TEAM SIMPLEXITY 2023 HydroX 2.0

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***Abstract* -- Team Simplexity is a continuing private team composed of 5 high schoolers from 2 high schools in San Diego, California. This season, we have created HydroX 2.0 that utilizes state-of-the-art software and hardware. Our AUV incorporates the *Qualcomm RB5* which processes all aspects of the sensors, thrusters, and vision processing. One 4K high resolution camera is at the heart of our vision processing & navigation system, and is located at the front of our acrylic enclosure. The PX4 firmware runs on the *RB5* to control the propulsion system and interfaces to several offboard sensors. Additionally, ROS2 runs our vision processing pipeline allowing OpenCV to process raw images, and in turn, publish commands to our navigational system. We have a propulsion system which utilizes the BLHeli32 firmware on two 4-in-1 ESCs. These are connected to eight *Blue Robotics T200* thrusters. We built several custom test apparatuses to characterize several aspects of the HydroX 2.0 to ensure we have a solid foundation to build upon for years to come.**

COMPETITION STRATEGY

The strategy this year was to design a simple AUV that could get in the water and could qualify to compete in the competition. Successfully navigating through the gate will be a major accomplishment for our team. Our team had significant commitments during the year and we could not dedicate time towards Robosub tasks until the summer. To achieve our goal we chose to purchase the Blue Robotics ROV heavy frame, thrusters, and 6” enclosure. This strategy allowed minimal design efforts of hull, thrusters, and watertight enclosure while providing a tried and true platform that could be extended in the years to come. The heavy configuration, with its eight thruster configuration, enables 6 degrees of freedom of motion. This platform has been proven by many teams over past competitions, as reliable, water tight, and flexible enough to add custom electronics and attachments. Our goal of being able to simply submerge, orient in the correct direction, and navigate through the gate helped us focus the electronics design as well. Qualcomm’s Robotics RB5 control computer, coupled with PNI’s high precision RM3100 magnetometer, and Invensense’s 6-axis IMU provide a platform for autonomous navigation. Although our goal is to use visual navigation, using the onboard cameras, our first attempt is to use simple dead reckoning to achieve our goal.

DESIGN CREATIVITY

Mechanical and CAD

Figure 1: CAD model of our completed HydroX 2.0

We utilized a waterproof cylindrical enclosure from Blue Robotics with a 6in diameter and 11.75in length with the lid on one side and connectors on the other. Two pressed fit o-rings make a watertight seal with the cylinder. To maximize the space that was available for our electronics, we prototyped several methods of mounting our electronics using 3D printed parts. This was an iterative process throughout the season that culminated with a design that was modular and offered solid usability. Figure 2 shows the CAD model of the 3D printed structure of the enclosure.

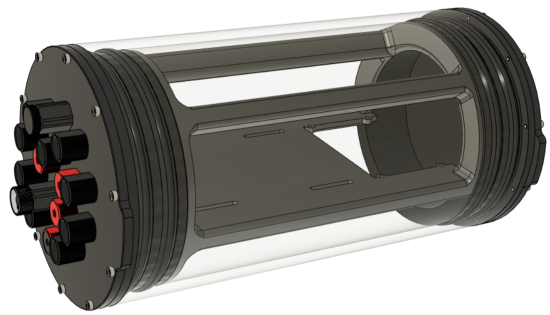

Figure 2: CAD of our custom 3D printed enclosure mounting system

To create the foundation of our enclosure we designed a cylindrical piece that ran the length of the enclosure. The enclosure structure is directly bolted to the connector lid so that we could pull all the electronics out as a single unit without any hassle. The structure of the electronics is 3D printed with acrylonitrile butadiene styrene (ABS) to be able to withstand high temperature without losing rigidity. The structure is made of two parts that are connected with screws that thread into one another. The battery is strapped onto the structure with velcro straps to allow for easy mounting and removal. The other electronics are directly screwed into the structure. In order for this to work we had to optimally position our hardware for ease of use when plugging in ethernet, power, or other connectors. Including the battery inside the electronics enclosure simplified the design.

