Design of the Steelhead Autonomous Underwater Vehicle for the International RoboSub Competition

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***Abstract*—UBC Subbot's submission to RoboSub 2023 is the Steelhead Autonomous Underwater Vehicle (AUV). A competition strategy is introduced which influences the following sections on design. We include novel elements design and produced in-house consisting of a uni-body aluminum enclosure and lid, custom gaskets and internal mounting, actuator and torpedo system, system control, navigation procedures, object recognition pipeline. We also include various examples from tests and experiments, and a second AUV for the purpose of parallelized developmental testing.**

***Index Terms*—robotics, navigation, autonomous, controls**

I. COMPETITION STRATEGY

Our competition strategy comes from prioritizing adaptability and reliability. As a fairly small team with limited resources, we focused on ensuring that the robot can complete tasks that are earlier in the competition while being mindful of potential design decisions in future iterations. Although the specific competition tasks are unknown every year, there are consistencies such as path finding, recognizing objects, manipulating objects, etc. With this in mind, we prioritized general functionalities such as object classification underwater through computer vision, general sensor systems, and a propulsion system with 5 degrees of freedom. We expect our robot to pass the gate and follow the path markers to the first task. Second, we aim to pick up the plate handle for the next task. Our adaptable design approach will let us improve our robot for future competitions to tackle more sophisticated competition tasks.

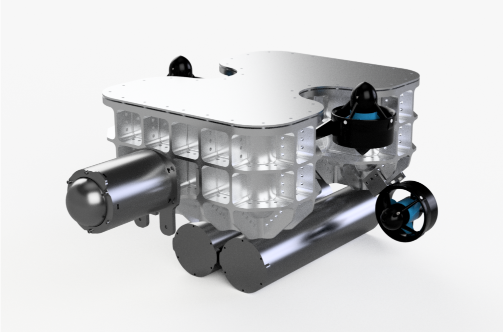

Fig. 1: Full robot CAD render

At competition, we plan to use 5 degrees of freedom and the five-thruster configuration to maneuver the vehicle and propel it through the gate. Before the competition begins, we will test our robot at the competition pool and calibrate it to adapt to the competition environment. Testing over multiple hours of the day will prepare the robot to handle different lighting and visibility conditions during competition.

II. NOVEL DESIGN ELEMENTS

A. Main Enclosure

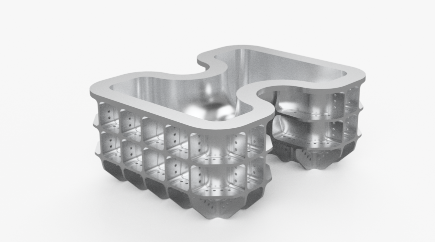

Fig. 2: Steelhead Hull

1) Design Goals: The primary objectives for the redesign of our main enclosure for Steelhead came from our past experience designing AUVs. First, We required a large enclosure that is easy to prototype and work in, both from the inside and outside, and that could function as both a pressure vessel and the primary chassis structure for our AUV to reduce mass and complexity. Second, We designed the enclosure not just to meet our needs for the present, but also the future. We specified a requirement for a 100m depth rating and corrosion resistance in marine conditions, and we designed features that will make the enclosure adaptable to future designs. Last, we had acquired a 100 kg block of aluminum at at scrap prices, which predefined our material selection and manufacturing methods for the main enclosure.

2) Uni-body Aluminum Hull Form: The hull consists of two halves, bridged together with a saddle shaped, semi circular tube, as shown in Figure 2. This unique geometry was largely driven by the need to shield the thrusters. Moreover, Having two halves reduced the peak stresses compared to a box design with similar dimensions. This was developed through multiple iterations using a combination of conventional calculations, finite element analysis, and generative design tools from Autodesk Fusion 360. The outer ribs further the compliance of each face, allowing us to make the hull walls thinner, while also providing convenient mounting structures for components. A tertiary feature of the ribs were increased heat dissipation into the surrounding environment, as electronics would be thermally mounted to the interior walls of the hull. A strut at the bottom center of the hull was added to provide further rigidity in the longitudinal direction and double in function as a mounting point for the lateral thruster.

