Desert WAVE: AUV Strategy, Design and Implementation for RoboSub 2021

K. Afshari, S. Anand, K. Arreguin, E. Ashton, I. Bushroe, J. Dirks, S. Ehrle, S. Ganti, P. Garibay Jaquez, B. Johnson, B. Koehl, S. Lee, S. Lepore, A. Mietus, M. Molnar, S. Nieto, J. Overby, L. Roty, A. Schoonover, M. Schoonover, M. Strube, A. Vaidya

Mentors: M. Cheng, G. Clark, B. Emami, D. Frank, B. Kahn, D. Kahn, A. Kurapati, F. Lajvardi, F. Nueperger

Abstract- **This year, Desert WAVE (Women in Autonomous Vehicle Engineering) prepared to complete all of the tasks at the RoboSub Competition quickly and accurately. While the team's first AUV, Phoenix, was able to achieve 3rd place at the 2019 competition without pneumatics capabilities, it was only able to complete certain tasks. To address this, this year Desert WAVE focused on developing its second more capable AUV, Dragon to complement Phoenix. The team completed the mechanical construction of Dragon and focused on further developing vision systems that will be used for both AUVs. The team primarily tested subsystems of Dragon separately, as they continued to be developed. This included testing the communication between hulls, testing the pneumatically operated marker dropper, grabber arm, and projectile launcher individually, and training Dragon to identify objects in the water using deep learning and HSV models. This paper describes the methods used to accomplish the full integration of subsystems and the physical manufacturing of Dragon.**

Keywords- **AUV, Women in Engineering, RoboSub Competition, Machine Learning**

I. Competition Strategy

At the start of the 2020-2021 competition season, Desert WAVE reviewed the previous year's performance and assessed which goals were achieved and which were not. The team also considered the feedback received from the 2020 judges to define the goals that would improve the deliverables for the next competition. This season, Desert WAVE focused on completing Dragon, the team's second AUV (Autonomous Underwater Vehicle). While the team's first AUV, Phoenix, is functional, Dragon is more capable, as it was designed and built with a pneumatics hull to allow it to complete challenges that require advanced manipulation. The goals the team focused on were to further develop the vision systems for both AUVs, improve the mechanisms designed for the challenges requiring advanced manipulation, and complete the construction of AUV Dragon. The similarity of Phoenix and Dragon's designs and the modularity of their components allowed innovation to come from smaller, test-based, iterative design changes. The team focused on the execution and optimization of systems that were conceived in previous years, rather than initial development of new ones.

At the RoboSub challenge course, Dragon will move quickly and attempt all of the tasks. As in 2019, Desert WAVE will use surveying techniques to generate waypoints, as shown in Figure 1, which the AUV will use to navigate to the vicinity of each task with a fiber-optic gyroscope (FOG) and doppler velocity log (DVL). Waypoint navigation will allow it to move quickly. Once near the task, Dragon will use a combination of HSV filtering and machine learning to detect the task objects. Desert WAVE will complete the tasks in the order outlined in Table I and Figure 2 to 23 Skidoo in less than 20 minutes.

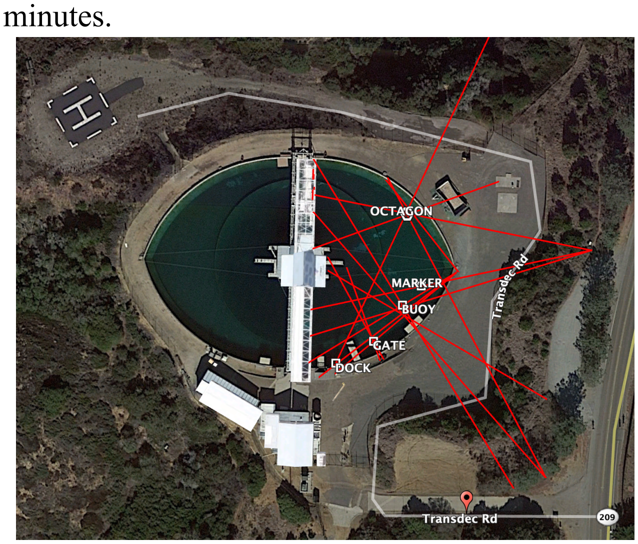

Fig. 1. Competition strategy.

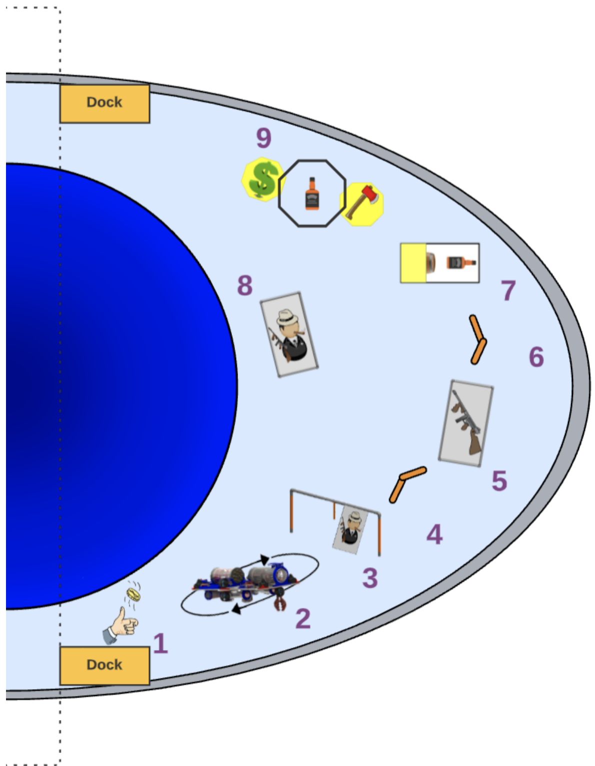

Fig. 2. Competition strategy.

