Beaver Country Day School RoboSub Team: The Development of the Prospero Mark II AUV

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***Abstract*—Prospero Mark II is BeaverAUV's submission to the 2017 RoboSub Competition. The AUV (Autonomous Underwater Vehicle) was designed and implemented by six high school students from Beaver Country Day School. It was designed as an iterative improvement over the previous Prospero AUV. While maintaining many of the same design concepts as the original Prospero AUV, Prospero Mark II features key design improvements to the usability, modularity, robustness, and functionality of the robot. The design was focused on creating a versatile, agile robot with functionality specialized for the RoboSub competition. Prospero Mark II was developed to be a fully functional robot with the capability of completing all RoboSub obstacles, while still being cost-effective to manufacture. This journal paper describes how BeaverAUV designed Prospero Mark II to accomplish these goals.**

I. Design Strategy

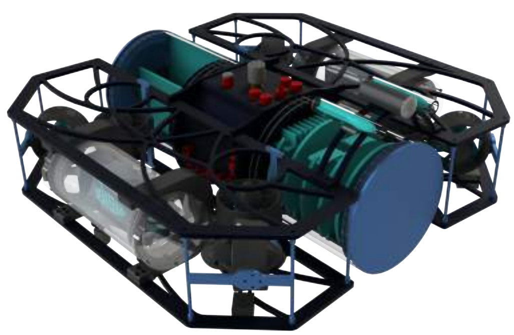

Figure 1. A Solidworks Rendering of Prospero Mark II

BeaverAUV designed Prospero Mark II to maintain the effective design features of the 2016 AUV, while iterating on problematic features. In order to keep the same basic operational principles as the 2016 vehicle, Prospero Mark II maintains the same basic frame design and thruster layout as the 2016 vehicle. The singular major conceptual change to the Prospero Mark II AUV is the inclusion of a custom aluminum center console which bisects the acrylic hull and provides all of the AUV's IO and mounts for electronic systems. The electronic systems were redesigned, and are split into two major components: the computer and the serial backplane electronics rack. The 2017 computer is far more powerful to support the new software systems, and the 2017 electronics rack features an I^2C interface to support modularity and decrease the total number of wires in the AUV. The majority of Prospero Mark II's software has been rewritten to create a more functional AUV which can complete more tasks. The software is based on a hierarchical state machine, which allows users to make rapid changes to top-level mission code. The other key change to the AUV's software is the inclusion of an RCNN (Region-Based Convolutional Neural Network) vision system which offers drastic performance increases over the previous Open Computer Vision appraoch.

II. Mechanical Design

Prospero Mark II's design comprises an aluminum frame mounted to a center console which provides the central structure of the AUV. Two acrylic hulls mount to the center console, and are capped by two aluminum end caps to form a watertight enclosure within the acrylic hulls and center console. Eight thrusters mount to the frame and provide six degree-of-freedom movement. Also mounted to the frame are four hydrophones for a passive sonar array, a water cooling radiator, external battery enclosures, and pneumatic equipment.

A. Center Console

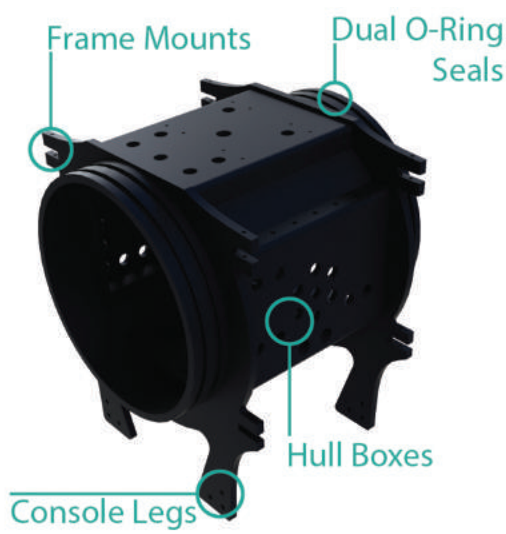

Figure 2. Prospero Mark II's Center Console

Prospero Mark II features a custom aluminum center console which serves as the mechanical core of the AUV. To the center console mounts all additional hardware. This allows all individual components to be removed from the center console without disassembling any other portion of the AUV. The center console comprises an aluminum tube with four CNC machined aluminum hull boxes welded to the sides. These hull boxes provide all of Prospero Mark II's inputs and outputs. Two sets of console legs serve as the feet of the AUV and provide mounting positions for Prospero Mark II's frame.

