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

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***Abstract*- Prospero is BeaverAUV's submission to the 2016 RoboSub Competition. It is an autonomous underwater vehicle (AUV) designed, constructed, and programmed by a group of five high school students at Beaver Country Day School. In an effort to create a functional robot that will continue to be operational in future years, the BeaverAUV team designed Prospero to be a simple, robust, modular, and expandable robot. BeaverAUV developed Prospero to avoid several mistakes which are common to first-year RoboSub teams. This journal paper describes how BeaverAUV designed Prospero to accomplish these goals.**

I. Introduction

The BeaverAUV team was created to allow students to work on a challenging engineering project in which they had to design and program a complex robot. The RoboSub competition was selected because building an AUV provided a unique set of challenges which interested the team. As members of a very small team of relatively inexperienced students, each member of the BeaverAUV team worked on several systems at once, and each member dedicated substantial time to the completion of Prospero.

II. Design Strategy

The 2016 RoboSub competition is BeaverAUV's inaugural RoboSub competition; thus, the design of Prospero was focused on creating a fully functional robot which could be reused and expanded in future years and could compete with more experienced teams. To accomplish this overarching goal, several smaller goals were developed. BeaverAUV designed Prospero to be simple and robust, utilizing as few watertight seals as possible, and only one, large watertight enclosure. To make Prospero as maneuverable and versatile as possible, it was designed to have reflectional symmetry across the XY, XZ, and YZ planes. Prospero was designed to have numerous places to mount additional hardware to add additional functionality in future years. Finally, BeaverAUV designed Prospero to be operated and repaired as easily as possible; the end caps, acrylic hull, and electronics rack are all removable without the use of tools, allowing any electronics or batteries to be swapped out very quickly and easily.

III. Mechanical Systems

Prospero's mechanical systems comprise an aluminum frame, an acrylic hull which is capped by two aluminum end caps, a series of modular mounting rails, and other auxiliary systems. Design of the mechanical systems was completed in CAD (computer aided design) software; specifically, Autodesk Fusion 360 was used. Parts were machined both in-house and through third-party sponsors. A combination of CNC (computer numerical control) routers, CNC five-axis mills, CNC waterjet cutters, and manual tools were used to fabricate parts.

A. Frame

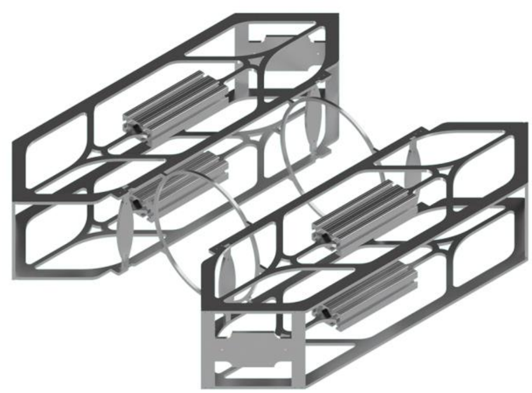

Fig 1. Prospero's aluminum frame.

The main purpose of Prosepro's frame is to define the structure of the AUV and to provide places to mount thrusters and other hardware. The frame was designed to be rigid, highly modular, and expandable. The frame is highly rigid because it is constructed with 0.25" aluminum plate, and assembled with screws rated to meet military specifications. The frame's modularity is a result of its screw-based construction; each component can be easily removed and repaired.

1) Thruster Mounting: In the final version of Prospero's frame, thrusters are mounted in the following positions:

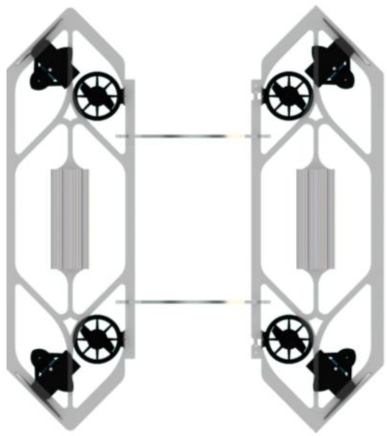

Fig 3. Prospero's final thruster layout.

