Triton Robosub
Techincal Design Report

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***Abstract*—The Triton Robosub team, representing the University of California, San Diego, dedicated most of the year to developing a new autonomous platform. Our experience in the 2019 competition, in addition to the resources we acquired in 2020, led us to create a new submarine addressing the issues we found in our previous design. However, COVID-19 limited our amount of in-person construction and development, meaning new strategies and overall goals were adapted to these novel constraints. With the experience earned from this year's focus on remote work and collaboration, we hope to finish development and meet our fellow competitors in 2022!**

I. Competition Strategy

At our first year at competition in 2019, we only managed to pass through the starting gate and attempted the buoy task, though we were not successful. Considering that last year's competition was cancelled, we were not able to test some of the developments we had made through improved machine learning models and localization techniques. Therefore, the plan for this year's competition was very ambitious as we tried to accomplish or at least attempt a variety of tasks that we had worked on.

The addition of a DVL and a sonar to our new submarine this year meant that we could better map our surroundings and navigate the competition course. This capability, in addition to the new submarine's grabber and torpedo systems, meant that we planned to complete the gate, buoy, bins, and torpedo tasks. Furthermore, we developed a hydrophone system this year meaning that we would also try to attempt the surfacing task. On top of all these new additions, we were able to perform deep dives into underwater depth imaging and machine learing-aided object recognition through ongoing research projects, and applied key findings to our competition control loop.

In essence, since our competition appearance in 2019, we have made great advances in our hardware and software stack for each competition task and are now eager to try our sub out. However, due to COVID-19, most of our testing was run in simulations; while simulation runs are good for testing general understanding of tasks and control code, we still await the next in-person competition to test our overall performance in a real-life setting.

Last year, we acknowledged the fact that trying to attempt each task was ambitious considering that we were only able to accomplish the gate at our first competition, but we remain confident that through designing a completely new submarine and reworking our software architecture to use Robot Operating System, we can perform well in the competition. Our advancements in deep learning and enhanced positioning sensors mean that navigating the pool is a less daunting task, and our new acoustic and infrared depth sensing technology allow us to view G-men and Bootleggers alike. Again, due to COVID-19 we were unable to test much of our code in a physical setting, instead relying on Unity to drive most of our software development and testing. Instead, while hardware

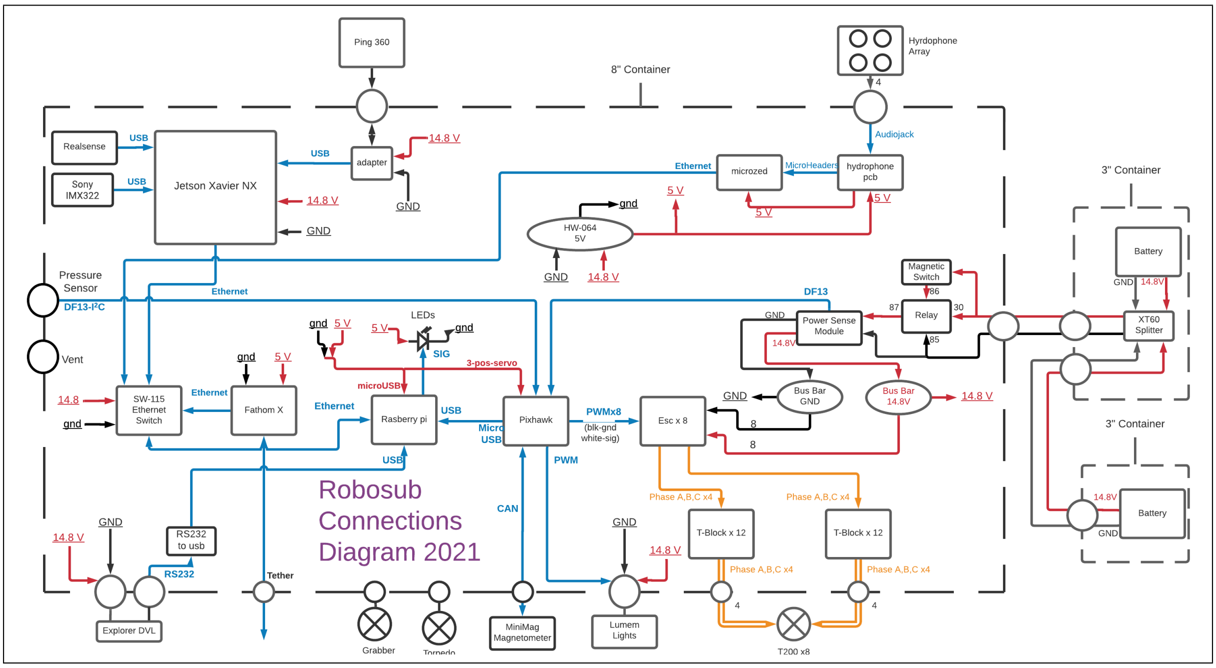

Figure 1: Electrical Block Diagram

teams worked on our new submarine for the majority of this year, software focused on setting up low-level sensor drivers and high-level decision making and architecture for this year. This ensures that when we shift into in-person testing, each task should be compartmentalized and simple to implement.

