San Diego State University Mechatronics Club REDEFIANCE Autonomous Underwater Vehicle: Design and Implementation

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Abstract—**Mechatronics is a student-run organization at San Diego State University that designs and builds unmanned vehicle systems and robotics. The club is comprised of 2 projects: Robosub and RobotX. The club has designed an Autonomous Underwater Vehicle (AUV), or RoboSub, to compete in the 19th Annual RoboSub competition hosted by the Association for Unmanned Vehicle Systems International (AUVSI) Foundation and Office of Naval Research (ONR) which will also serve as the AUV for the underwater portion of the RobotX competition. The competition is held in San Diego at the SPAWAR SSC's Pacific TRANSDEC pool in July and consists of navigating a brightly colored underwater obstacle course involving image processing tasks, maneuvering exercises, path following, torpedo launching, marker dropping, object manipulation, and acoustic recognition.**

I. Introduction

The Mechatronics Club's main objective is to design, program, and build a reliable and effective Autonomous Underwater Vehicle (AUV) that will compete in the AUVSI and ONR's International RoboSub Competition for many years to come. Ideally, the RoboSub will accomplish every task throughout the obstacle course and inspire future SDSU students to continue our work by improving upon the vehicle design. In order to create a reliable and effective AUV, the tasks were split and the team was divided into four subgroups; Mechanical, Electrical, Software, and Business team. With a lot of hard work and determination, the Mechatronics Club has successfully improved upon our second Autonomous Underwater Vehicle.

II. Design Overview

This year, our team focused on improving our existing system from last year's competition, *Defiance*. Based on much of what we learned last year, we knew that we could not afford to spend the time designing a brand new system from the ground up given our limited workforce. This year we were able to incorporate many features that were not present on the 2015 version of *Defiance*, such as Torpedos, a 4 degree of freedom Claw, a superior hydrophone placement, and a more robust Thruster positioning. The form factor of the custom electronics package has been reduced drastically. Additionally, with the existing platform, we were able to begin testing immediately to debug any existing errors in code.

The Sub, as shown in **Figure 1**, features a modular hull that allows access to certain sections depending on what the team needs to get to such as electrical components, cameras, main computers, etc. *ReDefiance's* weight has been decreased and a shifting buoyancy mechanism has been added. The vehicle includes two cameras, torpedo launchers, dropping mechanism, and an external frame that allows versatility with the placement of components.

Figure 1: **ReDefiance - 2016 Vehicle**

The design features eight thrusters providing propulsion in the forward, reverse, up, down, left, right, clockwise, counterclockwise, yaw, pitch, and roll. It is powered by two lithium-ion cell batteries placed in parallel and features a collection of inertial, visual, and pressure sensors that enable successful navigation through the obstacle course.

The design incorporates a fully custom and modular electronics package and a watertight sectional hull. The main computer features an Intel i7 Quad-Core processor for the new software graphical interface that is responsible for image processing and object detection, serial communication, mission planning, navigation, and manual control.

III. Mechanical Systems

Our mechanical team experienced massive growth in the fall, increasing from one dedicated person to over thirty different students, of all class levels. The greatest challenge we faced this year was one of management, logistics, and communications.

Many of the more experienced members in our organization found themselves thrust into leadership roles where they spent a majority of their time educating the junior members of our group. This year we focused on creating as much objects in-house as possible. In the past, exporting work to Machine shops has shown to be a lengthy process; a process that would leave many of our members with nothing to do or learn.

As such, all of the improvements made to *Defiance* were done 100% by our members, from raw metal to final testing.

A. Main Hull

One of the glaring issues from last year was our system's weight. Because we were dangerously close to becoming disqualified due to weight issues, we were forced to remove many components from the submarine which in turn reduced the stiffness & reliability of the system.

In order to cut back on weight, we took advantage of our Sub's modular design and replaced an aluminum bulkhead with an Acrylic tube, which gave us approximately 12 extra pounds to use for weapons systems.

B. Internal Frame

In addition to changing our bulkhead, we also re-evaluated our internal frame in order to more comfortably hold our electronics & sensors.

In the 2015 competition, our frame did not sufficiently support camera sensors, it did not give sufficient clearance to the DVL, and it was very difficult to reach much of the electronics without needing to remove the entire plate.

