Tartan Autonomous Underwater Vehicle

2023 Technical Design Report

Colm Barry, Alexander Blass, Tjaden Bridges, Theodore Chemel, Nader Daruvala, John Duncan, Sarah Fisher, Cole Herber, Rylan Morgan, Katerina Nikiforova, Micah Reich, Gleb Ryabtsev, Samuel Schaub, Ayush Shekhar, Victor Zayakov
Carnegie Mellon University
Pittsburgh, PA
team@tartanauv.com

***Abstract*—TartanAUV[1] is excited to present our entry into Robosub 2023, featuring two vehicles for the very first time. Kingfisher, our flagship vehicle, has been outfitted with a suite of actuators, acoustic sensors, and controls improvements. Albatross[2], our new research platform, has been designed from scratch to facilitate dynamics modeling and the development of custom sensors. In this paper, we begin by outlining our collaborative multi-vehicle strategy. We then examine the design and motivation behind a number of new mechanical, electrical, and software systems, including a torpedo launcher, suction manipulator, acoustic modem, and many more. Finally, we address our incredible set of sponsors and supporters, without whom none of this would have been possible. See you at TRANSDEC!**

I. Competition Goals

Throughout the past year, TartanAUV has thought carefully about how to divide our engineering resources to maximize both competition performance and educational value. Last year, we debuted our flagship vehicle, Kingfisher, as an all-in-one solution to many of the competition tasks. This year, we expanded our fleet with a second vehicle, Albatross, to tackle the challenges of inter-sub communication and task parallelization. With our vehicles competing side-by-side, we are excited to field a solution that can complete every task at Robosub 2023.

Our competition strategy sees Kingfisher as a mothership, performing precision manipulation and navigation tasks with a complete sensor and actuator suite. Meanwhile, Albatross focuses on simpler vision tasks that can be achieved with a reduced sensor payload, relying on Kingfisher for navigation and guidance. Specifically, Kingfisher improves on our performance from last year by executing the torpedo, marker, pinger, and manipulation tasks, while Albatross performs the buoy and surfacing tasks. Both vehicles will be in constant communication throughout a competition run using a set of newly developed acoustic systems. The benefits

[1]Authors presented in alphabetical order. For individual contributions and responsibilities, please visit our team website.

[2]As an homage to our team's beginnings, Albatross shares a name with our first vehicle which competed in 2019. The original Albatross was decommissioned so its components could be reincorporated into both vehicles.

of this strategy are threefold. First, Albatross can navigate through the competition course without a redundant and expensive set of navigation sensors by sharing the navigation capabilities already implemented on Kingfisher. Second, both vehicles can share information about the environment, enabling complex behaviors where one vehicle observes the other from a distance to provide another perspective of a difficult task. Finally, the two vehicles can perform tasks in parallel, minimizing the time of our competition runs to allow for more attempts within the allotted time.

II. Design Strategy

A. Design of Albatross Vehicle

Initially developed as a research platform for controls, perception, and sensor fusion work, Albatross is designed with symmetry, maneuverability, and maintenance in mind. Albatross exhibits total XZ-plane and near XY-plane symmetry, a center of gravity very close to the center of buoyancy, and similar mass distribution within its two electronics tubes. These design choices reduce the number of independent parameters required for an accurate dynamics model of the AUV, something that Kingfisher has struggled with in the past. Albatross weighs 32 pounds and is over-actuated with 4 lateral and 4 horizontal thrusters. Reducing the mass and including control authority in all six degrees of freedom (DoF) allows us to investigate vehicle controls in more dynamic situations involving faster accelerations and decoupled movements.

Within Albatross' electronics tubes, mounting is done with a modular rail system to allow for hot-swappable parts – mounting a new sensor requires cutting a single mounting plate and attaching it to the rails with a universal 3D-printed mount. Outside of the enclosures, a large bottom plate with exposed aluminum extrusion allows for easy mounting and swapping of external sensors like a sonar or DVL.

Albatross' electrical stack was designed to match that of Kingfisher's and uses the same battery, power distribution boards, thruster drivers, and computer. By replicating the electrical stacks between the two vehicles, any improvements made to one can easily be applied to the other, parts can be transplanted in the event of damage, and our team only needs to maintain one set of spare components.