1) Inputs and Outputs: The center console's four hull boxes feature extensive electrical, pneumatic, and water-cooling I/O. The top hull box features a wet-mateable underwater connector for an Ethernet connection to an external computer. Also on the top hull box are three kill switches for different situations (described in III: Electrical Design, and a vacuum pump port for pulling a mild vacuum within the AUV. On each side hull boxes are ports for Blue Robotics hull penetrators, which are used to run cables for thrusters, hydrophones, cameras, and all other external electronics. On the left hull box are eight threaded holes for pneumatic fittings which function both as inputs to the valves within the watertight enclosure and outputs to the pneumatic devices mounted to the frame. On the right hull box are two G1/4" threaded holes to run water cooling fluid from the internal computer to the external radiator.

2) Frame Mounts: The center console has two sets of console legs mounted to each side of the hull boxes. These function both as legs for the AUV and mounts to connect the frame to the center console. Each of the four main frame panels slot into the console legs, and are fixed in place with two screws. This allows the wings to be detached very easily, while providing a very sturdy connection between the center console and the frame.

3) Console Feet: The center console's legs feature mounting points for interchangeable feet. Feet can be added for both functional and aesthetic purposes. Different sets of feet were designed to make Prospero Mark II sturdy on a workbench, to soften impacts if the AUV collides with the bottom of a pool, and to add wheels for ease of transportation.

B. Frame

The frame is constructed of two main halves (wings), each of which comprises two waterjet-cut panels separated by thruster mounts and additional standoffs. Each wing can be removed from the center console by removing four screws. The frame provides Prospero Mark II's stability, modularity, and expandability.

Figure 3. Prospero Mark II's Frame

1) Thruster Layout: Prospero Mark II's thruster layout was not changed from the 2016 vehicle. Two Blue Robotics T200 thrusters mount to each half of the frame in a horizontal orientation to provide translation in the surge and sway directions, and rotation in the yaw direction. The horizontal thrusters are located in the corners of the AUV. Horizontal thrusters are mounted in a vectored configuration, rotated 45 degrees around the Z axis. This was done to increase the ease of use of the robot by not having any thrusters in front of either of the end caps, and to ensure that the AUV remains as compact as possible. Four Blue Robotics T100 thrusters mount to the frame in a vertical orientation to provide translation in the heave direction. The thrusters also provide minimal control of roll and pitch; however, the robot is designed and trimmed to be very stable to prevent rotation in the roll and pitch directions. Since maneuverability in these directions is unimportant, it was not prioritized and is not controlled throughout the RoboSub course.

Prospero Mark II uses the same thruster layout as the 2016 AUV because extensive testing and operation at the 2016 RoboSub competition proved it to provide ample maneuverability, speed, and efficiency in the water.

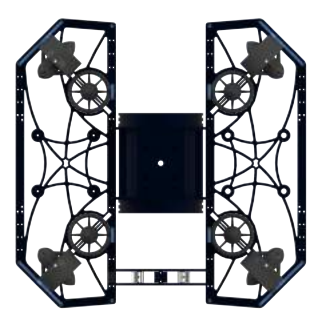

Figure 4. Prospero mark II's Thruster Layout

2) Dynamic Trim System: Prospero Mark II features an integrated trim system to allow for easy modification to the trim and buoyancy of the sub. Built into the the bottom panel of each wing are two rails which radiate from the center of the AUV. Custom cast lead weights can be easily attached and slid along these rails, effectively changing the trim of the sub. This offers substantial usability benefits because each weight can be moved by loosening just one screw.