II. Vehicle Design

A. Electrical

To compliment the new mechanical re-design of the sub, the electrical team designed a new internal electronics container. The previous robot's electronics were shared between two containers. So this year, the electrical team designed a single container to house all the electronics in a compact and modular fashion, as well as accommodating a new hydrophone subsystem, while making space for future boards. Figure 1 depicts the connections for this new chamber, and Figure 2 illustrates a Computer-Aided Design (CAD) model of the electronics.

The electrical team also sought to redesign their hydrophone subsystem. A previous analog hydrophone preamplifier proved to be very noisy and its response highly sensitive to component values. To minimize noise, the electrical team's strategy was to dynamically amplify the acoustic signals to utilize the entire range of the analog to digital converter, and to utilize a digital filter with a MicroZed FPGA.

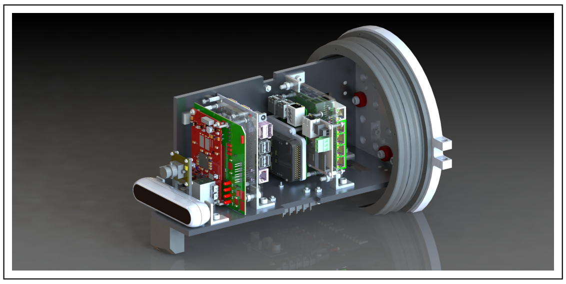

Figure 2: 3D render of Internal Electronics

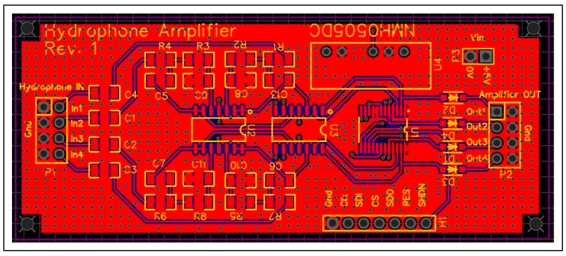

Figure 3: Dynamic Amplifier and Active Low-Pass Filter

Two prototype boards were designed. The first, depicted in Figure 3, features four active second-order sallen-key low-pass filters with a bandwidth of 47kHz and a four amplifiers based on a low-noise JFET-input opamp to match the H1c hydrophone's high impedance. The amplifier's feedback network includes an digital potentiometer that is controlled via Serial Peripheral Interface (SPI). It also has a voltage regulator that converts 5V to ±5V for the rest of the hydrophone subsystem.

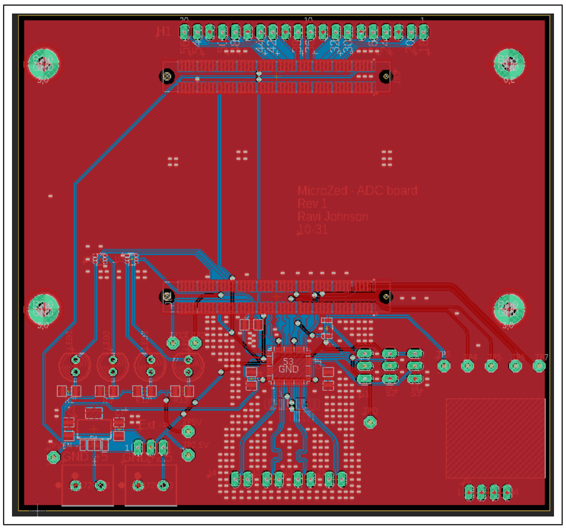

Figure 4: MicroZed Daughter-Board and Analog-to-Digital Converter

The second prototype board, depicted in Figure 4, is a daughter-board for the MicroZed FPGA. The outputs from the first board are sent to a a 16-Bit Analog-to-Digital converter with 5Msps/Ch (mega-samples per second per channel). The outputs of this chip sends the digital signals to the FPGA via 4 parallel SPI channels on the microheaders connecting the prototype board to the MicroZed. It is then planned to implement the digital chevychev filter on the FGPA which is then sent to the processor on the MicroZed via AXI bus where computations can be applied to calculate acoustic wave peaks for the dynamic amplification and to calculate the direction of the pingers, with a previously chosen time-difference of arrival (TDoA) algorithm. The direction will then be sent over a TCP connection to the robot's control algorithm to complete the rest of the mission. Power from the first board is connected to this board, which also powers the MicroZed via its microheaders, making the electrical team's hydrophone subsystem a standalone module.

B. *Software*

This year our situation forced our team to move to a completely virtual environment. Because of this, our software stack moved to a remote software development setup. This year we additionally focused on building up our simulation suite. We were able to add many improvements to the simulations including: cross-system communication, physics improvements, adding sensors, and more.