This took several iterations but we ended with a design that met all the requirements. This included ease of assembly and disassembly, and allowing for the plug and play mentality. We still have to do thermal analysis to ensure our cooling fan is sufficient to keep the temperatures near the plastic parts in a range where they will not deform. We also need to measure how mechanical vibrations caused by the fan will affect our IMU measurements.

We designed a tether box to house the *RAKwireless LX200V30* communication adapter. This module allows us to communicate to the AUV through an ethernet cable for testing. The box is 3D printed with ABS to be able to withstand outdoor use, and stay durable overtime. The seal is printed with TPU, a flexible filament that is able to stretch and compress, allowing us to create a watertight seal between the body and the lid. We incorporated waterproof connectors to make the adapter durable around the water environment.

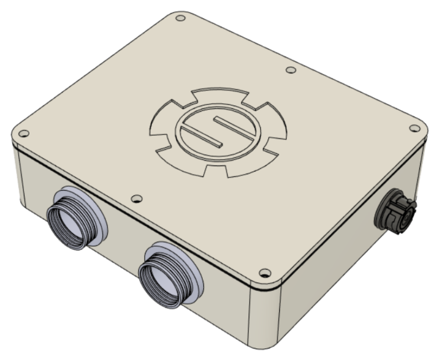

Figure 3: CAD model of the Tether Top Side Enclosure

Magnetic Kill Switch Design

According to section 4.3.1 of the RoboSub handbook, titled "AUV Requirements," it is a requirement for all participating vehicles to incorporate a clearly marked kill switch that can be easily activated by a diver. The kill switch should effectively disconnect the batteries from all propulsion components and devices on the Autonomous Underwater Vehicle (AUV). In compliance with this rule and to ensure our team's eligibility for the upcoming RoboSub 2023 competition, our team undertook the design and development of a magnetic kill switch. The primary objective of our magnetic kill switch is to instantly disable the thrusters. This is accomplished by disconnecting the Pulse Width Modulation (PWM) signals from the ESCs when the external safety magnet is pulled by a diver. This emergency failsafe ensures the thrusters are disabled, but leaves power connected to the RB5 computer to maintain data integrity.

The design was divided into three key components. Firstly, an external magnet was affixed to a small float, strategically positioned in a visible location on the external enclosure of the AUV. This placement ensures convenient accessibility for divers to pull the magnet when needed. The second component comprises a compact printed circuit board (PCB) housing two magnetic reed switches and two connectors. This PCB allows for the installation of magnetic switches in close proximity to the AUV's surface, which can be opened or closed by the external magnet. The third component involves another custom PCB featuring a four-channel Single Pole Single Throw (SPST) switch. Positioned within the connection pathway between the RB5 and the 4-in-1 ESC control signals, this PCB allows the transmission of motor control signals from the RB5 to the ESCs when the remote magnetic switch is closed. Conversely, when the external magnet is removed, the magnetic reed switch opens, interrupting the connection of control signals. When the reed switch opens, the Pulse Width Modulation (PWM) control signals stop. All ESCs stop driving their motors in the absence of a control. This straightforward and compact design allows the AUV's control electronics to remain powered while rendering the thrusters inoperative. This solution offers several advantages over other designs, including minimizing the risk of data corruption, facilitating immediate data extraction, and enabling quick initiation of subsequent runs.

The schematic of the Kill Switch PCB is illustrated in Figure 4, while Figure 5 presents the schematic of the magnetic switch PCB. These custom boards were designed using EasyEDA software, manufactured, and subsequently assembled.