TABLE I
TASKS DESERT WAVE WILL ATTEMPT

Order	Name	Task	Notes
1	With Moxy	Coin Flip	
2	Style Points	Change in Orientation	Roll twice in yaw direction
3	Choose your Side	Gate	
4	Path	Identify 1st Path marker	Follow the path towards the bins
5	Make the Grade	Buoy	Bump into appropriate buoy
6	Path	Identify 2nd Path marker	
7	Collecting	Bins	Lift cover, drop markers in correct bin
8	Survive the Shootout	Torpedo	Fire through small opening
9	Cash or Smash	Octagon	Surface with bottle in octagon, move to correct table

II. DESIGN CREATIVITY

This is the first year that Dragon is completely mechanically functional. Its computer hull was totally redesigned, and afterward the layout of its components on its frame was finalized and assembled. A modular hull design presented communication challenges that were tackled with telemetry. A plan for its vision systems, using both HSV and machine learning techniques, was further developed and put into action.

Dragon's design, as shown in Figure 3, was intended to be modular from the outset. Each of the two batteries has its own hull, supplying the thrusters and computer systems separately so that fluctuations in voltage from the thrusters do not affect the more delicate systems in the computer hull. The computer hull makes decisions and handles sensor processing while the thruster hull controls power to the thrusters. The pneumatics hull houses a custom pneumatics board and eight solenoids for each respective system. These solenoids actuate one inch stroke pistons that operate Dragon's projectile launcher, grabber, and marker dropper. Separating these systems into different hulls reduced the design complexity of each hull. It also allowed multiple team members to design the various hulls in parallel. In the event of a leak, separating the systems into five hulls will also contain damage to only one system. Once the pneumatics system is capable of autonomously actuating the cylinder, the team will test Dragon's ability to launch projectiles through an underwater target consistently. This will involve perfecting the AUV's ability to position itself in front of a target and then shoot accurately using its vision systems. The launcher was positioned directly above the front facing camera to make it easier to line up with a target.

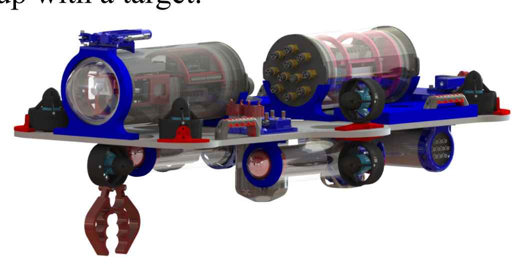
Fig. 3. CAD model of Dragon AUV.

Desert WAVE's first major challenge this competition year was to redesign and build Dragon's computer hull. It is powered by one of two 16.8 V batteries, and was designed in an iterative process to improve usability and visibility and maintain proper operational temperatures. The computer hull has three sets of ten LEDs, which provide visual feedback to the surface and divers to determine the status of the AUV. The final design houses the Jetson Xavier NX, a 3-axis fiber-optic gyro (FOG), two cameras, two fans, the power bus, a variety of switches, and two of Dragon's four custom boards (AUV main board and sensor fusion board). While the team's first AUV, Phoenix, only has one custom electrical board, Dragon features multiple boards to reduce stress on any one board. Debugging is also easier since problems can be isolated to a specific board, each of which acts as a breakpoint. Programmers can also detach the computer hull from Dragon and perform additional testing without requiring the rest of the AUV. For transport, the computer hull can be removed from the AUV and fixed to the temporary frame shown in Figure 4, coined as the "boogie board" by the team.

Fig. 4. Independent transportation of Dragon's computer hull.

There are two ways to disable Dragon: a mission switch and a kill switch. The mission switch, depicted in Figure 5, controls power to the thrusters and is triggered by a magnetic contact switch. The kill switch, a repurposed SubConn connector, controls the power to the AUV Main Board. If the mission switch fails, the kill switch can be removed to disable the AUV.

Dragon has the same configuration of 10 thrusters as Phoenix, which allows it to translate and rotate freely with redundancy. The thruster configuration also prioritizes speed to the number of runs that can be attempted during the mission and achieve the time bonus. Throughout the competition, the AUV will primarily move forward, so four thrusters are used to produce thrust in the surge direction. Four vertical thrusters allow the AUV to control its depth. Finally, two bow thrusters make minor alignment adjustments in the sway direction. All of the thrusters used on each AUV are placed along the perimeter of their frames, maximizing the moment that the thrusters exert on the AUVs to enable quick and efficient turning.

