Design and Construction of the Mechatronics 2017 AUV Vehicle: Perseverance

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Abstract - Perseverance is the new Mechatronics AUV designed for the 2017 Robonation Robosub competition. The main goal for mechanical, electrical, and software was to increase accessibility and user friendliness. The new design incorporates major changes to mechanical and software such as a completely new hull design and the addition of stereovision cameras as well as a completely new set of electrical boards. The software has changed drastically with an improved user friendly graphical user interface and the addition of neural networks for object detection.

I. Introduction

Mechatronics is an organization affiliated with San Diego State University and is composed of forty members. Since the team's conception in 2012, we have developed four vehicles: three autonomous submarines and one autonomous drone. As a team, we strive to create new autonomous systems for the experience as well a way of introducing more people into the fun and fascinating world of engineering. Every year we have both experienced and new members join the mechanical, electrical, and software teams. No matter how much background experience a new apprentice has, we always have them work on something new and to try and teach them something they have never done before. One of the most valuable rewards of the Robonation Robosub competition is the hands on learning that members will never receive in their classes.

This year, we have retired our previous submarine Defiance and developed a completely new AUV. The new submarine, Perseverance, has taken a year of planning, designing, and manufacturing to create.

A. Existing Work

Mechatronics has made three AUVs: Endeavour, Defiance, and Perseverance. These previous vehicles have provided heaps of experience and information for our latest design.

For the software team, there was very little existing work that was used this year. Most of the software had been completely abandoned with the exception of a few scripts dedicated for communicating with essential sensors on the AUV. However, there were many lessons learned from the years before that heavily influenced this year's software such as having an easy way to manipulate variables without having to hardcode them.

The electrical team built off the concept of previous vehicles using a backplane, daughter cards, and a primary computer. We modified that a bit this year with an active backplane, but the underlying idea remains the same.

The mechanical team learned from the mistakes of past designs and improved upon important features in Perseverance such as modularity and accessibility. To make Perseverance more expendable, we included diverse mounting points on the external and belly frame. In order to make the submarine more accessible, we implemented a single clamshell seal to easily access all internal components at once.

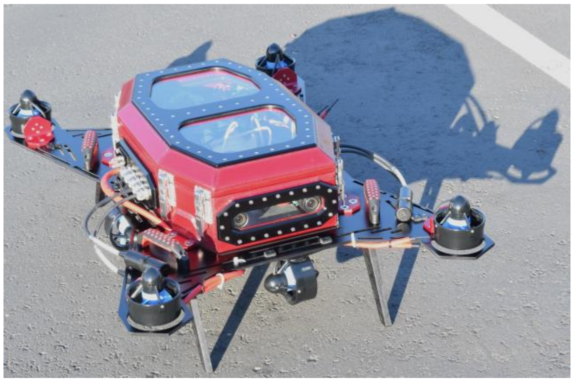

Fig. 1 Perseverance ready for pool testing

B. New Features and Improvements

The new AUV has many new design improvements in all three mechanical, electrical, and software fields.

Software improvements include the addition of stereovision cameras both forwards and downwards for calculating depth away from obstacles. We have also implemented neural networks for better object detection as well as more advancements to the computer vision process. There user interface has also been redone to make controlling the AUV more user friendly and easy to understand.

New electrical features this year include a new primary communication protocol, CAN bus, as well as a new secondary communication protocol, I2C. Another minor change this year is our battery voltage of 14.8V as opposed to 24V in previous vehicles.

The mechanical aspects of Perseverance sought for a complete overhaul of previous designs. Learning from restrictions of tubular cramped enclosures, tightly toleranced radial seals, permanent cable passthroughs and asymmetric overall layout, the new design aimed to learn from these lessons. New features of the mechanical systems include implementation of pneumatics for all actuation, plate aluminum construction with minimal machining, protective modular external frame, standardized fasteners for entire design, a single main seal, swappable IO panels for all cable pass throughs and large top viewing windows.

Fig. 2: Final CAD of Perseverance

II. Design Strategy

A. Approach

There were many design choices this year that were incorporated because of what had been learned at the last competition.

The new vehicle was designed with the thrusters in a specific orientation and distance from the center of gravity to provide a large moment for easier movement. The AUV is now capable of moving quickly through the water and turning rapidly. Rapid movement will help in the competition maneuver the obstacle course quickly and efficiently allowing the vehicle to achieve movements no other vehicle has been able to perform.