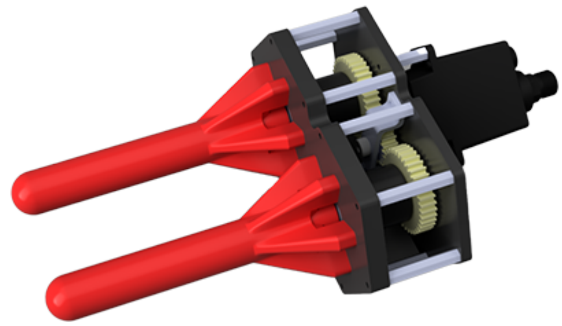

Fig. 1: The torpedo launcher loaded with two torpedoes.

B. Design of Torpedo Launcher

This year marks our team's first attempt at the torpedo task. Our torpedo launcher[1] uses a compressed spring to launch two passive, neutrally-buoyant torpedoes held in place with neodymium magnets. Magnets sit within each of the 6 fins to provide a total holding force of 60 pounds. Behind each torpedo is a spring held in compression with 30 pounds of force. To launch, the torpedo is twisted using a set of 6 pins geared to a servo, shearing the magnets apart and allowing the force of the spring to overcome the holding force of the magnets. A wing gear at the servo only engages one of the torpedoes at a time, allowing each to be fired independently. An initial design featured only four fins and four corresponding magnets, but we found this design likely to miss-fire from accidental contact with the torpedoes. To minimize this issue, we redesigned the torpedoes with six fins, raising the factor of safety from 1.3 to 2.

We considered traditional latch-based approaches for holding the torpedoes in place but settled on a magnetic design to maximize launch accuracy and reload speed. The magnetic design allows the torpedo to be simultaneously released from 6 points around its base, eliminating the potential for the torpedo to deflect on an asymmetric holding mechanism. Furthermore, by balancing the neodymium magnets with counterweights, the center of buoyancy (CB) can be carefully tuned to match the center of gravity (CG). This eliminates the moment that would be induced by differing positions of CB and CG that would cause the torpedo to skew off course. This design, however, added significant complexity and introduced failure points such as the magnets shattering, corroding, or misfiring. These issues are mitigated by storing the torpedoes separately from the launcher and by requiring eye protection to be worn while loading.

C. Design of Suction Manipulator

Kingfisher has also been outfitted with a general object manipulator, our team's first attempt at the manipulation tasks. Prior to the release of this year's task ideas, our team designed a claw manipulator mounted on a five-bar mechanism[3] to enable motion in the horizontal plane while keeping the claw facing forwards. This design targeted the manipulation tasks in previous years, where tall objects like bottles were placed on small tables without side walls. However, upon seeing the layout of this year's chevron task, this design was rendered ineffective by the table's six-inch walls.

We noticed the large, flat surfaces of the chevrons and how difficult they would be to grasp with a traditional claw manipulator. Since the manufacturing industry makes frequent use of suction-based manipulators for similar objects, we researched whether a similar approach could be applied underwater. An article by researchers at the Nara Institute of Science and Technology showed that it could be done [1], so we adapted their design to our own needs. We connected a COTS suction cup to a shrouded Blue Robotics T200 thruster, creating a compliant and precise manipulator.

The suction manipulator is mounted on a four-bar arm mechanism[2] which allows it to be raised and lowered while keeping it parallel with the top chevron surface. This top-down picking approach simplifies the motion planning needed to manipulate the chevrons: Kingfisher simply aligns itself with a chevron using its bottom camera, lowers the manipulator, applies suction, and dives straight down. As long as the suction manipulator makes contact with the top surface of the chevron, the grasp will succeed; any further downward motion will only force the arm to backdrive. Releasing the chevron in the desired position is as simple as stopping the thruster to cut off the suction force.

The fundamental tradeoff with our suction manipulator is between ease of use and holding force. The shrouded thruster design is an inefficient way to generate suction force compared to a traditional pump, but it was extremely easy to design and integrate. As a result, the holding force of the suction manipulator is quite low; aggressive maneuvers can allow drag forces to tear a grasped chevron away from the manipulator. However, the benefits of a top-down, orientation-independent grasp operation outweigh this issue. While a claw manipulator might provide a more secure hold once a chevron is grasped, we decided that the difficulty of planning the grasp itself would be a greater obstacle to reliability.

Fig. 2: The arm and suction manipulator in its raised and lowered configurations.

Fig. 3: The previous 5-bar arm and claw.