A major feature we added this year was cross-system communication. In order to simplify our system and avoid writing redundant algorithmic code for the submarine control system, we were able to use our existing control system in ROS. We have our systems setup to send sensor data from our Unity-based simulation to ROS. We then process our sensor data like our normal sub would do on its onboard computer (OBC). And finally, we can send our processed data back to Unity in order to visualize the response and continue our feedback loop. This has huge implications for our team because we are now free from testing future algorithms, RoboSub routines, and control-system code at a physical pool. We can now deploy our code to the simulation and refine any glaring issues and skip a huge part of the debug phase before testing in a real pool.

In addition to cross-device communication, we also added some major improvements to the simulation, two of which include physics improvements and the addition of sensors. In terms of physics improvements, we were able to add improvements to the buoyancy and acceleration of the water and how it react with our sub model. Our sub model would previously move through the water with ease since our water reacted very little to it. Now, the sub requires a realistic amount of force in order to move through the water and stay at certain depths. We also added sensors that we can attach to our sub models. Sensors we use like a Doppler Velocity Log (DVL), cameras, acceleration, and heading sensors were all able to track the data of the submarine model we had in place. This allowed us to get a realistic feedback loop between our algorithms on ROS and the reaction in Unity.

While our team did work heavily on our simulation suite, we were able to develop some cutting edge software that will run on our physical sub. Namely we developed a real-time sensor driver for our DVL in Python. While this itself may not sound impressive, we actually connected our DVL to a ”Visual Position Delta” (VPD) software that allowed us to accurately track the relative location of our sub underwater. We are utilizing a system that was designed to calculate real-time position using camera data, hence the ”Visual” part of VPD, and we were able to accomplish this using only the DVL data. This allows us to create very accurate routines for use not only in competition, but in underwater research.

On the topic of underwater research, we were able to work with 2 major research projects this academic year that not only utilized our current submarine technology, but we also developed software that had profound effects on the software we developed for RoboSub.

Earlier this year, the software team was able to compete in the AI Tracks competition hosted by NIWC Pacific. The focus of this competition was to design a system that could track a boat's location using a single camera. The team focused on using the popular YOLO object detection network [5], and tweaking it to our use case. Through this challenge, we were able to further understand the YOLO network architecture, train custom models, and improve inference speed significantly. This directly translated over to our object detection techniques for the Robosub competition.

We extended our results from AI Tracks into the underwater environment with FishSense, a research project dedicated to utilizing depth cameras underwater to automate fish length and biomass measurements. This opportunity allowed us to combine 3-dimensional data with various deep learning models (including YOLO) to identify fish and other objects and estimate their distance from the sub, and we hope to apply this technique to competition tasks like the torpedo and buoys as well.

C. Mechanical

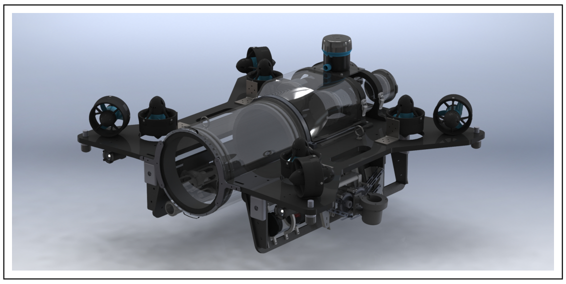

Figure 5: Isometric render of our 2021 AUV design.

This year's vehicle is the first design to use a custom made frame rather then a pre-built system. The custom vehicle design is based off the sensors and components that we selected for use in our AUV. Those components being: a Blue Robotics Ping360 Sonar, a Teledyne Explorer Doppler Velocity Log (DVL), 8 Blue Robotics T200 thrusters, 4 Aquarian H1C Hydrophones, an Intel D455 stereo camera, a web camera, a Blue Robotics 8” waterproof electronics container, a Blue Robotics 2” container, and 2 Blue Robotics 3” battery containers. A custom made grabber system and a custom made torpedo system are to be included in the future and space has been allocated on the frame for these two systems.

In the initial design stage it was identified that the placement of the DVL was to take priority as it was our most important sensor. The placement of the electronics container was the next priority as it was where the two cameras were going to be placed and it was also identified to have a large buoyant force. All other components were to be placed around these two components.

The DVL was placed at the bottom of the AUV where it would have a direct line of sight to the ground, and it was positioned so that the transducer would be at the center of rotation to allow for optimal motion tracking. A custom mount for the DVL was then made

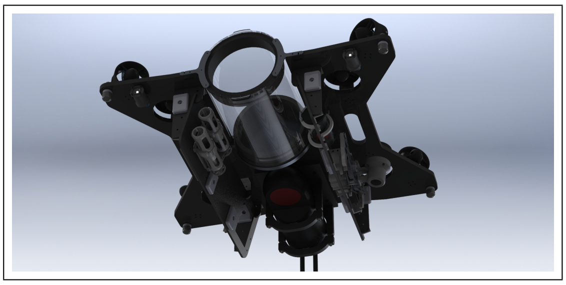

Figure 6: Bottom view of our 2021 AUV design.

to ensure that no sliding or rotation of the DVL would occur during movement through the water.