The addition of the stereovision cameras are also used for detecting depth. Having depth perception in the water is critical for locating obstacles and determining how the sub will move to reach the obstacles.

B. Design Choices

When designing the vehicle, all three disciplines focused on accessibility and ease of use rather than complexity. From experience with previous vehicles, it was obvious that lack of accessibility hindered the team at multiple instances at both testing and at the competition. Having a more accessible and more modifiable vehicle was more critical than trying to add designs that would be difficult to use.

In terms of software this was represented in the new design of the graphical user interface. With the simpler design, the software is much easier to use for new drivers and allows for access of only the software modules you need. When the software was originally being designed, there was the option of having it completely made in a higher language such as C++ but that idea was quickly abandoned over the simplicity of Python such that many people could understand the code without knowing how to program.

III. Vehicle Design

A. Mechanical Systems

The previous 3 years of competitions taught us many lessons and lent insight to design improvements that have since been implemented onto a new vehicle. The Mechatronics alumnus continues to serve as advisors to the team by providing insight from previous experience as well as notable observations of other competing teams. The mechanical team has spent long nights working to satisfy three major design premises: accessibility, cost effectiveness, and versatility. In short, the mechanical team focused their efforts on making Perseverance a testing platform capable of adapt to changing sensors, thrusters, software, or peripheral weapon systems. These broad motives for design decisions were thoroughly outlined and objectively defined into design requirements for each mechanical feature. Each primary mechanical feature served to satisfy every design requirement outlined.

Fig. 3: Accessible single sealed lid

1) Clamshell Hull

Driven by the design premises of accessibility, cost effectiveness and versatility, the main hull of Perseverance was in the center of it all. Accessibility was achieved through its one seal, a clamshell design shown in Fig. 3. This enables users to have maximum access to internal components without the impedance of tubular cramped spaces or multiple separate enclosures. Versatility of the this feature was achieved and the maximized size of the opening allows for a completely removable internal frame in future designs and modifications. The interior space is also considerably larger than currently needed to allow conductive heat sinking directly onto the hull and future installments. Lastly, the hull was cost effective such that it was made from a ¼’’ 6061 T6 AL plate, with minimal machining required for fabrication.

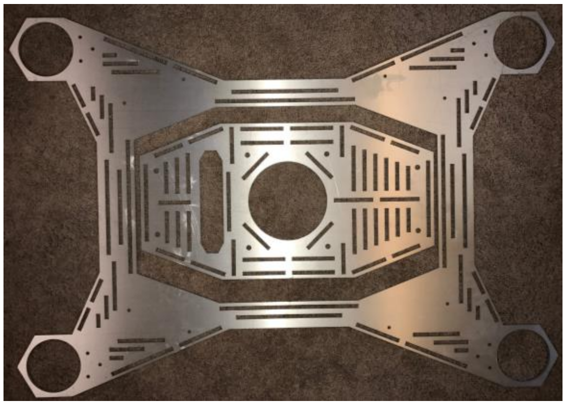

Fig 4: Main and belly frame with guide grooves

2. External Frame

The external frame was designed to serve as a protective mounting platform that could accommodate a wide range of potential weapon systems, sensors, thrusters, handles, or other future peripherals. Accessibility of externally mounted components was achieved through standardized fasters for all mounts and a wide range of guide slots for T nuts for ease of mounting. The easily water-jetted ¼'' AL frame in Fig. 4 is cheap and can be rapidly redesigned and swapped for alternative thruster configurations and mounting strategies. The multipurpose nature of the external frame also includes shrouds to protect the outermost thrusters and a protective geometry that cradles all sensors in the event of a collision.