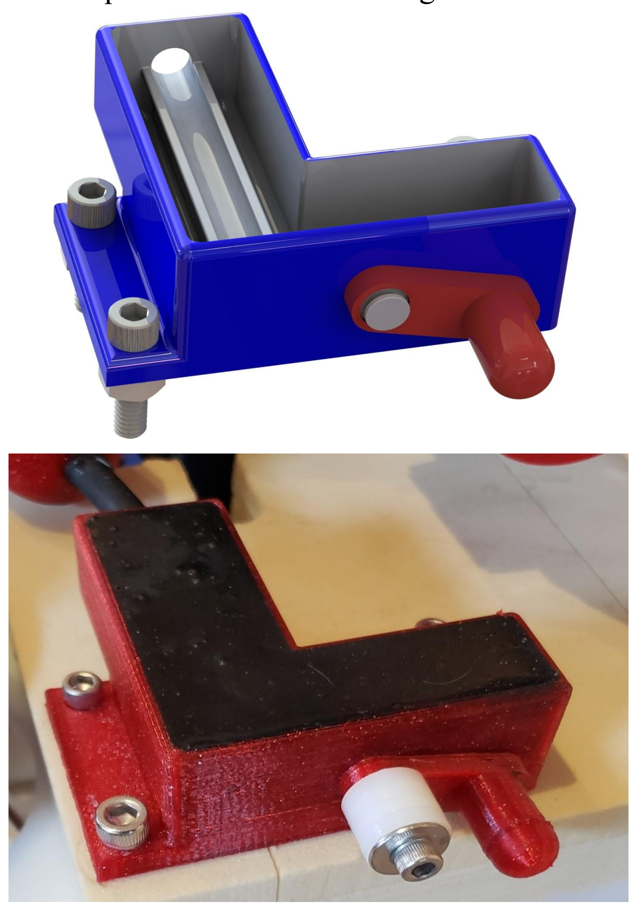

Fig. 5. CAD Model and physical mission switch.

Either AUV can lose the function of at least one thruster, and in some cases up to four, and still be fully maneuverable with adjustments to the software. The team is currently incorporating fault tolerance to both AUVs by programming them to automatically sense the failure of a thruster and adjust the power of the other thrusters accordingly.

A. Telemetry

Dragon's programming and electrical systems are unique in how they allow communication among the three main hulls. The telemetry data receives a real time status (heartbeat) of the eight active solenoids for the pneumatics board, running status of all ten thrusters from the thruster board, DVL, and additional sensors. Communicating back and forth from the main board, the team's system allows the AUVS to have current diagnostics displaying on a User Interface (UI). From this screen, the team can change the AUV's thruster configuration by adjusting which pins are in a ready state and which pins for thrusters get moved to an idle state. Using the UI, Dragon's pneumatic actuators, cameras, sensors, and the overall operation of Dragon can also be manipulated. This allows the AUV to be versatile in its approach to carry on with the team's competition strategy.

B. Vision Systems

Developing robust vision algorithms is a prerequisite for ensuring that Dragon can complete each challenge efficiently. Desert WAVE is working towards using HSV (Hue, Saturation, Value) filtering and deep learning conjointly for computer vision. Using both vision frameworks establishes redundancy in case one system fails during the competition.

Machine learning is one way that Dragon identifies and targets objects. In the past, the team used the Darknet YOLO architecture for real-time object detection, but upon further exploration of deep learning methods, switched to the MobileNet V2 architecture. The switch was motivated by the streamlined architecture's ease of use and well supported framework. YOLO is faster at real-time object detection for machine learning, but does not yield the same confidence levels (percentage of accuracy) as MobileNet V2. Additionally, MobileNet V2 provides a foundation for implementing deep learning, unlike YOLO which requires development from scratch. MobileNet V2 is built upon MobileNet, a convolutional neural network framework that utilizes depthwise separable convolutions for image classification and object detection [1]. During a convolution, a distinct filter, or kernel, is selected and the filter size is specified. Using this strategy, Dragon is able to take multiple images and compare the similarities of each image, allowing the AUV to use object detection, targeting certain images underwater with a higher level of confidence.

Desert WAVE also utilized a technique called Hue Saturation Value (HSV) filtering using functions from the OpenCV library. This image processing technique defines a numerical value to represent the attributes of a single pixel of color within an image in terms of its hue, saturation, and value of luminosity. The team was interested in finding the ranges of values that output the best results during specific environmental conditions that affect the reliability of this technique, such as weather conditions, sun angle, shadows, and water quality. The team used color values taken from video data collected from mission runs at the TRANSDEC facility during the 2019 RoboSub Competition. A color picking tool was used to extract the Red Green Blue (RGB) value of a pixel selected in the frame of the video, which was then converted to the HSV color space using a third party tool [2]. The team then conducted a study, coined the Value Study, to identify the most reliable range of H, S, and V values by taking a series of color samples from the path markers in those videos. The Value Study is further discussed in Experimental Results. Through this method, specific ranges of values could be defined for the weather conditions that affect the perception of an image. At the competition, the team would assess the weather conditions and deploy the program with the most appropriate settings. One concern of using only HSV for the vision system is the difficulty to produce reliable results in an underwater domain. There are many environmental factors that affect the reliability of this technique such as lighting conditions, shadows, and the water quality.

Another method used to combat the variability presented by these factors are addressed through object filtering. The Value Study method described earlier in this section effectively filters the image to create a binary image where only the desired object is visible. The remaining entities can then be further filtered out by their area. Polygonal bounding boxes are created around the pixels grouped in a specified color range within the image. These bounding boxes allow the area of the objects identified to be approximated. Since the size of the object is known, the bounded boxes are further filtered to ignore the polygons under a certain size criteria. Figure 6 shows this method tested on video data of a path marker from the 2019 RoboSub Competition. By combining this method of filtering by area with the method of HSV filtering, the team can increase the confidence of the system to more reliably identify the target.

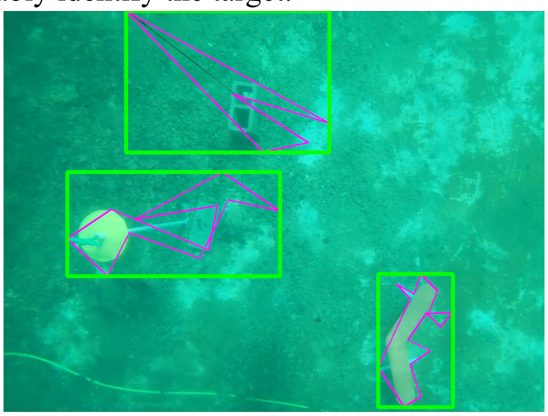

Fig. 6. Largest objects are detected after filtering. HSV filtering will next be applied to remove objects that do not match the color profile of the path markers.