Four Blue Robotics T-200 thrusters operate in the XY plane to provide translation in the surge and sway directions, and yaw (rotation around the vertical axis). The thrusters are mounted in the four corners of the AUV, at 45 degree angles relative to the AUV's X and Y axes. Although the mounting of the thrusters at 45 degree angles reduces the efficiency of the AUV when traveling at a heading of 0 degrees (straight forward), this layout was selected because it allowed the thrusters to be placed in the corners of the AUV so that they did not interfere with the front-facing camera or rear-mounted hull penetrators.

Four Blue Robotics T-100 thrusters operate vertically to provide translation in the heave direction, as well manipulation of roll and pitch. Earlier iterations of Prospero's frame had different vertical thruster layouts. The first iteration had three vertical thrusters:

Fig 2. Prospero's initial thruster layout.

This design was not used because the rear thruster would interfere with the rear hull penetrators, and would not allow the rear end cap to be easily removed. The second iteration used four vertical thrusters:

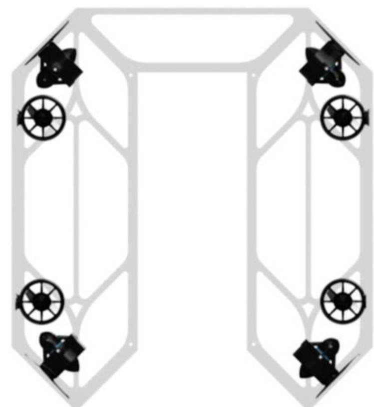

Fig 4. Prospero's second thruster layout.

This design was not selected because the vertical thrusters would impede the water flow of the horizontal thrusters. This led the thrusters to be moved to their final positions.

2) Circular Hull Supports: To support the acrylic hull and to connect the two sides of the frame, two circular supports were placed in the middle of the frame. While these supports do provide rigidity to the frame and support the hull, they have proved to be an insufficient solution. The hull and end caps, when attached to the frame, are still able to move vertically a small amount. This often causes the clamps which hold the end caps to the frame to release. To solve this, 3D printed clips were attached which both secures the position of the end cap relative to the frame, and prevents the clamps from releasing.

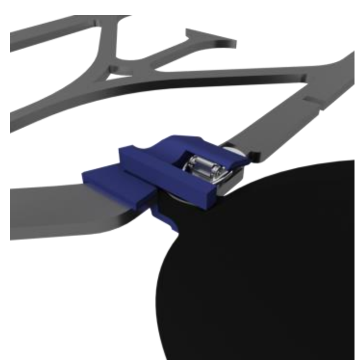

Fig 5. The 3D clip which holds end cap in place relative to the frame.

In future years, a more comprehensive solution will be implemented to more fully support the end caps and the hull.

3) Modular Mounting Rails: To increase both Prospero's modularity and the number of spots to mount additional hardware, four modular mounting rails were added. They are a standard aluminum extrusion which hardware can easily be mounted to and removed from.

4) Screw Selection: All screws used in the construction of Prospero's frame meet military specifications for strength and corrosion resistance [1]. Originally, the frame was assembled with standard pan-head machine screws; however, the heads of two screws later broke off for an unknown reason. After this, all screws were replaced with more durable screws to prevent more screws from breaking.

B. End Caps and Hull

The end caps were designed to cap the acrylic hull with watertight seals, and to attach the acrylic hull to the frame. The end caps were machined from aluminum and then anodized to provide additional corrosion resistance. The front end cap has a port for a front-facing camera, and the rear end cap has fifteen threaded holes which are used to insert hull penetrators to create watertight electrical connections from the outside of the hull to inside the hull. Each end cap is sealed with two O-rings. Small pins are included on each end cap to support the internal electronics rack.

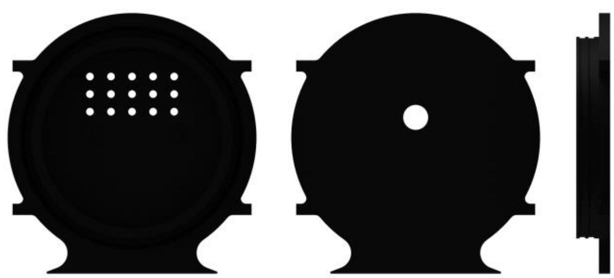

Fig 6. Prospero's rear and front end caps.

Originally, the end caps had heat dissipation fins modeled in to help prevent the electronics from overheating; however, they were later removed from the model because they increased the price to manufacture the end caps.