By adjusting plate thickness and geometries of the Frame, we were able to support our electronics & sensor systems fully.

C. Frame

- Modular frame made of aluminum 8020 rail provides many attachment points for thrusters, sensors, and weapons (torpedoes and dropper).
- The rigid frame provides strength for the entire submarine while adding minimal weight.

D. Weapons System

The weapons systems consist of a newly designed torpedo launcher as well as a payload dropping mechanism. The torpedo assembly consists of two tube assemblies, each with a custom designed and fabricated torpedo holder and spring. Both assemblies are activated by a single HiTec HS-5646WP servo. The servo arm actuates lever arms releasing the torpedo holders from their locking positions. The torpedoes are custom machined out of single blocks of Delrin, as well as the holders that they sit on to reduce friction. A press fitted dowel of 304 Stainless Steel keeps the torpedoes seated on their respective holders until fired.

The tubes are machined out of cylinders of carbon fiber with an open channel for the lever arm and holes along their axes to alleviate the pressure build up of water in front of the torpedo holders when being launched. The tubes are capped at each end by custom designed and machined 6061 aluminum end caps to allow the release of the torpedoes while catching the holders. To prevent corrosion all aluminum parts are anodized. As a further precaution against a voltage difference between the aluminum and carbon fiber, two zinc washer anodes are placed on the aft caps making electrical conductivity to all aluminum parts on the assembly.

The payload dropping mechanism follows a similar design to the previous year's sub. It consists of an enclosure made of Acrylic to house two ball bearings. Each compartment is activated by a HiTec HS-5646WP servo to release the payload to its desired target beneath the sub. The simplicity and reliability of this system earned its way back into the redesign of Defiance hardly changed.

E. Thrusters

Propulsion is provided by eight brushed-DC motor, high performance, SeaBotix BTD150 thrusters. The thrusters are mounted on the external frame and are oriented to provide six degrees of freedom. The sub is able to move freely in the forward, reverse, up, down, left, right, clockwise, counterclockwise, and roll left and right. The external frame also provides the ability to relocate the thrusters in order to improve movement in the water.

F. Battery Enclosures

The custom aluminum battery enclosures were welded and waterproofed in-house to hold the StarkPower Lithium Iron Phosphate batteries. In order to properly secure the power source for the sub, new latches were installed to reinforce the integrity of the enclosure. In 2015, the enclosures were mounted to the frame using threaded rods due to weight concerns. The mounting points were upgraded and replaced with 8020 rail after the total weight of the sub was decreased.

IV. Electrical Systems

The electrical systems consist of power distribution, custom built electronics and Commercial off-the-shelf (COTS) electronics. Defiance features 8 brushed-DC thrusters, a reliable power system, small electronics form factor, and an organized wire management. There are eight custom manufactured printed circuit boards (PCBs) that were designed, prototyped, assembled, debugged and integrated.

A. Power Distribution

The power sources for Defiance are two StarkPower Lithium Iron Phosphate 24V 10AH batteries that range from 21V to 30V with a maximum output current of 15A. A Mini-Box M4-ATX, 250W, 6V to 30V wide input intelligent automotive DC-DC power supply was used to power the main computer. There are two MiniBox DC-DC USB Converters that are used to supply the 6V and 24V power planes on the backplane.

B. Electronics

A fully custom and modular electronics package was created for Defiance. The electronics package consists of a passive backplane for use with 8 daughter cards that utilize PIC24 microcontrollers for communication and signaling. The modular design allowed the electrical team to divide the electronics design, verification, and testing (DVT) into manageable modules to thereby give all team members an opportunity to gain hands-on experience with printed circuit board (PCB) design and embedded systems programming.

C. Backplane & integration

The backplane, as shown in **Figure 2**, improved wire management and enabled a modular electronic design. Power and signal traces were routed within the 4 layers of the backplane. For serial communication within the backplane, UART signals must be logic level adjusted to RS-232 to prevent thruster noise from corrupting communication waveforms. Several voltage regulator module (VRM) PCB-PCB connectors were used to interconnect daughter cards to the backplane. Molex Mini-Fit connectors were used for wiring harnesses associated with DC-DC converters. On-Shore Technology (OST) terminal blocks facilitated phasing out Molex Mini-Fit Jr. Connectors, which were prone to severing wires just behind crimps due to normal wear and tear associated with vehicle maintenance and vibrations during operation. For ease of installation, pigtail wires attached to SEACON bulkhead connectors are inserted into the terminal blocks, thus eliminating the crimps that damage the wires.

