Design of the Steelhead Mini Autonomous Underwater Vehicle for the International RoboSub Competition 2024

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***Abstract*—UBC Subbots' submission to RoboSub 2024 is the Steelhead Mini Autonomous Underwater Vehicle (AUV). A competition strategy is introduced which influences the following sections on design, followed by a breakdown of design strategy. A discussion regarding the in-house design and production of novel elements includes aspects such as machined aluminum enclosures and lids, custom gaskets and internal mounting, an actuator and torpedo system, system control, navigation procedures, and an object recognition pipeline. We also include results from tests, experiments, and simulations, and a second AUV for the purpose of parallelized developmental testing.**

***Index Terms*—robotics, navigation, autonomous, controls, subsea, undergraduate, ROS, materials**

I. Competition Strategy

In preparation for Robosub 2024 we have focused our efforts transitioning from our Robosub 2023 AUV, Triton Mini, to our improved design, Steelhead Mini. This design implements a variety of new features including actuating capabilities and an additional degree of freedom (DoF). Our aim is to attempt as many tasks as we can, thus we prioritized general functionalities such as pathfinding, computer vision, maneuverability, manipulating objects, and torpedo design. During the competition, we expect the AUV to be able to complete Enter the Pacific (Gate), Hydrothermal Vent (Buoy), Ocean Temperatures (Bins), and Mapping (Torpedoes). These tasks were strategically chosen to play to the strengths of our actuators and software sub-teams, which consist mainly of new team members. If these tasks are completed successfully, they will provide a strong foundation of knowledge and increase team confidence to attempt more complicated tasks in the future. A complete CAD render of Steelhead Mini can be found in Figure 1.

The development of Steelhead Mini was derived from the ongoing design and fabrication of our uni-body hull AUV project known as Steelhead. It follows similar design principles to Steelhead; however it has been adapted from a unibody hull concept into one that relies on multiple enclosures and features enhanced maneuverability. The goals of the mechanical team were to develop a claw, torpedo systems, and manufacture underwater enclosures in-house. The electrical team focused on refining the electrical systems and developing a better battery management system. Software overhauled their simulation models, pathfinding algorithm, and mission planner. Lastly, the sound localization team has made a functioning prototype using hydrophones to detect signals underwater, which will be integrated into future iterations of Steelhead Mini.

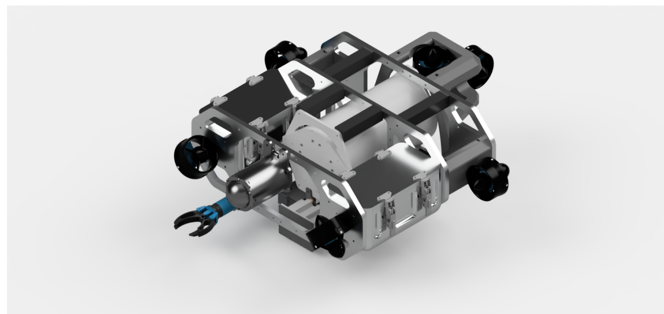

Fig. 1: Full Steelhead Mini CAD Render

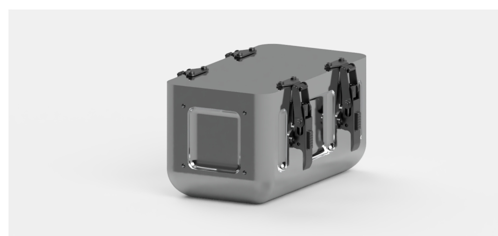

Fig. 2: Steelhead Mini Auxiliary Hull

II. Novel Design Elements

A. Initial Design

Due to tight time constraints and complex machining needs, Steelhead is unable to be completed in time for the 2024 Robosub competition. For more information about the design and testing of Steelhead, please refer to UBC Subbots' Robosub 2023 Technical Report [6].

B. Revised Design

Steelhead Mini is intended to serve as an intermediate step between previous years' AUV designs and the complexity of the Steelhead AUV. Therefore, the design goals of Steelhead directly influenced the goals of Steelhead Mini. It was developed with the team's competition strategy in mind, and allows for seamless integration of all subsystems meant to be installed on Steelhead. Steelhead Mini will fulfill future needs by acting as a test bench for the software and mechanical teams while the production of Steelhead is completed.