D. Design of Pinger Localizer

We kickstarted our team's acoustics program with the design and implementation of a pinger localizer based on a phased array[4]. Four hydrophones receive an incoming ultrasonic ping at slightly different times due to the finite speed of sound. We selected Aquarian AS-1 hydrophones because of their small diameter, which allows them to be placed within half a wavelength of each other to prevent phase aliasing. The raw hydrophone signals are amplified by Aquarian preamplifiers and then filtered and amplified by a custom frontend board. Then, the analog sample is digitized by a synchronized pair of Analog Devices ADALM-2000s. In software,

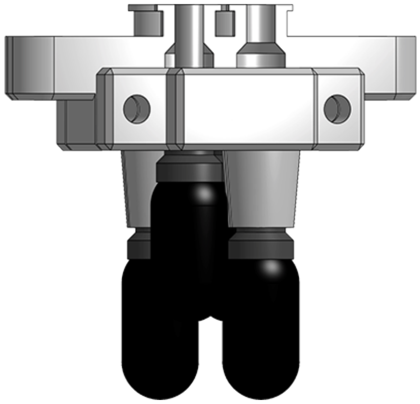

Fig. 4: The phased hydrophone array used in the pinger localizer.

the ping frequency is identified using the FFT and isolated by digital filters. Then, the cross-correlation is computed between channels to measure the phase shifts, which are combined with knowledge of the hydrophone positions to compute the direction of arrival (DoA) of the ping.

We chose this two-stage filter design – an initial analog filter paired with a tighter digital filter once the ping has been identified – in order to minimize false detections due to other acoustic noise. This approach was very successful in initial bench tests but broke down when tested on a moving vehicle. Unfortunately, our thrusters and electronic speed controllers (ESCs) operate at a frequency of 25 kHz, spewing electrical and acoustic interference well within the frequency band used by the pingers. Distinguishing a valid ping from this noise is quite difficult, so we identified a simpler approach: shutting off the thrusters when trying to acquire a ping. Thankfully, Kingfisher is close to neutrally buoyant and the pings repeat every few seconds, so the vehicle does not drift very far before a ping arrives and the thrusters can be restarted.

E. Design of Acoustic Modem

A significant motivation for our construction of a second vehicle this year was the opportunity to tackle the challenges of underwater acoustic communication. Inspired by the work of Xia [2], we developed a scratch-built ultrasonic acoustic modem. Our two vehicles are outfitted with a piezoelectric transducer cast in a custom polyurethane mold and connected to a bidirectional modem driver. To transmit a signal, we use four power MOSFETs arranged in an H-bridge configuration, which provides the highest possible amplitude with a single positive power supply. To receive, we use an instrumentation amplifier, Butterworth bandpass filter, and variable gain amplifier (VGA). The VGA allows the receiver to dynamically respond to changes in signal strength caused by environmental factors such as vehicle motion and multipath interference. The analog output of the VGA is then sampled by the analog-to-digital converter (ADC) onboard a Teensy 4.1 microcontroller.

Implementing modulation and demodulation in software on the Teensy microcontroller gave us the flexibility to evaluate various modulation schemes without modifying our hardware design. We began with the simplest possible scheme: frequency-shift keying (FSK) [3] operating at frequencies of 50 kHz and 55 kHz. However, experiments in a small benchtop bucket and in our large water tank showed significant multipath interference; some acoustic energy would follow longer paths between the transmitter and receiver by reflecting off of the walls, interfering with subsequent transmissions. After further experimentation, we determined that Gaussian frequency shift keying with direct sequence spread spectrum (GFSK-DSSS) offers the optimal balance between bitrate and interference rejection for our use case. Our chosen carrier frequencies are still 50 kHz and 55 kHz, now with a DSSS chip rate of 2500 chips per second. Each information bit corresponds to an 11-bit Barker code, resulting in a bitrate of 230 bits per second. Using spread spectrum modulation to distribute the signal energy over a broader bandwidth reduces the likelihood of interference changing the demodulated signal, dramatically increasing resilience to multipath effects.