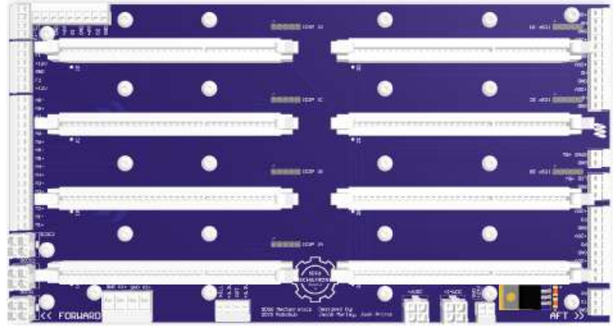

Figure 2: Custom PCB Backplane

D. Power Management & Undervoltage detection (PMUD)

The Power Management and Undervoltage Detection (PMUD) board, shown in **Figure 3**, delivers power to the backplane from the two parallel batteries. PMUD monitors and routes battery power to the DC-DC converters, thrusters, and weapons. PMUD utilizes two Linear Technology LTC2946 Power Monitors for precise battery voltage and current measurements, which are communicated to the main computer and logged on a Microchip 24AA1025 1024Kbit Serial EEPROM for engineering analysis. PMUD contains two 15A fuses for circuit protection. Additionally, PMUD contains kill switch circuitry comprised of two mechanical relays in series (one software controlled and the other hardware controlled) to physically disconnect 4 power from thrusters and weapons and not from the DC-DC converters.

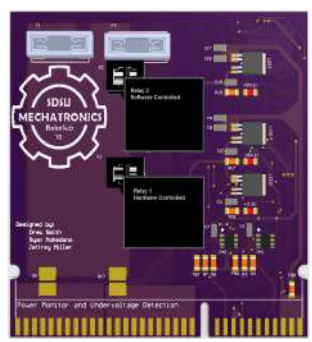

Figure 3: PMUD Board

E. Thruster Control Board (TCB)

The Thruster Control Board (TCB), shown in Figure 7, drives four SeaBotix BTD150 Brushed DC thrusters. As a result, there are two TCBs onboard Defiance to accommodate 8 thrusters. During normal operation, each TCB receives power from the 6V plane and delivers unregulated battery power to four H-bridge circuits to drive the thrusters. The H-bridge circuitry is comprised of an Allegro A3941 Full Bridge Driver IC and four N-channel MOSFETs. TCB monitors current consumption in the each thruster with Allegro ACS712 Hall Effect Current Sensors, which is then communicated to the main computer and logged on a 2GB microSD card for engineering analysis. For safety purposes, when the kill switch is engaged the unregulated battery power is physically disconnected from both TCBs by PMUD to prevent thruster operation.

F. Weapons Control Board (WCB)

The Weapons Control Board (WCB), show in **Figure 4**, controls and supplies power to two HiTEC HS-5646WP waterproof servos. When actuated, the servos control the launching two torpedoes and dropping two ball bearings. In addition, WCB contains a SN74HC126NSR Quad Buffer/Line Driver, which converts Universal Asynchronous Receive Transmit (UART) to Transistor-Transistor Logic (TTL) half duplex asynchronous serial communication and transfers it to the four Dynamixel AX-18A servos that make up the underwater manipulator. To supply power to Dynamixel servos, WCB includes an on board buck converter which steps battery power down to provide 12V and 6A. For safety purposes, when the kill switch is engaged the unregulated battery power is physically disconnected from buck converter by PMUD to prevent actuator operation.