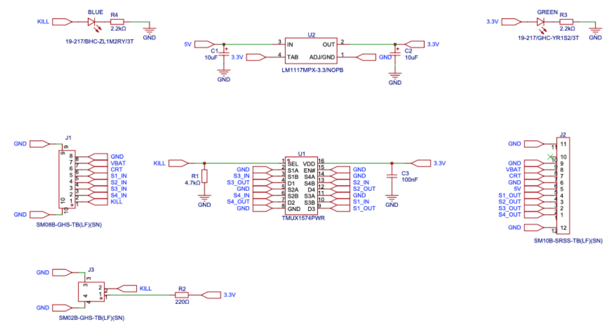

Figure 4 Kill Switch Schematic

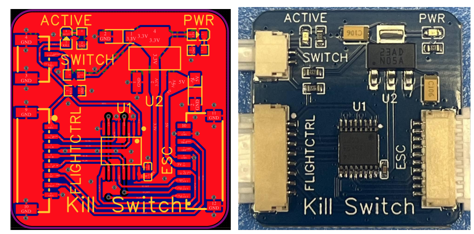

Figure 5 Kill Switch PCB

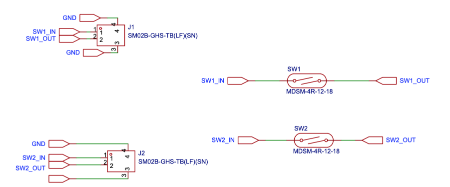

Figure 6 Magnetic Switch Schematic

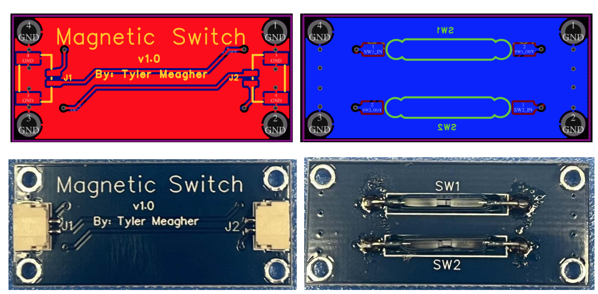

Figure 7 Magnetic Switch PCB

This year we leveraged an off-the-shelf enclosure and frame structure from *Blue Robotics* to speed the development process. After working through the mission requirements, we found 8 thrusters would be the best way to meet the 3 DOF motion requirements. We originally had a 6 thruster design from 2021, but adding two thrusters enhanced maneuverability in the z axis and pitching/rolling the sub Figure 8 shows the general thruster placement with 6 thrusters from 2021 and the 8 thruster configuration on HydroX 2.0.

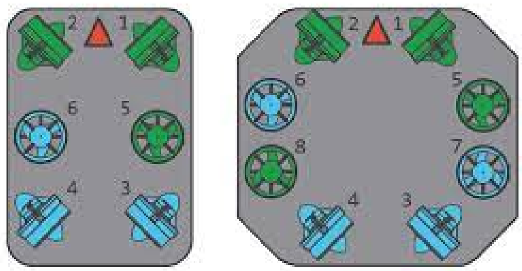

Figure 8: 2021 (Left) and 2023 (Right) thruster orientation. The red arrow indicates the front of the robot. Blue is clockwise direction motors and green is counter-clockwise

The choice of angling 4 thrusters towards the middle of HydroX 2.0 instead of straight forward allows the robot to move in the x-y plane (using strafing) without physically rotating HydroX first. We decided while navigation the field, we will by primarily be moving more forward than strafing, so we rotated the 45 degree looking thrusters so that they would be 30 degrees from an imaginary line along the enclosure instead of 45. Because of limited battery capacity, we decided to implement this change so we can input less current into the thrusters to move the UAV forward because less force is being wasted pushing against the motor across creating no net force.

Electronics

The *Blue Robotics* T200 thrusters propelling the Robosub are a three-phase brushless motor optimized for underwater navigation. The thrusters operate at 7-20V but work best at 16V which fits well with our 4S LiPo battery. At 16V, it can provide a maximum of 5.25 kg of force (~51.45 N) and draws 24A (390W) at full throttle. All 8 thrusters are controlled by two *Hobbywing* 4-in-1 ESCs which support 60A of current on each channel at up to 20V.

