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San Diego State University
Mechatronics Club

Autonomous Underwater Vehicle: Design and Implementation

MECHATRONICS
SAN DIEGO STATE UNIVERSITY

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***Abstract* – The Mechatronics Club is a robotics oriented and project based student organization at San Diego State University that consists of members from the Engineering, Business, and Computer Science disciplines. For the first time, the Mechatronics Club has designed an Autonomous Underwater Vehicle (AUV) to compete in the 17th Annual RoboSub competition hosted by the Association for Unmanned Vehicle Systems International (AUVSI) and Office of Naval Research (ONR). The competition consists of navigating through a brightly-colored underwater obstacle course involving image processing tasks, maneuvering exercises, path following, torpedo launching, marker dropping, manipulation tasks, acoustic recognition, and more. This year, the team has designed a RoboSub capable of performing the image processing tasks such as passing through the validation gate and completing the buoy obstacles, launching torpedoes at targets, dropping the markers into bins, and circumnavigating around maneuvering exercises.**

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. As a first year team, the toughest challenge was that there were no previous vehicles or code to build on; the AUV had to be built from scratch by a team of Engineering and Computer Science students without the help of mentors or professors. In order to create a reliable and effective AUV, the tasks were split and the team was divided into five subgroups; Mechanical, Electrical, Software, Embedded, and Business. With a lot of hard work and determination, the Mechatronics Club successfully designed and built our first Autonomous Underwater Vehicle.

II. DESIGN OVERVIEW

The sub was designed with key features and capabilities allowing it to compete in the AUVSI and ONR's RoboSub Competition. Since this is our first year competing, many different schemes were considered and modeled when developing the initial concept. Attending last year's competition gave us insight on how to build the sub most effectively; as a result, we made the design flexible.

The sub, as shown in **Figure 1**, features a single-hull design with an internal layout that enables access to all of the electrical components. The vehicle includes two integrated camera enclosures, two torpedo launchers, a dropping mechanism, and an external frame that allows versatility with the placement of components. The design features six thrusters mounted along the external frame providing propulsion in the forward, reverse, up, down, left, right, clockwise, and counterclockwise directions. The sub is powered by two lithium-ion cell batteries and features a collection of inertial, visual, and pressure sensors that enable successful navigation through the obstacle course and data logging. The design includes two watertight bulkheads on the front and back end of the hull to make underwater electrical connections via wet-pluggable connectors. The main computer is located onboard and features a dual-core Intel processor for image processing, serial communication, mission planning, and navigation software.

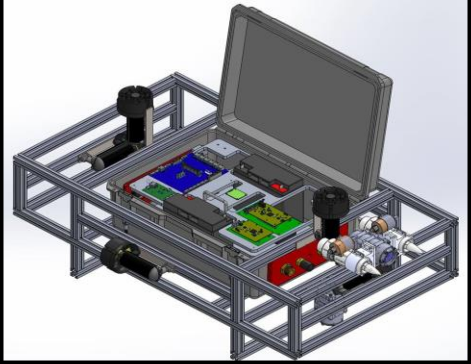

Figure. 1: A SolidWorks rendering of the 2014 vehicle.

III. MECHANICAL SYSTEMS

The mechanical system consists of the main hull with internal electronics housing, external frame structure, camera enclosures, torpedo launchers, and marker dropping mechanism. The main hull and camera enclosures provide water protection for all the electrical components, while the external frame structure provides mounting locations and protection for the thrusters, camera enclosures, torpedo launchers, and dropping mechanism.

A. Frame

The external frame structure, as shown in **Figure 2**, is 80/20 Adjustable Aluminum Extrusion which provides modularity and flexibility for relocating thrusters, cameras, torpedo launchers, and the dropping mechanism as needed. The frame and main hull is designed to be neutrally buoyant in the water. Each component mount is strategically placed along the extrusion to allow even weight distribution.

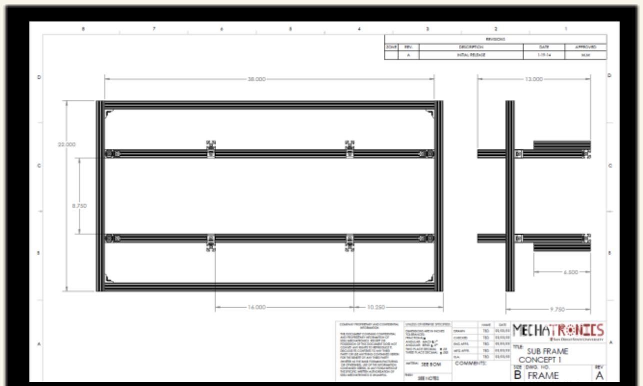

Figure. 2: A SolidWorks sketch of the 80/20 frame structure.