F. Improvements to Electronics Systems

The power distribution systems of our vehicles were upgraded this year in order to increase power output, improve reliability, and enable easier design iterations in the future. The most apparent change is the separation of our power distribution board (PDB) into two stacked printed circuit boards. A larger board houses the regulated power supplies, and a smaller board stacks on top to provide thruster power distribution. This change was necessary due

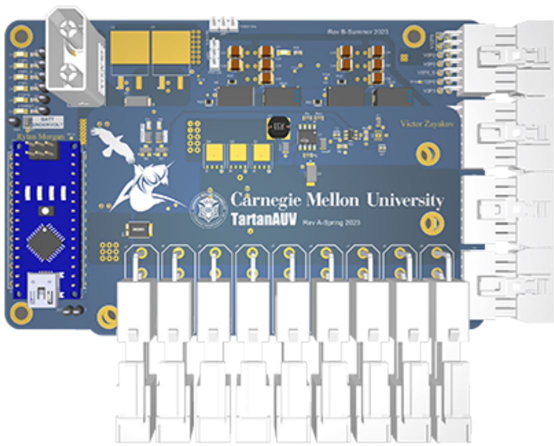

Fig. 5: The power distribution board stack.

to the addition of a dedicated 12V regulator to the PDB, taking up space previously used by the thruster connectors. The new PDB stack[5] features a six-layer main board topped by a two-layer thruster board with heavier copper pours. The cost of manufacturing was minimized since the larger regulator board no longer needed the heavy copper pours to handle thruster current, and the design of the two boards could be iterated on in parallel. As a result, we were able to add useful features such as an onboard microcontroller for output monitoring and control.

G. Improvements to Controls Systems

Although our state estimation and navigation systems performed well, Kingfisher's performance at Robosub 2022 was limited by controls issues from a poorly tuned dynamics model. Its asymmetric design leads to complicated dynamic effects, especially coupling between motions in the forward and pitch directions. To account for these effects, we use a full 6-DoF dynamics model presented by Fossen [4], [5] to compute the required force to achieve a desired acceleration, given the vehicle's current orientation and velocity. This model includes over thirty parameters, each of which must be properly tuned in order to produce accurate force estimates.

In the past, we attempted to tune all of these parameters by hand, adjusting parameters until commanded vehicle accelerations matched the measured values. In practice, such a process is intractable. This year, we designed and implemented an automatic dynamics parameter estimator based upon a Sigma-Point Kalman Filter (SPKF) [6]. This estimator runs in real-time while the vehicle moves around, continually estimating the accelerations for a large set of perturbed parameters. By comparing these different estimates to the true measured accelerations, the estimator is able to update the parameters to better match reality.

H. Improvements to Perception Systems

The global mapping system was redesigned this year to improve processing speed and limit map overpopulation. While the previous system struggled with accurately representing more than one object at a time, the new system is not only prepared for detections of different objects, but also those sourced from different detectors like our updated vision [7], [8] and sonar systems.

We limited redundant object detections by implementing run-time tracker filtering and a more flexible detection-to-tracker matching algorithm [9], [10] using a linear similarity cost model. Alongside distance and tag comparison, the model integrates factors like tracker confidence and expected object count, resisting mislabels and false detections from noisy sensors by favoring trackers with more recent and numerous detections. Stray trackers are identified using measures of relevance and accuracy and eventually deleted by the new decay model.

The new mapping system also integrates a real-time surveying system into Kingfisher's competition strategy. Survey objects are found using sonar scanning, which clusters sound feedback into detections of unknown objects outside of visual range.

In early iterations of the current system, these untagged trackers were standalone, unable to interact with the rest of the map due to tag mismatches. After giving trackers an allowance to match across object tags if other matching criteria fit well enough, the new system now actively merges detections from different sensors and accounts for detection mislabels. This flexibility allows sonar detections to match with an existing tracker or be instantiated as an untagged tracker, recording potential locations to explore and identify later during a competition run.

III. Testing Strategy

We are extremely lucky to have moved our workspace into the Field Robotics Center this year, which maintains a 12-foot water tank dedicated to AUV testing. With easy access to time in the pool, we were able to water-test our vehicles much more frequently than in the past. However, preparing a vehicle for a full water test is a slow and complicated process, and our ability to investigate any issues is limited once the vehicle is submerged. With this in mind, we pursued a hybrid testing strategy that mixes simulation, bench tests, and water tests.

We continued our use of the UUV Simulator [11] package with Gazebo which enables constant software testing on our personal machines. Since both Gazebo and our software stack are built on the Robot Operating System (ROS), our software runs the same way in simulation and on real vehicles. We focused on closing the simulation gap early in the year, refining models of our vehicles and the environment to more closely match reality. To further this effort, we developed custom plugins for Gazebo that simulate our specific navigation sensors and cameras. As a result, many software changes could be validated without ever touching the water.