3) Hull Production: The production of our hull was conducted with a focus on cost savings. We procured a large block of 6061 T-6 Aluminum from a local tool and die maker and used this for our unibody hull. First, we faced the block on a manual mill to ensure the sides were flat and square. We then cut pockets and drilled holes into the faces along the longest axis of the block, as shown below in Figure X. The manual mill was used because of its larger cutting area. Next, we moved the block to the CNC mill for the more detailed interior elements. We used a Tormach 1100 MX for this operation. Because of the limitations with tool holding and stiffness concerns, we limited the cuts on the Tormach to 60 millimeters. After this operation was complete, we moved the hull to a larger HAAS UMC-750 for the deeper cuts. This tool is paid for based on time, so we wanted to limit the time on the machine as much as possible. We consulted with the technicians who work for the UBC mechanical engineering department in order to optimize our cutting operation and minimize the machine time required. For our hull, the most important surface finish is that of the mating surfaces to the lid, near the top of the enclosure. For these surfaces, we worked with the UBC mechanical engineering technicians to ensure we had the best possible finish. The other surfaces in the hull were less critical, so their finish could be sacrificed for faster machining time.

4) Custom Neoprene Seals and Lid: The custom seal derived its design from O-rings around a cylindrical enclosure. Our main enclosure has an unconventional shape which prevented us from using off-the-shelf O-rings. By looking at different water-tight enclosure designs, we decided to use two seals: one mated with the surface of the enclosure and the other mated with the wall of the enclosure (Figure 3). Two seals would provide redundancy in keeping the enclosure water-tight. The lid itself was produced in a similar manner to the main enclosure.

5) Internal Component Layout and Mounting: The enclosure was split into two distinct zones. One was for ”high-powered” electronics such as ESCs, high-current cabling, and actuator controllers. The other was for ”low-powered” and sensitive components such as hydrophones, underwater cameras, the main computer, and the tether interface. Each side had their own suite of penetrators and their own battery connection, which decreased the likelihood of signal interference. This also limited the need for longer cable runs.

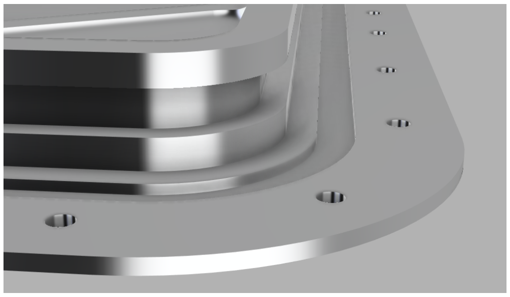

Fig. 3: One seal goes on the horizontal face, while another is on a vertical face.

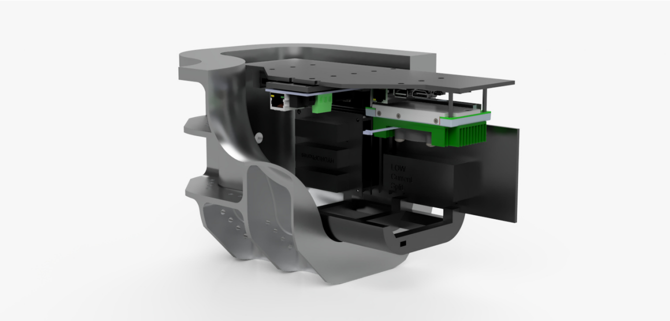

Fig. 4: Low Power Mounting System

To mount these components, the electrical components were mounted around the location of cable penetrators, utilizing a wall and ceiling mounting system as seen in Figure 4. Determining which components to mount on the lid and which to mount on the side were found by tracking which components shared the most connections together, minimizing the amount of connector plugging required when moving the lid.

Circuit boards for the hydrophones or the actuators were stacked with standoffs on 3D-printed boards that utilized a grid pattern to accommodate various layouts of circuit boards. Cable Management was done via zip ties and glued-in 3D printed cable guides.

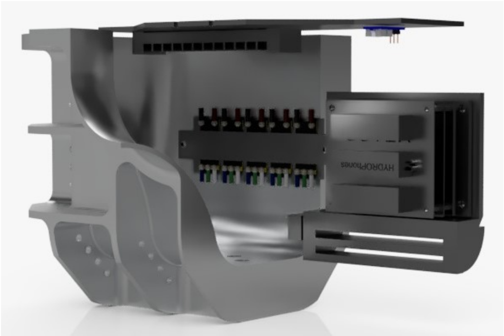

Fig. 5: High Power (ESC) Mounting

In the high-power zone, ESCs were mounted on a plate with their heat spreaders directly on the enclosure walls, then further separated by insulators, evidenced in Figure 5. By doing so, the heat would dissipate into the aluminum enclosure and to the surrounding water.

