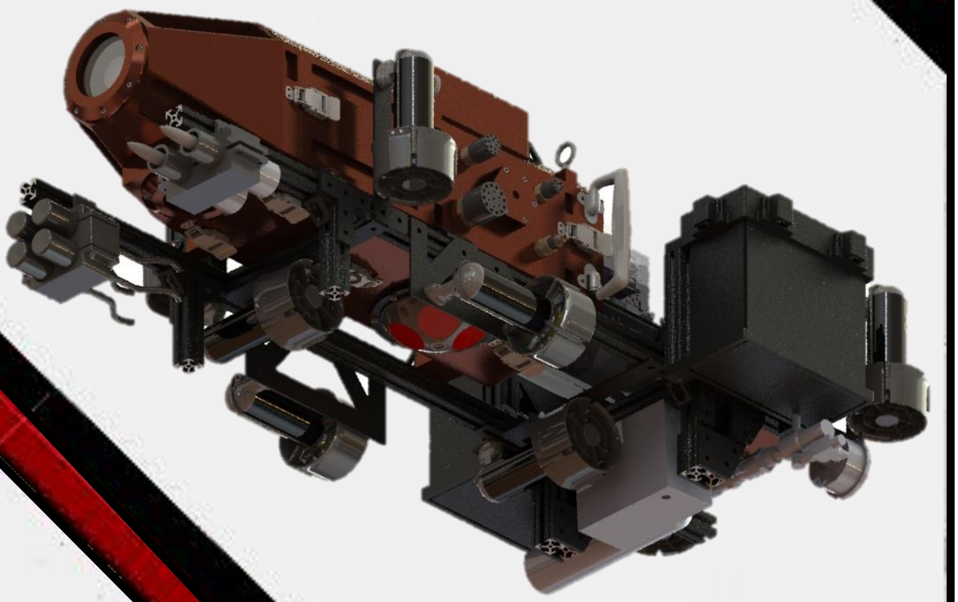

2014 -
2015

San Diego State University
Mechatronics Club

DEFIANCE

Autonomous Underwater Vehicle: Design and Implementation

MECHATRONICS
SAN DIEGO STATE
UNIVERSITY

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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 3 different departments: Robosub, RoboAir, and Mechatronics 101. The club has designed an Autonomous Underwater Vehicle (AUV), or RoboSub, to compete in the 18th Annual RoboSub competition hosted by the Association for Unmanned Vehicle Systems International (AUVSI) Foundation and Office of Naval Research (ONR). 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.

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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. The competition is held in the team's hometown of San Diego at the SPAWAR SSC's Pacific TRANSDEC pool during July. 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 successfully designed and built our second Autonomous Underwater Vehicle.

II. Design Overview

This year, the vehicle was completely redesigned compared to last year's vehicle. After gaining enough experience from the previous year, we were able to incorporate a lot of features that fixed problems we encountered previously. With all the insight, we were able to effectively build a flexible and modular sub to compete in this year's competition. 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. The vehicle includes two cameras, torpedo launchers, dropping mechanism, and an external frame that allows versatility with the placement of components.

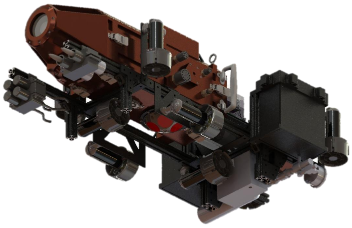

Figure 1: Defiance - 2015 Vehicle

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. A new sensor we were able to incorporate this year is a Doppler Velocity Log which will be able to pinpoint the sub's position and velocity while it's in the water. 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

The mechanical team is heavily involved in applying mechanics of materials, heat transfer, fluid mechanics, materials science, solid modeling, drafting and also common industry practices such as product data management and planning around vendor turn-around times.

From a mechanical standpoint, almost every aspect of this year's vehicle has been transformed completely. Defiance features a far more compact and streamlined form factor. The main chassis changed from a large bulky enclosure to a series of individual hull sections for a more modular approach. Our outer frame is far more compact and weighs much less as opposed to last year's vehicle. Its new design allows for up to 13 different components to be mounted to it simultaneously. The Inner Frame, lighter and easier to attach, allows for more mounting real estate for all the interior sensitive equipment.

A. Frame

The external frame structure, as shown in **Figure 2**, is anodized 80/20 Adjustable Aluminum Extrusion which provides modularity and flexibility for relocating the sub's components such as the thrusters and weapons systems. The frame is designed to be neutrally buoyant in the water. Each component mount is strategically placed along the extrusion to allow even weight distribution.