Fig 5: IO panel blanks for accommodating changes

3. IO Panels

The In Out (IO) panel designs shown in Fig.5 were driven by lessons from previous limitations of permanent cable passthroughs used with our competition vehicles in the past. Additionally, the IO panels are specifically made to be easily replaced by duplicate blanks that are anodized and ready for redesign to accommodate new cable glands, tapped holes, cable pass throughs, or pneumatic hose. All interfaces from the internal watertight hull pass through these panels, effectively eliminating the need for permanent passthrough fixtures mounted to the hull. Cable glands were chosen for cable pass throughs for all thrusters and hydrophones. These were prefered over the permanent, epoxy sealed cable pass throughs of the past as they did not require the sacrifice of cables in the event of replacing or moving thrusters upon a new external frame design. The pneumatics are all connected to single barbed tube fittings, all routed through a compact custom fabricated IO port that enables the vehicle to have a total of fourteen pneumatic hose outputs. This provides more than enough pneumatic outputs for all weapons systems and the ability to implement more pneumatically actuated weapons in the future.

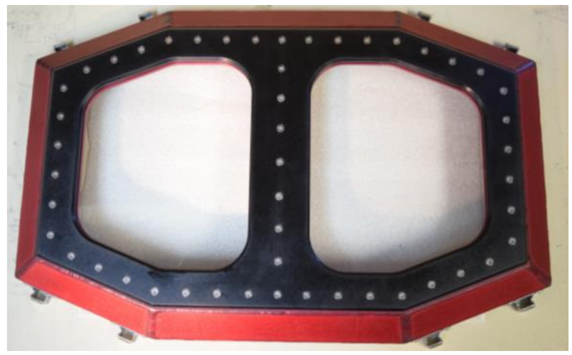

Fig. 6: Top viewing windows

4. Viewing Windows

The viewing windows of Perseverance have a fairly obvious function of allowing the downward and forward stereo vision cameras view the surroundings unobstructed. Additionally, the stereo vision windows are wide enough to accommodate a range of stereo vision camera spacing, laser for depth perception, or even new upgrades. These optical sensors are mounted on an extruded aluminum, 8020 rail for ease of adjusting iris spacing. The top viewing window serve to facilitate testing and the monitoring of internal conditions of Perseverance. This includes the ability to view relevant LED readouts, visual inspection for leaks, interfacing with the onboard LCD screen, and monitoring battery depletion when untethered.

Fig. 7: Back IO port with kill switches, thruster cables, and ethernet tether

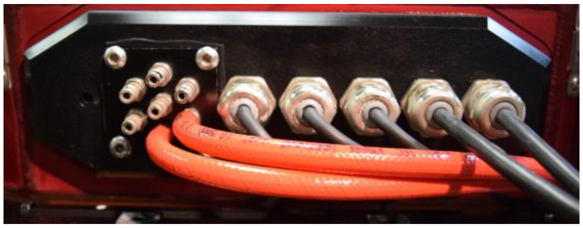

Fig. 8: Lateral IO port with nonpermanent cable glands and pneumatic hose barbs

5. Pneumatics

Pneumatics were chosen to power peripheral manipulators and weapon systems due to the wide range of off the shelf actuators, ease of implementation and proven reliability. The pneumatics were triggered through a solenoid-manifold assembly and all hoses were routed out of compact pneumatic IO ports. Each pneumatic line includes a one-way check valve to prevent water from backing into the manifold. The purposeful decision to accommodate more pneumatic outputs was made to enable the option of future upgrades.

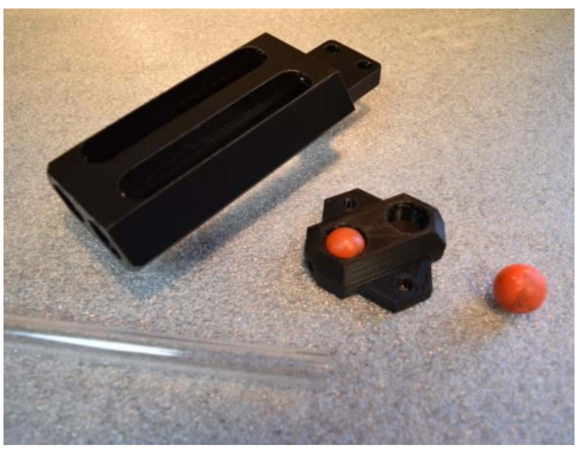

Fig.9: Torpedo launcher (left) and dropper and payload (right)

The pneumatically fired torpedo launcher was designed to fire two torpedoes in a consistent and reliable trajectory. The housing and torpedos were 3D printed from PLA and o-rings were added to the torpedoes to ensure a tight seal in the barrel of the launch tubes. The launcher was aligned strategically with the forward facing cameras for ease image recognition and targeting.