B. Auxillary Systems

1) Battery Enclosures: The battery enclosures are auxiliary cylindrical enclosures mounted under the main enclosure. These were chosen to be separate in order to allow for the changing of batteries during competition. To mount them, a custom ring clamp locked with a compression latch was implemented for tool-less mounting. The electrical connection implements external connectors from Blue Trail Engineering, adapted for our uni-body enclosure. This allows us to swap the batteries without opening the main enclosure, maintaining watertight reliability.

2) Actuators Gripper Claw and Torpedo: The actuation system consisted of two main components: the gripper, and the torpedo launcher. The torpedo launcher is a spring actuated system capable of firing two torpedoes in succession. Along with the other actuator components, they are powered by a 20-Kilogram servo motor that was modified to being fully waterproof. The torpedoes are pre-loaded with the springs, held in place, then released using the servo motor. The torpedo design uses a longer body with a consistent cross section after the sharp tip and 4 fins at the base. The gripper is single axis claw system capable of downwards movement and retraction under the AUV. The claw uses long, thin claws with a rack and pinion design for reaching under the chevron's top plate and clamp it from the sides then lift the chevron from that top plate. It can also be used for the "bins" task, since the claws can drag the handle of the lid.

C. Control System

1) Main Control System: The control system of Steelhead consists of five major components: a trajectory generator, a waypoint system, a PID controller, an unscented Kalman filter (UKF) state estimator, and a thrust allocator.

The trajectory generator receives target poses from the computer vision system. Based on the type of the target, it generates a series of waypoints for the waypoint system. This series of waypoints allows the AUV to move in an optimal way, like keeping the target in sight, and taking advantage of the AUV's higher maneuverability in the x- and yaw-axis.

The waypoint system keeps track of the state of the AUV and the target state, calculating the error between them for the PID controller. In addition, it notifies the trajectory generator when a waypoint is achieved so that the AUV can move on to the next target.

The PID controller controls four degrees of freedom: linear, horizontal straightness, vertical straightness, and yaw. The AUV relies on the positions of the center of mass and center of buoyancy to passively control roll and pitch. The output is a vector of desired forces on the four degrees of freedom that is passed to the thrust allocator.

The thrust allocator takes into account the surge, heave, and sway contributions of each thruster, as well as its position relative to the center of mass. This allows it to adequately allocate force output for each thruster to achieve the desired movement. The configuration of thruster allocation is highly configurable, and it allows for up to six thrusters for future-proofing.

The UKF state estimator uses input from sensors like the IMU to estimate the current pose of the AUV. UKF is chosen for its more accurate estimation of non-linear systems and ease of sensor fusion.

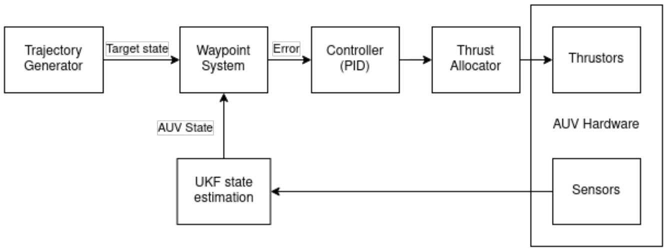

Fig. 6: Block diagram of the software control system used by the Steelhead AUV.

2) Actuator Control: We employ a dedicated Teensy 4.0 microcontroller for control of our actuator servos. This board is soldered via pin headers to a breadboard-style through-hole PCB mounted within the main enclosure. The servos and accompanying actuators are situated outside of any enclosures and were made waterproof. The servo wiring enters the main enclosure through the rear end cap via waterproof cable penetrators. These wires are then soldered to the aforementioned PCB such that they align with any of the Teensy's digitalWrite enabled output pins. Each actuator operation (e.g., the firing of one of our two torpedoes at a time) is mapped to a different digitalRead enabled input pin. Once the computer vision module determines it is the appropriate time to activate an actuator operation, it sends a high signal to the corresponding input pin on the Teensy. This activates the corresponding pre-programmed servo procedure, thereby initiating the relevant actuator operation. The Teensy's firmware was written using the Arduino IDE with Teensyduino add-on.