C. Hulls and End Caps

Two 7.5” ID x 8” OD acrylic tubes serve as Prospero Mark II’s main hulls. They form axial o-ring seals with both the center console and two custom aluminum end caps. Unlike the 2016 AUV in which the hull was structurally essential to the AUV, Prospero Mark II’s hulls function solely as a cover for the electronics. The end caps were designed to remain permanently in one side of each hulls. The hull and end cap assemblies can be removed and replaced without disconnecting any electronics or removing any screws. This has proven to provide a drastic increase to usability.

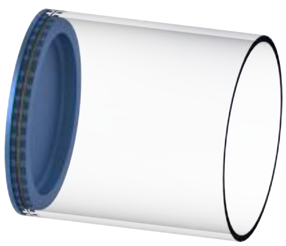

Figure 5. Prospero Mark II’s Hull and End Cap Assembly

D. External Battery Enclosures

Two Blue Robotics 4” Diameter hulls mount to the frame as external battery enclosures. This allows batteries to be easily swapped without disassembling the robot. The enclosures also contain additional ballast weights.

E. Pneumatics

Prospero Mark II uses a CO_2-based pneumatic system to fire torpedos, to drop markers, and to actuate a gripper. The air supply is a 9oz CO_2 paintball tank. Originally, the system was designed for a compressed air tank; however, this proved to have insufficient capacity and was thus replaced by the paintball tank.

1) Torpedos: Prospero Mark II is equipped with two pneumatically-fired torpedoes. They are actuated by switching two Clippard Maximatic valves which release a burst of air through two PVC tubes. This launches the torpedos. The projectiles are 3d printed with a density such that they are slightly positively buoyant.

2) Dropper: The dropper is actuated by firing a pneumatic cylinder. This pushes steel bearings from a vertical magazine to a tube which allows the bearings to drop. The magazine is able to hold six bearings.

3) Gripper: Prospero Mark II’s gripper is actuated by a spring-return cylinder. It is 3d printed to allow the gripper’s fingers to be redesigned to pick any object.

Figure 6. Prospero Mark II’s Pneumatic Gripper

F. Electronics Mount

Prospero Mark II’s electronics rack is split into two sections. The stern hull contains a custom a mounting system for a custom watercooled computer. The bow hull contains a rack for all auxilary electronics on a custom I^2C interface.

1) Electronics Rack: The electronics rack features an MDF backplane with six breakout boards to mount electrical systems. MDF was selected because during the 2016 competition it proved to be structurally sturdy and absorptive enough to deal with minor leaks.

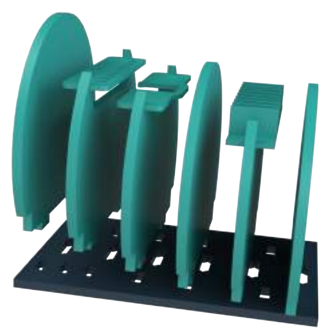

Figure 7. Serial Interface Electronics Rack

2) Computer Mount: The computer mount was designed to maximize compactness, which necessarily sacrificed some ease of use. Both the main motherboard and the graphics card mount vertically, requiring a PCIE riser ribbon cable to connect the graphics card to the motherboard. Because of how compact the computer mount is, all cables and water cooling tubing are very close together, making them difficult to replace and troubleshoot. This problem could have been avoided by increasing the diameter of the main hulls to decrease the space constraint. Initially, the computer mount was made from MDF; however, it quickly became clear that the MDF was not strong enough and was replaced by acrylic. The computer mount is anchored to the bottom and side hull boxes of the center console.

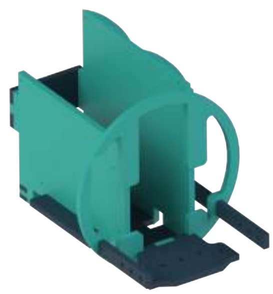

Figure 8. Computer Mount

III. Electrical Design

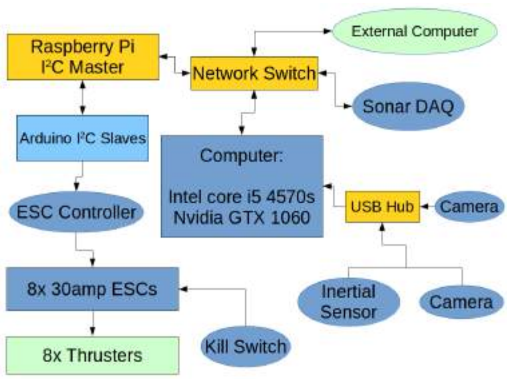

Figure 9. Prospero Mark II's Electronics Systems

Prospero Mark II's electronics were designed to be as compact and modular as possible. A combination of off-the-shelf components and custom-designed PCBs and circuitry were used to assemble the electronics. The main computer, a water-cooled desktop-class computer, communicates with auxiliary electronics through a combination of USB and ethernet.