1) Design Goals: Steelhead Mini consists of two small machined enclosures rather than a uni-body machined hull as shown in Figure 2. The separated enclosures emulate the distinct halves found on Steelhead's saddle-shaped figure [6] while allowing for faster production. Additionally, aluminum extrusions are located around the perimeter of the AUV to allow for components and thrusters to be easily mounted and adjusted, replicating the numerous mounting points found on Steelhead's exterior. Contrary to Steelhead, Steelhead Mini is low cost and able to be manufactured in a short period of time. Most materials, internal components, and thrusters are repurposed from previous years' AUVs, and suitable blocks of aluminum for the enclosures were purchased at scrap prices. Both enclosures are the same size and shape, and use the same toolpath to save time.

2) Production Methods: Once the Steelhead Mini concept was designed and virtually assembled using Onshape, HSMWorks was used to generate a toolpath and verify part geometry. G-code from the CAM software was imported to Tormach's PathPilot CNC controller. The CAM was completed over the course of three days. Next, the main enclosures as well as the actuators enclosure were machined from large 6061 aluminum blocks, which were purchased from a local scrap metal depot. Two blocks with dimensions of 5"x7"x11" were cut from a block four feet in length using a horizontal band saw with support from the UBC Mechanical Engineering machine shop. These blocks were placed on a Tormach 1100 MX CNC mill to be faced and machined into the two main enclosures. The actuators enclosure and all enclosure lids were similarly prepared using a Tormach 1100 MX with support from the UBC Integrated Engineering machine shop. The first enclosure took approximately 24 hours to machine; we expect that the second, identical enclosure will take half the time.

3) Custom Neoprene Seals and Lid: The custom seal derived its design from O-rings around a cylindrical enclosure as in Figure 3. Our main enclosure has an unconventional shape which prevented us from using off-the-shelf O-rings. For the size of the enclosure, we designed it to use one 1/8" face seal in order to maximize the internal volume for components. The lid is a machined 1/2" plate, which will compress the seals into the groove. The lid will be secured with stainless steel clamps for easy installation and removal of the lid.

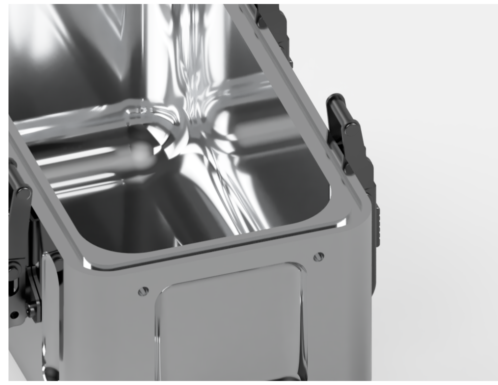

Fig. 3: 1/8" Face seal in the enclosure groove

4) Internal Component Layout and Mounting: The two machined enclosures contain all electronics with the exception of the battery and its monitoring system. One enclosure contains "high-powered" electronics such as electronic speed controls (ESCs) and high-current cabling, while the other contains "low-powered", sensitive electronics. The separation of these components reduces signal interference. Penetrators are located on the lids and interiors of each enclosure to make components accessible, and follow a layout strategy similar to the one detailed in the Robosub 2023 Technical Report [6].

