University of Riverside, California Autonomous Underwater Vehicle Design and Implementation of SeaDragon

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***Abstract*—The SeaDragon is an autonomous underwater vehicle (AUV) developed by a team of undergraduate students at the University of California Riverside (UCR). This will be the second underwater AUV developed at UCR for the AUVSI RoboSub competition. The vessel is comprised of a custom built 8020 aluminum frame that supports 8 motors and houses a casted acrylic tube. The motors are configured to provide 6 degrees of freedom and the acrylic tube encloses all water sensitive components.**

I. INTRODUCTION

The purpose of the University of California, Riverside's RoboSub Project is to build an Autonomous Underwater Vehicle (AUV). This project is undertaken by a multidisciplinary team of undergraduates who work to bring all individual subsystems of the submarine into a single, functioning system. Once the submarine is completed, the UCR RoboSub Project plans to bring it to San Diego to compete in the RoboSub International Competition during the last week of July at the TRANSDEC pool in the SPAWAR facility.

II. DESIGN STRATEGY

With the previous submarine, Seagoat, from last year being officially retired due to its degrading structure, a new design has been made to improve upon what fell short with the Seagoat. Using ideas shared by competitors last year, the SeaDragon incorporates newly learned concepts with some original concepts designed by the UCR Robosub Project.

A. Mechanical Systems

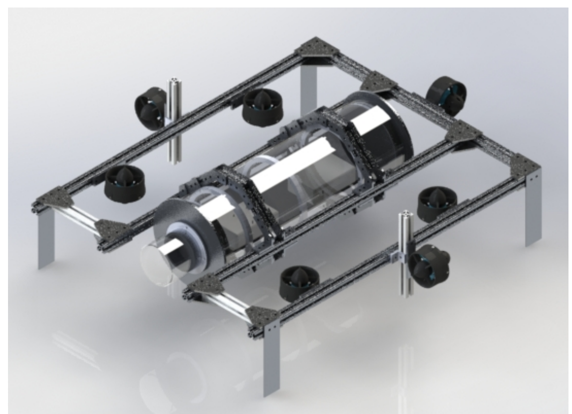

Fig 1. Final Design Render

The main construct of the submarine consists of six systems: the frame, the chassis, motor configuration, electronics rack, claw, and electronics enclosures. Using knowledge from last year's submarine, in regard to what worked and did not work, the current mechanical systems improved upon the Seagoat.

1) Frame: The frame is primarily constructed with 8020 aluminum, with its slotted design allowing for easy attachment of auxiliary parts and manipulability. One type of attachment is the motor mounting bracket.

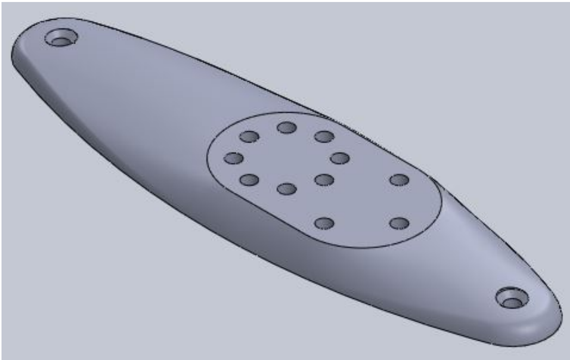

Fig 2. Blue Robotics Mounting Bracket

The Blue Robotics motors have their own custom designed brackets. Figure 2 was a Solidworks model taken off of Blue Robotics' website. [1] to accommodate the 8020 slot, based off the stock Blue Robotics mounting bracket that was used last year. The 8020 bars let the motors slide along them, and one of the concerns with last year's submarine was the distances from the motors to the submarine's center of buoyancy. If the motor placement was fixed, then the thrust exerted by the thrusters could potentially generate unequal moments about the center of buoyancy of the submarine. This could be alleviated by the PID controller, but to save effort for the software team, the sliding mechanic reduces the necessity for a robust PID controller.