A. Power Distribution

The power distribution system provides the correct voltages to all of the electronics. Two 4-cell lithium ion batteries supply power to the AUV. Each battery's output splits to two rails. One side of each split feeds four of the ESCs. The other side of each split runs to a DC-DC converters which output 20V. The supplies are only merged after the two DC-DC converters (which have integrated back-power prevention) to prevent back-charging of the batteries. The combined 20V output is used to power the computer and all other electronics.

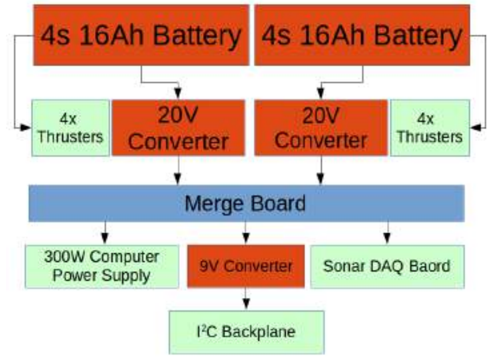

Figure 10. Prospero Mark II's Power Distribution System

B. Serial Backplane

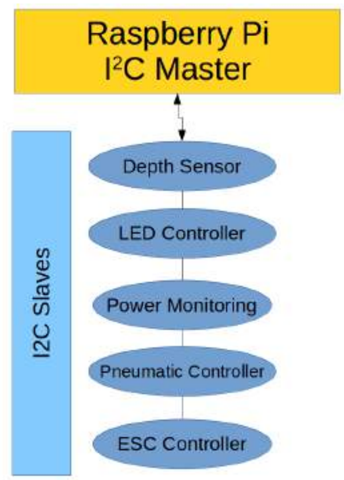

Figure 11. Custom I^2C Interface

The serial backplane provides serial communication throughout the AUV's auxiliary electronics systems. A Raspberry Pi serves as the master which manages communication to six slaves. One slave is a depth sensor, while the other five are arduinos which operate on custom breakout board PCBs. The breakout board PCBs mount arduinos, and provide a simple IO interface for the specific electronics each breakout board was designed for. Each breakout board has a board-edge connector which plugs into the serial backplane, which provides power and an I^2C bus to each breakout board.

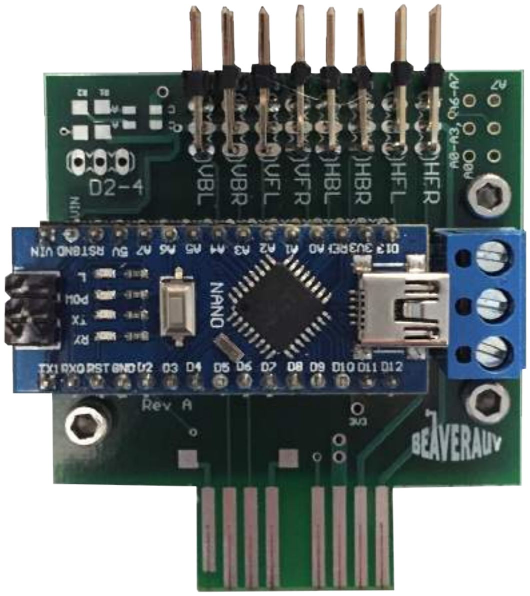

Figure 12. The ESC Controller Breakout Board with Eight ESC Output Ports.