The pneumatically launched dropper was designed to release two ⅝’’ ball bearings with a short burst of pressurized air. Ball bearing were chosen for the dropper task to ensure a consistent drop pattern offered by the spherical, uniform drag. It was centrally aligned, adjacent to the downward facing stereo cameras, easing the alignment of image recognition for the dropper bins event.

Fig. 10: Thruster configuration of Perseverance

6. Thrusters

We chose the T200 due to the low cost, energy efficiency and high thrust-to-weight ratio. Four thrusters are used for vertical movement, two for forward and backward movement, and two for strafing side to side. This thruster configuration gives us six degrees of freedom. These eight thrusters are protected by the external frame and legs in the event of a collision. Their mounting configuration can be dynamically changed if needed.

B. Electrical Systems

The electrical system in Perseverance was designed with the goal to be simple and modular, while providing an elegant yet rugged solution. The primary focus of the system this year has been a redesign of the backplane, switching from individually routed board edge connectors to uniformly routed D-sub 37 connectors. With this routing technique in place, any daughter card may be placed within any daughter card slot on the backplane. This design simplified the routing on the backplane, and also simplified assembly once inside Perseverance

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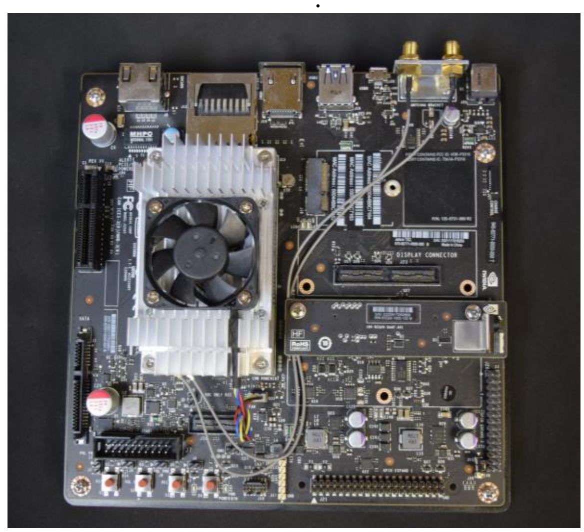


Fig. 11: Jetson Tegra X2

1. Jetson Tegra X2

A Jetson Tegra X2 is being used as the main computer. This development board runs Ubuntu 16.04 and was chosen because of its capability of running multiple intense processes including computer vision and neural networks. The processing power of this device allows us to run multiple intensive threads at the same time.

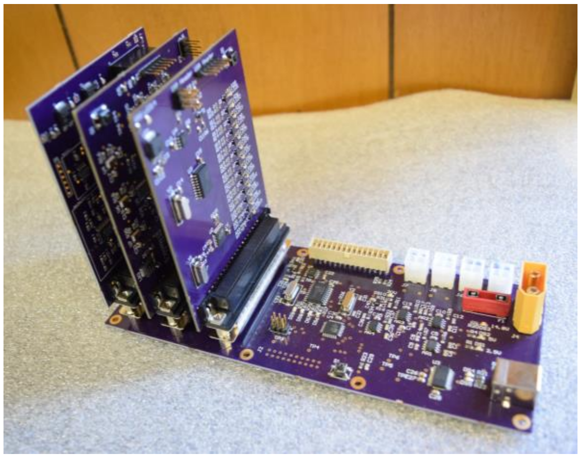


Fig. 12: Motherboard / Backplane

2.Motherboard / Backplane

Our backplane this year took on a much more active role than in the past. The backplane handles power conditioning and distribution, as well as the more traditional role of signal routing and distribution. The primary addition to the backplane this year is the incorporation CAN bus to USB technology. This required the use of an ATmega328PB microcontroller on the backplane, which then upgraded it from a passive backplane to an active motherboard.

3. CAN Bus

We utilized CAN (controller area network) bus to communicate between our daughter cards with a simple high / low line setup. Each device on the bus requires a controller and a transceiver, which converts the Rx and Tx data to CANh and CANl. One of the primary benefits of using CAN bus is the large number of message IDs available and the masking abilities built into the controller. In order to safely utilize the CAN bus with the Tegra TX2, a breakout board had to be developed. An isolator circuit was built into this board in order to provide protection to the Tegra in the event of a major CAN bus malfunction

4. Sensor Interface Board

The sensor interface board (SIB) is our primary means of communication between the Tegra and the physical world around us. It incorporates three internal pressure sensors, three internal temperature sensors, and three external pressure sensors. The internal sensors interface with an ATmega328PB microcontroller over an I2C bus, and the external pressure sensors output a current proportional to pressure to a simple current loop and low pass filter. The microcontroller continually passes data to the primary computer via CAN bus.