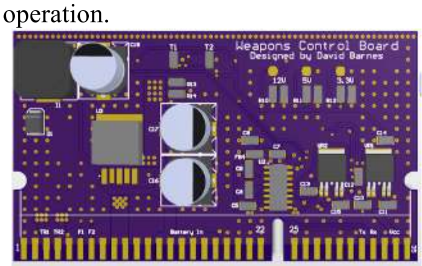

Figure 4: Weapons Control Board

G. Communications board (COM)

The USB to RS-232 communications board (COM), as seen in **Figure 5**, is a custom serial communications hub that fits the modular daughter card form factor. The COM board facilitates communication between the main computer and potentially 7 daughter cards connected to the backplane. Serial communication signals are interpreted by FTDI chips and logic level adjusted by Texas Instruments MAX-232E integrated circuits (IC). The COM board features transmit and receive LEDs to aid debugging. Two USB Type-B connectors were used for cable support to reduce strain on the PCB dielectric material.

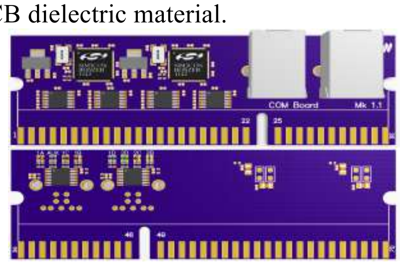

Figure 5: Communications Board

H. Sensor Interference Board (SIB)

The Sensor Interface Board (SIB), shown in **Figure 6**, features triple redundant sensors for measuring internal temperature, internal pressure, internal humidity, external pressure and leaks inside of the vehicle. A Microchip PIC24FJ32GB004 microcontroller was used to communicate with all of the sensors over Inter Integrated Circuit (I2C) and send the sensor data to the main computer. In order to measure the conditions inside of the vehicle we used a Texas Instruments LM92 Temperature sensor for temperature, a Freescale Semiconductor MPL115A2 Miniature Barometer for pressure and a Honeywell HIH6030 humidity sensor for humidity. External pressure transducers measure depth of the vehicle.

The SIB also features leak detection functionality which makes use of 3 custom built leak detection probes which are located in the forward, middle, and aft sections of the vehicle. The leak detection probes consist of a long strand of copper wire wrapped in paper that has been soaked in salt-water and dried, then another strand of copper wire is wound around the paper. When the water touches the leak detection probes it creates a small electrical potential that is then measured by the Analog-to-Digital (ADC) module on the microcontroller. A loud piezo buzzer will sound and bright LEDs will flash to indicate which section of the vehicle contains the leak.

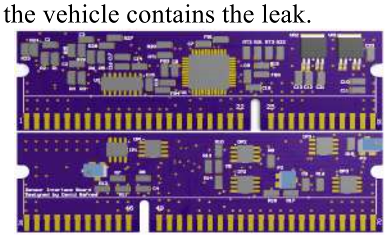

Figure 6: Sensor Interface Board

I. Hydrophones & direction rendering analysis system (HYDRAS)

The Hydrophones and Direction Rendering Analysis System (HYDRAS) board contains two different ways of locating an underwater pinger, "Time of Arrival" and "Phase Shift".

For the "Time of Arrival" method, the signal received by the two horizontally spaced hydrophones pass through a Linear Technology LTC1068 bandpass filter (BPF). The BPF filters out all signals outside of its bandwidth, which is selected by a PWM signal. The filtered signal then passes to a Linear Technology LT1677 Op Amp which rectifies the signal in order for the output to be read by the comparators on the PIC24FJ32GB004 for synchronous sampling. The microcontroller samples the signal until the comparator events are triggered, and then analyzes the data to find the time difference of the signal in each hydrophone. The time difference is then sent to the main computer for the final bearing to be calculated. This solution benefits from a large spacing between hydrophones and due to our setup this method the will only determine the bearing of the pinger relative to Defiance and not the elevation.

The "Phase Shift" method, as shown in **Figure 6**, takes advantage of the Digital Signal Processing capabilities on the Microchip dsPIC33EP64GS502, in order to measure the phase angle between the two real sinusoids received by the hydrophones. The analog signal first rectified by using a Linear Technology LT1677 Op Amp and is then converted to a digital signal using the high-speed, 12-bit, parallel Analog-to-Digital (ADC) modules on the dsPIC. The unprocessed ADC readings are sent to the main computer and processed for heading information.