C. Computer

The computer runs all of the AUV's mission code, image processing, and major calculations. It is based on an Intel Core i5 4570s quad-core CPU and an NVidia GTX 1060 graphics processor. This computer was selected because it is the most cost-effective and compact computer which can run the vision system. It is water-cooled with a custom closed-loop water cooling apparatus which pumps water across heatsinks on the CPU and GPU and through a radiator which mounts to the frame of the AUV in the water. This provides very effective heat transfer; under maximum load, the CPU never reaches above 40° celcius.

D. Sonar

Four Aquarian Audio h2c hydrophones capture audio for Prospero Mark II's sonar system. A custom PCB is used to provide the required 9V bias voltage to each hydrophone, and then to remove this DC offset before processing. Data acquisition is handled by a SonarTech Signal-DAQ-8, an 8-channel DAQ designed specifically for acquisition of hydrophone sonar data. The main computer communicates with the DAQ through Ethernet. The Singal-DAQ-8 was selected because it provides 8 channels of 192Khz simultaneous sampling, and is designed to operate in conditions similar to that of the RoboSub competition. It is also simple to communicate with via UDP/IP.

E. Kill Switch

Prospero Mark II has three kill switches managed by a custom kill switch control PCB. The primary kill switch is a 'Soft Kill', which triggers the software state machine to enter a 'kill' state which sets all thrusters to off. This switch is used as the mission control switch to begin and end the mission. The second kill switch is a 'Hard Kill' switch which switches a large relay to disconnect power to all ESCs. This is used if the robot is behaving erratically. The final kill switch is an 'Emergency Kill' switch which switches the ESC power relay, and shuts off the DC-DC converters which power all other electronics (including the computer). This is only to be used during major leaks because of the damage which can be caused by suddenly disconnecting power to the computer.

F. Sensors

Prospero Mark II is equipped with two main sensors to detect movement. A 9 axis VectorNav VN-100 Rugged IMU (Inertial Measurement Unit) is used to provide accurate acceleration and rotation data. The IMU records accelerometer, gyroscope, and magnetometer data. The IMU is very capable at providing an accurate heading while filtering out any magnetic noise which would otherwise impede the functionality of the magnetometers.

Prospero Mark II also uses a Blue Robotics depth sensor to detect the depth of the AUV. It is used both to set depth waypoints throughout the mission and to ensure that the robot does not surface before the mission is complete.

As of the time of the submission of this journal paper, the BeaverAUV team is in the process of developing a rudimentary distance sensor. The design consists of an idle propeller which faces forward such that the propeller spins when the AUV drives forwards. The propeller has three magnets mounted to it which are read by a hall-effect sensor to form a basic rotary encoder. These encoder ticks are then calibrated to measure forward distance.

IV. Software

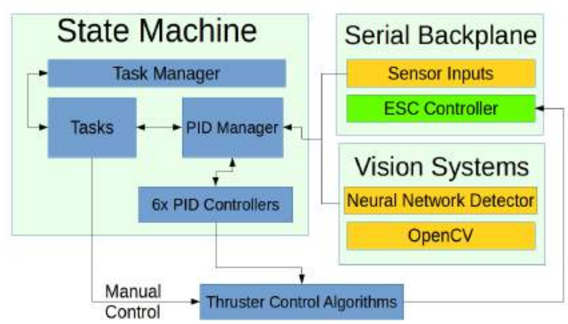

Figure 13. Prospero Mark II's Software Systems

Prospero Mark II's software allows the AUV to operate autonomously. Robot Operating System (ROS) is the core of the software system. ROS is used primarily as a communication interface to link together the various different programs which are executed on the AUV. ROS also allows for easy implementation of configurable launch files and monitoring of task data. All code is available on github.com/beaverauv.

A. State Machine

Prospero Mark II's state machine is the main controller for the AUV's mission code. It is written using the C++ Machine Objects (MACHO) library [1]. It provides an object-oriented approach to mission code which allows individual tasks (states) to be written independently of eachother, and then intelligently switched between. The state machine provides hierarchical control of the AUV. Each task within the top-level Task Manager state machine is also its own state machine, which in turn can contain multiple states and additional state machines. Switching between tasks can be handled both within each individual task and by the Task Manager. The state machine also allows the AUV to continuously monitor the mission without interrupting a task. For example, the state machine constantly checks the depth of the AUV to ensure it does not surface before the mission is complete. This persistent code can be run both at the level of the Task Manager and at each individual task.