The component that controls all the ESCs and the thrusters for autonomous movement is the *Qualcomm* Robotics RB5 Platform. The RB5 communicates with the ESCs through a PWM wire using the DSHOT protocol which unlike traditional PWM protocol allows motor telemetry data to be received from the ESCs as well. The RB5 is also equipped with the *Sony* IMX577-AACK Sensor Module and *OMNIVISION*'s OV9282 used for image processing.

Other than the cameras, the RB5 is also connected to a MS5837 depth sensor which is able to measure up to at most 30 bar (300m depth). All of the Robosub's telemetry is able to be communicated using Ethernet via a wired tether to a computer outside the robosub in real time for testing. Because the tether is over 300 ft. long, two *RAKWireless* PLC LX200V30 on each side are needed in order to send data using the homelink protocol. The maximum transmission rate is 500Mbps.

All the electronics onboard are powered by a 10Ah, 4S *Lumenier* LiPo battery. The *Lumenier* LiPo battery operates at 16.8V at full charge and 14.8V when mostly discharged. The AUV draws an average current of 30A, so with its 10Ah capacity, the LiPo battery is able to power the robosub for 20 minutes or two rounds between each charge. The Lumenier LiPo battery was chosen since its lithium ion technology along with the use of solid polymer as the electrolyte gives the battery more safety as well as a high power density, meaning it is able to provide enough energy to power the entire AUV without taking up too much space inside. More information about thruster efficiency can be found in the Experimental Results section.

Software

Figure X is a control diagram of the different software running on the HydroX 2.0. The vision processing system and ESCs all have independent software stacks running on them, which is controlled by the *RB5.* The microprocessor on the two 4-in-1 ESCs runs the BLHeli32 firmware which allows for setting the rotation of the motors, bidirectional control of each thruster, and current limiting with the built-in current sensors. Furthemore, the RB5 communicates with each of the eight ESCs over a 1 wire interface, with the magnetic kill switch running in between. The ESC supports the DSHOT protocol, a digital protocol, and unlike the traditional PWM protocol, allows us to query telemetry data from the ESC (like temperature, voltage, current and RPMs). Additionally, the RB5 runs the PX4 firmware, which is an open source firmware for professional drone piloting. To support our HydroX 2.0, we customized the PX4 firmware by creating custom airframe and actuator settings to deal with the unique propulsion system on the vehicle. To achieve accurate attitude control, we utilize the compass readings from the *PNI* RM3100.

The PX4 firmware with our custom modifications was flashed onto the *Qualcomm RB5.* Drivers in the PX4 software identified external sensors connected via I2C and TCP. Furthermore, we utilize two *RAKwireless LX200V30* which are composed of the *Qualcomm QCA7420.* One of these boards is located onboard, towards the front of the acrylic enclosure, and the other is located offboard near the connected computer; this allows for decoding ethernet data over several hundred meters of tether, upon gathering testing data.

To test our vision processing pipelines within a realistic environment without requiring the use of the physical sub, we sought to explore simulations. By utilizing Gazebo, an open-source 3D robotics simulator, we were able to gain a better understanding about the physics properties associated with an underwater vehicle. Gazebo's realistic underwater simulations also enabled us to experiment between a six thruster configuration, as was utilized in 2021, and an eight thruster configuration. The Unity simulation with the Transdec environment also enabled us to import the computer-aided-design (CAD) model of our sub. The simulation utilized was composed of one client representing the flight controller and another client as the computer processor. The two clients received sensor data and controller input from the server and translated this to thruster commands allowing for AUV movement.