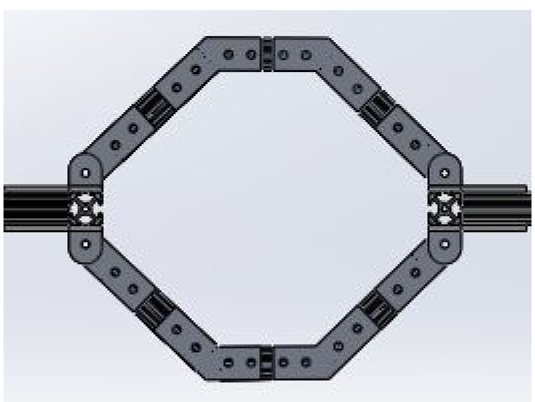

Fig 3. Front View of the Chassis Hex Assembly

As mentioned, the 8020's design for easy attachment of components also played into the placement of the acrylic tube chassis. The idea is to allow easy removal of the tube, so a clamping mechanism was designed to satisfy that idea. For the event of a compromised electrical system due to water breach, the salvageability of the interior electronics is a high priority, so to be able to program the submarine to surface after a leak detection and be able to quickly retrieve the chassis is important.

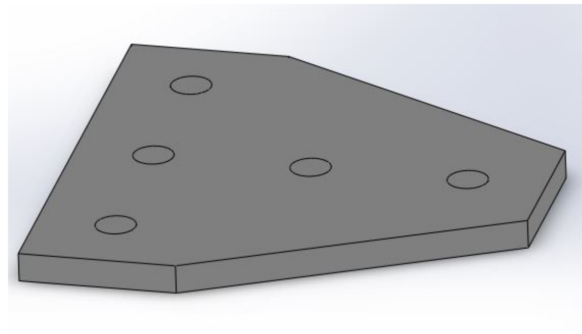

Fig 4. Frame Fastener

Lastly, joining the 8020 bars and components implements custom machined fasteners based on parts available in the market, and this is due to the availability of raw metal supplied by Industrial Metal Supply. One sort of fastener is seen above in Figure 4. Carriage bolts and hex nuts from Lowes are used to secure the fasteners to the 8020 bar.

2) Chassis: The chassis which is the electronics hub is an acrylic tube that has an aluminum shelf.

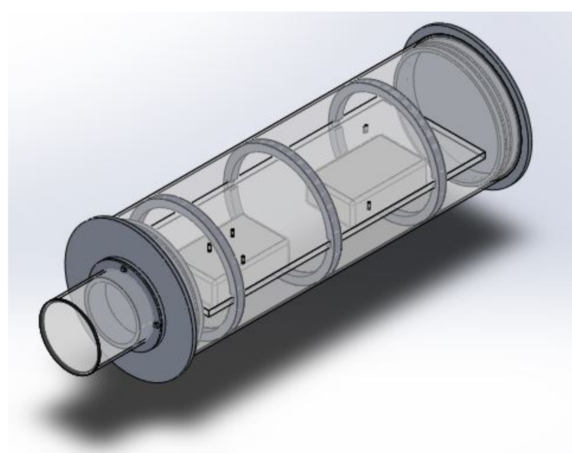

Fig 5. Chassis Assembly

The tube is a step up from the Seagoat's electronics hub, because it is easier to waterproof than the Pelican Case used last year. The circular, cast acrylic tube lets its smooth interior surface to come into contact with sealing o-rings, thus waterproofing was intuitive and simple.