The components are screwed directly into the mounts and are designed the frame with flexibility in mind. This design allows us to find the best configuration.

B. Main Hull and Internal Electronics Housing

The main hull is a Pelican IM2600 Storm Case which houses the computer, batteries, and all other electronics. Since this is our first year competing, we chose a hull that is lightweight, durable, and watertight, as well as inexpensive. The Pelican case met all the requirements and allows for organization and accessibility to all the electrical components. The hull is located in the center of the external frame structure providing equal moments of inertia on all sides, ensuring stability when maneuvering throughout the obstacles in the water.

The Internal Electronics Housing, as shown in **Figure 3**, was designed to organize all the electronics for easy access and heat dissipation. The housing is made of 6061 Aluminum and features a hinge mechanism allowing for even more organization of the bigger components underneath. The housing provides wire organization and creates an efficient and structured layout for all the electrical components.

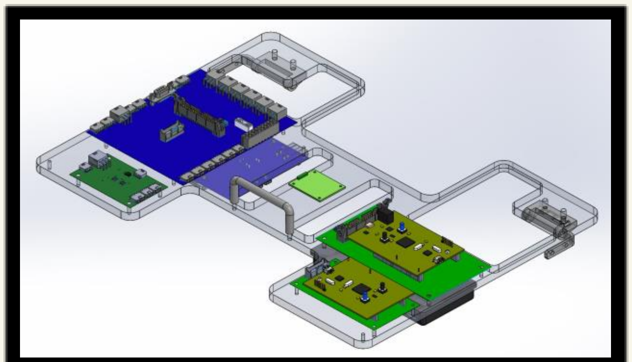

Figure. 3: A SolidWorks model of the Internal Electronics Housing.

C. Actuators

The actuator system, as shown in **Figure 4**, consists of torpedo launchers and marker dropping mechanism. The torpedoes are 3D printed with Low-Density Polyethylene (LDPE) material which has a density that is slightly less than water. This allows the torpedoes to be propelled through the water and then slowly rise to the surface making it easier to locate them after being launched. The LDPE material provides the torpedoes with buoyancy as well as strength to travel accurately throughout the water. The torpedoes are spring loaded and activated by 12 volt solenoids that launch them in a spiral motion.

The marker dropping mechanism was also 3D printed but with Polycarbonate material. This allows the mechanism to be tough and dimensionally stable. The markers, which are stainless steel spheres, are held in place in the mechanism until a servo motor is activated. The servo rotates the mechanism around until the spheres are dropped through the opening and fall into the obstacle bin.

Figure. 4: SolidWorks renderings of the Sub's actuator systems.

D. Thrusters

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

E. Camera Enclosures

The camera enclosures were custom designed and manufactured from 6061 Aircraft Grade Aluminum. As shown in **Figure 5**, the housing was created to provide a waterproof housing for the image processing and navigation cameras. The camera enclosure is composed of five separate components. There is a front, middle, and rear housing, a lens holder, and a camera mount that is used to attach the housing to the frame. Each component is locked together with a key lock insert to ensure a secure connection.

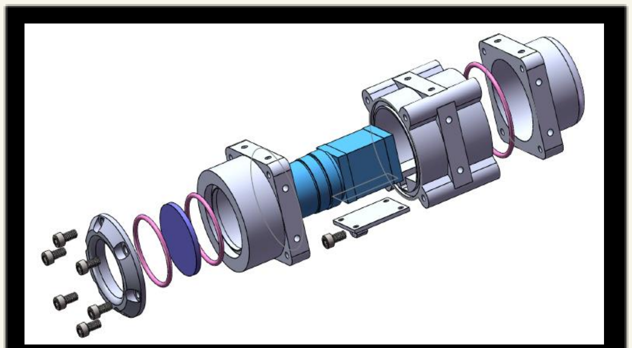

Figure. 5: A SolidWorks exploded rendering of the camera enclosure.