III. Experimental Results

Experimental tests were conducted and continue to be performed on Dragon to examine the reliability of the structural, electronic, and programming components. The team performed unit tests on the software used for the pneumatics, thruster, and vision systems using a Teensy 4.0 Development board before testing code on any circuit boards. The marker dropper, grabber arm, and projectile launcher were tested for performance before being attached to the frame. The marker dropper was completed during the previous competition and more information can be found in our previous technical design report [3].

Upon completion of the mechanical, electrical, and programming tests, Dragon will have been involved in 200+ *hours* of water trials and will continue to be improved upon while awaiting the next competition. Unit tests of the solenoids' ability to actuate pneumatic cylinders, and unit tests of the thrusters, have been written and will be completed by the end of the summer of 2021. Integration tests, including testing communication between thrusters and boards, communication to the sensors using LED strips, and machine learning will be completed by December. The team then intends to begin testing basic navigation and machine vision underwater by January, and attempt completing individual missions gradually throughout the spring semester of 2022. Next, the team will start stringing missions together in sequence to simulate full competition runs by June of next year.

A. Structure

Once the computer hull's internal structure was complete and its length was determined, the layout of the components on the frame were finalized in SolidWorks. To verify that the mounting holes were located properly in the CAD model, the team mounted components to a laser-cut wooden prototype frame. Dragon was weighed and put in water with this wooden frame to evaluate its buoyancy. This test is pictured in Figure 7. Since wood is lighter than PVC (the material originally intended for the frame), this was not a perfect test of overall buoyancy, but revealed the relative balance between port and starboard, and bow and stern.

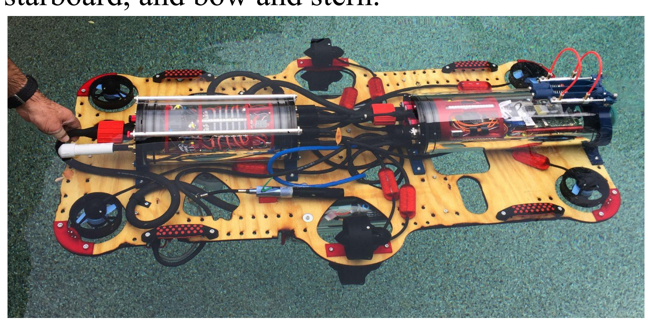

Fig. 7. Buoyancy test of Dragon with wooden frame.

Dragon's frame was originally intended to be manufactured out of PVC, like Phoenix, but using a PVC caused the AUV to naturally sink. HDPE is lighter than PVC and closer to the density of water, which is 0.97 *grams/cm*^{3}, whereas PVC has a density of 1.42 *grams/cm*^{3}. As a more neutrally buoyant and lighter material, it helped reduce the weight of Dragon's frame, shown in Figure 8. Reducing the weight of the AUV allows the team to earn more points at the competition and means that less foam was needed to adjust its buoyancy.

Fig. 8. HDPE frame being cut on a CNC router.

Initial buoyancy tests revealed that Dragon tended to pitch upwards in the front, so the team used polyurethane foam to balance the stern of the AUV. The material has a low density but resists hydrostatic pressures at depths up to 300 *m* below the surface. Once this foam was added, further testing showed that the AUV also listed slightly to its starboard side due to the weight of the marker dropper payload. An additional 1082 *cm*^{3} of foam was added at the stern to balance the AUV, shown in Figure 9. With these final adjustments the AUV was balanced and its buoyancy was slightly positive.

Fig. 9. Buoyancy test of Dragon with foam and its final frame constructed out of HDPE.

B. *Manipulation*

To assess the functionality and performance of the grabber arm, the team conducted two tests. The first test involved using solenoids to activate the pneumatic cylinder responsible for opening and closing the grabber arm. Once the pneumatic cylinder was activated, the arm was used to lift two wooden blocks, each weighing approximately 102 *grams*, as shown in Figure 10.

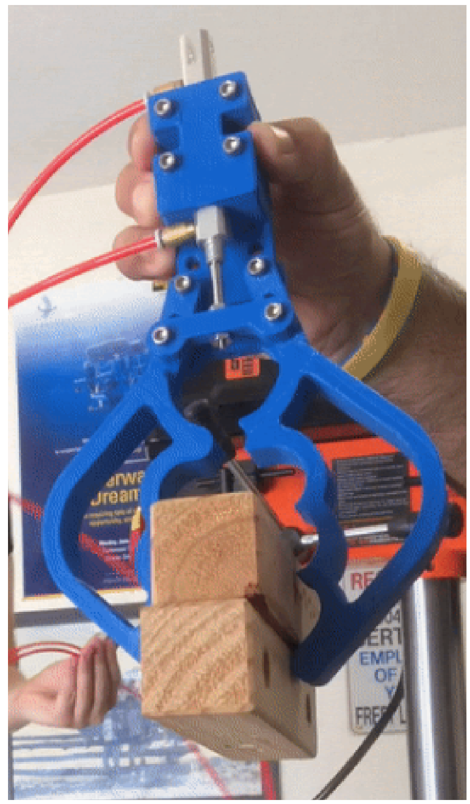

Fig. 10. Testing grabber arm with a solenoid.

Figure 11 shows a second test, where a scale was used to determine the grip strength of the arm. This measured approximately 683 *grams*. Both tests verified the grabber arm is capable of grasping and lifting objects.