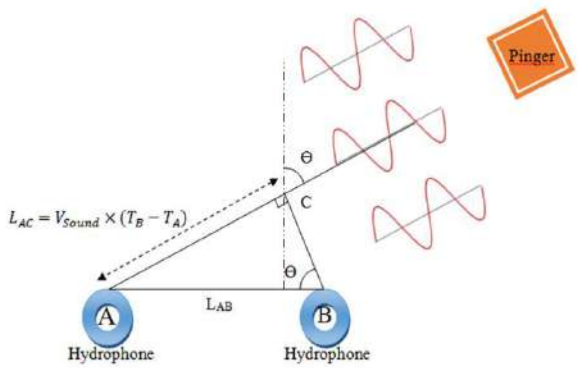

Figure 6: Phase Shift Method

J. Doppler velocity log communications board (DVL COM)

The Doppler Velocity Log Communications board (DVL COM), shown in **Figure 7**, is a custom serial communications hub that fits the form factor of the Doppler Velocity Log (DVL). See the Communications Board section for more information on design and operation.

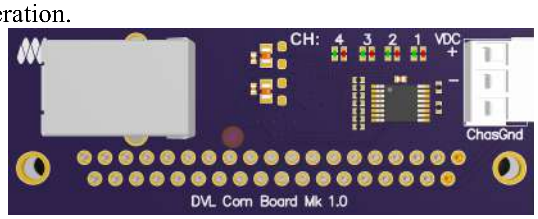

Figure 7: Doppler Velocity Log Communications Board

V. Sensors

A. Cameras

The sub utilizes two cameras for image processing, object detection, and navigation. The DFK 23UV024 and DFK 23U274, shown in **Figure 8**, are USB 3.0 Color Industrial cameras manufactured by the Imaging Source. Each camera is located in the frontal hull section of the vehicle. One camera is used for forward vision and the other is used for downward vision. The forward facing camera utilizes a 6 a wide angle lens and is responsible for image processing and object detection of the course obstacles, as well as navigation. The downward facing camera is responsible for tracking the course path and detecting the obstacles at the bottom of the pool.

Figure 8: DFK 23U274 Camera

B. Attitude heading reference system (AHRS)

The Sparton GEDC-60 AHRS, as shown in **Figure 9**, measures spatial orientation. The Sparton AHRS features a Kalman filter that provides accurate heading by eliminating electromagnetic interference from yaw, pitch, and roll solutions. It includes a 3-Axis measurement in the X, Y, and Z direction and features yaw, pitch, and roll all at low power consumption which is ideal for our vehicle. We are using three AHRS for triple redundancy in order to get the most accurate readings.

Figure 9: Altitude Heading Reference System

C. Pressure Transducers

In order to measure the depth of the vehicle, three absolute pressure transducers were incorporated into the hull of the vehicle. The MEAS 5254 30psi Pressure Transducer, as shown in **Figure 10**, is used in calculating depth and is capable of operating up to 30psi. We are also using triple redundancy with the pressure transducers in order to get a more accurate reading for depth. The pressure transducer measures the pressure, relative to 0psi, when the sub is submerged underwater and then is passed to the Sensor Interface Board (SIB) to convert the pressure into depth in water.

Figure 10: Pressure Transducers

D. Doppler velocity log

The Teledyne RDI Explorer Doppler Velocity Log (DVL), shown in **Figure 11**, provides precise velocity and altitude updates that are helpful when performing underwater tasks. With velocity, we are then able to integrate and calculate the position of the vehicle which will allow us to map out the pool and create waypoints where the obstacles are located in order to successfully navigate through the course.

Figure 11: Teledyne RDI Explorer Doppler Velocity Log

E. Hydrophones

There are four Sparton Navigation and Exploration PHOD-1 Hydrophones, as shown in **Figure 12**, that were used for Defiance. The Hydrophones are supplied 20V from the backplane and require 10mA for operation. They are usable for frequencies between 10Hz and 50KHz. These are necessary for one of the obstacles where the vehicle has to find the pinger that is emitting a certain frequency and rise to the surface above it inside an octagon.

Figure 12: Sparton PHOD-1 Hydrophone

VI. SOFTWARE SYSTEM

All of the vehicle's high level functionality, including completing the obstacle tasks, image processing and object detection, serial communication, mission planning, 3D modeling and animation, and navigation is accomplished through the vehicle's software system. This year, a brand new customizable graphical user interface (GUI), was programmed and implemented that incorporates all of the high level functionality. It is built upon a Windows 7 Professional PC and is primarily written in the Python programming language; other features in the software system utilize the C programming language.