The enclosure was designed to be robust to ensure water-tight capability and provide ease of use. The camera enclosures are mounted directly to the external frame and are positioned to provide the optimal viewing angle.

IV. ELECTRICAL SYSTEMS

The electrical systems provide power and communication between the main computer, external devices, micro-controllers, and several custom manufactured printed circuit boards (PCBs). There are eight PCBs that were designed, sent in for fabrication, and populated with components. These PCBs consist of the Battery Management and Undervoltage Detection Board, shields for the STM32F0 and STM32F4 micro-controllers, Motor Control boards, a Merge board, Weapons Control Board, Leak Detection board, and an IR LED board.

A. Power System

The power system consists of two STARKPOWER "UltraEnergy" 24V 10AH Lithium Ion batteries. The batteries are split into two categories, "Dirty Power" and "Clean Power". The "Dirty Power" battery provides power to the Battery Management and Undervoltage Detection (BMUD) board which in turn provides power to the weapons and the six thrusters that propel the sub. The "Clean Power" battery also connects to the BMUD board but provides power to the main computer and the micro-controllers. By splitting the batteries into two categories, electromagnetic interference (EMI) is isolated from the sensitive computer processors.

B. Battery Management and Undervoltage Detection Board (BMUD)

BMUD, as shown in **Figure 6**, is where the vehicle's battery power is distributed. The primary role of BMUD is to monitor battery voltages and to alert the main computer via the STM32F0 micro-controller to surface when a battery needs to be replaced. The secondary role of BMUD is to provide voltage and current data to the STM32F0 to be sent to the main computer for data logging and estimating power consumption. Additionally, BMUD contains the circuitry of the kill switch, which will allow divers to deactivate the thrusters and weapons systems for safety.

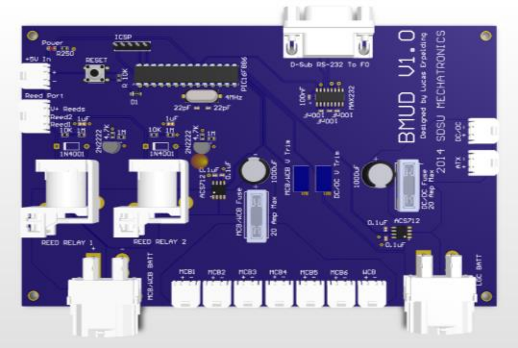

Figure. 6: An Altium rendering of the BMUD Board.

C. Merge Board

The Merge Board, as shown in **Figure 7**, was designed to reduce the complexity of the wiring harnesses by neatly routing and organizing connections. The STM32F0 and STM32F4 Discovery Board's control and observer signals are routed through the Merge Board. The control signals correspond with the pulse width modulation (PWM) of the motors to set the speed while the observer signals read in the current speed value. The Merge Board also distributes 5V power to the other PCBs and sensors.

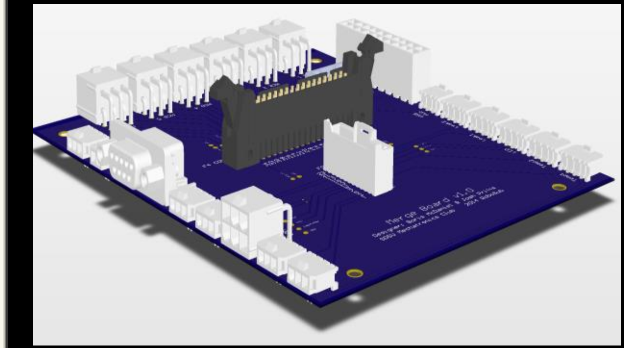

Figure. 7: An Altium rendering of the Merge Board.