While developing our pinger localizer and acoustic modem systems, we refined our approach to bench testing by setting up a dedicated test stand next to our electronics workspace. A bucket of water with mounting features allowed us to probe circuit boards on the bench while connected directly to hydrophones and transducers in the water – something that would be impossible during a full water test. We took a similar approach to test our power distribution boards; using a load generator allowed us to fully verify the board functionality without needing to modify the vehicles.

Once new systems were fully integrated and ready for testing on the vehicle, we ran water tests in both the Field Robotics Center tank and the Cohon University Center pool. Our networking setup shares connectivity with the sub over a local WiFi network, so multiple users could connect simultaneously to monitor the performance of different systems. We also took advantage of ROS' data logging functionality to record large data bags during every test, later distributed to team members for further analysis offline. Since this recorded data can be streamed back into ROS, we were able to record sensor and thruster data, for example, and replay it to evaluate changes to our state estimation software at a later time. In all, our team spent more than 30 hours with vehicles in the water over the course of the year, with the majority of this testing time concentrated in May as new systems neared completion.

IV. Acknowledgments

TartanAUV would like to thank Carnegie Mellon University faculty members Melisa Orta Martinez and Michael Kaess for their incredible mentorship and support as a newly recognized student organization. We would like to thank Chuck Whittaker, Tim Angert, George Kantor, and the Field Robotics Center for access to the Robotics Institute machine shop, water testing facilities, and work and storage space. We would also like to thank Alicia Gorman and the Carnegie Mellon Athletics Department for access to the Cohon University Center pool for additional pool testing time. We would like to thank Catherine Copetas from the School of Computer Science for her invaluable help in negotiating sponsorships and interacting with university officials. We would like to thank all 35 of the donors to the 2023 TartanAUV crowdfunding campaign, making our team's attendance at this year's competition possible. Finally, we would like to thank each of our corporate sponsors: Gold (Movella, Altium), Silver (Hakko, Leidos), Bronze (Lockheed Martin, IMC), and Friends (PCBWay). We look forward to everyone's continued support in our effort to bring RoboSub to the Carnegie Mellon University community and beyond.

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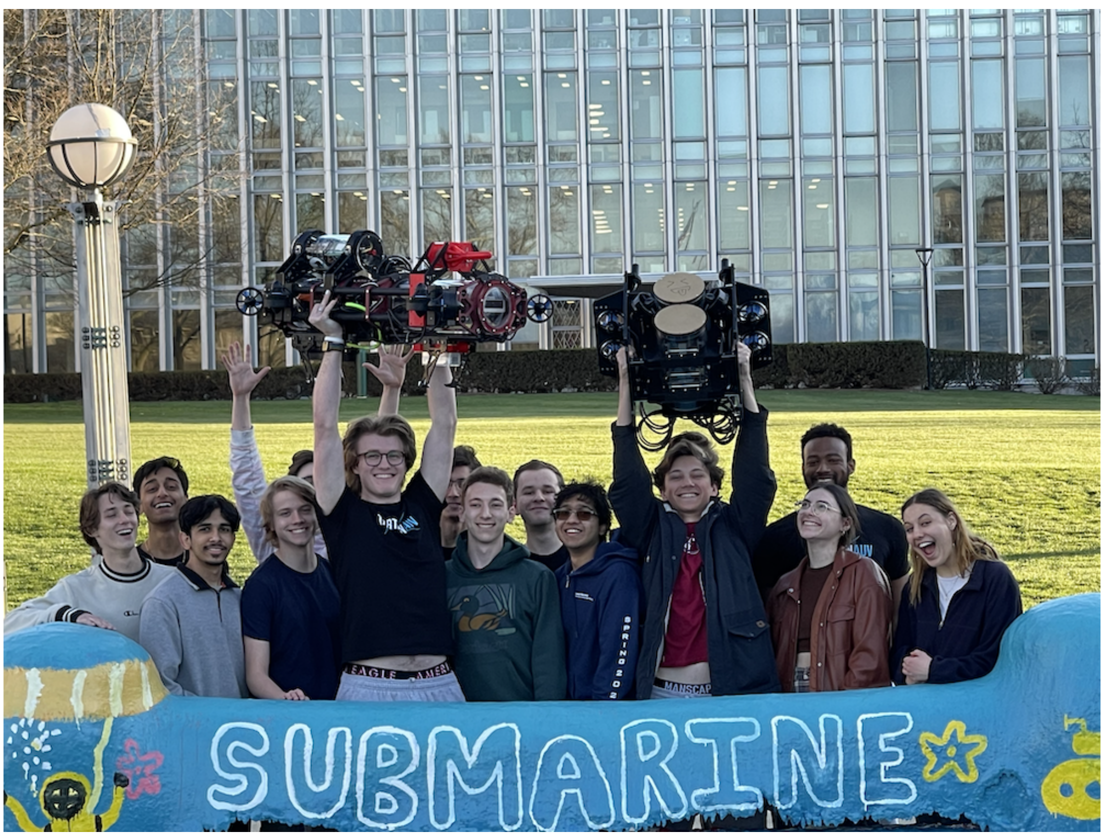

Fig. 6: Painting the Fence is a Carnegie Mellon tradition that our team participates in annually.