B. PID Controllers

All of Prospero Mark II's movement is handled by six PID controllers, one for each degree of freedom of the AUV. In the 2016 AUV, the roll and pitch PID loops were disabled because they were not needed and provided unnecesary burden on the computer. As of the time of writing this journal paper, they are enabled on Prospero Mark II because there is far more computational power available on the new computer; however, if they prove to be unnecesary in extended testing they will be disabled.

The information sent to the PID controllers is managed by a PID manager. The PID manager provides functions to set the setpoint, current state, and the input type for each PID controller. The input type tells the PID controller which input data (i.e. vision or IMU data) to use to control the current state of the controller. It also provides functions such as checking if a PID loop is stable at the given setpoint.

C. Serial Interface

The serial interface is controlled by I^2C. The Rasberry Pi master sends and recieves data to and from the six slaves. The arduino slaves run auxiliary code which interprets sensor data, controls mission indicator LEDs, monitors the AUV's power, and switches pneumatic valves.

D. Vision

Prospero Mark II's vision system is primarily based on a Faster-RCNN (Faster Region-Based Convolutional Neural Network) machine learning algorithm developed by the Cornell University Department of Computer Science [2]. It was selected over our previous OpenCV-based approach because it provides more accurate detection of objects in a wider range of conditions. It also allows for bounding boxes around objects, which allows the output data from the RCNN to be fed directly into the PID manager.

The neural network is supplemented by OpenCV. The machine learning algorithm primarily recognizes the contours of objects. This makes it challenging to identify similar objects of different colors, especially the multiple buoys. OpenCV is used to identify colors within the region detected by the neural network to specifically identify these similar items.

The main disadvantage of the machine learning approach is that it requires a large amount of computational power. Running this Faster-RCNN algorithm necessitates a desktop-class computer with a dedicated graphics card. This requires the computer to be water-cooled, which is mechanically very challenging and consumes a large portion of the physical space in the AUV. At this point, it is unclear whether or not the benefits of such advanced image recognition outweigh the effort and complications caused by building such a large computer into the AUV. It is likely that OpenCV or similar tools could have been used for almost as consistent detection with substantially less computing power.

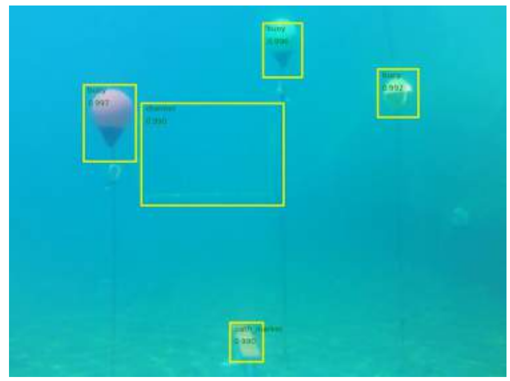

Figure 14. The Fast-RCNN identifying objects in the RoboSub course.

E. Sonar

Prospero Mark II's sonar system is based on hyperbolic multiateration of TDOA (Time Difference of Arrival) data. Samples are collected from the four hydrophones and band-pass filtered to eliminate noise outside the frequency of the pinger. The four input signals are then cross-correlated to determine the TDOA of each pair of signals. Each of these time differences are used to form a two-dimensional hyperbola of possible pinger locations. The Newton-Raphson method is used to find the intersections of each pair of hyperbolas, and then these intersections are clustered using K-Means clustering to approximate the location of the pinger. As of the time of the submission of this journal paper, the sonar algorithms are untested using real-world data since data acquisition has not been successfully accomplished.

F. Thruster Control

The thruster controller recieves translation and rotation data as percentages from either the PID controllers or directly from the mission code. From these values the thruster controller computes how fast to run each thruster. The thruster controller applies the neccesary translations to the data to accomodate the vectored thruster configuration. This data is then sent to the ESC Controller Breakout Board through the Serial Backplane.