Future tests will evaluate the grabber arm's pick-up and drop accuracy and structural strength. Based on the results of these tests, the team will make modifications to the grabber arm that may include adding a rubber coating for improved grip, reconstructing the arm with a more durable material such as carbon fiber, and redesigning its mount for safe storage during transport in and out of water.

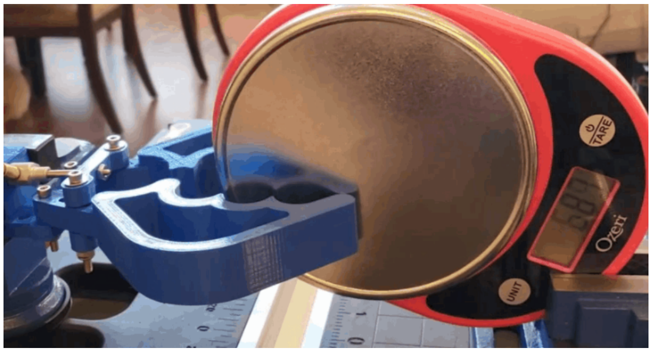

Fig. 11. Testing grip strength of the grabber arm.

The projectile launcher, in Figure 12, is operated by two pneumatic cylinders, one for each projectile. Each one opens a hatch to release a PLA projectile from a bay that is powered by a compressed spring. Before the launcher was attached to the AUV, it was tested in a bathtub. The projectiles launched straight forward, but rose to the surface almost immediately due to their buoyancy. More projectiles were printed at greater infill percentages until a nearly neutral but slightly positive buoyancy was achieved. The launcher was attached to the AUV and manually tested in a pool. It was found to launch in a straight line for 1 *m*, even with disturbances in the water, and only started to rise to the surface after a few seconds. However, the projectiles were produced with fused deposition modeling, which adds melted plastic to a part in layers and is inherently porous. As such, this design will soak up water and become less buoyant the longer it is submerged. The team will attempt to achieve a consistent density in the next year by printing the projectiles with SLA (stereolithography), which is a watertight form of additive manufacturing. The projectiles will be printed slightly above and below neutral density to account for any minor differences in the density of water between the water at the TRANSDEC facility and the pool used for testing.

C. Thrusters

Thruster code has been written for Dragon, but currently Desert WAVE's UI is being changed to allow adjustment of the thrusters should any thrusters fail during the competition. As explained in the Design Creativity Section, with ten thrusters, redundancy has been built into the design of Dragon. The AUV can have any one thruster fail or certain combinations of up to four thrusters and still be able to achieve full mobility. It would be preferable for Dragon to have all ten thrusters running, but the AUV only needs six degrees of freedom to be operational. To achieve this, the programming sub-team is setting up a redundancy panel in the UI that allows the AUV to reconfigure and recalibrate different thruster configurations to allow for that change of orientation in the shortest amount of time. The benefit to this is that if a thruster fails during a run at the competition and there isn't time to replace it, the thruster code could be quickly reconfigured to allow the AUV to navigate without the failed thruster.

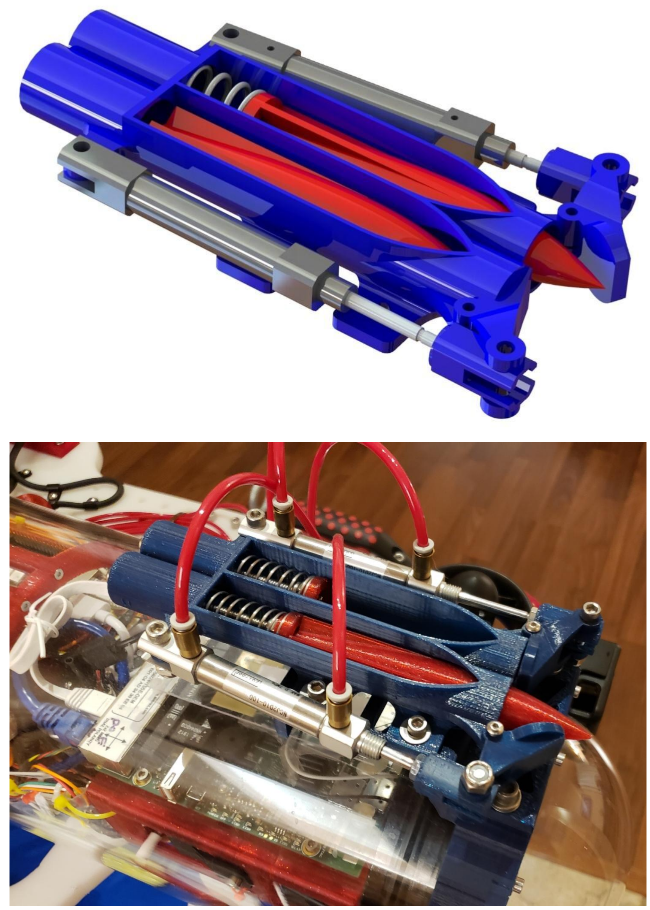

Fig. 12. CAD Model and physical projectile launcher.

Upon completion of the redundancy panel, unit tests will be performed first on the computer hull to verify that the signal is being transmitted from the thruster code (similar to the pneumatics code that was tested). With the success of unit testing verified by the LEDs in the computer hull, the testing will move to verifying communication between the computer hull and the thruster board. Performing bench tests, Dragon will first be tested with all ten thrusters to indicate that the modification to the UI panel did not affect the overall operation. Dragon will then be tested for losing one or more thrusters in multiple configurations.