TABLE I: Kingfisher Components

Component	Vendor	Model/Type	Specs	Custom/Purchased	Cost	Year of Purchase
ASV Hull Form / Platform	Custom	Main Enclosure	NA	Custom	NA	2019
	Blue Robotics	Acrylic 4” Enclosure	Specs	Purchased	$286	2019
Waterproof Connectors	Blue Trail	20x Cobalt	Specs	Purchased	$42-$65 ea.	2019
	Subconn	Ethernet Circular	Specs	Purchased	$250	2019
Propulsion	Blue Robotics	9x T200 Thruster	Specs	Purchased	$200 ea.	2019
Power System	Custom	Power Distribution Board	NA	Custom	NA	2023
Motor Controls	Blue Robotics	9x Basic ESC	Specs	Purchased	$36 ea.	2019
	Polulu	Mini Maestro 18 Channel	Specs	Purchased	$42	2023
CPU	Nvidia	AGX Orin	Specs	Purchased	$2000	2023
Teleoperation	NA	Personal Computers	NA	NA	NA	NA
Compass	NA	See IMU	NA	NA	NA	NA
Inertial Measurement Unit	Movella / Xsens	MTi-200	Specs	Purchased	$500 (Discounted)	2019
Doppler Velocity Logger	Teledyne Marine	Pathfinder	Specs	Purchased	$20000 (Discounted)	2019
Cameras	Luxonis	2x Oak-D S2 POE	Specs	Purchased	$400 ea.	2023
Hydrophones	Aquarian	4x AS-1 Hydrophone	Specs	Purchased	$400 ea.	2022
Vision	YOLO V3, Darknet ROS			Custom	NA	NA
Localization and Mapping	Global Map, SBL Acoustics			Custom	NA	NA
Autonomy	Inverse Dynamics, PID Controller			Custom	NA	NA
Open Source Software	ROS, OpenCV, Gazebo, UUV Simulator, Darknet ROS			Custom	NA	NA

TABLE II: Albatross Components

Component	Vendor	Model/Type	Specs	Custom/Purchased	Cost	Year of Purchase
ASV Hull Form / Platform	Custom	Main Frame	NA	Custom	NA	2023
	Blue Robotics	2x Acrylic 6” Enclosure	Specs	Purchased	$350 ea.	2023
Waterproof Connectors	Blue Trail	10x Cobalt	Specs	Purchased	$42-$65 ea.	2023
	Subconn	Ethernet Circular	Specs	Purchased	$250	2019
Propulsion	Blue Robotics	8x T200 Thruster	Specs	Purchased	$200 ea.	2019
Power System	Custom	Power Distribution Board	NA	Custom	NA	2023
Motor Controls	Blue Robotics	8x Basic ESC	Specs	Purchased	$36 ea.	2019
	Polulu	Mini Maestro 12 Channel	Specs	Purchased	$30	2023
CPU	Nvidia	AGX Xavier	Specs	Purchased	$2000	2019
Teleoperation	NA	Personal Computers	NA	NA	NA	NA
Compass	NA	See IMU	NA	NA	NA	NA
Inertial Measurement Unit	Movella / Xsens	MTi-300	Specs	Purchased	$0 (Discounted)	2023
Doppler Velocity Logger	NA	NA	NA	NA	NA	NA
Cameras	Luxonis	OAK-D S2	Specs	Purchased	$250	2023
Hydrophones	Sparton	4x PHOD-1 Hydrophone	Specs	Purchased	$500 ea.	2019
Vision	YOLO V3, Darknet ROS			Custom	NA	NA
Localization and Mapping	Global Map, SBL Acoustics			Custom	NA	NA
Autonomy	Inverse Dynamics, PID Controller			Custom	NA	NA
Open Source Software	ROS, OpenCV, Gazebo, UUV Simulator, Darknet ROS			Custom	NA	NA