Amador Valley Robotics Club: Design of Nemo AUV 2020

Daniel Zhou (President); Software: Suhas Nagar (VP), Charles Jin, Craig Wang, Lily Cheng, Michael Li, Neil Allavarpu, Phoebe Tang, Serena Zhou, Vincent Wang; Mechanical: Sri Parasaram (VP), Andrew Delevaux, Dylan Kwong, Isabelle Lo, Ishan Duriseti, Richard Bai, Steven Li; Electrical: Maxim Vovenko (VP), Edward Ding, Justin Yu; Business: Athan Yang (VP), Myra Qin, Ethan Apalis, Arvind Swamynathan, Meera Swamynathan, Matthew Lim.

***Abstract*—Nemo is AVBotz's new vehicle. Conceived in 2018 and refined through the 2019-2020 season, Nemo takes the best of Marlin and improves on its shortcomings. Nemo makes it easier for software to test their code, allows flexible mechanical modifications, optimizes the arrangement of internal electronics, and uses an active water cooling system for thermal management.**

I. Competition Strategy

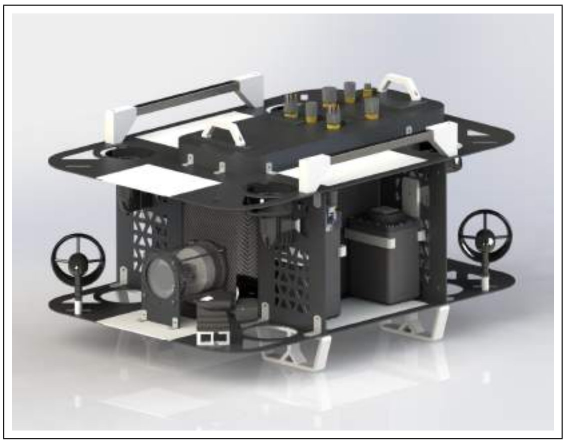

Figure 1: Render of Our AUV: Nemo

II. Vehicle Design

A. Software

ROS: The main software stack runs on Ubuntu 18.04 with ROS (Robot Operating System), a set of libraries and tools meant for cutting-edge robotics development. We use ROS because of its built-in message passing interface. Additionally, ROS provides us with easy integration for our code with the simulation software and with ORB-SLAM. Each part of the software runs on a separate ROS node, the main ones being vision, camera, mission, and control.

Control: The control software, Nautical, runs on the ATMega2560 microcontroller and communicates with the main computer over serial. It handles state estimation and low-level communication to the hardware through serial UART pins. Each state, or submarine position, is represented with six degrees of freedom: X, Y, Z, roll, pitch, and yaw. The states are relative to a NED (North-East-Down) coordinate plane. A Kalman filter fuses the data from each sensor to reduce noise for more accurate state estimation, and euler angles are used to convert between frames of reference. To control the submarine, there are six tuned PID controllers that facilitate movement between the current position and a desired destination.

Pinger Localization: Using a Xilinx Artix-7 FPGA, we decided to increase the consistency of the hydrophones mission by switching to the MUSIC algorithm to calculate the Direction of Arrival (DOA) instead of running a Discrete Fourier Trasnform. MUSIC is a lot more robust in calculating the direction of arrival since it requires less intermediate calculations which reduces the amount of error. In order to find the estimated angle, we then applied a linear search across a set of potential angles to find the angle which

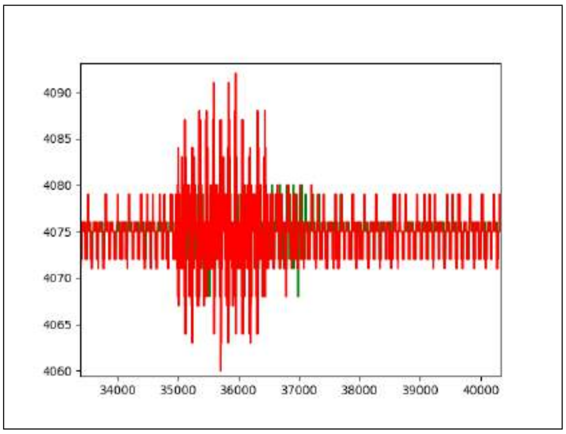

Figure 2: Hydrophone data

produced the maximum result.