5. Hydrophone and Direction Rendering Analysis System

Hydrophone and Direction Rendering Analysis System (HYDRAS) is a passive SONAR system which detects and differentiates between two separate pinger signals and provides navigation to the target pinger by determining its relative bearing and elevation. The HYDRAS board is one of two boards in Perseverance which utilizes four layers. This was needed for proper routing of the many signals on the board. HYDRAS is the only board in Perseverance which utilizes a PIC24 microcontroller as opposed to an ATmega328PB. The reason for this choice is for the additional ADC (analog to digital converters) pins on the PIC24. The PIC24 system takes two hydrophone signals and will send them through a Low Pass Filter followed by an amplification stage, rectification stage, and amplitude adjustment stage to turn the signals into a DC signal to be read by the Comparators. The Comparators will monitor for a low to high signal change and will measure the difference of arrival time between the signals, then it will calculate the heading of the pingers.

6. Digital / Weapons Control Board

The digital / weapons control board consolidated two of our previous daughter cards, the thruster and weapon control boards. The reasoning behind this choice was molded by our thruster and electronic speed controller selection, which are able to be controlled via I2C, or inter-integrated-circuit. Similar to CAN bus, I2C uses only two lines, in this case a clock line and a data line. An ATmega328PB microcontroller is utilized on this board to control the I2C lines, as well as thirteen GPIO (general purpose input / output) pins to trigger various weapons, such as lasers, torpedoes, droppers, and numerous channels for a pneumatic claw. The switching circuitry for these weapons utilizes an N-channel MOSfet which acts as a switch when activated by the microcontroller. In this case we decided to provide constant power to all of our weapons and switch ground, as it is the standard with most CAN enabled vehicles.

7. Power Supply

The power system for Perseverance is completely custom built this year, including the control system and the battery packs themselves. The batteries consist of 2x 16000mAh Li-Po (lithium polymer) batteries joined in parallel, capable of 320A burst output current and nearly 6 hours of testing time before a recharge is required.

In addition, custom made battery packs were made using 18650 cell Li-Ion (lithium ion) batteries. These batteries provide a much higher energy density than traditional Li-Po batteries, enabling us to reduce the size and weight of our battery packs while retaining the same power output capabilities.

To distribute the power among the subsystems in Perseverance, a 150A battery management system was developed, capable of removing power to thrusters without any computer interaction required. In addition, a circuit is provided to cycle power to all other subsystems in the event a hard restart is required while in the water.

Fig. 13: Forward - stereo vision cameras

8. Hydrophones

3x Sparton PHOD-1 hydrophones passively listen for pings on frequencies between the range of 25 kHz to 40 kHz in 0.5 kHz intervals, and communicate to the main computer via an RS-232 connection to allow for navigation within a four-foot radius. After receiving data from the hydrophones, the sub is capable of triangulating the location of their origin, allowing us to accurately move to the correct pinger.

9. Doppler Velocity Log

The doppler velocity log (DVL) in Perseverance is a Teledyne Explorer. It provides velocity and positional data by emitting ultrasonic pings which bounce of a surface below the vehicle and are then recorded by the sensor. The data is then sent through a kalman filter and provides then provides position and velocity relative to an origin, usually where the DVL is initialized.

11. Attitude Heading Reference System

3x Sparton GEDC-6 attitude heading reference system (AHRS) eliminate nearly all external magnetic disturbances that affect heading accuracy. In addition, they provide 3D absolute magnetic field measurement and full 360° tilt-compensated heading, pitch, and roll data.

10. Pressure Transducers

The pressure transducers used to calculate external pressure and determine the AUV’s depth are industrial pressure sensors with 0.1% accuracy including linearity, hysteresis, and random deviations. They are implemented with triple redundancy and compensating logic to ensure stable measurements are always available and interpreted correctly in case of error.