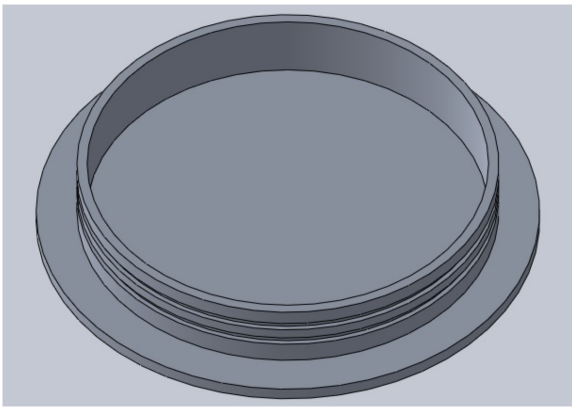

Fig 6. Chassis End Cap

In the figure above, sealing off the ends of the tube uses custom machined aluminum endcaps. The double o-ring sealing introduces an additional barrier in case of water breach, and following what was learned last year, the custom o-rings were made using an o-ring splicing jig to precisely cut rubber cords to match the groove cut into the endcaps. The grooves were dimensioned according to recommended dimensions. [2]

3) Motors and Configuration: The motors and their configuration is the same as the Seagoat's, but more consideration was put in as to why the current configuration is preferred compared to another well-liked configuration.

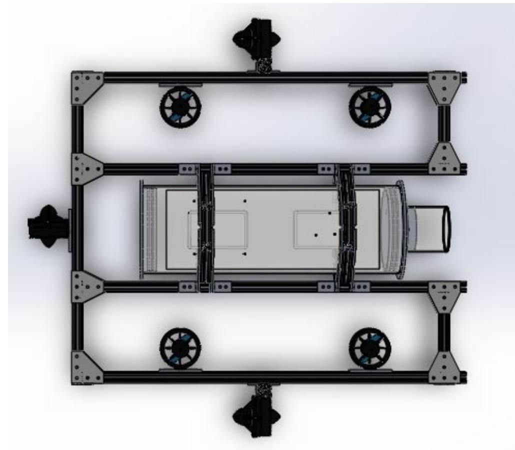

Fig 7. Top View of the Submarine. There are two motors that provide forward thrust and yaw rotation. One motor that is dedicated to yaw rotational thrust. The other four motors provide downward or upward thrust.

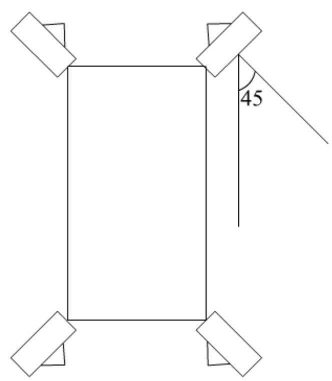

Fig 8. "45 Degree" Offset Thruster Configuration

Based on the thrust (as a function of a reference velocity) exerted by the motors, the power required to achieve the thrust and getting the resultant velocity is:

$$P = F(vref) \cdot v \quad \textbf{(1)}$$

The current configuration would have a net power draw of:

$$Pnet = 2F \cdot v \quad \textbf{(2)}$$

The configuration shown in Figure 8 uses a bit of trigonometry, but assuming a completely 45 degree offset, then the power draw for forward thrust would be:

$$Pnet = 4 \cdot Fcos(45) \cdot v \quad \textbf{(3)}$$

$$Pnet = 2.83F \cdot v \quad \textbf{(4)}$$

Comparing the power draw to a fixed thrust input shows that to use the configuration in Figure 8, it would draw 41.5% more power than the current configuration.

4) Electronics Shelf: The electronics rack is made out of a sheet of aluminum. This sheet was machined down to the dimensions of 1/4x7.5x15 6/8 inches. Being that the shelf is made out of aluminum, the plate also acts as a heat sink for all the electronics. The tradeoff however is that having a machined part requires additional manufacturing and equipment. Another tradeoff is weight. Instead of using aluminum, a lighter material could have been used.

5) Claw: The claw manipulator utilizes a drawer slide for linear actuation. A servo drives the drawer slide through a rack and pinion design. With the claw 3D printed and attached to the end of the slide, a servo is provides the actuation for the closing of the claw. The claw design is illustrated in the figure X below.