Vision: Due to rapid advancements in machine learning based object detection, we have upgraded from the older Faster RCNN to the newer EfficientDet, implemented with Tensorflow API; with the newer model, we have been able to significantly reduce training and inference speeds while improving accuracy. Furthermore, it has also allowed us to run the model using standard laptops without hefty GPUs, which is a convenient characteristic for simulations. However, a large portion of the model's achievements is possible due to our OpenCV underwater image enhancement, which increases the quality of our training data, allowing for a vastly expanded vision range in murky waters; ultimately, the combined synergy has allowed us to perform fast and accurate detection of competition objects, including gate and bins.

Image Enhancement: To complement our new machine learning model, we added an image enhancement algorithm improve our detection accuracy. As light travels through water, high-frequency colors (like red, orange, and yellow) disappear. To add on, particles in the water become enhanced by the camera's light source. As a result, images taken underwater have an added blue-green cast and become distorted by backscatter. To improve our AUV's object recognition accuracy, we implemented an algorithm to restore the images' original colors. With the help of OpenCV, we converted images taken into mat format and the modified pixel values for each

Figure 3: Before and After

channel. In order to balance the colors on the image, the algorithm finds a high and a low percentile for these values and averages the rest out to normalize the colors.

B. Mechanical

The main focus of Mechanical this year was the design and manufacturing of our next generation AUV, Nemo. Using advanced techniques such as FEA, FDM, and Generative Design, Nemo was designed to tackle some of Marlin's largest structural issues.

Carbon Enclosures: Almost all of the watertight enclosures on Nemo are made of carbon fiber. Carbon fiber has a higher strength-to-weight ratio compared to other common materials such as aluminum alloy. Carbon fiber parts also have advantages in fabrication, allowing for unique shapes with virtually no material being ”milled” away. Aluminum sealing lips are bonded to the carbon parts using an epoxy adhesive. O-rings were selected as the sealing device due to their proven reliability and their cost.

Battery Box: In previous years, batteries were placed inside the main enclosure, making it difficult to replace batteries during pool tests. To address this, we added external battery boxes to Nemo's design. The design consists of a lip, lid, and a carbon hull. The four draw latches allow for tight water sealing while also allowing quick access to the batteries.

Hydrophones and Auxiliary Box: In order to increase our scoring output from previous years, we decided to include hydrophones as part of our vehicle design. The hydrophones electronics enclosure consists of a carbon shell and an aluminum lip and lid, housing our custom PCB and amplifiers. The Auxiliary Box is identical to the hydrophone enclosure and it is used to house secondary electronics that require frequent access. Both enclosures are sealed with a single EPDM - ring.

Main Electronics Bay (MEB): The MEB is the largest enclosure of our vehicle. It contains all our major electronics including the GPU and CPU. Similar to the other carbon enclosures, it consists of a carbon fiber shell and an aluminum lip and lid. It is pressurized from 5 to 15 psi, eliminating external pressure forces. This also allows for the detection of a seal failure without the ingress of any water. The MEB is sealed with two rubber o-rings. The lid is connected to the electronics rack of our vehicle, allowing for easy access to the main electronics.

Camera Enclosure: The camera enclosure was designed to house the front camera of Nemo. The enclosure has front and back aluminum plates connected through aluminum rods. The lens of the enclosure is made with scratch resistant acrylic and the enclosure is made out of cast acrylic, ensuring clean vision while also keeping the camera secure. The pod is sealed with two double radial o-ring seals on the front and rear, as well as a face seal on the rear plate.

Conduit Panel: The conduit panel was designed to connect internal electronics with external systems. The conduit panel consists of two aluminum plates sandwiching the MEB hull. In addition, the conduit panel holds two presta valves, which are used to pressurize the MEB. The setup is sealed by a single rubber o ring.

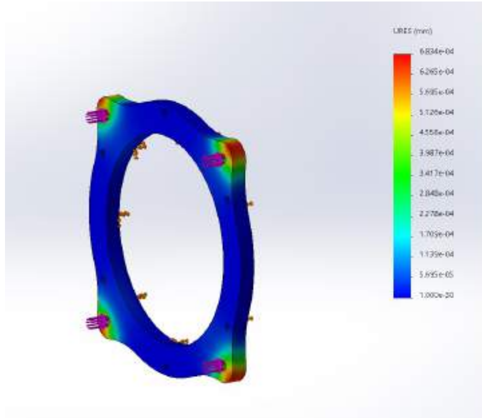

Figure 4: Camera Enclosure Back Plate FEA Displacement Plot

Electronics Rack: The electronics rack is necessary to organize and support electrical components in the MEB. Plywood was chosen as the material due to its high strength-to-cost ratio. The design consists of multiple plates which hold the electronics as well as side panels for structural integrity. This design allows for the electronics and wiring to be more organized and cooling to be more efficient, a major issue on Marlin. The rack is attached to the MEB lid so that electronics are easy to remove and service if necessary.