V. Experimental Test Results

As of the time of the submission of this journal paper, Prospero Mark II has been in the water for approximately five hours of watertight testing. It does not yet drive, which has limited our ability to collect experimental test results. The test results used to inform our design come from a combination of BeaverAUV's experience at the 2016 competition with a very similar robot, and through testing of individual components in isolation of each other.

A. 2016 Competition

The BeaverAUV team competed with the Prospero AUV in the 19th RoboSub competition. This provided much of the insight necessary to complete an effective redesign of the AUV for the 20th competition. Testing of the Prospero AUV showed it to be exceptionally stable and maneuverable. Its flat, symmetrical design combined with a low center of mass allowed it to remain very balanced in the water. Our tests with the 2016 robot demonstrated that Prospero could achieve adequately high speeds for the majority of the mission while running at approximately 30 percent of the available power, which allowed Prospero to be very energy efficient. Our tests of the 2016 AUV caused us to keep these aforementioned features in the Prospero Mark II AUV.

Testing of the 2016 AUV also revealed several design flaws to be fixed in the 2017 AUV. While the 2016 AUV was relatively capable and exceptionally cost-effective to produce, major sacrifices were made to usability. Servicing electronics required disconnecting several connectors and removing the electronics from the AUV. This led to the minimum down time for any repair being over ten minutes. In the 2017 AUV usability was increased by the introduction of a center console to mount the electronics, and the development of the serial backplane to make servicing individual electronic components easier.

Extended use of the original Prospero's software revealed several fundamental flaws of the code. The 2016 state machine was based on a series of C++ case switches which created serious limitations to the robustness of the code. The two major limitations were the difficulty of arbitrarily switching between tasks and the inability to run persistent code alongside the mission code. The difficulty of switching between states necessitated very simple, linear logic which could not support intelligent decision making regarding mission planning. This was remedied through the use of the MACHO library. The inability to run persistent code alongside all tasks meant that the AUV could not reasonably run constant top-level checks for depth, leaks, or other mission conditions. The MACHO library solved this problem as well.

B. Watertight Testing

Initial testing of the water-tightness of Prospero Mark II revealed several leaks. The pneumatic and water cooling ports in the center console leaked, allowing a large amount of water into the hull. It is estimated that 30-50mL of water entered the hull every 10 minutes. This was fixed by replacing all barbs and plugs in the center console to ones with more robust o-rings. This has proven effective.

C. Sonar Algorithm Prototyping

Sonar algorithms were developed before sonar data acquisition was accomplished. Algorithms were developed using the Desmos online calculator to simulate TDOA data which was entered into multilateration and clustering algorithms. Said simulation is available at www.desmos.com/calculator/ao2yahybxn.

D. Vision Algorithm Testing

The vision machine learning algorithm was tested using footage the BeaverAUV team recorded during the 2016 competition, as well as footage from other teams. This was used to train the Faster-RCNN in a variety of situations to make the algorithm as adaptable to different run conditions as possible. Testing has shown that the neural network can identify new footage in all run conditions we could find footage of, including variances in lighting and the clearness of the water. This is a substantial improvement over the 2016 AUV's vision system which became defunct if weather conditions changed throughout the day.

Acknowledgment

BeaverAUV would like to thank Jayne Everson, the team's faculty advisor, for her continued, dedicated support of the project. The authors would also like to thank Beaver Country Day School for facilitating and funding the project. The team also thanks Jacob Jenks of the Montana State University RoboSub team who worked to help the BeaverAUV team implement the R-CNN vision algorithms.

Several sponsors contributed to the BeaverAUV team. Granite State Manufacturing machined the center console and end caps. The frame, end caps, and center console were anodized by Anoplate. Interstate Pneumatic Manufacturing provided the team with a regulator for the pneumatic system. Synqor provided the team with two high-performance DC-DC power supplies. Advanced Circuits provided a sponsorship to manufacture the breakout boards for the serial backplane. Solidworks provided the team with licenses to their 3d modeling software, and Mathworks provided licenses to their suite of software.

References

[1] Eduard Hiti. "Macho - C++ Machine Objects". In: (2007).

[2] Shaoqing Ren et al. "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks". In: (2015).