Figure 2: 80/20 Frame Structure

The components are screwed directly into the mounts and are designed with flexibility in mind. The modularity of the outer frame also gives us the ability to manipulate where the vehicle's center of gravity will be. This design allows us to find the best configuration and adjust if needed.

B. Main Hull and Inner Frame

The main hull features custom designed and machined subsections that piece together to form the main chassis. Each section of the hull has an integrated latching system which allows for individual sections of the chassis to be removed. This allows for easy access to critical internal areas of the sub that require constant maintenance and adjustments such as sensors, circuit boards, etc. The front half of the vehicle houses the on-board cameras and the main processing computer. At the center rests the Doppler velocity log, pressure transducers as well as the main bulkheads through which all internal systems connect to the exterior hardware. Sitting on top of the central hub rests the sensor module which houses three attitude heading referencing systems (AHRS) as well as the kill and reset switches.

The rear portion of the submarine houses all power management boards. All these components mount to the internal frame, as seen in **Figure 3**, which is split into two light weight Aluminum 6061 plates. If the need to get more hands on arises, these plates are also designed to slide out of the submarine with ease so that the software and electrical team members can get up close and personal with the internal hardware.

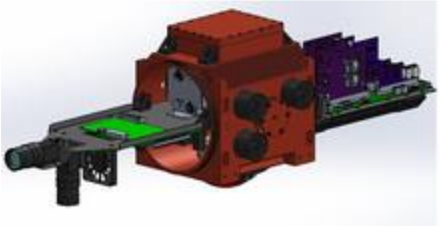

Figure 3: Inner Frame

C. Heat Transfer

The new design switched materials from plastic to 6061 aluminum allowing Defiance to take advantage of the temperature differences it will be exposed to. Running the length of the submarine is a series of channels machined directly into the chassis itself, these are meant to act as heat sinks. They strategically run parallel to the flow of water in order to induce accelerated heat transfer through an increase in surface area. Defiance's slow travel speed means the flow will remain laminar through out the length of the channels meaning more effective heat transfer.

D. Weapons Systems

The weapons system consists of two pneumatically launched torpedoes, shown in **Figure** 4, two pneumatically actuated claws, and a servo driven payload dropping mechanism. Actuators are activated by sending electrical impulses to servo motors and solenoid coils on the pneumatic valves of the respective actuator.

The pneumatics system is composed of a high-pressure CO2 tank, pressure regulator, solenoid valves, pneumatic cylinders, and plastic tubing. As a result, the pneumatic valves open up and trigger a cylinder to expand or contract. The change in length of the cylinders influence the actions of a respective weapon system. For example, when launching a torpedo, an electrical impulse is sent to the corresponding valve, opening it, thus extending the piston attached to the torpedo at high speed. The amount of force placed on the torpedo at that instant, propels it through the water.

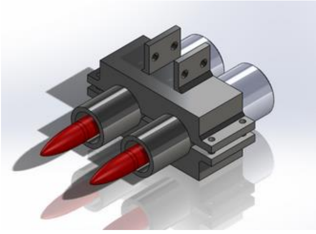

Figure 4: Torpedo Weapons System

The same concept can be applied to the claws; the claws would either open or close depending on which pneumatic solenoid valve was triggered. There are two valves controlling both of the claws, one for open, one for close position. The speed of these actuators is adjusted through variable flow regulators, which limit the amount of air passing into the pistons.

The dropping mechanism utilizes a different mode of triggering. In this case, a servo rotates a feeder containing steel ball bearings.

D. 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.

IV. Electrical Systems

The electrical systems consist of power distribution and electronics. When compared to our last year's vehicle Endeavor, Defiance features two additional brushed-DC thrusters, increased power system reliability, reduced electronics form factor, and improved wire management. There are nine custom manufactured printed circuit boards (PCBs) that were designed, sent in for fabrication, and populated with components.

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 Mini-Box 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 and Integration

The backplane, as shown in **Figure 5,** 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. Server 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.

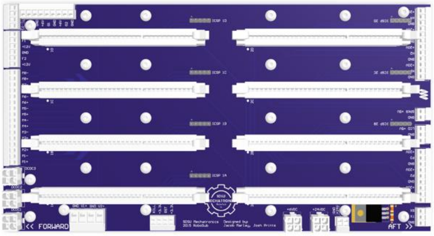

Figure 5: Custom PCB Backplane

D. Power Management and Undervoltage Detection (PMUD)

The Power Management and Undervoltage Detection (PMUD) board, shown in **Figure 6,** 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 2GB microSD card 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 power from thrusters and weapons and not from the DC-DC converters.