11. Temperature Sensors

The temperature sensors monitor the ambient temperature inside the sub to provide awareness of potential overheating to the main computer.

10. Cameras

The Blackfly 0.5 MP USB3 Color Cameras were chosen for our vision system. Two cameras face forward and two downward for stereovision capabilities in both directions.

C. Software Systems

The software for this year is composed of Python for the main process and communication with all the sensors and C++ for the computer vision process and neural networks. Using the Jetson TX2 with Ubuntu 16.04 there is a lot of processing power in the vehicle. There have been many lessons since the last competition, and since then the team has decided to design the software with three main design goals in mind: *Modularity*, *Obstacle Detection*, and *User Friendliness*.

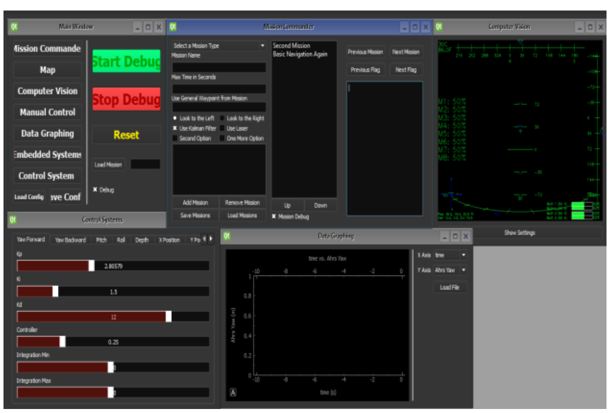
Modularity was a necessity because it was obvious that the code that was written before was not meant to be modified or expanded. The new designed needed to be easy to make changes such that at any point in the future we can add new modules without affecting other aspects of the software.

There was a need to improve obstacle detection after having issues with waypoints from the previous year. The software team discovered the importance of having better obstacle detection in order to move away from the use of waypoints. With better obstacle detection, the AUV can move to generalized waypoints near where the obstacle is located and then search the area for the obstacle without specifically giving directions to the correct location.

After having past members have difficulty understanding the way the software worked, there was a desire for the new version to be very user friendly. Many members outside of the software team would be unable to use the software as there was little explanation as to which modules control which aspects of the sub. There would also be issues in the past were code would have to be rewritten on the spot as some values were hardcoded as there was not an easy way to change them within the GUI. With this new design we wanted to make it possible that anyone could quickly use the software and understand it.

1. Graphical User Interface

The GUI has been completely redesigned from the ground up using PyQt as a framework. By choosing to use PyQt, the GUI has become much more streamlined and much easier to use and helps to understand exactly how the data is coming in. This new GUI has been designed modularly, allowing us to create as many *widgets* as is needed as well as the ability to close and move widgets for accessibility. With this new design, the GUI is easy to understand for a member who is just looking at the software for the first time. With this new design, anyone on the team is capable of starting the AUV and view



incoming data.

Fig. 14: Redesigned Graphical User Interface

The *Mission Planner* process has been completely rewritten. Mission planner is the way in which the drivers program Perseverance and plan in what order to maneuver obstacles as well as provide supplementary parameters for missions. This new version of Mission Planner allows for debugging missions in real time with the ability to step through missions. Stepping through a missions allows for easier debugging and testing as a certain aspect of a mission can be tested multiple times and still be isolated from the rest of the missions. This new version has also been designed to be as modular as possible to fit the design goals, making it easy to add new types of missions if necessary.

2. Control Systems

The control system is composed of PID controls. We have a total of seven PIDs for autonomous mode which are used for movement in all six degrees of freedom as well as one for movement backwards. We also have another seven PIDs for manual control that are used during testing for human controlled movement when not in autonomous mode. As a requirement for one of the main software design goals, the PIDs were designed to be more easily changed using a sliders. With the use of sliders the values of the PIDs could be changed rapidly and on the spot in the water. This was a major improvement from the year before in which the values for PIDs were hard coded and were difficult to attune. With this new design it is possible to tune PIDs to the correct values within a day which is significantly faster than the software from last year.