Fig 9. Claw Design

6) Enclosures: With all the major electrical components housed within the acrylic tube. To pass the wires through the enclosure, Blue Robotics cable penetrators were used. A side profile of how the penetrator interfaced with the inside of the submarine to the outside is illustrated in figure 10. [3] This penetrator is seated through machined holes of the end caps of the chassis.

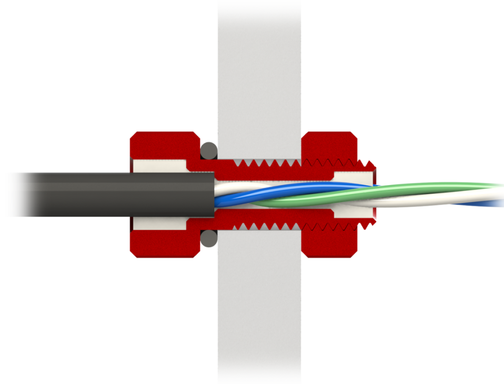

Fig 10. Blue Robotics Connectors

The camera housings bear a similar design to the main chassis. The camera is housed inside a smaller casted acrylic tube, and has an end cap to allow for accessibility to the inside. The wires are fed through the end cap using a penetrator. Instead of another end cap on the other side, a circular sheet of acrylic is bonded to the tube. To keep the camera in place, a 3D printed mount secures the camera to the tube.

7) Concepts: The figures 11 and 12 are some of the concept drawings for the frame and chassis of the submarine.

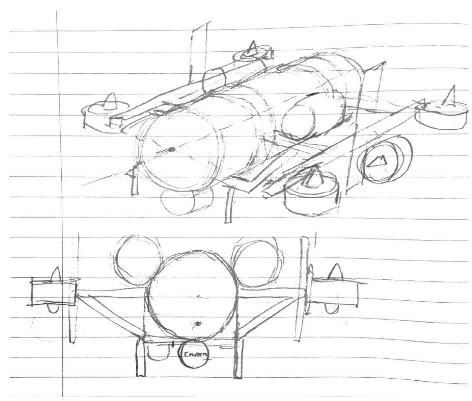

Fig. 11. Concept Design 1

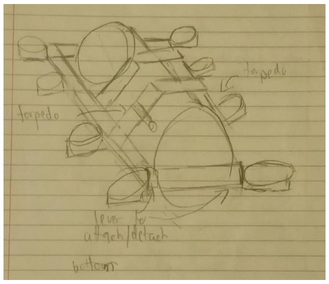

Fig. 12. Concept Design 2

B. Electrical Systems

1) Power Systems: The submarine is powered by two 4 cell, 14.8 volt, 12000 mAh, 30C VENOM lithium Ion batteries. The power is distributed using a Matek HUBOSD8 power distribution board. This board provides the necessary voltage to all onboard sensors and thrusters. An LM317T voltage regulator is used to step the 14.8 volts down to 5 volts in order to power all microcontrollers. All thrusters can be instantly switched ON/OFF through the use of a high amperage MOSFET and a magnetic switch.

2) Control System: There are multiple controllers in the sub to run its many tasks. The main “brain’ of the submarine is the Intel NUC, which is used for mission planning and computer vision processing. Two STM32s and a BeagleBone Green are used to communicate between sensors and the NUC.

3) Hydrophones:

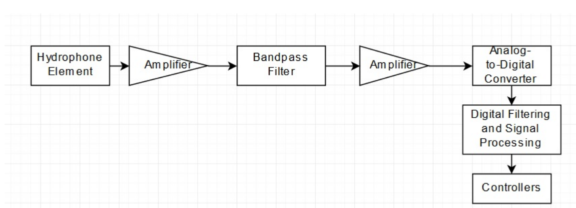

Fig 13. Hydrophone Signal Flow Chart

The hydrophones elements in use are the Teledyne Reson TC4013 hydrophone.