Mounting Planes: On our previous vehicle, Marlin, a major issue was the asymmetrical cross section, with the bottom cross section being heavier than the top. This caused Marlin to pitch forward when attempting to move forward. In addition, modularity on the frame was an issue. To tackle this, Nemo has double frames aligned parallel vertically, creating a symmetrical cross section. Additionally, the two frames have modular panels used to hold different modules. Because these panels are made using additive manufacturing, they can be configured to seat different types of elements, allowing Nemo to be ready for any task.

Props: In addition to designing, manufacturing, and maintaining the team's vehicles, Mechanical also has the responsibility of designing props for our Software Team to use.

These props included bins, which were made out of corrugated plastic, allowing the bin to be durable yet inexpensive. Weights and water holes were added to the sides, allowing the bin to sink faster and in turn making our many pool tests much more efficient.

C. Electrical

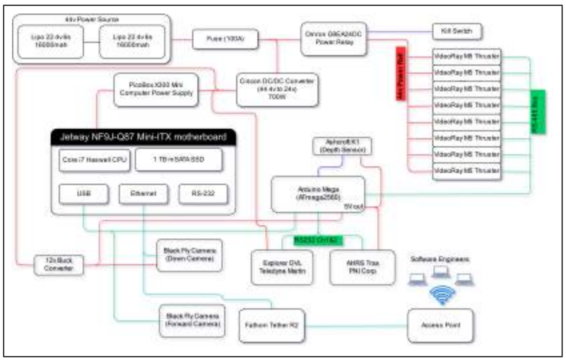

Figure 5: Overview of Nemo's electrical system

Power Delivery: The vehicle's power delivery system is designed to meet the high power requirements of the hardware. We provide two main voltage rails (48v and 24v) to power systems, with 48v directly powering thrusters, and 24v (produced from 48v) powering all other subsystems inside the main electronics bay. The upshot of this strategy allows us to hook a second external 24v supply in parallel with that of the internal toggle-able 24v supply and maintain continuous power to the submarine electronics. This allows the AUV to remain on all day at the competition site, and allows us to use smaller batteries, saving us weight and also maintaining higher reputability during testing.

Internal Communications: The sub's internal components communicate over large spectrum of protocols. To organize them, they are split into two separate domains. The first domain controls the submarine and is centered around the Arduino, linked to all low-level sensors and manipulators. The second domain commands the submarine and is linked to vision, networking, and the Arduino. Together, these two domains make up the command and control for Nemo, and allow for parallel workflow as changes can be made simultaneously to both domains with few compatibility issues arising. These two different domains also also allow for a simplified simulation of the sub as the command section can be easily manipulated with a very simple model of the competition.

Tether: The sub's tether has been upgraded to handle gigabit speeds which makes it easier to alter and troubleshoot command code, as we have the bandwidth to observe real-time the behavior of the code and what the submarine sees. The tether is also neutrally buoyant, which helps with testing as the cable is less likely to wrap around props and is easier to manage.

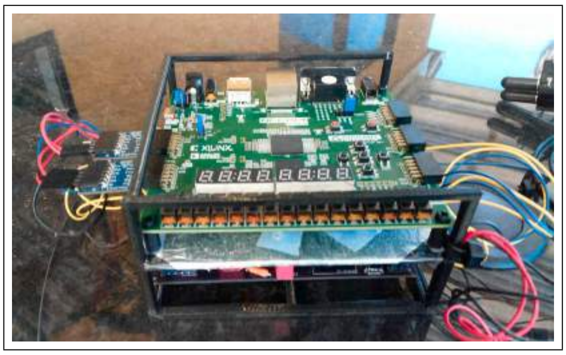

Figure 6: FPGA with hydrophone circuits

Hydrophones: The hydrophones circuit has been improved from the previous generation. The amplifier circuit is now discreetly separated into 3 stages following the recommendations for analog design and is using custom manufactured PCBs to mitigate interference noise. The data processing circuit has now been upgraded to an FPGA with custom programming that allows for the software team to code in C algorithms to process the data and return an angle and estimated distance, while utilizing the high speed capabilities of low level FPGA programming to collect the data at sample rates of around 700ks/s. This results in a significantly faster development cycle as software members do not need to learn Verilog or VHDL to make use of the capabilities and features of an fpga.

