, three sensors were added; the MPU-9250 [14], MS5803-14A65 [15], and HIH-5031-001 [16] sensors. The MPU-9250 and MS5803-14A65 were attached on a potted board filled with epoxy and was mounted on the underside of the ROV. The MPU-9250 sensors is an Inertial Measurement Unit that determines the orientation of the ROV. The MS5803-14A65 is a depth sensor that detects absolute pressure, and is used to determine the depth of the ROV. Read outs from the depth sensor were tested in a swimming pool to validate the accuracy of the sensor. The HIH-5031-001 sensor is physically mounted on top of the controller board, and reads the changes in the humidity level inside the acrylic cylinder in case of a water leakage. All of these read outs are displayed on the right side of the user interface.

E. Piston Ballast

Fig. 7. Fully assembly of the piston ballast used to control the depth of the ROV.

Automated ballasting and depth control systems for underwater robotic vehicles are an intense area of oceanic research that has been explored since the 1990's [17] [18]. The dynamics of these underwater systems are highly nonlinear, and the hydrodynamic coefficients vary greatly within different operating conditions. For the purposes of this project, a simplified ballast system as depicted in **Fig. 7** was developed such that a working proof-of-concept demonstrating feasibility of the system could be produced within the timeframe of the project [19].

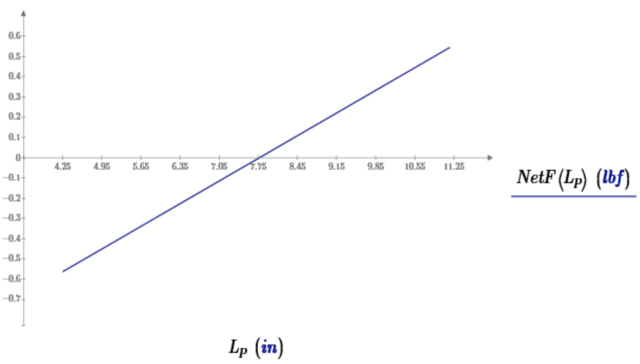

Fig. 8. Plot depicting the buoyant force generated by the piston ballast. Negative values to the left indicate the ROV is sinking, while positive value to the right indicate that the ROV is generating lift from fluid displacement.

The piston ballast system is an electromechanical assembly used to modulate the lifting buoyant force on the ROV as shown in **Fig. 8**. This is done by incrementally controlling the volume of water displaced inside the piston ballast. The primary purpose of the piston ballast was to extend the operational runtime and prolong a single of charge of the ROV system. This was achieved by minimizing the power consumed through the use of the vertical motor to maintain and adjust depth. The system was assembled using a selected 64 oz.-in NEMA 17 stepper motor and self-locking 10mm diameter 2mm pitch leadscrew pairing, rechargeable 12V power supply, PCB, and Raspberry Pi controller, polyvinyl chloride sheet stock and tubing, oil-resistant soft Buna-N O-rings 3/32" width with dash number 134, and mechanical fasteners. An initial prototype was designed using similar building materials to test the concept of the piston ballast. The final product is enclosed by a transparent PVC chamber, and was bored out to allow fitting of the stepper motor. The carriage of the piston ballast was CNC machined from a sheet stock and was assembled to create the necessary groove to seat the main O-ring seal. This subsystem was initially tested unpowered in a body of water at a depth of no greater than two feet to check for water leakage. The subsystem was then activated and cycled through the length of the leadscrew to verify that the seals would not fail due to compression. Another test was performed on the piston ballast to determine the vacuum drawn by the expansion of the piston would be sufficient to prevent the stepper from walking the carriage out of the chamber tube and flooding the electronics.

The torque required to raise the carriage at the design condition depth of 25 feet underwater was calculated using

$$Tra\left(d_i\right)=\frac{W\left(d_i\right)\cdot d_m}{2}\cdot\frac{f\cdot\pi\cdot d_m+L\cdot\cos\left(\alpha_n\right)}{\pi\cdot d_m\cdot\cos\left(\alpha_n\right)-f\cdot L} \tag{3}$$

and the torque required to lower the carriage was calculated by:

$$Tla\left(d_i\right)=\frac{W\left(d_i\right)\cdot d_m}{2}\cdot\frac{f\cdot\pi\cdot d_m-L\cdot\cos\left(\alpha_n\right)}{\pi\cdot d_m\cdot\cos\left(\alpha_n\right)+f\cdot L}+\frac{W\left(A_c\right)\cdot f_c\cdot d_c}{2} \tag{4}$$

It was noted that the load W was dependent upon the inner diameter of the pipe that would correspond to the outer diameter of the carriage traveling linearly along the leadscrew. Using thermos-physical properties evaluated at ambient air temperature of 68°F, the temperature rise of the material was found to be 75.85°F which resulted in a final temperature below the melting temperature of polyvinyl chloride at approximately 140°F.