The electronics container was placed towards the front of the AUV where the two cameras would have an unobstructed line of sight forward. A cut out in the frame was made so that the container could sit in the middle. This, along with thruster placement, ensured that the center of mass and buoyancy was at the middle of the AUV to prevent unintentional pitch, yaw, or rotation during acceleration. The mount for the electronics container was designed so that the user could easily remove the container without having to remove the electronics stack allowing for quick and easy access to the components inside.

Inside the electronics container, the electronics stack held all of the boards and the two cameras for the AUV. To optimize space and heat dissipation, it was designed as two aluminum, L-shaped plates. The aluminum plates would be directly connected to the rear aluminum end-cap which would transfer the heat from the boards into the outside environment.

The 8 thrusters were placed to ensure that the center of thrust, in all directions, would be along the center of mass, and to ensure that the AUV would have a full 6 degrees of freedom in movement. To achieve this 4 thrusters were place horizontally at a 45 degree angle to allow for forward, backward, left and right motion as well as yaw control. The other 4 thrusters were placed vertically to allow for up, down, roll, and pitch control.

The two battery containers were placed behind the electronics container to reduce the amount of drag produced and to ensure that the battery cables would reach the electronics container. The Ping360 Sonar was placed on top of the battery containers to ensure that it had an unobstructed 360 degree view of it's surroundings.

The hydrophones were placed at the corners of the AUV to optimize their ability to pick up the signals given off by the pingers.

The system also required an external IMU, since it made use of a compass it needed to be isolated away from the electromagnetic disruptions inside the electronics container. For this reason it was placed on the lower legs of the AUV in a 2” Blue Robotics container, this was the furthest free space allowing it to be away from both the main electronics and the batteries.

III. Experimental Results

Due to the remote nature of circuit simulation and PCB software design, the electrical team was able to successfully prototype two boards for the hydrophone subsystem, after extensive circuit review processes with our mentors. Each board was independently tested before integration of both boards. For example, the dynamic amplification was tested by controlling the wipers of the digital potentiometer through a SPI communication interface on Figure 7. The results show that for the planned closed loop system of dynamic amplification to occur, each resistive value and corresponding gain value will have to be mapped to 256 nonlinear positions.

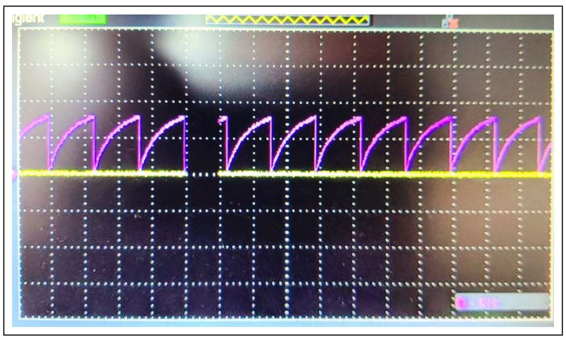

Figure 7: Nonlinear Control of Hydrophone Subsystem's Dynamic Amplification

Integration of both the boards and filtering a pinger into a form fit for signal processing proved to be successful after some hardships. Lack of proper pool facilities due to COVID-19 meant the electrical team had to find alternate solutions for water testing the hydrophone subsystem. A small tub of water was just enough to house a pinger and a hydrophone. This allowed the electrical team to perform integration tests with the custom boards, MicroZed, and oscilloscope (for probing of test points) on Figures 8 and 9.

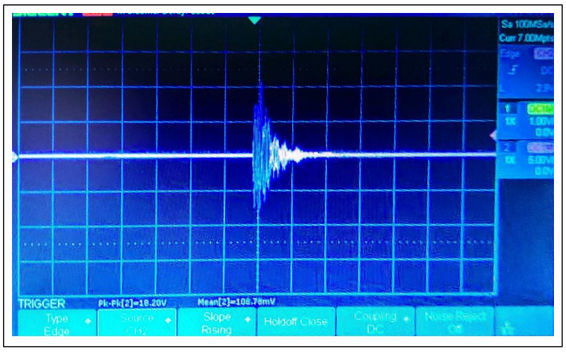

Figure 8: Unfiltered Pinger at 37.5 kHz

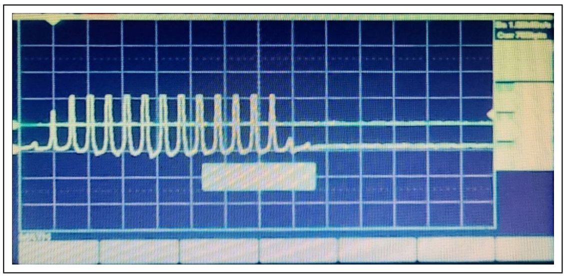

Figure 9: Filtered Pinger at 37.5 kHz with Electrical Team's Custom Boards

The filtered and clipped pinger signal was shown by simulations to have the necessary information to determine the frequency of the pinger, after it was filtered additionally by a chevychev filter and converted into the frequency domain by a Fourier transform. With this information shown in Figure 10 and last year's simulations of TDoA on MATLAB, the electrical team is confident that localizing a pinger in a pool setting will be feasible for the next in-person competition. This was not possible to test out this year due to the previously mentioned issue with not having a proper pool available. The hydrophone array required for utilization with the TDoA algorithm is physically larger than the tub used for testing of the pinger and the rest of the hydrophone subsystem. However, the electrical team is excited to return in the fall for fully in-person facilities to test out this highly important subsystem, because at Triton Robosub's debut competition, they were not able to participate in the missions that were only accessible by localizing the pingers.