Fig 14. TC4013 Hydrophone

These elements are usable at frequencies between 1Hz - 170 kHz, which more than accommodate for the frequency ranges of the pinger. These elements can be arranged in an array in conjunction with various methods of detecting the direction of a pinger. The method utilized for the hydrophone array is time delay between the hydrophone elements. Each signal received by the elements is initially put through an amplifier and analog filtering. The amplifiers used for this system is the LT6200 op amp. For analog filtering, a custom built 5^{th} order bandpass filter was implemented, which attenuates frequencies not within the 20-40 kHz range. The signals are then amplified and converted to digital signal via an Analog-to-Digital Converter (ADC). A Butterworth digital filter implemented by the NUC further attenuates unwanted frequencies. With the desired frequency, the NUC will compare the signals received and send a heading to the controllers. This system was not able to be implemented due to time and budget constraints.

4) IMU: To obtain inertial data of the sub, an MPU-6050(triple axis accelerometer, triple axis gyroscope) and an HMC5883L (triple axis magnetometer) are used. An STM32F411 microcontroller communicates with these sensors through I2C protocol. The data is then fused using Madgwick & Mahony’s MARG (Magnetic, Angular Rate, and Gravity) filter to obtain accurate yaw, pitch, and roll angles.

Fig 15. MPU-6050


Fig 16. HMC5883L compass

c) Pressure Sensor


Fig 17. Bar30 pressure sensor

The pressure sensor being used is the Bar30. The pressure sensor implementation allows the sub to verify depth changes and whether there has been a leak in the sub. The operating pressure at which the sensor operates is rated at 0-30 bar (0-300m in water).

5) Microcontroller Shields: Multiple single sided circuit boards were made to be used a shields for the STM32. The power management shield allows the STM32 to connect to all 16 temperature sensors, 7 current sensors, pressure sensors, and humidity sensor. Current sensors were used to monitor the amount of current being drawn from each thruster. In the case of excess current draw, all power will be shut off and the vehicle will surface. The humidity sensor allows for easy detection of a leak in the sub. The motor shield allows for easy connection between the esc's and the STM32.

C. Software

1) Operating Systems: The majority of the code written for this project is done so on a linux operating system running on the Intel NUC. Linux is a common operating system for development courses at the University of California Riverside, and was chosen due to the team's familiarity with it. This choice created several challenges for the team as linux is a desktop operating system, rather than a robotic operating system.

2) Finite State Machine: A finite state machine framework was developed to control real time tasks using POSIX interfaces on the linux operating system. This state machine framework was designed using object oriented design principles and based on a procedural state machine design by Frank Vahid for the Embedded Systems courses at the University of California, Riverside.

Using a real time state machine separates the behavior of the system into separate state actions. The state actions are executed periodically in consistent time intervals. This real time consistency allows for the synchronization of parallel and dependant tasks in the overall design.

3) Vision: The visual recognition software designed here uses salient object detection to analyze the shape and color of objects using OpenCV libraries. This data is then compared against an array of objects known to be in the competition pool to determine which object is to be targeted.

The saliency algorithm used here is the fine grained saliency algorithm included in OpenCV's github repository. The contours of the salient objects are then extracted and used to create bounding ellipses. These ellipses are then used to extract the average color value of the bounded region in the original image. Color values are then combined with the contour information from the saliency map to create an array of objects which are described by their position, shape, and color which can be passed to a mission control task for use in automation.

4) Recording: It should be noted here that the software team believe machine learning algorithms can be used to create a much more reliable computer vision algorithm. A requirement of machine learning is a large amount of collected data from which to learn. So it has been made a point that the current design will collect data in the way of recording video of all runs in the competition pool which can be used for future teams as training and testing data in machine learning algorithms.