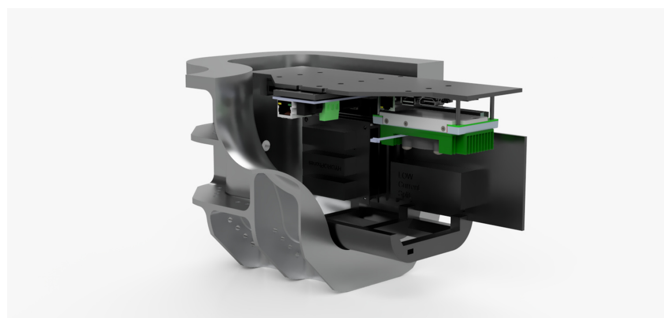

Fig. 4: Low Power Mounting System

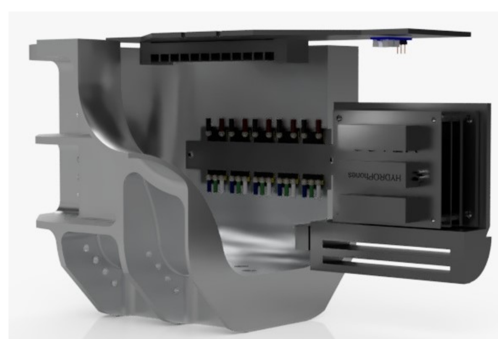

Fig. 5: High Power (ESC) Mounting

C. Actuators

1) Claw: We planned to build a claw in-house using a servo and machined parts, and prototyped potential concepts. Two concepts were selected for further development: a design utilizing an elastic element, and a gear-based mechanism. Functioning prototypes for both concepts were designed and 3D printed as shown in Figures 6 and 7.

Fig. 6: 3D-printed prototype of the elastically-driven claw design

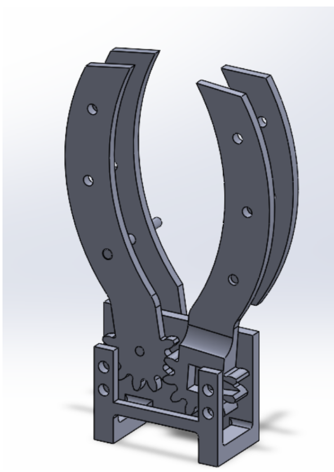

Fig. 7: CAD model of the gear-driven claw design

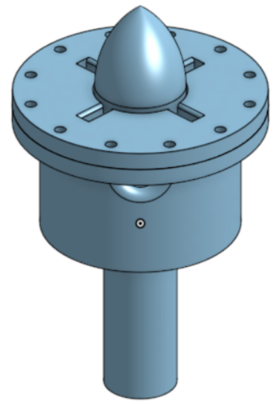

Fig. 8: Torpedo Final Design

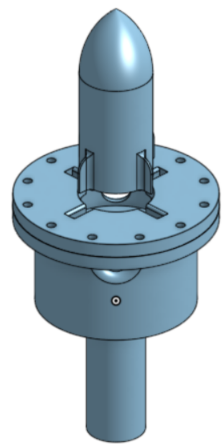

Fig. 9: Launching Torpedo Rotating the shaft aligns the fins with the opening, launching the torpedo

While these prototypes provided us with experience tackling a technical challenge, they were neither robust nor consistent at picking up objects. In the interest of time, we decided to move away from our in-house claw and purchased a pre-built underwater claw from ROVMaker, as shown in Figure 1. This decision allowed us to fast-track the design phase and focus on integrating the claw with the rest of our systems. Our future goal is to continue development of a specialised claw of our own design.

2) Torpedo System and Dropper: During development of the torpedo launcher, we realised that the dropper and torpedo tasks are very similar. Thus, we opted to use the same mechanism for both systems, which can be seen in Figure 8. The dropper points downward, while the torpedo launcher points forward. The decision to use a single design simplifies the challenge and allows for more testing.

The mechanism operates by loading the torpedo with a spring. A square hole is cut in the back of the torpedo, allowing it to connect to a shaft. The shaft is then rotated by the servo for actuation purposes. When the servo turns the shaft, the torpedo rotates and is released. This can be seen in Figure 9. The High Torque 40 KG Motor Micro Servo from ROVMaker is used due to its waterproof certification and high power output. The final design is compact and can be easily manufactured via 3D printing.

The torpedo's geometry was designed in such a way as to minimise drag. Computational flow dynamics (CFD) simulations were performed to assess the design. The impact of the square hole cut to attach the torpedo to the shaft is minimal in increasing the drag of the torpedo. A more thorough simulation will be done to further optimise the shape of the torpedo.

3) Enclosure: All actuator systems are mounted to a single enclosure, which houses the electronic components. The guiding philosophy for this design was modularity. The intent was to make the actuator systems largely independent from the main structure of the robot. The enclosure can be seen in Figure 10.