A. Main Computer

The software system uses an ASUS mini-ITX motherboard equipped with an Intel i7-4790k Quad-Core Processor, 8GB of Memory, and a 256GB SSD. The computer's small form factor, as shown in **Figure 13**, is efficient for space management in the main hull and the fast processor allows for seamless execution of the software GUI.

Figure 13: Sub's main computer – ASUS mini-ITX

B. Software Graphic User Interface

This year we continued using the graphical user interface (GUI) we developed last year. It is user friendly and will allow team members to: create user profiles, customize graphic gauges, select parameters for image processing and mission planning, manually control the vehicle, communicate with our embedded systems, and display a 3D model of the vehicle in its environment. The GUI, as shown in **Figure 14**, displays gauges of the vehicle's status which includes its yaw, pitch, and roll, depth, position and velocity, voltage and current levels, duty cycle percentages of the motors, alerts/warnings, and internal temperature for detecting leaks.

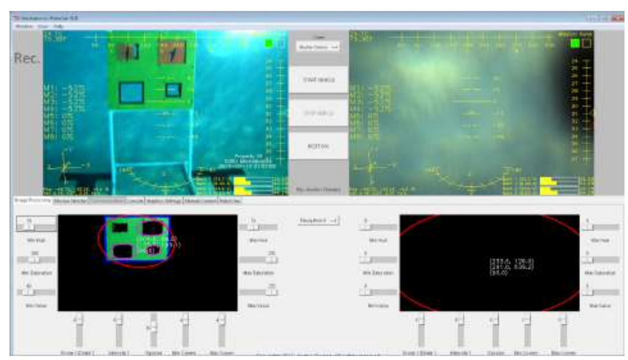

Figure 14: Software GUI

C. Image Processing

Image processing throughout the obstacle course is accomplished with the GUI using OpenCV and the Python programming language. OpenCV is an Open Source Computer Vision Library developed by Intel that features many image processing algorithms for filtering images and object detection. Utilizing OpenCV with Python, the team was able to develop our own algorithms for detecting objects that contain a specific Hue, Saturation, and Value (HSV), as well as a certain number of contours. For a user to track an object through the GUI, they must click and drag the mouse to create a rectangle to establish a region of interest (ROI). The Image Processing tab has sliders that will then immediately snap into place for the HSV parameters.

The user has the option to manually change the HSV parameters to get a more accurate track on the object. In addition, segmentation and shape detection were added to make the algorithms more robust. Given a situation where the vehicle needed to respond based on the shape present in an image it is tracking, it is able to compare the number of angles found between a contour to do so. This is done by segmenting the image, removing the background and other objects outside of the region of interest. The software looks for the number of angles to determine the shape detected on this segmented image for higher fidelity results.

D. Mission Planning

By having predefined blocks of code written for each one of the missions, we can choose which missions we want to execute from a list, what order the vehicle executes them in, and have users enter in various parameters for each mission, as shown in **Figure 15**.

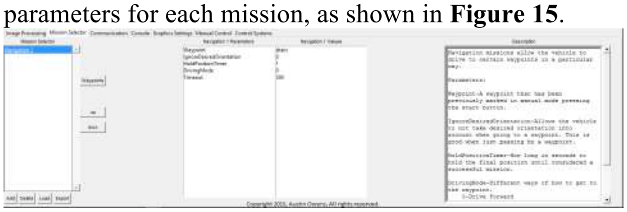

Figure 15: Mission Planning

Users can save the mission lists they create to their own user profile so that the list may be imported later on.

E. Embedded Device Communication

For easy debugging, the software team incorporated a communications tab, as shown in **Figure 16**, that allows us to automatically see which PIC24F boards are connected to the PC and send various commands to the embedded devices that a user can select from a list. This year, changes were made to the Communications Tab to make it a clickable interface. Users no longer have to type in the code, they simply select the function, enter the parameters, and click run. This setup is much easier for the general individual.