D. F0 and F4 Shields

There are two micro-controllers used to control the sub, the STM32F0 and STM32F4 Discovery Boards. In order to organize wire management, two shields were designed, manufactured, and populated for the boards. Both the F0 and F4 Shields contain two headers that run along the outer edge of the board where the STM32F0 and STM32F4 Discovery Boards can be connected directly. The output pins are routed into a single ribbon cable. This ribbon cable is then connected to the Merge Board. Both shields can be seen in **Figure 8.**

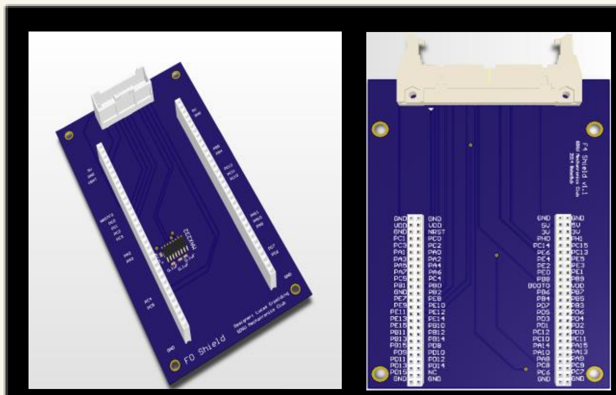

Figure. 8: An Altium rendering of the F0 and F4 Shield.

E. IR LED Board

In order to measure the speed of each thruster, the IR LED board was created. The board, shown in **Figure 9,** will generate a 38 KHz carrier signal using a 555 timer and it also utilizes an infrared (IR) LED and detection sensor. The IR LED is placed on the outward end of the propeller and the IR detection sensor is placed on the inward side of the propeller. As the propeller passes between the two devices, the carrier signal will be interrupted. The detection sensor will then filter out the carrier signal, leaving only the pertinent propeller interrupt square wave. The period of the thruster speed wave is determined by dividing the propeller interrupt square wave by two since each thruster has two propellers. The square waves created by the rotations of the thruster propellers are then sent to the STM32F4 Discovery board which interprets the reading. Based off the reading, the speeds of the thrusters are adjusted in a negative feedback control loop.

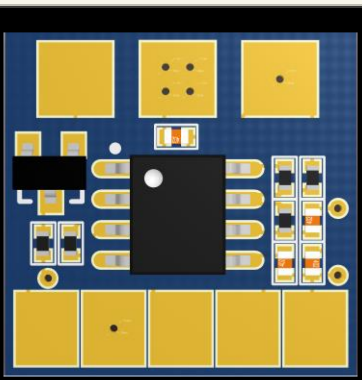

Figure. 9: An Altium rendering of the IR LED Board.

F. Motor Control

Shown in **Figure 10**, six Motor Control Boards (MCB) were designed and fabricated for the six thrusters on the vehicle. The boards utilize Galvanic Isolation and H-bridge Integrated Circuits to provide protection for the STM32F4. The MCBs also provide amplification of the Pulse Width Modulation (PWM) signal for the Brushed-DC SeaBotix thrusters.

Figure. 10: Fabricated Motor Control Boards.

G. Weapons Control and Leak Detection

The Weapons Control Board (WCB), shown in **Figure 11**, was designed to operate the torpedo launcher and dropping mechanism task. The WCB's main purpose is to protect the micro-controller from the noise and back-EMF (Electromotive Force) produced by the inductive solenoid load of the torpedo launchers.

The Leak Detection Board was designed to sense water entering the perimeter of the main hull. The board is placed in a corner of the main hull and has two exposed copper wires running in parallel. If water enters the sub and connects with the exposed copper wire, a signal will be sent to surface the sub.

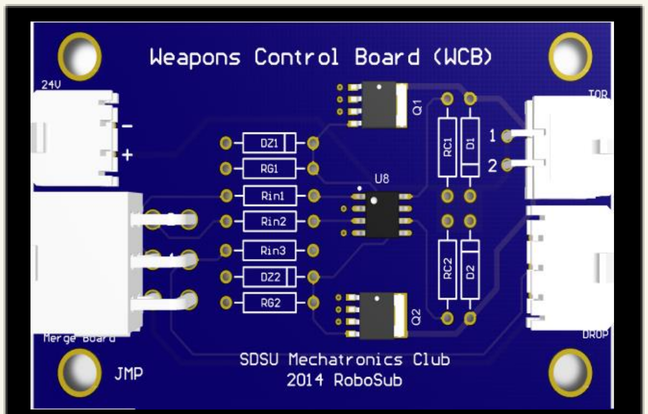

Figure. 11: An Altium rendering of the Weapons Control Board.

V. MICRO-CONTROLLERS AND SENSORS

The sub has of two main micro-controllers and a collection of sensors. The micro-controllers are the STM32F0 and STM32F4 Discovery Boards, shown in **Figure 12.** The sensors onboard are capable of observing the sub's environment and observing the relative position. The sensors consist of two cameras, a PNI Trax Altitude Heading Reference System (AHRS), a Pressure Transducer, and a Leak Detection Board.