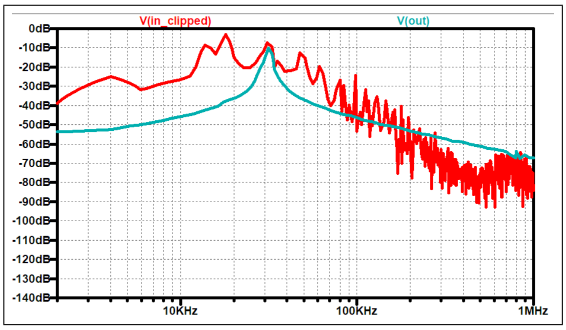

Figure 10: Clipped signal at 37.5 kHz and Noise Passing Through a Chevyshev Filter

Deep learning was much more successful this year. By utilizing new data augmentation techniques, we were able to reach high accuracy on test images taken from the 2019 competition, even when objects were in murky water and a fair distance away. Our experiences through AI Tracks at Sea and FishSense also helped us hone our skills in developing highly tuned models, and we are excited to use our new techniques and ideas with real props at in-person tests.

While experimenting with new controls architectures, we discovered that utilizing the ArduSub framework as we have been is inefficient with the use of custom sensors such as the Doppler Velocity Log (DVL). Because ArduSub is simply a modified fork of the ArduPilot library, many parts of it are specific to airborne drones, and do not function with our application. Next year, we aim to move away from this solution and implement a new controls architecture from scratch that will allow us to better integrate custom sensors.

Finally, from a mechanical standpoint we are making the final changes on our 2021 build, and look forward to this upcoming fall when we can put our new design to the test.

IV. Acknowledgements

Triton Robosub greatly appreciates the support of our faculty advisors: Ryan Kastner in the CSE department and Curt Schurgers in the ECE department. Their mentorship aided our decision-making and kept our focus on getting results. We would also like to thank Nathan Hui for his help and advice throughout the year. Through his guidance, we were able to learn a great deal about design, manufacturing and testing. A special thanks to the Kastner Research Group for providing the base BlueROV2 and a cutting edge laboratory space where we could work

We would also like to thank the Scripps Institution of Oceanography for allowing us to perform tests in the Keck pool throughout the year. The data and results gathered from these tests have proved invaluable to us. Another thanks to the CSE department as a whole for helping us navigate the post-COVID world, and thank you to financial advisors Jacqueline Le and Aleesa Lopez for your aid in ordering parts and supplies. Finally, we would like to acknowledge the tremendous work of the UC San Diego Health system for expediting vaccine doses, enabling proper safety protocols and protecting our members and fellow students.

Financial support this past year was crucial to our success. Thanks to the generous support of the Jacobs School of Engineering IDEA Center and the Triton Engineering Student Council, as well as the support of local companies like BrainCorp Inc, Teledyne Marine and Epsilon Systems, we were able to purchase raw materials for our new submarine, as well as various competition fees. We look forward to expanding our reach in our community in the future for even better innovative design.

References

[1] Adam Kelly, “Create COCO Annotations From Scratch”. https://www.immersivelimit.com/tutorials/create-coco-annotations-from-scratch.

[2] Blue Robotics.“BlueROV2 Assembly,” https://bluerobotics.com/learn/bluerov2-assembly/.

[3] Blue Robotics, “ArduSub”, https://www.ardusub.com/.

[4] F. Gustafsson and F. Gunnarsson, ”Positioning using time-difference of arrival measurements,” *2003 IEEE International Conference on Acoustics, Speech, and Signal Processsing, 2003. Proceedings.* (ICASSP ’03)., Hong Kong, 2003, pp. VI-553, doi: 10.1109/ICASSP.2003.1201741.

[5] pjreddie, “YOLO: Real-Time Object Detection”. https://pjreddie.com/darknet/yolo/.

[6] Razavi Behzad, “Analog Filters”, in *Fundamentals of Microelectronics*, 2nd Edition, Hoboken, New Jersey, USA: Wiley, 2013, ch. 15, Second-Order Filters and Active Filters, 720-743.