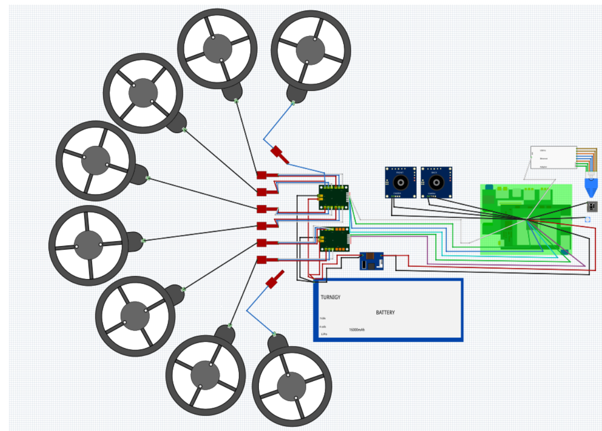

Figure 9: the Fritzing diagram of all components found in the enclusoure.

Experimental Results

Thruster Testing

To characterize the T200 thrusters running on our HydroX 2.0 we made a thruster tester apparatus. This involved transferring the force from the thruster to an S-type load cell through a pivot arm. The load cell distance from the pivot point was equal to that of the thrusters. This resulted in compression and tension forces applied to the load cell that were directly proportional to the force created by our T200 thrusters. In addition, a high precision 20V, 50 amp, variable DC power supply was used to characterize the T200's power usage at different operating voltages and PWM values. For the electronics, an ESP32 microcontroller was connected to a HX711 load cell amplifier to measure the force imparted on the load cell by the thrusters. The ESP32 was also connected to a pair of ESCs to control the speed of the thrusters by changing the PWM values. A webserver running on the ESP32, communicated over WiFi to a host computer which provided the user interface. It also provided the ability to store the experimental results. Figure 8 is a picture of the apparatus.

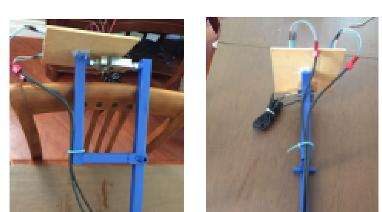

Figure 10: Blue Robotics T200 thruster characterization

The user interface allowed for running manually as well as running in an automatic mode. When in the automatic mode, our microcontroller would send PWM signals from 1500 to 1900 and 1500 to 1100 microseconds in steps of +/- 25 microseconds to the ESC. Measurements were taken at each step and the mean force, current, and standard deviations were recorded every 5 seconds. These measurements were written to a csv file on the host computer for later analysis. We ran the experiment over several different voltages. We processed the results to come up with a characterization graph of the T200 thrusters as shown in Figure 9. This is a plot of the mean force, in pounds of thrust, vs the PWM signal length, in microseconds. Each graph represents a different operating voltage.

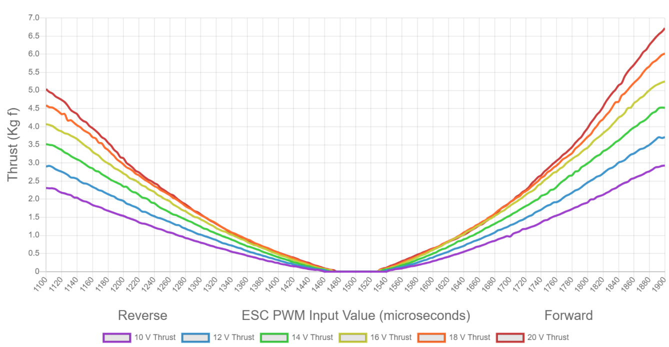

Figure 11: Blue Robotics T200 thruster characterization

We drew two conclusions from this testing. First, we determined a 16Ah, 4S, LiPo battery would provide the required power and energy storage for our HydroX to complete 2 runs in a 20 minute time span. Second, we determined that our four horizontal thruster configuration would have greater than 25lbs of static force at max power. We plan to verify this on our AUV in the coming weeks.

For getting accurate depth measurements we used TE Connectivity's MS5837 30 Bar pressure sensor. The MS5837-30Ba is "a new generation of high resolution pressure sensors with I2C bus interface for depth measurement systems with a water depth resolution of 2 mm"[3]. To test our depth sensor we prototyped an apparatus that made use of an ESP32, the MS5837, and a small pressure vessel. This apparatus allowed us to test the software, and develop accurate drivers needed for the PX4 firmware. The small pressure vessel allowed simulating different depths without going in the water. Figure 10 shows our depth sensor prototype and our pressure test vessel.