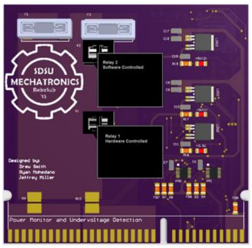

Figure 6: PMUD Board

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.

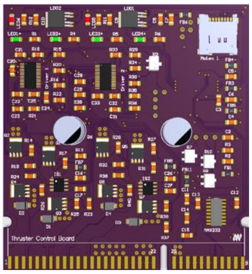

Figure 7: Thruster Control Board

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), shown in **Figure 8**, powers and controls launching two torpedoes, dropping two ball bearings, and operating two grabbers. The WCB features re-usable control outputs that can be used with numerous actuators. Since weapons are a new addition, this functionality was deemed necessary by project management to facilitate prototyping of several different weapons systems designs.

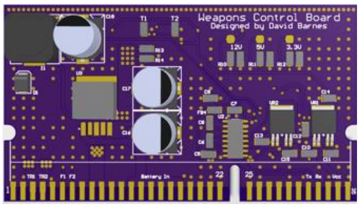

Figure 8: Weapons Control Board

The WCB has LED indicators for safety during prototyping and development. The WCB has a 12V buck converter with a large capacitor bank for actuators requiring large pulsed current. For safety purposes, when the kill switch is engaged the unregulated battery power is physically disconnected from 12V buck converter by PMUD to prevent actuator operation, but only after the capacitor bank discharges.

G. Communications Board (COM)

The USB to RS-232 communications board (COM), as seen in **Figure 9**, is a custom serial communications hub that fits the modular daughter card form factor. The COM 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.

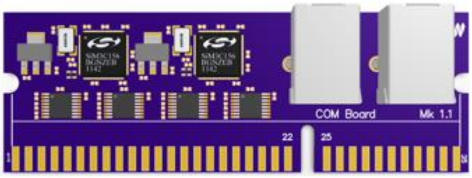

Figure 9: Communications Board

H. Sensor Interface Board (SIB)

The Sensor Interface Board (SIB), shown in **Figure 10,** features triple redundant sensors and filtering for internal temperature, internal pressure, and external pressure. Internal temperature sensor data is logged for engineering analysis. Internal pressure transducers are used for leak detection. External pressure transducers measure depth of the vehicle.

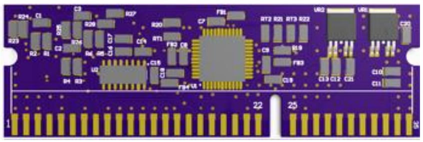

Figure 10: Sensor Interface Board

I. Hydrophones and Direction Rendering Analysis System (HYDRAS)

The Hydrophones and Direction Rendering Analysis System (HYDRAS) board, shown in **Figure 11**, makes use of a square array of four hydrophone acoustic sensors to locate underwater pingers. HYDRAS features three 7-segment displays to show desired frequency, heading angle, and ascent angle. pinger signals induced in each hydrophone pass through an Analog Devices AD8010 Operational Amplifier, a Linear Technology LTC1068 band pass filter (BPF), and a resistive network before being sampled by a PIC24 microcontroller. The decoy pinger signal is removed by the BPF, so HYDRAS can iterate complex algorithms to determine the direction to the target pinger.

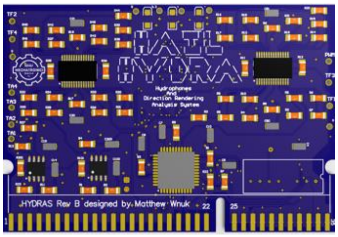

Figure 11: HYDRAS Board

J. Doppler Velocity Log Communications Board (DVL COM)

The Doppler Velocity Log Communications board (DVL COM), shown in **Figure 12**, 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.

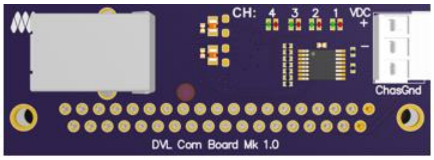

Figure 12: DVL COM Board

V. Sensors

The sensors onboard Defiance are capable of observing the sub's environment and the relative position of the vehicle. The sensors consist of two cameras, three Sparton GEDC-60 Attitude Heading Reference Systems (AHRS), three pressure transducers, a Teledyne RDI Explorer Doppler Velocity Log, and three Sparton PHOD-1 Hydrophones.

A. Cameras

The sub utilizes two cameras for image processing, object detection, and navigation. The DFK 23UV024 and DFK 23U274, shown in **Figure 13**, 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 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 depth and the course path and detecting the obstacles at the bottom of the pool.