Computing: Nemo's high-level mission control and vision code runs on a Mini-ITX motherboard with an i7-4790t processor, augmented with 16GB of RAM and a

1TB SSD allowing for extensive logging of vision, hydrophone, and control data. A GTX 1080 Ti is connected to the motherboard to allow for running extensive real-time neural networks. Finally, an Arduino 2560 is used to handle control of the submarine and acts as an abstraction layer for the command code running on the computer.

III. Experimental Results

A. Simulation

As a result of the shelter in place orders resulting in the cancellation of a summer's worth of pool testing, we streamlined more effort into creating a working simulator for our AUV; we utilized UWSim and Freefloating Gazebo, which is a package that uses Gazebo for the physics simulation and UWSim for the rendering. These packages are compatible with ROS, reducing the hassle of integrating our mission code into the simulator. Our mechanical and electrical members created 3D models of the TRANSDEC environment including the gate, the 2019 buoys, a simple bin, as well as a simple octagon. Our first few iterations of the simulator were only kinematic, as we started with only teleporting our sub to desired states. However, as we continued to focus more effort into increasing its capabilities, we were finally able to integrate thrusters and velocities with the help of Freefloating Gazebo, creating a more realistic underwater scenario. With a working simulator, we are now able to rapidly test new algorithms and mission functions without the need for in-person pool tests.

B. Real World Testing

A result of extensive real world testing has led us to discover small issues in electrical wiring and power delivery (pd). We found that due to a previous design decision our Attitude Heading Reference system would drift an unpredictable and unacceptable amount through out a run of the competition. To mitigate this we attempted rewire pd current tests indicate that it successfully dropped drift to less then 5 degrees in a 30minute static test. Another result of real world testing showed that software's acquisition of the replacement gtx1080ti was had lead to a new phenomena of crashes caused by overwhelming of the computer power supply unit. This taught us a valuable lesson regarding power management, it can usually be fixed with software.

IV. Acknowledgements

Furthermore, we would like to thank the following sponsors for donating their resources: Datron Dynamics West, Teledyne Marine, MacArtney Underwater Technology, ACP Composites, and PNI Sensor Corporation. Without the contributions of these sponsors along with our sponsors from previous years, AVBotz would not be where we are today.

References

[1] Huang J, Rathod V, Sun C, Zhu M, Korattikara A, Fathi A, Fischer I, Wojna Z, Song Y, Guadarrama S, Murphy K, CVPR 2017 *"Speed/accuracy trade-offs for modern convolutional object detectors."*

[2] Barret Z, Vijay V, Jonathon S, Quoc V *"Learning Transferable Architectures for Scalable Image Recognition."*

[3] Clement G, Oisin A, Gabriel B *"Unsupervised Monocular Depth Estimation with Left-Right Consistency."*

[4] Morgan Q, Brian G, Ken C, Josh F, Tully F, Jeremy L, Eric B, Rob W, Andrew N *"ROS: An Open-Source Robot Operating System."*

[5] Sebastian T *"Particle Filters in Robotics."*

[6] Zhen C, Jonathan M, and Cassondra P *"Acoustic Pinger Locator (APL) Subsystem."*

APPENDIX A
SPECIFICATIONS

Table I: General

Team Size	30 people
HW/SW Expertise Ratio	1:1
Testing Time: simulation	100+ hours
Testing Time: in-water	100+ hours

Table II: Mechanical Components

Component	**Vendor**	**Model/Type**	**Specifications**
Frame	Custom	Aluminum 6061-T6	Hard-Anodized Density 2.7 g/cm^3 Strong corrosion resistance
Main Waterproof Electronics Enclosure	Custom	Carbon Fiber Hull sealed with a bonded aluminum lip and 2 EPDM O-rings	Dimensions: 24.45 in (62.10 cm) x 8.95 in (22.73 cm) x 13.50 in (34.20 cm)
Waterproof Connectors	SubConn	Circular Series	[Varies Based on Series] Micro-Circular Series Power Series Coax Series
Battery enclosures	Custom	Carbon Fiber body with bonded aluminum lip and lid, single dovetail o-ring seal	Dimensions: 4.13 in (10.5 cm) x 4.13 in (10.5 cm) x 9.42 in (23.95 cm)
Thrusters	VideoRay	M5 Thrusters	Power Input: 48V DC Max Thrust: 23lbs built-in electronic speed controllers
Propellers	VideoRay	Standard propellers	90mm (3.5 inches) 3 blade propeller with collet (smooth shaft)