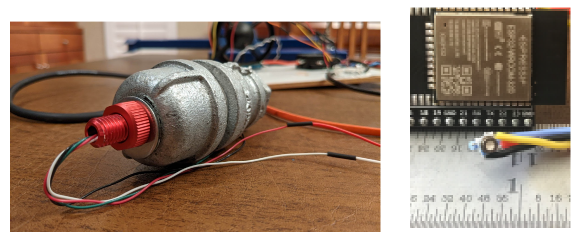

Figure 12: Our depth sensor prototype and pressure testing vessel

We also developed an apparatus and method to measure our center of gravity (CG) and center of buoyancy (CB). Using a scale, the internal 3D compass, and our CAD models we can experimentally find the CG and CB locations. Measuring the force and heading from multiple points both in, and out, of the water allows us to determine these locations with the help of our CAD model. Our two PVC ballast tubes and our battery holder allow for adjustments in the CG and CB. This is important so we can maintain symmetry of our propulsion system. This task is ongoing, and we plan to make more measurements over the coming weeks. Figure 11 are pictures of this testing.

Acknowledgements

We would like to thank our mentors and parents for all their support. Without their help and encouragement we would not have been able to undertake such a major project. We would also like to thank Qualcomm, General Atomics, Blue Trail Engineering, Blue Robotics, Motovisio, and RISE for their generous support.

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Appendix A

Components	Vendor	Model/Type	Specs	Number	Status
Frame	Blue Robotics	BlueROV2 frame	Black HDPE	1	Installed
Waterproof Housing	Blue Robotics	4" diameter acrylic with end caps	Acrylic	1	Installed
Thruster	Blue Robotics	T200		8	Installed
Motor Control	Hobbywind	60A 4-in-1	60A / 6S/ 4 Ch	2	Installed
Depth Sensor	TE Connectivity	MS5837	30 Bar	1	Installed
Propellors	Blue Robotics	T200 Thrusters		8	Installed
Battery	Lumenier	Lipo Battery	10000Ah 4s 25c	1	Installed
Control Computer	Qualcomm	RB5	QRB5165 SOM with 8 core ARM processor Includes 3-axis gyroscope and accelerometer		Installed
Internal Comm Network	Ethernet, I2C, SPI, RS-232, USB				Installed
External Comm Network	1Gbit Ethernet, WiFi				Installed
Ethernet Current Converter	Qualcomm	Homelink chip QCA7005	QFN 68 pins	2 (1 on each end)	Installed
Compass / Magnetometer	PNI	RM3100	± 1100 μT	1	Installed

Components	Vendor	Model/Type	Specs	Number	Status
Frame	Blue Robotics	BlueROV2 frame	Black HDPE	1	Installed
Waterproof Housing	Blue Robotics	4" diameter acrylic with end caps	Acrylic	1	Installed
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Motor Control	Hobbywind	60A 4-in-1	60A / 6S/ 4 Ch	2	Installed
Depth Sensor	TE Connectivity	MS5837	30 Bar	1	Installed
IMU	Multiple	Included on RB5	3-axis accelerometer w/ gyroscope	5	Installed
Vision	Qualcomm	Mounted on RB5	4k30fps	2	Installed
Algorithms: Vision	OpenCV				Planning
Algorithms: Localization and Mapping	SLAM				Planning
Algorithms: Autonomy	PX4, ROS2, OpenCV				Used throughout season
Open Source Software	Yocto, Ubuntu, C++, Python, JavaScriptC, ROS2				All programs Used throughout season
Schematic/Fritzing Software	Fritzing, EasyEDA Pro,				All programs Used throughout season
CAD software	Solidworks, Fusion 360				All programs Used throughout season
Expertise Ratio	3 Hardware 2 Software				In use
Team Size	5				In use
TestingTime Simulation	Gazebo				
Test Time	~30H				