[7] Washington State University, “Palouse Robosub Technical Documentation”, http://robosub.eecs.wsu.edu/wiki/ee/hydrophones/start?s[]=hydrophone

Appendix A
Specifications

Table I: General

Team Size	37 people
HW/SW Expertise Ratio	17:13
Testing Time: simulation	100+ hours
Testing Time: in-water	10+ hours

Table II: Mechanical Components

Component	**Vendor**	**Model/Type**	**Specifications**
Frame	Custom	Aluminum T6061	Density 2.7 g/cm Strong corrosion resistance
Waterproof Housing	BlueRobotics	8” Acrylic hull	https://bluerobotics.com/store/watertight-enclosures/8-series/wte8-asm-r1/
Waterproof Connectors	BlueRobotics	Potted Cable Penetrator	https://bluerobotics.com/store/cables-connectors/penetrators/penetrator-vp/
Thrusters	BlueRobotics	T200	https://bluerobotics.com/store/thrusters/t100-t200-thrusters/t200-thruster-r2-rp/
Propellers	BlueRobotics	Standard propellers	https://bluerobotics.com/store/thrusters/t100-t200-thrusters/t200-propeller-set-r3-rp/

Table III: Electrical Components: Power

Component	Vendor	Model/Type	Specifications
Battery x2	Blue Robotics	Lithium-Ion	14.8V 18 Ah
Relay	TE Connectivity	F7 Series	24 VDC, 50 A
Power Sensor	Blue Robotics	Power Sense Module	Max Voltage: 25.2V Max Current Sensing: 100A
Buck Converter	Amazon	HW-064	Input: 4 - 38V Output Current: 5 A 75W Maximum

Table IV: Electrical Components: Controls

Component	Vendor	Model/Type	Specifications
Computer	NVIDIA	Jetson Xavier NX	GPU: 384-core NVIDIA Volta GPU with 48 Tensor Cores CPU: 6Core NVIDIA Carmel ARM v8.2 64-bit Memory: 8 GB 128-bit LPDDR4x
Microcontroller	Rasberry Pi	3 Model B	CPU: Quad Core 1.2 GHz Broadcom BCM2837 64-bit Memory: 1 GB RAM
Flight Controller	Pixhawk	Pixhawk 1	CPU: STM32F427 180 MHz ARM Cortex M4 with signle-precision FPU Memory: 256 KB SRAM (L1)
Motor Controller	Blue Robotics	Basic ESC	7-26 V, 30 A max current
External Comm Interface	Blue Robotics	Fathom-X Tether Interface	80 Mbps Ethernet
Internal Comm Network	Brain Boxes	SW-115	5 Port Gigabit Ethernet

Table V: Electrical Components: Sensors

Component	Vendor	Model/Type	Specifications
Sonar	Blue Robotics	Ping360	Acoustic Frequency 750 kHz Beamwidth - Horizontal: 2 deg Beamwidth - Vertical: 25 deg Maximum Range: 50 m Continuous 260 degree scan
Doppler Velocity Log	Teledyne	Explorer	Bottom Tracking Altitude: 81 m Water Profiling Range: 35 m Center Frequency: 613.4 kHz
Magnetometer	GeoDevice	Minimag	Principle of Operation: Overhauser effect Range: 20,000/110,000 nT Sensitivity: 0.01 nT Resolution: 0.0001 nT Sampling Rate: 5 Hz
Depth Camera	Intel	RealSense D455	Depth Field of View: 87 deg x 58 deg 1280 x 720 Resolution, 90 fps
Front Camera	Sony	IMX322	1080P HD Resolution, 30 fps
External Camera	ROVMAKER	HORUS-S10	1080P HD Resolution, 25 fps

Table VI: Electrical Components: Hydrophones

Component	Vendor	Model/Type	Specifications
Hydrophones 4x	Aquarian Audio	H1c	Sensitivity: -190 dB re: 1V/uPa Useful range: 1Hz to 100kHz Polar Response: Omnidirectional
Amplifier Board Quad JFET OpAmp Quad Digital Potentiometer	Custom Texas Instruments Analog Devices	None TL074 AD5263	None Low Noise/Input Bias Current 256-Position, End-to-end resistance: 20 kOhm, 50 kOhm, 200 kOhm
Daughter-Board Analog-to-Digital Converter	Custom Analog Devices	None LTC2325-16	None 5Msps/Ch, Four Channel Guaranteed 16-Bit 8Vp-p Differential Inputs with Wide Input Common Mode Range
Development Board	Xilinx	MicroZed	Zynq-7000 SoC Memory: 1 GB DDR3 SDRAM 128 Mb QSPI Flash

Table VII: Software

Programming Language 1	C++
Programming Language 2	Python
Operating System	Ubuntu 18.04
Open Source Software	YOLO, OpenCV (Image Processing Library), ROS (Robot Operating System)
Algorithms: Vision 1	OpenCV HSV Filtering, Gaussian Blur, Contour Detection
Algorithms: Vision 2	Custom YOLOv3
Algorithms: Acoustic	Online DFT, First Order Infinite Impulse Response Filter, Phase Shift
Algorithms: Localization and Mapping	Vision Position Delta (VPD), Kalman Filter
Algorithms:	Custom State Machine

Appendix B
Community Outreach

A main focus of Triton Robosub is to participate in outreach events to further the engineering community around us. We collaborated with various organizations at UCSD like NeuroTech (see Figure 11), Women in Computing, and Society of Hispanic Professional Engineers to introduce topics like signal processing and robotics to engineering communities who might be interested in what RoboSub involves. Furthermore, COVID-19 inspired us to focus on our online presence: improving social media outlets, redesigning our website, and setting up an online streaming profile so that online audiences can see our tests live! We've even had the opportunity to test at sites like the Birch Aquarium, and through our Twitch account we were able to bring a little taste of sea life to viewers at home (as depicted in Figure 13).