3) Architecture: Our software architecture uses the ROS2 framework and runs on a Jetson TX2. ROS2 provides various common robotics tools, allowing us to focus on developing the custom behaviors of our AUV. Extensive logging capabilities of ROS2 also allow for easy debugging and diagnostics. In addition, ROS2 is language-agnostic, so different parts of the system can be written in different languages. For applications requiring low-latency processing, we use C++, while Python is used primarily as a high-level interface for managing our pipeline. Our custom pipeline manager can be configured to execute arbitrary sequences of actions, starting and stopping nodes based on published feedback according to criteria we define.

D. Computer Vision System

1) Object Recognition: The gate and marker tasks require detection of orange objects. For these tasks, we segment the image in the HSV colour space, which better models perceptual changes in colour than RGB. We then apply a convex hull algorithm to detect the gate and markers. After detecting these objects, we perform simple pose estimation relative to the AUV, providing targets for the control system. Before any image processing, we also correct the distortion of images due to the lens or enclosure.

III. INTEGRATION, VERIFICATION, VALIDATION

During production, it was essential to verify the feasibility of designs in parallel. With out team's resources, we sought to integrate different parts of the system in different stages, testing them in their respective environments, verifying and validating that they do indeed meet the design requirements.

1) Software Simulation: Our testing and verification focus was on our simulation environment since it provides a cheaper, safer, and faster way to test our AUV, as well as collect ample synthetic data.

The simulation environment we deployed was developed using the open-source simulation tool Gazebo, which allowed us to create a simulation description format (SDF) file representing our robot. The SDF description imported an STL-format model of our robot from SOLIDWORKS and applied mechanical properties such as inertia and damping to generate realistic restoring forces on the vehicle. Using this environment, we developed camera, position, gyroscope and depth sensor emulators, as well as thruster driver emulators in the form of plugins that interact with our control pipeline. We implemented buoyancy and hydrodynamic force plugins that use the second-order equations of motion for the AUV, including position, velocity and acceleration values at each iteration of the simulator's update loop. These calculate the environment forces acting on the AUV at any given time. Other than in-house plugins, we also made use of open-source Gazebo plugins for robot localization and IMU emulation.

Using models of the AUV and gate, we were able to test our control and gate detection systems. During simulation, the AUV was able to reliably detect the gate, calculate the forces required to move to the gate, and apply those forces using thrusters. With limited pool access, simulation allows us to iron out issues with our system, and be more efficient during pool testing in the real world.

2) Material Testing: Extensive testing was necessary to ensure that all design requirements were met due to the challenging nature of designing and constructing this component. A goal for our team is to be more environmentally conscious by looking for local sources for materials. Manufacturing companies tend to have discarded material once they complete their contracted orders. The team went to local metal recycling sites and collected material suitable for Steelhead. Certain specifications of quality are required for the AUV's environment, which meant careful pickings at recycling sites. For our stock, we knew the material was Aluminum but did not know exactly which alloy. We obtained a some data through material testing to see if they met our standards. The methods we had access to aren't the best, but it provided enough information to understand and advance our design.

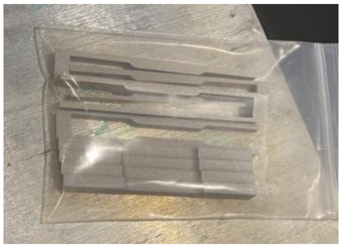

Fig. 7: Test samples cut from the stock of mystery aluminum

The examination used was a tensile test and required some preparation before testing. To perform tests, we sought support from the Department of Materials Engineering at the University of British Columbia. We prepared samples to the lab's standard by producing a small billet for testing before further processing it. The tensile sample was in the shape of a square with dimensions, of 6mm x 6mm. A special machine cut the Aluminum outlines which cuts in and around, leaving a sample used for testing. During the preparation procedures, there was a degree of uncertainty, meaning the dimensions given may not be exact. To improve precision, we conducted multiple test runs was to account for errors. There were a total of 4 tests which can be seen in Figure 7.