C. Droppers

The droppers were designed to drop a marker into a bin. The dropper mounts to the modular mounting rails, and the marker is housed inside of the dropper. The dropper is activated by a push-pull solenoid which, when actuated, releases the marker and causes it to fall vertically through a guide tube. The marker is a streamlined torpedo shape with fins to guide its fall. A stainless steel ball bearing was mounted inside the marker to add weight. Both the marker and the dropper were 3D printed.

D. Hydrophone mounting

Hydrophones are mounted to an aluminum plate which is mounted to the modular mounting rails. The hydrophone mount was designed to place the hydrophones as far apart from each other as possible, while still remaining completely rigid. Mounting the hydrophones as far apart as possible makes processing the signals easier; the signals received by each of the hydrophones becomes more different as the hydrophones get further apart.

E. Color Calibration Arm

When completing vision tracking underwater, changes in water quality and changes in the environment can drastically change the image which the camera sees. To solve this problem, a color-calibration card was mounted to an arm on the robot which is actuated by a DC brushless motor. When actuated, the arm pushes the color-calibration card in front of the downward-facing camera. This allows the vision processing to recalibrate while in use if necessary.

F. Trim Sliders

To ensure that Prospero is able to maneuver as accurately and effortlessly as possible, it is important to keep the AUV's trim (weight distribution) even. To allow for easy adjustments to Prospero's trim, four trim sliders were placed on the underside of the AUV. Four aluminum rails are mounted to the underside of Prospero so that they radiate out from the center of the AUV. One pound lead diving weights were attached to 3D printed carriages which slide in the aluminum rails. Adjusting the positioning of these four weights adjusts the trim of Prospero.

G. Electronics Rack

The electronics rack is used to mount all the electrical systems within the hull. It provides space to mount the main computer, microcontrollers, power distribution, and other electrical systems. The batteries are mounted within the electronics rack so that they are unable to move out of position, regardless of the orientation of the AUV. The IMU (Inertial Measurement Unit) is mounted so that it is centered in all three axes.

IV. Electrical Systems

Prospero’s electrical systems were designed to be as simple and robust as possible. Commercially-available parts were used as much as possible to simplify the design and conserve time. Prospero’s electrical systems are mounted on the electronics rack within the acrylic hull. The electrical systems allow Prospero to operate for an estimated three hours of testing on a single charge.

A. Power Distribution

Two 16Ah batteries, each running at 14.8 volts, are used to power the AUV. Each battery is connected to a merge board, which distributes power to the eight total ESCs (Electronic Speed Controllers). Three 5V DC/DC UBEC (Universal Battery Eliminator Circuit) converters are used to convert the 14.8Vdc from the batteries to 5Vdc. This 5Vdc rail is then split to provide power for the main computer and a USB hub which powers other electronics.

B. Central Computer

The main computer is an ODROID XU4. This features Samsung Exynos5422 Cortex™-A15 2 GHz and Cortex™-A7 octa-core CPUs, along with a Mali-t628 MP6 GPU and 2GB of DDR3 Ram. Because it is able to select which of its cores to use at any given moment, the ODROID is able to maintain acceptable image processing and computational speeds, while having low power consumption.

C. Thruster Communication

Each thruster is connected to its own ESC which uses a PWM (Pulse-Width Modulation) signal to control the three coils of the brushless motors. Each thruster is connected to an Arduino Pro Mini which controls the low-level PWM signals which the ESCs receive.

D. Sensors

Prospero uses several sensors to determine its location and orientation in the water.

1) Orientation: Prospero uses an IMU (Inertial Measurement Unit) and a depth sensor to determine its orientation in the water. The IMU is a VectorNav VN-100T Rugged, which provides linear and rotational acceleration data, and rotational data from a magnetometer. A Blue Robotics Bar30 Pressure sensor measures the depth of the vehicle.

2) Cameras: Prospero uses two Microsoft LifeCam USB cameras in order to provide the images used for image tracking. The primary camera is located in the front of the AUV and faces forward. The second camera looks downwards. Both cameras use lenses with a diagonal field of view of 73 degrees. Each camera outputs 1280p x 720p video at 30 frames per second.

3) Hydrophones: Four Aquarian Audio H2c hydrophones are used in an array to interact with the sonar pinger. The hydrophones' only amplification comes from two USB audio adapters, each of which runs on a CM108AH audio processing chip. Each audio adapter process the signal from two hydrophones, reading one signal as the left side signal and one signal as the right side signal. The audio adapters provide 5v bias power which is less than what is recommended for the H2c hydrophones; however, this has proved to be sufficient.