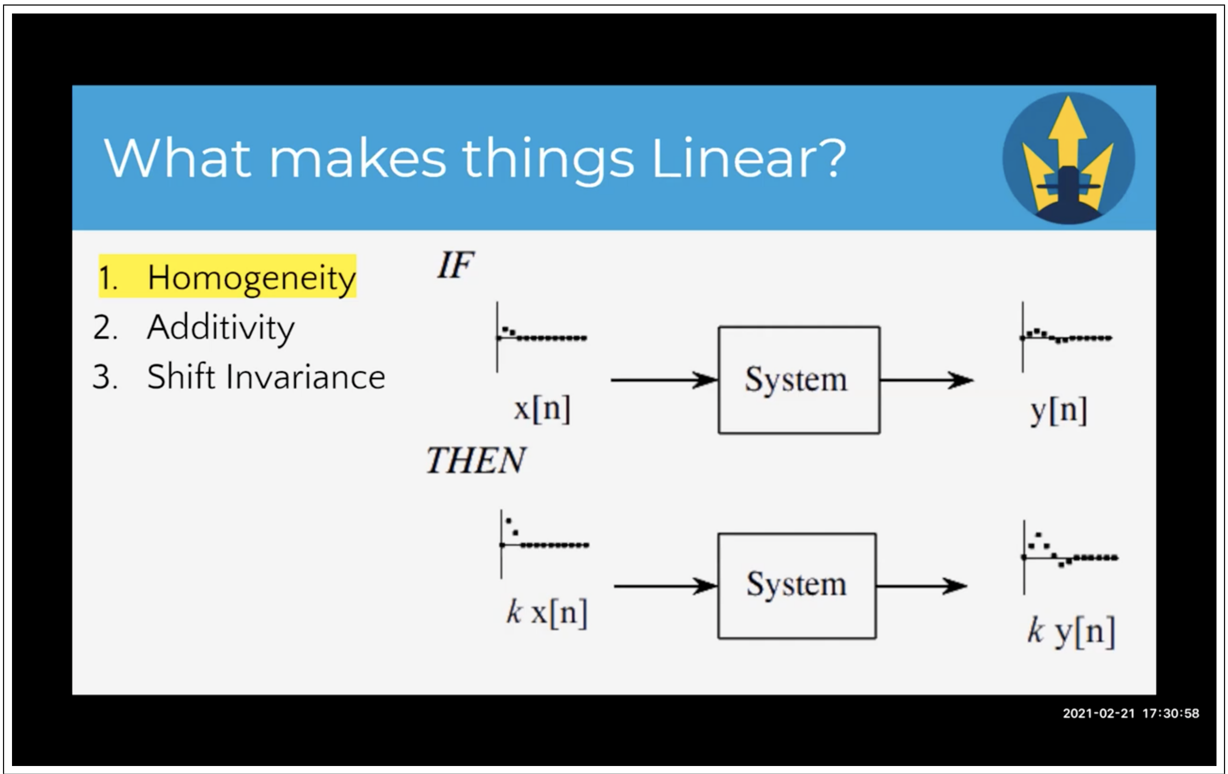

Figure 11: Screenshot from our workshop with fellow student org NeuroTechX, on the topic of Digital Signal Processing.

On a technical side, Triton Robosub has also worked our way into more research projects at UCSD, including FishSense. This research project is trying to focus on studying underwater marine life through depth sensors; by providing an underwater platform and software to this project, Triton Robosub has helped FishSense publish in San Diego's Oceans Conference! For more information on this project, please visit e4e.ucsd.edu/fishsense. We are actively talking to other research groups at San Diego including the Scripps Institute of Oceanography to explore other research opportunities that Triton Robosub could contribute to.

With everybody returning to in-person events for the upcoming year, we are excited to connect with the San Diego engineering community and get them excited about underwater robotics! We hope to host joint testing sessions and other events with fellow San Diego RoboSub teams, continue refining our workshop content, and teach our peers and future generations about engineering.