Table III: Electrical Components: Low Level Control

Component	**Vendor**	**Model/Type**	**Specifications**
Control Board	Rugged Circuits	Rugged MEGA	Microcontroller: ATMega 2560 expanded with Arduino Protoshield
Inertial Measurement Unit (IMU)	PNI Sensor	TRAX AHRS	Communication: RS232 Static Heading Accuracy: .3° Non-static Heading Accuracy: 2.0° Tilt Resolution: .01°
Depth / Pressure Sensor	Ashcroft	Model K1	Accuracy: ±0.50% or ±1.00% span Pressure Ranges: Vacuum to 20,000 PSI
Doppler Velocity Log (DVL)	Teledyne Marine	Explorer DVL	Type: Phased Array Transducer Frequency: 600kHz Max Depth: 1000m

Table IV: Electrical Components: Main Computer

Component	Vendor	Model/Type	Specifications
CPU	Intel	i7-4790T	Number of Cores: 4 Number of Threads: 8 Processor Base Freq: 2.7GHz Max Turbo Freq: 3.9GHz
Motherboard	Jetway	NG9J-Q87 Mini ITX	USB 2.0 Ports: 4 USB 3.0 Ports: 2 HDMI Ports: 1 PCI-E 3.0 x 16 Slots: 1 RJ45 LAN Ports: 2
RAM	Corsair	Vengeance 16GB	2x8GB DDR3 SODIMM RAM Memory Speed: 1600MHz
Storage	Samsung	1TB mSATA 860 EVO SSD	Max Seq Read Speed: 550 Mb/s Max Seq Write Speed: 520 Mb/s
GPU	Nvidia	GTX 1080ti	CUDA Cores: 3584 Memory: 11GB GDDR5X Max Power: 250W

Table V: Electrical Components: Cameras

Component	Vendor	Model/Type	Specifications
Front Camera	FLIR	BFS-U3-200S6	Resolution: 5472 x 3648 Megapixels: 20MP Frame Rate: 18FPS Sensor Type: CMOS
Front Camera Lens	Computar	V0828-MPY	Mount: C Mount Horizontal Angle: 77.3° Vertical Angle: 61.7°
Down Camera	FLIR	BFS-U3-13Y3C-C	Resolution: 1280 x 1024 Megapixels: 1.3MP Frame Rate: 170FPS Sensor Type: CMOS
Down Camera Lens	Theia	SY125M	Focal Length: 1.3mm Resolution: $\leq$5MP Mount: CS Mount Horizontal Angle: 135° Vertical Angle: 119°

Table VI: Electrical Components: Hydrophones

Component	**Vendor**	**Model/Type**	**Specifications**
Hydrophones	Teledyne Reson	TC4013	Frequency Range: 1Hz to 170kHz Resistant to seawater
Data Acquisition and Signal Processing	Digilent	Nexys 4 DDR Artix-7	Block RAM: 4,860 Kbits Logic Slices: 15,850 Internal clock: 450MHz+ DDR2: 128 MiB

Table VII: Software

Programming Language 1	C++
Programming Language 2	Python
Operating System	Ubuntu 18.04
Open Source Software	OpenCV (Image Processing Library), ROS (Robot Operating System)
Algorithms: Vision 1	OpenCV K-Means Clustering, Canny Edge Detection, Gaussian and Median Blur, Contour Detection, Blob Detection
Algorithms: Vision 2	Tensorflow using the FasterRCNN framework
Algorithms: Acoustic	Online DFT, First Order Infinite Impulse Response Filter, Phase Shift
Algorithms: Localization and Mapping	Kalman Filter
Algorithms: Autonomy	Markov Decision Process

Appendix B
Community Outreach

AVBotz members participate in multiple community outreach events throughout the year to inspire younger students to pursue STEM fields. Over the course of the academic school year, members of our team taught students at our local middle schools every week. The team has also revived a monthly newsletter that the audience can subscribe through via Mailchimp. The newsletter consists of what each division is working on in that month. The newsletter and other outreach attempts are all promoted on social media such as Instagram and LinkedIn. The AVBotz team also presented the submarine at IGNITE, an event centered around innovative arts and technologies. Through all these different outreach events, our team members hope to promote robotics and engineering and inspire students to explore the field of robotics.