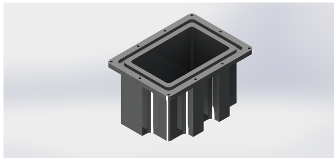

Fig. 10: Actuators Enclosure

D. Battery and Camera Enclosures

The battery is placed in the central acrylic cylindrical enclosure shown in Figure 1. The mounting of this enclosure was designed such that one end can be opened up. This enclosure also allows the fitting of two batteries and various power management hardware. Coming out of the enclosure are power and signal cables. The penetrators used are dry-connects from Blue Trail Engineering, and MacArtney SubConn wet-connects for the thruster enclosure. The camera enclosure is in its previous 3” Blue Robotics Acrylic Enclosure, and hosts two low-light USB cameras.

E. Control System

1) Main Control System: The control system of Steelhead Mini consists of five major components: a trajectory generator, a way-point system, a PID controller, an unscented Kalman filter (UKF) state estimator, and a thrust allocator. The communications between these modules are handled by the new Mission Planner. 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.

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 as a Docker container. 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.

The software architecture runs on the TX2 as a Docker container. Using Docker increases overall reliability as it takes only few minutes to deploy on a spare TX2, if any hardware issues arises. This infrastructure as code (IaC) approach also enables versioning of our software environment, making changes to it visible and allowing easy rollbacks.

4) Mission Planner: The mission planner coordinates the AUV’s ROS2 nodes using the BehaviorTree (BT) library. It is comprised of a ‘controller’ ROS2 node, and several BT nodes, organised into trees and subtrees – one for each task. The

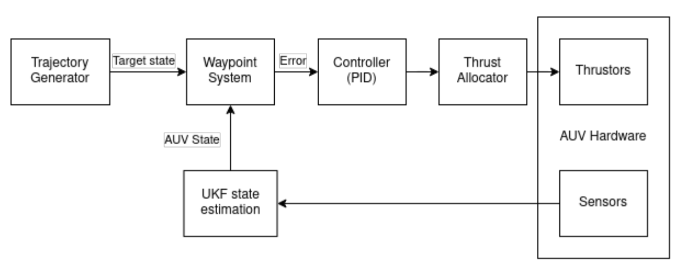

Fig. 11: Block diagram of the software control system used by the Steelhead AUV.

'controller' node subscribes to the other packages' topics, and interprets their data to determine which nodes to call, and with what instructions. For example, once the object recognition package detects the start gate, the mission planner sends an instruction to the trajectory generator to approach it. The tree architecture is designed to be pseudo-parallel, so that if at any point a condition is no longer met, the associated action can be terminated and re-tried. A diagram of the tree architecture can be seen in Appendix B.

5) 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.

To detect objects, we upgraded to the YOLOv8 object detection model which we fine-tuned on the Roboflow platform. The model was fine-tuned using a dataset generated on Unity of images of gates and markers underwater from various angles. This should reflect the actual environment of our AUV.

F. Power System

1) Battery Monitoring: Our electronic safety system uses Arduino to monitor the real-time battery level to ensure it is above the minimum required level to prevent device damage. Three differential op-amps isolate each battery from each level, making the system available to monitor each battery. Our system contains two different shutdown switches: 1. Emergency shutdown switch 2. Battery charging switch The emergency switch is a magnetic switch which can be pulled to cut off the main power from the robot in an emergency. A battery charging switch is a mechanical switch for battery charging situations when the main system needs to be isolated from the battery when the battery is getting charged.

2) Various Output: Our main system has five different voltage output levels: 5V, 7V, 9V, 12V, and 14.3V. Taking the battery monitor output as input, the main system contains five outputs per voltage level. Other than 14.3V, the raw voltage output from the battery, each voltage output is created using a voltage regulator.

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. Simulation also allows us to catch any overlooked error and serve as a quick prototype tool for any idea we want to implement.

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. ROS2 was used to ties different part of the AUV together and makes it easier to replicate testing.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.