E. Start and Kill Switches

A kill switch is used so that power to Prospero’s thrusters can be cut at any given time if something malfunctions. A start switch is used to signal the AUV to begin to start the run. For each switch, a reed switch is placed inside the hull, and a magnet is embedded in a pin which rests on top of the hull and by default activates the reed switch. When the pin for the start switch is removed, the computer begins to execute the mission code. When the pin is removed for the kill switch, power is cut to a series of relays which cuts power to the thrusters. The computer is signaled to enter an ‘emergency kill’ state which prevents the thrusters from running again until both the start and kill pins have been replaced, and then the start pin is again removed.

V. Software Systems

Prospero’s software systems, like its mechanical systems, were designed to be as modular as possible. The software systems were designed to be object-oriented. Each program has several layers of abstraction to increase modularity and usability. All of Prospero’s software has been open-sourced and is available on http://github.com/BeaverAUV.

A. Robot Operating System

ROS (Robot Operating System) is the main architecture that all of Prospero’s programs are built around. It provides a simple yet robust framework that allows different nodes (individual executable programs) to communicate and share information with each other. This allows for simple passing of data between programs. ROS has a large open source development community that allows it to provide support for many different devices and libraries.

B. State Machine

Prospero uses a state machine to control task management. The ROS package SMACH is used to manage the state machine. Each task which the AUV must complete is programmed to a different state; as each state is activated, the robot executes different programs corresponding to different tasks.

An ‘emergency kill’ state is used when the kill switch is activated to ensure that the thrusters do not continue to run when the robot is powered back on. This allows the kill switch to shut off power to the thrusters without shutting off power to the computer, while still ensuring that thrusters will not continue to run upon returning power to the thrusters.

C. Motor Control

Prospero’s motor control allows accurate movement in six axes (surge, sway, heave, roll, pitch, and yaw). The motor controller inputs the vehicle’s desired movement in these six axes, and calculates how fast to drive each thruster to achieve the desired movement. Each axis is controlled by a PID (Proportional Integral Derivative) controller to ensure accurate movement. Prospero’s PID loops were tuned to ensure consistent performance. First, the maximum speed of the AUV was determined so the PID loops could compare an input of speed from the IMU to the percentage of speed provided by the motor controllers. Then, the proportional, derivative, and integral terms of each PID controller were adjusted until each controller performed consistently.

After the desired thruster values have been determined, the motor control calls several services (functions in ROS which can be used across nodes) to communicate with the Arduinos and control the ESCs. Data is passed to Arduinos over a serial interface. The Arduinos monitor the PWM values and update them as needed.

D. Hydrophones Signal Processing

Prospero’s hydrophone system uses digital signal processing to complete all the filtering and localization of the signal received from the acoustic pinger. The software first works to identify when the pinger is emitting a ping. Then, the signals from the four hydrophones are recorded and stored as .WAV files in two-second increments to ensure that each recording captures an entire ping. An IIR (Infinite Impulse Response) bandpass filter is used to crudely filter the signals. Then, the filtered signals from two hydrophones are compared using cross-correlation to determine the TDOA (Time Difference Of Arrival) of the two signals. The TDOA represents the time difference between when the two hydrophones received the signal; this is converted to a difference of distance by multiplying by the speed of sound in water, about 1482m/s. Using this difference in distance, a hyperboloid is constructed which represents every possible location of the pinger. This is repeated for two more combinations of two hydrophones. After three hyperboloids have been constructed, they are compared to find an intersection which represents the location of the pinger. If an intersection cannot be found, the position of the pinger is approximated by looking for areas where the three hyperboloids come close to intersecting.

E. Vision Tracking

BeaverAUV implemented a vision tracking system that allows for accurate underwater movement using various objects as way-points. Vision tracking is handled by Open Computer Vision (OpenCV), an open source image processing library. Three main algorithms were developed for vision tracking: image thresholding, color calibration and movement calculations.

1) Image Thresholding: After the image is received from the camera, the image is processed in the RGB (Red Green Blue) colorspace. Using a series of preset RGB ranges, all color is removed from the image—aside from those which fall into the predetermined RGB ranges—and then stored as a threshold image. A threshold image is a binary image, where white pixels represent pixels where the original color of the pixel is within the predetermined RGB ranges; black pixels occur when the original color of the pixel is not within the predetermined RGB ranges.