3. Computer Vision

The computer vision system has been redesigned with the goal of improving object detection and is composed of libraries such as OpenCV, Dlib, Vision Works, and Darknet. Using neural networks, the AUV is capable of detecting obstacles by learning how they look outside of the water.The neural networks use the darknet neural network framework and is built with the You Only Look Once (YOLO) object detection system which is already trained on many everyday objects. We then trained it on our obstacles so that we it can locate the obstacles in the water. The data set was composed of hundreds of labeled photos both above and below the water with artificial static to increase the robustness of the networks. After the sub has located the obstacle, it will begin tracking the object using the DLIB library as to make sure the obstacle remains in the frame as well as not having to run the neural network continuously. Once the AUV has located an obstacle, it then attempts to get the relative position and orientation of the obstacle relative to itself using algorithms such as ransac in order to detect shapes within the images and corner detection methods in Vision Works.

There are two systems for depth detection: The stereovision cameras and the Oclaro Diodes. The use of stereovision provides depth by taking in two images from each camera and comparing the changes in pixel locations to determine how far away a point is. By using Vision Work's stereovision library, a disparity map is created and is used in conjunction with object detection to locate the corner points of an obstacle to determine its depth. This process generates a point cloud which allows the sub not only to determine how far away an obstacle is but also where it is located in space. The second method in which the sub determines depth is through the use of diodes. These diodes produce a bright beam of light that can shine on the obstacle even at far distances and in murky water. After the diode is activated, the computer vision process will look for the reflected light that is emitted from the obstacle and use trigonometry to determine how far the obstacle is located.

There is also a backup computer vision system in place in the event that the object detection from the neural networks does not work as planned in the murky water. This system is based off hue-saturation-value filtering and contour analysis. Using these methods the sub could identify the buoys, torpedo boards, and the dropper bins but without the precision that the neural networks provide. This is the same method used with the previous AUV which

4. Embedded Systems

As the AUV contains custom electrical boards, a standard communication protocol needed to be developed. The boards had been programmed and designed to communicate using CAN bus which also made it simple to integrate with the Jetson TX2 which has the CAN bus communication protocol built in. We have designed our own communication packets to to allow for the communication with multiple boards.

III. Experimental Results

A. Prototyping

1. Movement Vehicle Test Bed: The vehicle test bed was a senior design project which was sponsored by Mechatronics. This vehicle served as way for the software team to work on their code before the actual vehicle was prepared. This vehicle helped debug much of the movement code which helped save time fixing simple mistakes that would have also needed to be fixed for the final vehicle.

2. A to scale replica of the AUV was constructed out of cardboard to test fit all internals and brianstorm wire management and internal frame designs.

B. Mathematical Modeling

1. Movement Algorithms: The control system algorithms work much better on this new design as the location of the thrusters give them a more substantial moment when moving the AUV. Because of this there needs to be more work in accounting the orientation of the vehicle when operating the thrusters. For example, if the vehicle were to flip upside down, its orientation is not accounted for when calculating depth PIDs, meaning the vehicle will attempt to move upwards which would translate it to move downwards until hitting the bottom of the pool.

C. Simulations

1. FEA analysis, through Solidworks, was used to inform the design of the external frame. A two point lift from the far diagonal thruster shrouds was simulated at 135lbs to ensure no plastic yielding would occur. Additionally, FEA was used to verify the ¼'' 6061 T6 aluminum hull and the acrylic windows could withstand a maximum depth of 45 feet.

D. Testing

1. Movement Testing: We were able to test movement with the AUV a month before the competition. Movement was very fluid and much faster than previous design. With this new design it is possible to hold the sub at more extreme angles.

2. Computer Vision Testing: Much of the computer vision testing was done out of water. A lot of the work was created in individual parts which made it difficult to combine them into one main process. When data is inputted manually the output will give near perfect position and orientation, but autonomous corner detection still needs refinement as of the writing of this paper.

3. Weapon Systems Testing: Repetitive firing of both the dropper and torpedo launcher were completed to fine tune the accuracy the systems. The torpedo geometry was changed over time as slender, elongated torpedoes proved to be more reliable.

4. Buoyancy and Leak Testing: Total weight was simulated prior to loading electrical components. This enables us to shift peripherally mounted components to ensure a level and neutral plane of the sub at rest. Leak testing was progressively completed, starting with blank IO panels. Increasing by fifteen minute intervals of static pressure tests, followed increasing depths. Also, dynamic shaking and surface breach tests were completed to replicate worst case scenarios.

IV. Acknowledgements

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