The piston ballast is controlled through a PID controller algorithm using a Raspberry Pi. When the script is running on the Raspberry Pi, the carriage inside the piston ballast chamber moved forward or backwards to displace water. Depending on the displacement of piston ballast displays enough water, the underwater drone will generate lift, establish neutral buoyancy or begin sinking. The user can determine the rate at which the ROV is sinking by allowing additional water into the chamber. The driver circuit onboard the buoy provides power to and drives the stepper motor of the piston ballast. The EAGLE was used to design and create a schematic of the PCB. The prototype of the PCB was tested on a breadboard along with the Raspberry Pi and stepper motor. The final PCB design interfaces with the Raspberry Pi, power supply, and stepper board. 3.3V to 5V step up 74LVC245 to interface the Raspberry Pi 3.3V GPIO pins to the 5V logic needed by the stepper motor driver. The 5V inverter, SN54HC04, takes input signals to generate outputs. The signal pairs are used to polarize the stepper motor driver, L293D, and takes in the 12V from the power supply to rotate the motor. The 5V voltage regulator converts the 12V power supply to 5V to power the electronics. It is located onboard the buoy and is connected to the piston ballast through 20-feet wires. **Fig. 9** displays the final prototype as installed upon the ROV system.

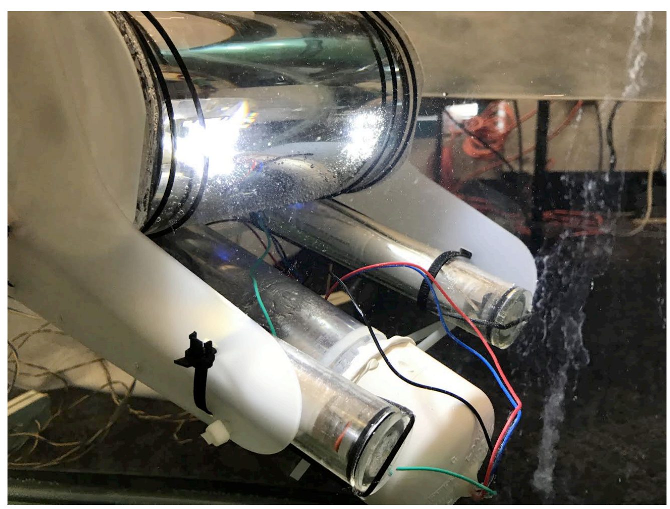

Fig. 9. The piston ballast system installed and maintaining depth of the ROV in a water tank without vertical motor input.

III. Project Management

Each of the proposed FPR goals were either completed or satisfied according to the faculty members from the Department of Environmental Conservation. The team is made up of students from different engineering disciplines;

computer systems engineering, electrical engineering, and mechanical engineering. Each member of the team offers skills that contribute uniquely to the team. Emil Safonov focused enabling wireless controls on the ROV and wrote scripts for the cockpit software. Calvin Tran worked on designing the PCB to control the voltage, as well as the PID script on the Raspberry Pi for the piston ballast. Emil and Calvin worked together to incorporate the IMU/pressure and humidity sensors on the ROV and having it displayed on the user interface. Kevin Tong designed and built the initial and final prototypes of the piston ballast. He worked closely with Calvin to write the PID script that controls the mechanical components of the piston ballast. Tony Hua focused the design of the buoy, while performing water seal tests for the ROV. The project required an interdisciplinary collaboration across different engineering fields in order to succeed. The team met twice a week since the beginning on the project to discuss issues/accomplishment and work on the FPR deliverables. Documentations such as the presentation slides and information on each subsystem were uploaded to a shared network drive available to everyone on the team. Each teammate took turn contacting and scheduling meetings with the advisors, evaluators, and faculty members from the Department of Environmental Conservation.

IV. Conclusion

Since the midway design review, the team has successfully tested the underwater drone in a lake environment. The first semester was focused on the ROV as the team was able to restore the device to its operational state and identify the root cause for water leakage. Most of the additional features that implemented were finished in the second semester with some of the prototyping completed in the first.

With the addition of the piston ballast, the underwater drone was able to remain extended underwater operations from 1.5 hours according to the manufacturer to 2.5 hours. This will significantly aid the researcher in conducted longer operations. The additional sensors will allow the user to evaluate the humidity levels in the acrylic cylinder where the electronics are located, and determine the depth/orientation of the underwater drone. The read outs from the sensors are shown on the right side of the cockpit software. The Wi-Fi buoy improves cable management by reducing the overall length of the tether from 300 feet to 20 feet. This reduces the possibility of entanglement, which would require a diver to go underwater and retrieve the ROV. In addition, the Wi-Fi buoy allows the user to connect to the ROV via Wi-Fi up to 250 feet before experiencing a notable drop in video quality from the camera. The user can record the video footages on a local hard drive up to 10-minute at a time, which will allow the researchers to keep records of their work. Lastly, the video quality on the camera is 1080p Full HD at 30 fps. With the addition of the LED light array, this provides the user clear visuals of the lake bed.

Acknowledgment

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