In-water testing will be performed after all programming code has been debugged and tested, first by testing ten fully operational thrusters and then placing one or more thrusters in idle to time Dragon's runs. Potential issues with the redundancy panel for Dragon is the change over time from running all ten thrusters to changing the configuration of the AUV on the UI. The team knew that changing the configuration of the thrusters could add additional minutes to Dragon's run and could delay the possibility of reaching every obstacle. For this reason, the team started working on the UI panel for thrusters redundancy code ahead of schedule, solely to time Dragon's run while changing the configurations.

D. Vision Systems

To better identify objects, the team improved the AUVs' vision systems for optimal visualization and precision of image detection. The team discussed methods for computer vision at the beginning of the season. Some of the methods considered were reliable and effective, but along with HSV (previously discussed in Design Creativity), a convolutional deep learning network called MobileNet Architecture was chosen for the team's vision strategy. This method of machine learning was chosen due to the effectiveness of targeting images already programmed into the computer system. The AUVs will use these methods for object detection as they produce an increase in targeting accuracy percentages.

To increase the accuracy of the results from the HSV model, a Value Study was conducted on the in-water data collected at the 2019 RoboSub Competition. The method used in this Value Study was to extract pixels from the color samples, convert the value, plug them into the program, and compare the success of the results. This technique was applied to many videos which included a variety of distortions caused by environmental factors like lighting conditions, shadows, and water quality/movement. The motivation behind this study was to determine which conditions created the most distortion and identify values that had the highest "success" across the most common types of conditions. The team also explored functions within the OpenCV library. By changing the order of the processing done upon the images, the team learned that some orders produced better results than others. Both the order in which the functions were applied and the parameters passed affected the results. As such, manipulating these can "tune" the image processing in a way that produces more favorable and reliable results, as seen in Figure 13. Once the tuning was done, this technique was applied to other conditions in order to identify the most reliable values to use depending on the environmental conditions present. This method makes the vision systems more robust as they are optimized for the environmental conditions.

The team began developing this code in 2020 by taking the images needed for deep learning. Each image that the AUV will need to identify in the competition, such as the G-Man or the axe, was categorized into a "class" that the neural network would have to learn to recognize separately. Team members, even those not in the programming team, took images of one class each in different orientations. This allowed the team to take the images in under a month, so that more time could be focused on other aspects of the project.

The team started by taking 1,000 images (100 different pictures for each class) in different orientations, settings, and lighting conditions to gather as much data as possible, allowing the computer to recognize different patterns of these images. From there, the team suspended additional images underwater and used a GoPro to capture more images. These images provide more variety in shadows and other spectrums of light visibility that one could expect to see during the competition. This gathered data is being used in the deep learning programming process. After this data was collected, the Python library TensorFlow is being used to numerically compile a neural network so the AUVs can target any shape or variety of the object from the collected data. Results from this process can be seen in Figure 14.

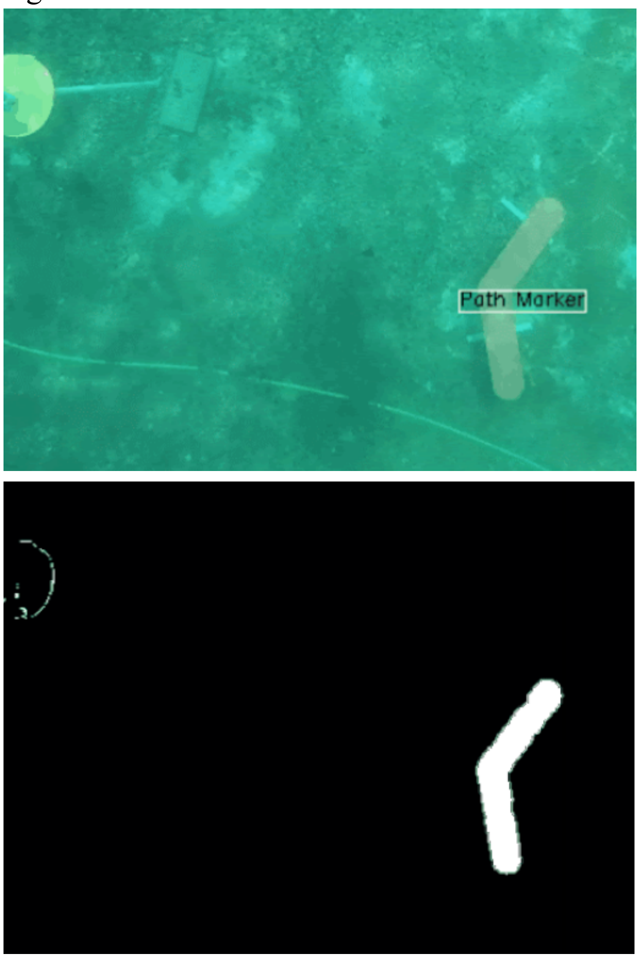

Fig. 13. Identification of path marker in a video from 2019.

The main issue that the team faced while training these neural networks was that the program has only received a targeting accuracy of 87%. This issue could be due to lack of variation in picture orientation and visibility. As such, Desert WAVE plans to increase this accuracy to 99% by augmenting the current 1000 images to 10,000+ with increased variety in the orientations to improve the accuracy rating to 99%. Once this is achieved, the team will test the AUVs' system underwater in different conditions to verify that the above water accuracy ratings reflect the same success rate underwater.