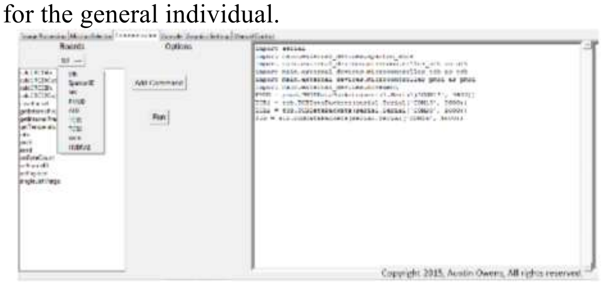

Figure 16: Communications Tab

F. Control & Navigation

To accurately control and navigate the sub underwater, the DVL, Pressure Transducers, and AHRS's are used synergistically to create a closed loop control system. PID controllers are used to prevent overshoot as well as keeping the vehicle on track if it gets knocked off course. Transformation matrices are used to capture the location and orientation (pose) of the vehicle and allows us to use linear algebraic algorithms to have full control over the vehicle in 3D space.

The user can push a button in the GUI that puts the vehicle into manual control mode, as shown in **Figure 17**, where the user can operate the vehicle with a joystick controller. The joystick controller has two modes; one mode allows the user to freely maneuver the vehicle, the other mode locks the vehicle's orientation in place but still allows it to translate along all axes. It's possible to lock the vehicle's orientations by using the AHRS's as a closed loop control system. By applying the right PID controllers, the vehicle will find its way back on course as fast as possible without overshoot. The GUI also has graphic gauges that represent the desired and actual orientations and translations of the vehicle.

Figure 17: Manual Control Tab

G. Console Log

In order to see various sensor readings or general data in the GUI, there is a console tab, as shown in **Figure 18**, that allows users to select what data they are interested in displaying in live time to the GUI console. The software does this by redirecting the standard output from print statements and sends them to the GUI console instead. Users can choose to export the data to a file that can be read by excel for further analysis.

Figure 18: Console Tab

H. Graphic interface customization

The GUI is very customizable and members can make their own user profile and personalize it to how they prefer, as seen in **Figure 19**. The software remembers various things about the user's actions including the missions and image processing values they have selected, the position, color, and number of gauges they display during their sessions, and the last member that was using the program. Upon restarting the software, it can restore all of the user's previous settings.

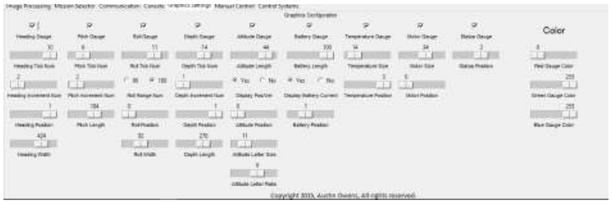

Figure 19: Graphics Setting Tab

I. RoboClaw Tab

A tab was created in the graphical user interface (GUI) that allows the sub to control a four degree of freedom (DOF) robotic arm. It interfaces with Dynamixel's AX-12, AX-18, or MX-28 servos using half-duplex universal asynchronous receiver/transmitter (UART). When connected, the software reads the EEPROM values from the servos and displays them in the proper fields. RAM values are read from a text file if any were saved. The user controls the claw's movement by changing x, y, and z coordinates or changing the angles between the servos. For this to work, forward and inverse kinematics for the claw had to be derived. A matrix was also found such that transformation between the origin of the claw and the camera's coordinate system are possible. It is plausible that two solutions exist, given our current configuration, for any given position of the end effector (EE). To deal with this, two configurations were included so that the user can move the claw to a particular point in space using a solution or its inverse. If the user presses the record button, followed by subsequently moving the claw, the motion can be played back at different sample rates. To make the software as generic as possible, the number of servos, servo model, and forward/inverse kinematics can be changed by the user. This will allow future software and mechanical teams to design their own robotic arms with only minor software changes.

Experimental results

This year we were able to test the AUV approximately 60 hours, a significant increase over last year. Through continued testing, significant drift backwards was detected. The placement of the forward thrusters was adjusted to correct for the drift. A 'Position Lock' was also developed in software so that the AUV will stay in position using feedback from the DVL while tasks such as image processing or manipulate take place. Thanks to this, the success rate for clearing obstacles based on an image processing task or manipulation increased from 50% to 80%

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