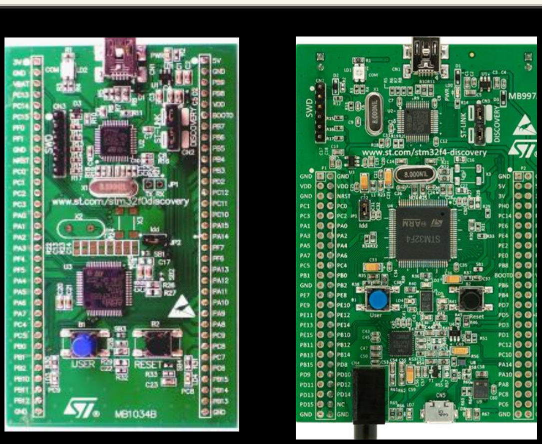

Figure. 12: The STM32F0 and STM32F4 micro-controllers.

A. STM32F0 and STM32F4 Discovery Boards

The STM32F0 Discovery board is a micro-controller that features a Cortex-M0 processor and is responsible for all the weapon-related tasks, such as firing the torpedoes and the dropping mechanism. The STM32F0 also interacts with the BMUD board to determine the status of the batteries, the kill switch, the torpedoes, and the dropper. The STM32F0 also interacts with the leak detection sensor in case water is detected within the case.

The STM32F4 Discovery board is more powerful and features a Cortex-M4 processer. The STM32F4 is responsible for motor control of the thrusters, interaction with the pressure transducer, and interaction with the IR LED board to identify the current speed of the thrusters. The Discovery boards are the work horse for the main computer to the external devices. The micro-controllers have been programmed to receive commands from the main computer. Interface between the computer and the STM32F0 Discovery board is accomplished through USART serial communication while the interface between the STM32F4 Discovery board is accomplished through USB serial communication.

B. Cameras

The sub utilizes two cameras for image processing 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 encased in the waterproof camera module enclosure designed by the mechanical team. One camera is used for downward vision while the other is used for forward vision. The downward facing camera is responsible for tracking the depth and the course path on the bottom of the pool. The forward facing camera utilizes a wide angle lens and is responsible for image processing and object detection of the course obstacles, as well as navigation.

Figure. 13: The DFK 23U274 USB 3.0 Color Industrial Camera.

C. PNI Trax Altitude Heading Reference System (AHRS)

The PNI Sensor Corporation Trax AHRS, shown in **Figure 14**, measures spatial orientation. The Trax AHRS features a Kalman filter that provides accurate heading by eliminating electromagnetic interference from roll, pitch, and yaw 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.

Figure. 14: The PNI Trax Altitude Heading Reference System.

D. Pressure Transducer

In order to measure the depth of the vehicle relative to the bottom of the TRANSDEC pool, a pressure sensor was selected. The MEAS US331 00005-030pg Pressure Transducer, as shown in **Figure 15**, monitors the depth and is capable of operating up to 30psi which is equivalent to an underwater depth of about 69ft. When the sub is submerged underwater, the water pressure is measured by the transducer which then interacts with the STM32F4 Discovery board to accurately estimate the depth and then maintain a constant depth.

Figure. 15: The MEAS US331 Pressure Transducer.

E. Leak Detection Sensor Board

The Leak Detection Sensor, as shown in **Figure 16**, was custom designed by the Electrical team and detects if there is any water that enters the Sub. All the important electronics are located inside the sub, so it was absolutely necessary to have a sensor that would be able to alert the team in order to avoid any costly damage.

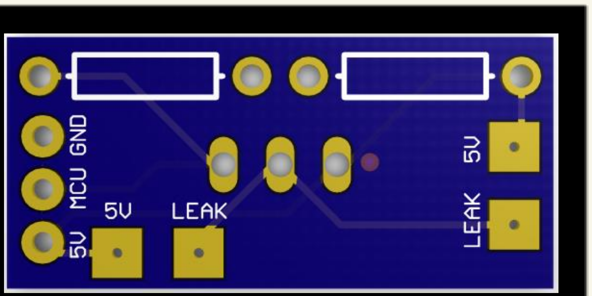

Figure. 16: An Altium rendering of the Leak Detection Board.