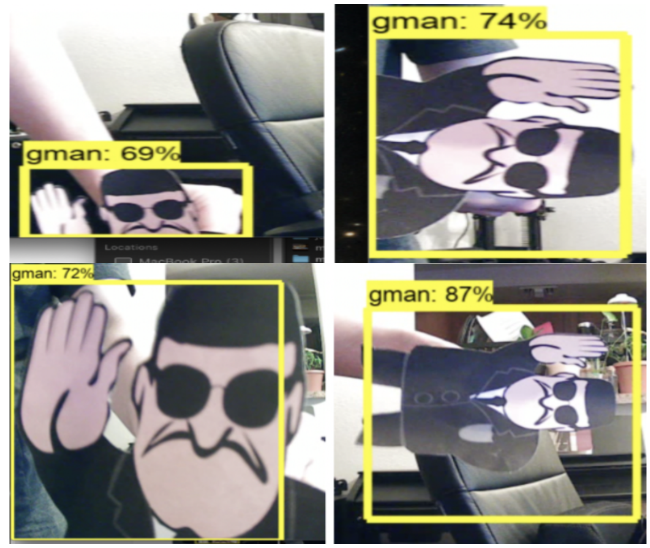

Fig. 14. Confidence level increases after training with a larger data set.

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The team is also grateful for their mentors, whose guidance allowed the team to continue learning and stay connected throughout the pandemic.

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Appendix A: Component Specifications

Phoenix

Component	Vendor	Model/Type	Specs	Cost	Status
Buoyancy control	Blue Robotics	• Stainless steel ballast x10 • Subsea Buoyancy Foam: R-3312	• .43 *lbf* • 8"x4"x.5"	• $9.00 x10 • $9.00 x5	Installed
Frame	Port Plastics	PVC sheet	.5" thick	$70.00	Installed
Waterproof Housing	Blue Robotics	• 8" enclosure x1 • 3" enclosure x2	• 24" long • 11.75" long	• $253.00 x1 • $46.00 x2	Installed
Waterproof Connectors	Blue Robotics	Pentrator x 20	Anodized aluminum	$200.00	Installed
Thrusters	Blue Robotics	• T100 Thruster x6 • T200 Thruster x4	• Max thrust: 5.2 *lbf* • Max thrust: 11.2 *lbf*	• $119.00 x6 • $169.00 x4	Installed
Motor Control	Blue Robotics	Basic ESC x10	30*A* brushless ESC	$25.00 x10	Installed
High Level Control	Mouser	Teensy 3.2 Dev board	ARM processor	$32.50	Installed
Actuators	Lowes	Sprinkler valve	24*V*	$12.00	Installed
Propellers	Blue Robotics	• T100 Propellers x6 • T200 Propellers x4	• 3" diameter • 3" diameter	Came with thrusters	Installed
Battery	Blue Robotics	LiPo batteries x2	4 cell, 18*Ah*, 16.8*V*	$289.00 x2	Installed
Converter	Drok	LM2596	12v-24v at 2 amp	$11.00	Installed
Regulator	Drok	Drok 98483	1V-36V at 12 amps	11.87	Installed
5*V* Power Supply	Vicor	Development board	20*A*, 5*V*	$120.00	Installed
CPU	NVIDIA	Jetson	256-Core NVIDIA Pascal GPU, Dual-Core NVIDIA Denver 64-Bit CPU	$598.00	Installed
Internal Comm Network	Simrex Corporation	WiFi Radio	5*GHz*	$200.00	Installed
External Comm Interface	MCI Networks	Fiber Optic Transceiver	5V ST / Ethernet set	$250.00	Installed
Internal Measurement Unit (IMU)	Sparkfun	Razor IMU	3-axis	$30.00	Installed
Doppler Velocity Log	Teledyne	Explorer 600	4-Head	$20,000.00	Installed
Camera(s)	Leopard Imaging	LI-IMX274-MIPI-M12 x2	1/2.5" 8.51M CMOS HD digital imager	$249.00 x2	Installed
Hydrophones	Advanced Navigation	Subsonus	Range of 1000*m*	$5,000.00	Installed
Algorithms: vision	MobileNet, Gaussian, Canny, approxPolyPD, Dilate				
Algorithms: acoustics	Included with Subsonus				
Algorithms: localization and mapping	Waypoint navigation				
Algorithms: Autonomy	Linear State machine				
Open source software	OpenCV				
Team size	22				
HW/SW expertise ratio	14/9				
Testing time: simulation	20 *hours*				
Testing Time: in-water	37 *hours*				
Programming Languages	C++ and Java				