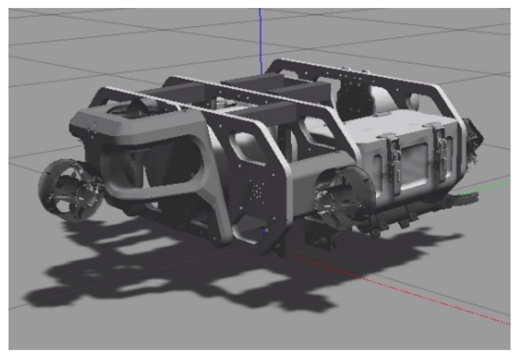

Fig. 12: Steelhead Mini frame in gazebo

Our new Steelhead Mini enclosure can be seen in Figure 12 and the gate navigation test in Figure 13. 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.

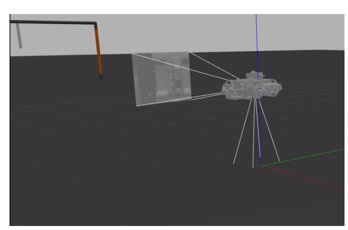

Fig. 13: Gazebo gate navigation test

2) Mechanical Testing: The two aluminum enclosures were tested with Finite Element Analysis (FEA) in Fusion 360 at depths of 30, 50, and 100 meters. These depths were chosen based on competition requirements and to retain the same functionality as the original Steelhead AUV. The stresses and deflection was minimal. Pressure testing using a vacuum pump was utilized to test the custom-made O-rings and verify the watertight properties of the rectangular enclosures.

Fig. 14: Scale model test enclosure

3) Enclosure Testing: 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 15.

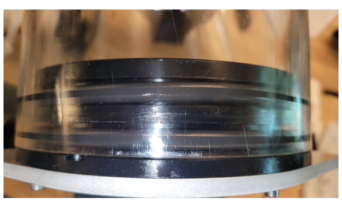

Fig. 15: The 3/16" Neoprene O-ring installed into the 8" Blue Robotics Flange

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 Mini. This mini-AUV in Figure 16 is made of of four systems: the main enclosure, thrusters, battery, and cameras.

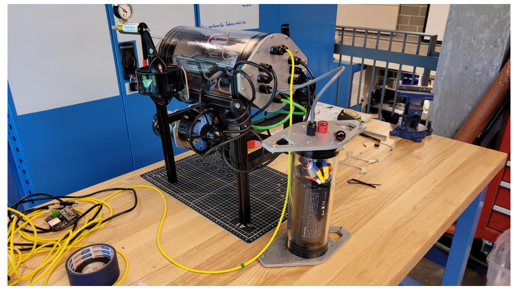

Fig. 16: TritonMini

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 SteelheadMini, primarily the thruster control components. The thruster arrangement mimicked the one planned for Steelhead. These are demonstrated in Figure 16

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. The software team were also able to deploy their new navigation system into the real world. Once Steelhead-Mini's mechanical components are complete, components will be transplanted over.

Acknowledgments

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References

[1] T. Marques, "Design and validation of pressure vessels for optimized payload in subsea applications," Thesis for: Master's, 2021, doi: 10.13140/RG.2.2.21870.13121.

[2] T. Ueda, K. Yamada and Y. Tanaka, "Underwater Image Synthesis from RGB-D Images and its Application to Deep Underwater Image Restoration," 2019 IEEE International Conference on Image Processing (ICIP), 2019, pp. 2115-2119, doi: 10.1109/ICIP.2019.8803195.

[3] T. I. Fossen, Handbook of marine craft hydrodynamics and motion control. Hoboken N.J.: Wiley, 2021.