Figure 13: DFK 23U274 Camera

B. Attitude Heading Reference System (AHRS)

The Sparton GEDC-60 AHRS, as shown in **Figure 14,** 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 14: Sparton Attitude Heading Reference System

C. Pressure Transducers

In order to measure the depth of the vehicle relative to the bottom of the TRANSDEC pool, three pressure transducers were incorporate into the vehicle. The MEAS 15psi Pressure Transducer, as shown in **Figure 15**, monitors the depth and is capable of operating up to 15psi. We are also using triple redundancy with the pressure transducers in order to get the most accurate readings for depth. When the sub is submerged underwater, the water presser is measure by the transducer which then interacts with the Sensor Interface Board (SIB) to accurately estimate the depth and then maintain a constant depth.

Figure 15: MEAS 15psi Pressure Transducer

D. Doppler Velocity Log (DVL)

The Teledyne RDI Explorer Doppler Velocity Log (DVL), shown in **Figure 16**, 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 16: Teledyne RDI Explorer Doppler Velocity Log

E. Hydrophones

There are four Sparton Navigation and Exploration PHOD-1 Hydrophones, as shown in **Figure 17**, that were used for Defiance. Three are required and one hydrophone serves as a spare.

Figure 17: Sparton PHOD-1 Hydrophone

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.

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 18**, is efficient for space management in the main hull and the fast processor allows for seamless execution of the software GUI.

Figure 18: Sub's main computer – ASUS mini-ITX

B. Software Graphic User Interface

This year we developed a brand new graphical user interface (GUI) that 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 19**, 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 19: Software GUI

This graphical user interface will allow future teams of Mechatronics to easily monitor and control all aspects of the vehicle.

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.

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 20.**

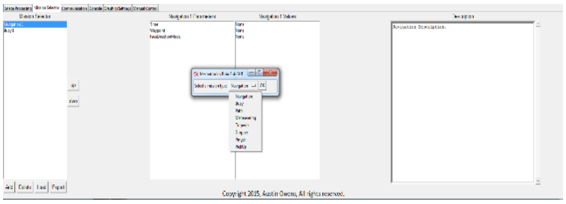

Figure 20: Mission Planning

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 21**, that allows us to automatically see which boards are connected to the PC and send various commands to the embedded devices that a user can select from a list. Because the communications tab includes a script where commands can be entered and executed, the script can also serve as a general access point to code in python.

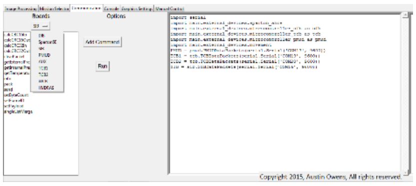

Figure 21: Communications Tab

F. Control and 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 22**, 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.

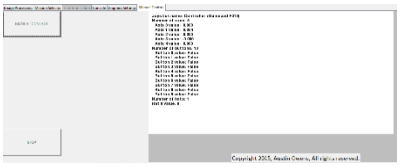

Figure 22: Manual Control Tab

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 23**, 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.

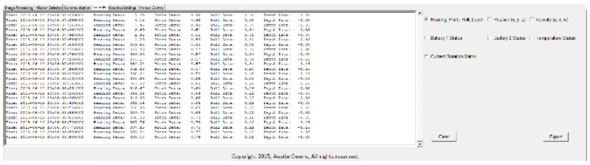

Figure 23: Console Tab

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 24**. 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.

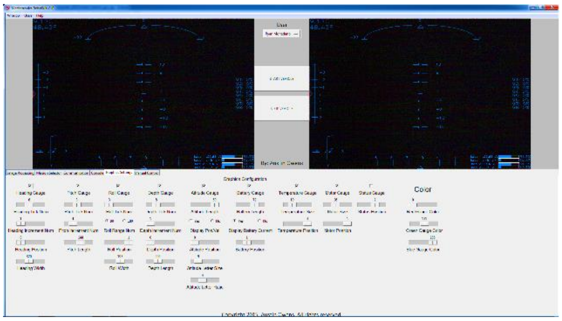

Figure 24: Graphics Settings Tab

Acknowledgements

Mechatronics would like to thank all the individuals and companies that have supported us over the year on our RoboSub Project. We depend immensely on the support from our corporate sponsors for the necessary funding, hardware, materials, and equipment to be competitive in this competition. We would like to thank:

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Silver Sponsors: General Atomics Aeronautical

Bronze Sponsors: Teledyne RDI, ThinkTank Photo, Harvest, Teledyne SeaBotix, SEACON, Northrup Grumman, Teledyne Benthos, MicroChip, Industrial Metal Supply, MathWorks, Wrike, and Sparton.