Fig 7: Color Thresholding Example. The image on the left is being processed. The image on the right is the threshold image that results when the predetermined RGB ranges includes the bright orange color.

2) Color Calibration: In water, the perceived color of any given object can change frequently and dramatically due to changes in the environment, especially changes in sunlight. This causes a need for accurate color calibration. In order to calibrate, the image tracking software sets the aforementioned RGB ranges to a set of initial RGB range values which have been chosen through testing. A small card—meant for photographers to calibrate both color and white balance—is used as a reference point to accurately calibrate color. The card has extremely accurate colors printed on it, including the shades of red, green and orange used on RoboSub obstacles. For each color, once the calibration card has moved in front of the camera, the program steps through several variations of the RGB range values. The best settings are determined by measuring the area of the detected portion of the card, and comparing it to the known area of the detected portion of the physical card.

3) Movement Calculations: The tracked object's location relative to the AUV is found by calculating its centroid, and finding the position of the centroid on a XY coordinate plane which is defined by the individual pixels of the image which is being processed. Based on the coordinates of the object's centroid, the movement algorithms decide how to move depending on what task it is currently set to. To do this, the image is split into several sections. These sections change depending on the task. By default, the image is split horizontally into three columns; the center column is the smallest and the left and right columns are equal and larger. If the centroid of the tracked object is in the left or right columns, a signal is sent to the motor control software which causes the AUV to translate or rotate left or right. The center column is then split vertically into three rows. Based on the location of the centroid of the tracked object relative to the three columns, the AUV is signaled to increase or decrease its depth so that the object becomes centered in the coordinate plane. Once the object is within the center section, the AUV is signaled to move forwards, and to automatically compensate if the object moves outside the center.

Fig 8: Default image sections settings.

VI. Experimental Test Results

Testing of Prospero was completed primarily through in-water tests. Before Prospero enters the water, a pump is used to depressurize the hull. This is used to test that the hull is airtight before it is placed in water.

A. Buoyancy Testing

As of the time of the submission of this paper, Prospero has been in water for approximately four hours and twenty minutes. Initial buoyancy tests were completed to determine how much additional weight needed to be added to the hull to cause it to be neutrally buoyant. It was determined that approximately 11.8kg of weight needed to be added to the empty hull to cause the AUV to be neutrally buoyant. Because it is ideal for the AUV to be slightly positively buoyant in case the thrusters stop operating, it was determined that 11.3kg of weight should be added to the hull. The electronics – especially the batteries – account for approximately 4kgs of this, and lead diving weights are used to compensate for the rest.

B. Watertight Testing

Additional tests were completed to ensure that Prospero can remain watertight over an extended period of time. Two small leaks were found in hull penetrators of the rear end cap. It was discovered that water was entering the thruster cables where the wires were connected to the thrusters, and then traveling through the wires and slowly dripping into the hull. The problem was solved by adding additional liquid electrical tape and marine epoxy to the thruster connections.

VII. Acknowledgments

The BeaverAUV team could not have had any of the success which it has had without the generous support of sponsors and mentors. Their financial and technical advice has been indispensable throughout the development of Prospero. BeaverAUV would especially like to thank our faculty advisors: Ms. Elisa Shapiro, Ms. Jayne Everson, and Dr. Zoz Brooks. We would also like to thank the other RoboSub teams, especially CUAUV, which have provided incredibly valuable technical advice which they have gained throughout their previous years at RoboSub.

BeaverAUV would also like to thank our sponsors: Granite State Manufacturing, Blue Robotics, American Steel and Aluminum, MathWorks, and VectorNav. We would also like to thank the administration of Beaver Country Day School which has provided lab space and funding for the BeaverAUV team.

VIII. References

[1] Federal specification: screw, machine, slotted, cross recessed or hexagon head, FF-S-92B, 1974

IX. Appendix – Outreach Activities

BeaverAUV has made an effort to become engaged in the Greater Boston community. Within Beaver Country Day School, team members have aided in middle school robotics programs. Team members have helped teach students 3D modeling, 3D printing, programming, and other robotics skills. BeaverAUV also plans to present their work to the Boys and Girls Club of Lawrence. The team will allow the children at the Boys and Girls club to drive Prospero with a gamepad.