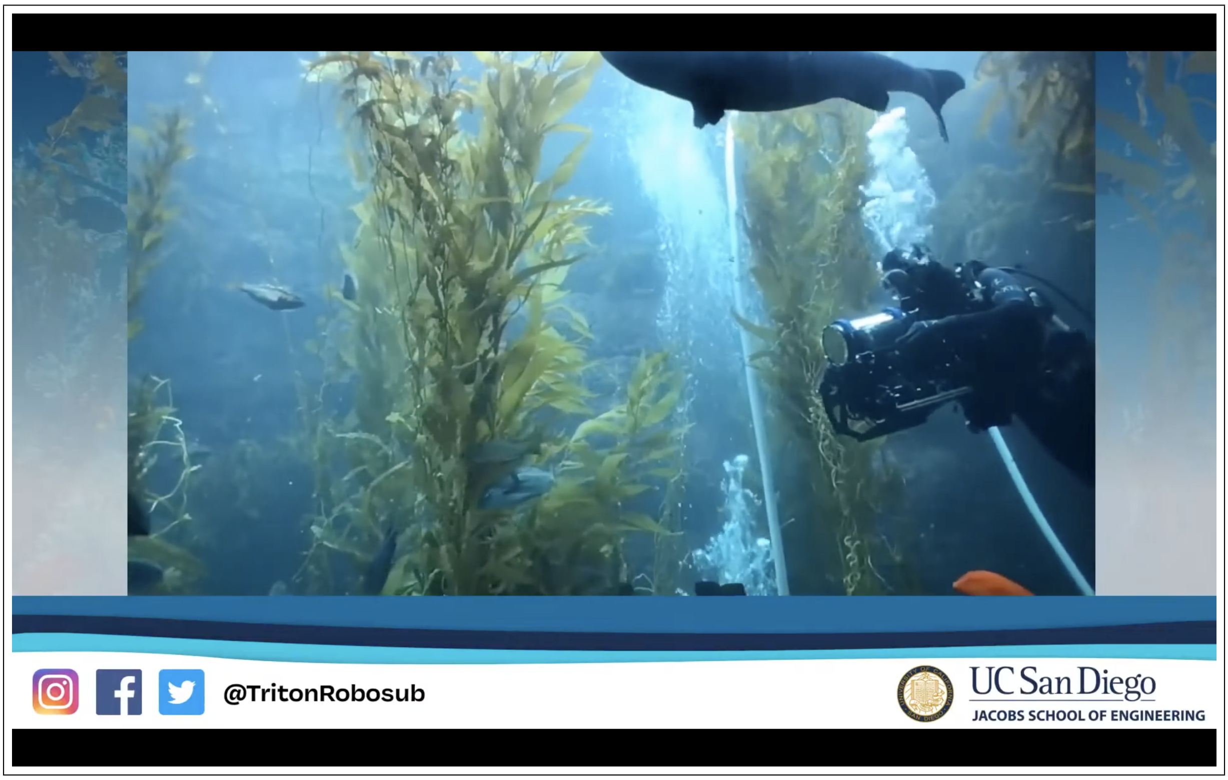

Figure 12: Screenshot from our Birch Aquarium test livestream.

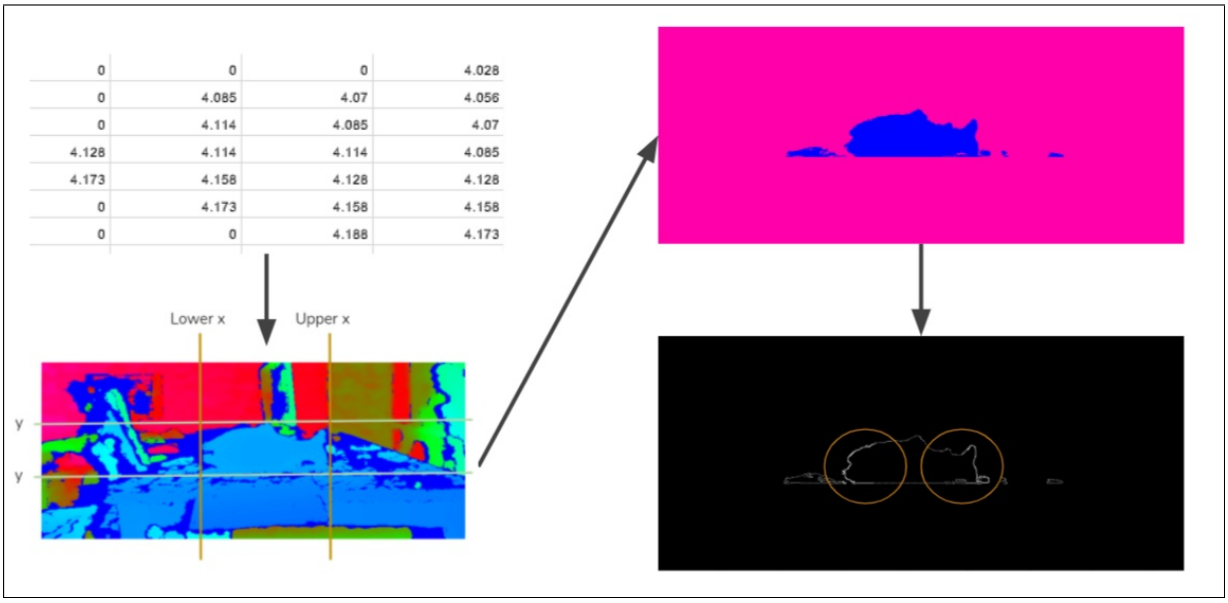

Figure 13: Illustration of FishSense depth processing pipeline. A similar pipeline will be employed for the upcoming RoboSub competition.