VI. SOFTWARE SYSTEM

All of the sub's high level functionality, including completing the obstacle tasks, image processing, serial communication with the micro-controllers, and navigation is accomplished through the vehicle's software system. The software system 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 and MATLAB.

A. Computer

The software system uses an Intel NUC D54250WYK Mini PC, as shown in **Figure 17**, which features a Haswell Intel Core i5-4250U processer along with 8GB of memory and a 120GB mSATA drive. The computer also features two USB 3.0 ports dedicated specifically to the two cameras used for image processing. The computer's small form factor is efficient for space management in the main hull.

Figure. 17: The Intel NUC D54250WYK Mini PC.

B. Image Processing

Object detection and navigation through the obstacle course is accomplished using OpenCV in the Python programming language. OpenCV is an Open Source Computer Vision Library developed by Intel that features many image processing algorithms for filtering an image, object detection, and much more. Utilizing OpenCV with Python, the team was able to develop custom algorithms for object detection and image processing, plan missions, interpret sensor data, and perform the competition obstacle tasks.

The cameras detect the obstacles by applying a Hue, Saturation, and Value (HSV) filter on the incoming images. With the help of OpenCV's algorithms, the sub is able to filter out any noise in an image to locate an object, as shown in **Figure 18.** The team implemented an interface that allows the user to highlight a region of interest by dragging a box over a selected object. Once the region has been selected, the interface automatically sets the parameters of Hue, Saturation, and Value of the object allowing it to be tracked.

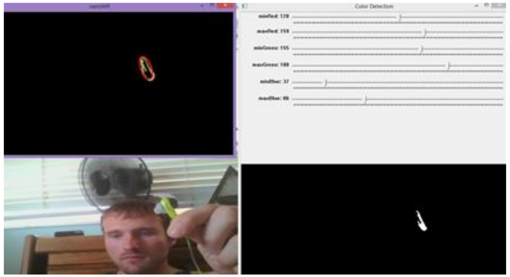

Figure. 18: An Image Processing Example using the interface.

When the RoboSub locates an object using Image Processing and the lighting changes as the day goes on, the object disappears. However, with HSV adjustments, compensations are made within the saturation and value range of saturation to adjust for varying lighting conditions.

C. Control and Navigation

To accurately control and navigate the sub underwater, image processing algorithms are combined with data received from the sensors and micro-controllers onboard. When the sub needs to locate the first obstacle and navigate to it, it reads in the image from the front facing camera. Once an image is filtered and the object is targeted, the main computer sends a command to the STM32F4 micro-controller to enable the appropriate thrusters on and maneuver to the target. This process happens in a continuous loop with the main computer in constant communication with all electronics onboard to ensure that the object is being located and the sub is able to navigate to it. It also must be in constant communication to ensure that the sub maintains a constant depth and consistent heading. Once the task has been completed, the system continues on to the next mission that has been programmed. With the help of the electronics, the sub is able to accomplish each competition task.

To test out all the image processing algorithms combined with data received from the devices, the software team was able to program an Xbox 360 controller and successfully control and navigate the sub manually. As shown in **Figure 19**, the Xbox controller is connected to the main computer and is programmed to control the speed of the thrusters. When the analog stick of the Xbox controller is pushed forward, it communicates with computer which sends a command to the STM32F4 microcontroller which enables the speed of the thrusters depending on how far up the analog stick is pushed.

Figure. 19: A XBOX 360 Controller manually controlling a thruster.

D. Mission Planning

With the limited amount of sensors onboard the sub, specific and complex algorithms were written in the Image Processing code for the competition tasks. Each situation that the sub could be faced with when navigating through each obstacle was taken into consideration when programming. The coding algorithms accommodate for any errors the sub could potentially face and allow it to successfully complete each task.

AKNOWLEDGEMENTS

Mechatronics Club 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 RoboSub Competition so we would especially like to thank:

Titanium Sponsors: Cymer and Hewlett Packard

Platinum Sponsors: Altium

Gold Sponsors: Boeing

Silver Sponsors: SeaBotix, SEACON, Electro Rent Corporation, MathWorks, General Atomics Aeronautical, Agilent Technologies, PNI Sensor Corporation, Harvest, Sparton, Industrial Metal Supply Company, SolidWorks, and Intel.