III. VEHICLE DESIGN

A. Mechanical Systems

1) Frame: As mentioned before, 8020 was selected as the primary material to construct the bulk of the frame. To reduce the weight as much as possible while maintaining some rigidity, the 1 inch square cross-section bar was selected to satisfy the concerns for weight, price, and strength. With the profile seen, ¼ inch by 1 inch carriage bolts fit in the slot of the 8020 fairly well, because of its square shape just below the head of the screw. At many occasions though, there were screws that could not fit because the tolerances had a significant variance. As a cheap solution, putting in effort to find the best screws to fit in keeps the expenditures low. For the weight concerns, it was more viable to design a submarine to be light as possible, not only to satisfy the rules of the competition, but also to allow flexibility for future planning. Mass can always be added, but if the submarine is carelessly designed without consideration for weight, removing mass to lighten the submarine is a more difficult task than to add mass.

2) Chassis: The acrylic tube is a significant demarcation from the Pelican Case in the Seagoat. Originally, the Seagoat did experiment with an acrylic tube similar to the Seadragon, however, the budget and resources did not create a usable system, so a modified Pelican Case was put in place of the tube. The team took advice from other schools, and learned that a cast acrylic tube was better than an extruded tube for a face seal, due to less protrusions on the surface. Hence, the Seadragon uses a 8.25 inch by 24 inch cast acrylic tube to be the electronics hub. The larger volume in comparison to the Pelican Case used last year gives the team more flexibility electronics planning and more space to work. For future generations of Robosub, having the large space allows them to build upon the submarine iteratively.

3) Endcap: The endcaps were machined by Martinez and Turek, Inc according to parts designed by the mechanical team. Seen in the figure below, the endcap was based on two primary goals: to seal, and to be able to remove. However, several issues arose upon receiving the machined parts. First, the initial diameter of the endcap with respect to the tube's inner diameter was too large, and could not fit into the tube. Thus, the endcap was filed down to allow a small clearance fit into the tube. Second, the volume of air inside the tube made fitting the endcap inside the tube another task to fix. The solution was simple, however. A 23/36 inch hole was drilled into the endcap, and tapped following the NPT standard for a ½ inch plug. [4] The plug was put into the endcap, and wrapped with teflon tape and lubricated. With the plug prepared, one endcap was put into one end of the tube, and the endcap that was tapped was put on the tube. The hole allowed the air inside the tube to escape, and then when both endcaps are on, the plug was put in so the tube with the endcaps were enclosed.

IV. EXPERIMENTAL RESULTS

1) Waterproofing: The waterproofing methods is broken down into several phases: I) once the endcaps were prepared, the sealability between the tube and the endcap is tested II) following the success of phase I, the second phase tests the Blue Robotics Penetrators seal, after drilling into the endcap. III) the third phase is the final waterproofing step, and tests the submarine's electronics. Any additional steps is continual testing of the submarine software and AI.

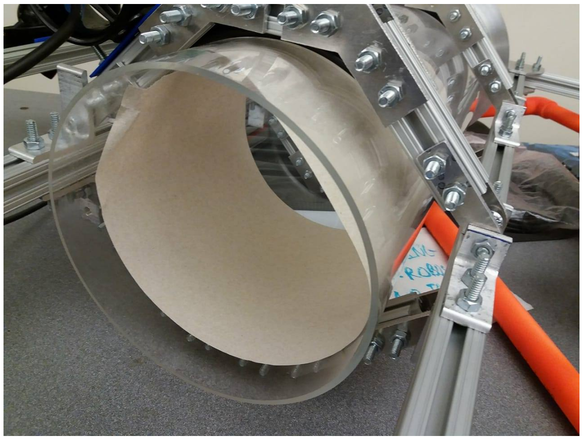

Fig 18. Paper towels lining the acrylic chassis in preparation for water testing.

To determine the leak locations of the chassis, paper towels line the inside of the acrylic. This is demonstrated in figure 18. As well as the walls of the tube, paper towels are also wrapped around the wiring. At the time of this journal being published, the chassis being fully waterproofed was yet to be achieved.

V. ACKNOWLEDGEMENTS

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- Mathaudhu Research
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