One test we performed subjected the sample to a tensile load where we examined the potential UTS (Ultimate Tensile Strength) of the material. It was important to do this, as we were uncertain of the material's worst case scenario. This was a concern for production as the material could be too difficult to machine. In another test, we measured the stress exerted through elongation. Afterwards, the data was used to measure the stress and strain of the material. We initially thought the material was Aluminum T6 6061. Through analysis however, the material had a higher stress value and a lower strain, suggesting 2024 alloy. Based on our initial material requirements and comparing it to our preliminary design, the material was suitable for the main enclosure.

3) Enclosure Testing: To test the feasibility of a custom enclosure, a few items were produced. A small scale version of the hull and lid were made to test our production capabilities, shown in Figure 8.

Fig. 8: Scale model test enclosure

With this small enclosure, we found the optimal strategies for working with our material to produce the tolerances that we desired. Additionally, we also tested a new tool for creating the channels for a custom seal. We used a keyseat cutter on another scale model resulting in a wall-face channel for the Neoprene seal.

4) Seal Testing: A test using Blue Robotics enclosures was devised as a benchmark for proper o-ring enclosure design. We tested 2 seal-joining methods: adhesive bonding, and vulcanization. We utilized an instant contact adhesive from Weicon made for Neoprene o-rings. For the vulcanization method, we heated a thin hobby knife to a temperature that would melt the o-ring ends, then once melting each end, joined them. This was then placed into the Blue Robotics 8" Series enclosure in Figure 9.

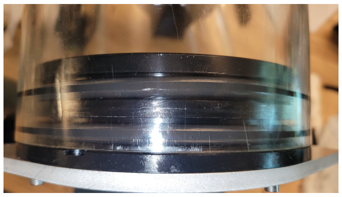

Fig. 9: The 3/16" Neoprene O-ring installed into the 8" Blue Robotics Flange

Due to limited access to a pool or a similar large body of water, we opted to perform the test with the vacuum method, where a difference in pressure between the inside and outer atmosphere would simulate a certain depth of water. This was done using a hand-operated hand-pump with a dial indicator reading the current pressure inside the sealed hull. We first calibrated our pump to measure drop in pressure, then we installed a vacuum vent plug on the enclosure and pulled the vacuum to be equivalent of being 6 metres underwater. The result was a success, as the only drop in vacuum pressure was the calibration that we performed on the pump itself.

5) Triton Mini: The creation of a testing AUV was born from a need to integrate multiple aspects of the system onto one platform during the construction of Steelhead. The first plan was to adapt the previous robot "Triton" into a testing platform, but we opted to transplant some systems into a smaller, more manageable package. This mini-AUV in Figure 10 is made of of four systems: the main enclosure, thrusters, battery, and cameras.

The AUV was quick to assemble and disassemble. Components were be able to be replaced and moved to the primary AUV when testing is complete. It also mirrored the electrical layout that was installed on Steelhead, primarily the thruster control components. The thruster arrangement mimicked the one planned for Steelhead. These are demonstrated in Figure 10

The components involved were the same as those that would be used on Steelhead (See Appendix A). All of these components were not installed in a way that caused an irreversible change to its base configuration. For example, ESCs and motors were not soldered together but rather utilizes high-power crimp connectors. The actuator was not installed on this platform, and only one battery was used due to shorter run times.

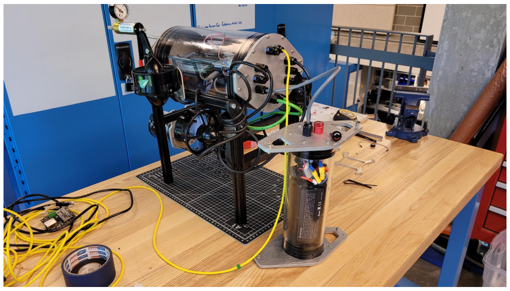

Fig. 10: TritonMini

With the assembly and deployment of TritonMini, we were able to determine shortcomings in the electrical integration of the system, while also giving our team experience in AUV assembly. In particular, we found that there was an issue with signal noise in the camera cabling as they were too close to the high-frequency cabling of the ESCs. We were also able to estimate the total power draw when the system is operating. The software team was able to finally deploy their new navigation system into the real world, while not needing to wait for the full completion of Steelhead.