DRAGON

Component	Vendor	Model/Type	Specs	Cost	Status
Buoyancy control	Blue Robotics	• Subsea Buoyancy Foam: R-3312	• 8”x4”x.5” • 12”x6”x1”	• $9.00 x10 • $9.00 x5	Installed
Frame	Port Plastics	HDPE sheet	.5” thick	$125.00	Installed
Waterproof Housing	• Port Plastics • Blue Robotics • Blue Robotics	• 6” enclosure • 6” enclosure • 3” enclosure x3	• 20” long • 11” long • 11.75” long	• $125.00 x1 • $98.00 • $86.00 x3	Installed
Waterproof Connectors	MacArtney	• Optical Series • Circular Series		• $5,000.00 • $3,000.00	Installed
Thrusters	Blue Robotics	• T100 Thruster x10 • T200 Thruster x6	• Max thrust: 5.2 *lbf* • Max thrust: 11.2 *lbf*	• $119.00 x10 • $169.00 x6	Installed
Motor Control	Blue Robotics	Basic ESC x16	30*A* brushless ESC	$25 x16	Installed
High Level Control	• Sparkfun • JLC PCB	• Teensy 4.0 Dev board x4 • AUV Mainboard • Sensor Board • Thruster Board • Pneumatics Board	ARM processor	• $24.80 x4 • ~$65.00 for each custom PCB	Installed
Actuators	SMC Pneumatics	• Cylinder - Single Acting Spring Return Cylinder • 3/2 Solenoid Valve	• NCJ2D10-200S • 5VDC-SY113-SMO-PM3-F	• $16.36 x8 • $30.38 x8	Installed
Propellers	Blue Robotics	• T100 Propellers x10 • T200 Propellers x6	• 3” diameter • 3” diameter	Came with thrusters	Installed
Battery	Blue Robotics	LiPo batteries x2	4 cell, 18*Ah*, 16.8*V*	$289.00 x2	Installed
Converter	HJ Garden	Adjustable Step-Up Boost Converter Module	DC-DC 3V-32V to 5V-35V 4A	$11.59	Installed
CPU	NVIDIA	Jetson Xavier	6-core NVIDIA Carmel ARM®v8.2 64-bit CPU 6 MB L2 + 4 MB L3	$399.00	Installed
Internal Comm Network	Simrex Corporation	WiFi Radio	5*GHz*	$200.00	Installed
External Comm Interface	Simrex Corporation	WiFi Fiber Optic Transceiver	ST/Ethernet set	$40.00	Installed
Inertial Measurement Unit	Built into FOG unit				
Fiber Optic Gyro with built in IMU	KVH Industries	DSP-1760	3-axis	$17,000.00	Installed
Doppler Velocity Log	Nortek	DVL 1000	300 m max operational depth	$14,960	Installed
Camera(s)	Leopard Imaging	LI-IMX274-MIPI-M12 x2	1/2.5" 8.51M CMOS HD digital imager	$365.55 x2	Installed
Hydrophones	Advanced Navigation	Subsonus	Range of 1000*m*	$12,000.00	Installed
Manipulator	Custom design	3D printed			Installed
Algorithms: vision	MobileNet, Gaussian, Canny, approxPolyPD, Dilate				
Algorithms: acoustics	Included with Subsonus				
Algorithms:localization and mapping	Waypoint navigation				
Algorithms: Autonomy	Linear State machine				
Open source software	OpenCV				
Team size	22				
HW/SW expertise ratio	11/11				
Testing time: simulation	0 *hours*				
Testing Time: in-water	5 *hours*				
Programming Languages	C++ and Java				

APPENDIX B: OUTREACH

Desert WAVE aspires to empower future women engineers and provide them with educational opportunities to succeed. This year, the team organized a series of virtual events to connect with community members, ranging from elementary-aged students to professionals in industry. Desert WAVE's 2021 virtual outreach initiatives included a toy hack, mentoring a local high school robotics team, presenting at conferences such as Makerbot's Shaping the Future 3D Printing in Education Virtual Summit [4] and the ProSocial Values Community International Conference [5], collaborating with other RoboSub and engineering teams, and supporting other programs, specifically, the National SeaPerch Challenge and the Science Olympiad National Tournament [6]. This section will highlight a few initiatives in which the team is most proud of.

Over the years, Desert WAVE has worked with a high school community robotics team based in Chandler, AZ. Like Desert WAVE, they are also part of the Si Se Puede Foundation's larger initiative to provide high quality STEM opportunities to girls and women. During the COVID pandemic, the high school students lost their space to work on their robot. Despite this, they still found a way to work on their robot by having it travel from house to house. Inspired by the high school students' resilience, several members of Desert WAVE opened the garage in their home to provide them with a more permanent place to meet and work. This space, affectionately named the "WAVE House" by the high school students, served as a place for them to build and test their robot, as well as compete. Additionally, several Desert WAVE members helped mentor the younger students.

The high school students also supported Desert WAVE in their outreach initiatives. For example, in April 2021, Desert WAVE hosted a toy hack: a community event dedicated to modifying toys to make them more accessible to children with disabilities. Students from Desert WAVE and its little sister robotics team, came together to add large, button-like switches to electronically powered toys in parallel with the existing switches on these toys, as shown in Figure 15. The intention was to allow children who have low muscle strength or poor fine motor control to operate these toys more easily. In addition, robotics students gained experience with circuits and soldering, and learned about assistive technology. Ultimately, this event produced 11 toys which were donated to classrooms, families, and therapists through ACCEL, Arizona Centers for Comprehensive Education and Life Skills. The hope is that these toys will help their users connect with their peers, feel included, learn cause-and-effect relationships, and develop muscular strength [7].

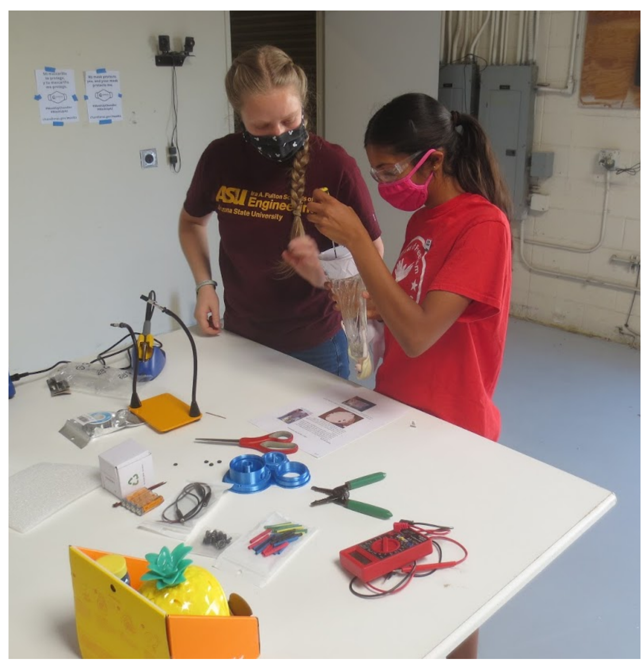

Fig. 15. Desert WAVE member adapting a toy with a high school student