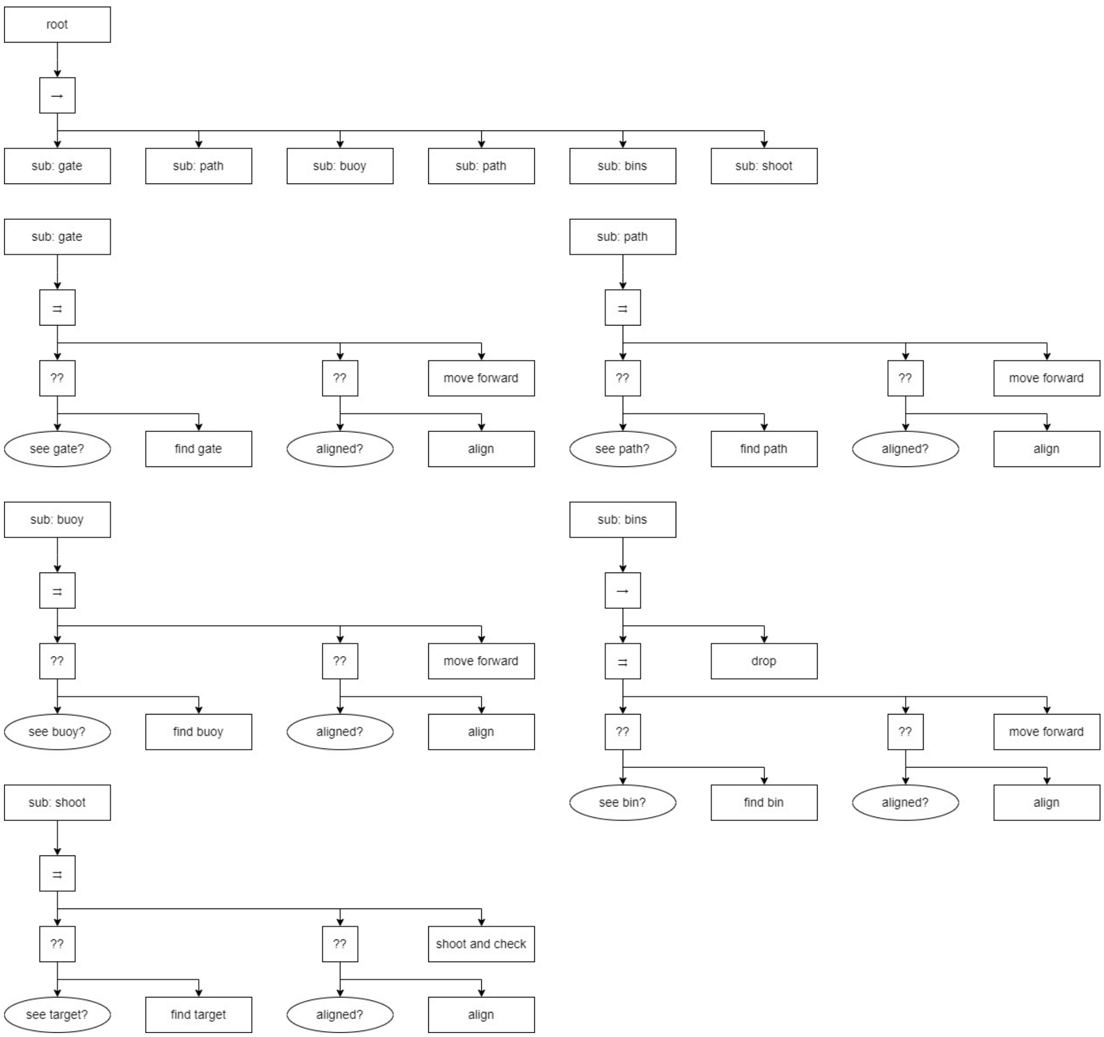
[4] J. H. A. M. Vervoort, Modeling and Control of an Unmanned Underwater Vehicle. Christchurch, New Zealand: University of Canterbury, 2008.

[5] L. A. Gonzalez, DESIGN, MODELLING AND CONTROL OF AN AUTONOMOUS UNDERWATER VEHICLE. The University of Western Australia, 2004.

[6] V. Moreno, C. Fletcher, I. Su, L. Gallant, J. Wu, A. Pinto, D. Qaimari, C. Polloway, R. Remo, F. Kuan, Design of the Steelhead Autonomous Underwater Vehicle for the Internaltional Robosub Competition. UBC Subbots University of British Columbia, 2023

Appendix A: Triton AUV Component Specification

Component	Vendor	Model/Type	Spec	Cost (if new)	Status
Foam Ballast	Blue Robotics	closed-cell polyurethane foam	R-3318	250	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	6" 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, 10Ah)	https://bluerobotics.com/store/comm-control-power/powersupplies-batteries/battery-lp-4s-10ah/	200	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			UBC Aquatic Center, about 30 hours	Free	



Appendix B: Mission Planner BehaviorTree Architecture