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Appendix A: Triton AUV Component Specification

Component	Vendor	Model/Type	Spec	Cost (if new)	Status
Foam Ballast	Salvaged	closed-cell polyurethane foam	Unknown	Legacy	Installed
Stainless Steel dive Weights	Blue Robotics	SS Ballast Weight	https://bluerobotics.com/store/watertight-enclosures/ballast/ballast-200g-r2-rp/	12x$9.00	Installed
Frame	In-house	190lbs aluminum		$840	Machining
Waterproof Housing: Battery	Blue Robotics	3" watertight enclosure	https://bluerobotics.com/store/watertight-enclosures/3-series/wte3-asm-r1/	Legacy	Installed
Waterproof Housing: Cameras	Blue Robotics	3" watertight enclosure	https://bluerobotics.com/store/watertight-enclosures/3-series/wte3-asm-r1/	Legacy	Selected
Waterproof Housing: Hydrophone	Blue Robotics	3" watertight enclosure	https://bluerobotics.com/store/watertight-enclosures/3-series/wte3-asm-r1/	$184.00	Selected
Waterproof Connectors	Blue Trail Engineering	Cobalt 14 Bulkhead Connectors	https://www.bluetrailengineering.com/product-page/cobalt-14-bulkhead-connector	$506	Installed
Thrusters	Blue Robotics	T200 Thruster	https://bluerobotics.com/store/thrusters/t100-t200-thrusters/t200-thruster-r2-rp/	5x$179 + Legacy	installed
Motor Control	Blue Robotics	Basic ESC	https://bluerobotics.com/store/thrusters/speed-controllers/besc30-r3/	5x$27 + Legacy	Installed
High Level Control	Teensy	Teensy 4.0	https://www.pjrc.com/store/teensy40.html	$19.95	Purchased
Propellers	Blue Robotics	T200 Thruster Propellers		Included with thursters	Installed
Battery 1	Blue Robotics	Lithium-ion Battery (14.8V, 18Ah)	https://bluerobotics.com/store/comm-control-power/powersupplies-batteries/battery-li-4s-18ah-r3/	Legacy	Installed
CPU	NVIDIA	Jetson TX2	https://developer.nvidia.com/embedded/jetson-tx2	Legacy	Installed
CPU Carrier Board	Connect Tech	Orbitty Carrier for NVIDIA® Jetson™ TX2/TX2i	https://connecttech.com/ftp/pdf/ASG003.pdf	Legacy	Installed
Internal Measurement Units (IMU)	Fidget	PhidgetSpatial Precision 3/3/3 High Resolution	https://www.phidgets.com/?&prodid=32	Legacy	Installed
Camera	Blue Robotics	Low-Light HD USB Camera	https://bluerobotics.com/store/sensors-sonars-cameras/cameras/cam-usb-low-light-r1/	2x$99.99	Selected
Hydrophones	Aquarian	AS-1 Hydrophones	https://www.aquarianaudio.com/as-1-hydrophone.html	5x$395	Purchased
Depth Sensor	Blue Robotics	Bar30 High-Resolution 300m Depth/Pressure Sensor	https://bluerobotics.com/store/sensors-sonars-cameras/sensors/bar30-sensor-r1/	Legacy	Installed
Programming Language 1	C++			Free	Installed
Programming Language 2	Python			Free	Installed
Open Source Software	ROS2	Foxy Fitzroy		Free	Installed
Algorithms: Vision	In-house	Underwater Image Synthesis, Gate/Marker Detection		Free	Installed
Algorithms: Acoustics	In-house	Bandpass FIR Filter, Cross Correlation, Time Difference of Arrival, Multilateration, Beamforming		Free	Selected
Algorithms: Navigation/Control	In-house	PID controller		Free	Installed
Algorithms: Localization	Charles River Analytics, Inc.	Unscented Kalman filter	https://github.com/cra-ros-pkg/robot_localization	Free	Installed
Battery Management System	In-house		circuit designed from scratch from basic components	$100 (PCB + components, for both batteries)	Installed
Team Size			20		
Expertise Ratio (Hardware:Software)			19:7		
Testing Time: Simulation			30h		
Testing Time: In-water			0h (COVID restrictions)		