TEAM SIMPLEXITY 2024 - *High Tide*

Aiden Afshar, Alex Battikha, Daniel Yang, Dmitry Moryakov, Hudson Kim, Neil Zhu, Sudhish Ambley, Thomas Fernandez, Tyler Meagher

***Abstract* -- Team Simplexity is a continuing private team composed of 9 students from 3 high schools in San Diego, California. This season, we have created "High Tide" utilizing state-of-the-art software, electronics, mechanical systems and our own custom frame. Our AUV's, *High Tide* and last year's *HydroX 2.0* incorporate the *Qualcomm RB5* to process all aspects of the sensors, thrusters, and vision. With a focus on modularity and efficiency, *High Tide* has been built to perform a multitude of tasks and provide a robust foundation for future development. Our mechanical efforts have centered around our new sub design, while electrical work has focused on designing and testing a new PCB for our killswitch, and software has revolved around creating a robust computer vision pipeline for the sub.**

Competition Strategy

A. *Design of our High Tide Vehicle*

High Tide is designed to be a highly modular and expandable AUV platform. The main structure of the frame is composed of 4 hollow steel tubes to allow easy component mounting and reconfigurability of the AUV's centers of gravity and buoyancy. The steel tube construction enables rapid prototyping as the main structure of the frame does not need to be modified over time; only the 3D printed components need to be replaced when a design is updated.

We had two goals for reducing hydrodynamic drag on the High Tide vehicle. Number one: reduce the frontal area, and number two: reduce the drag coefficient. With the components mounted in line with each other, the frontal area of the vehicle is minimized, and the hydrodynamic drag is reduced.

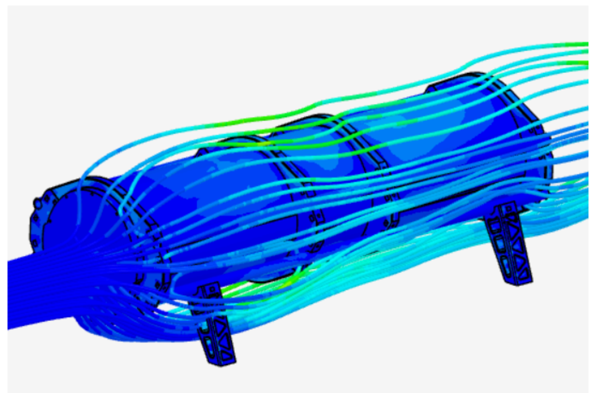

Figure 1: Computational Fluid Dynamics (CFD) simulation on the High Tide Vehicle in Simscale

Additionally, we ran Computational Fluid Dynamics (CFD) simulations on the hydrodynamics of the vehicle. Through multiple iterations of the design, we were able to minimize the flow separation at the bottom of the vehicle induced by the landing legs and the enclosure mount. Thus, reducing drag caused by pressure difference. Our final version of the *High Tide* vehicle has a drag coefficient (C_D) of 1.1 and a frontal area of only 0.051 m^2. A significant improvement in comparison to *HydroX 2.0*, which has a higher C_D of 1.4 and a frontal area of 0.094 m^2.

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

Figure 2: Drag equation utilized during CFD simulation

While thinking of ways to further optimize the efficiency, we realized that the majority of the AUV's movement will be forward and backward; strafing side to side is only required when aligning with certain tasks. Thus, mounting the thrusters at the standard 45° angle is not the optimal choice for efficiency. We opted for a thruster angle at 25°; through our calculations, we found that this thruster angle increases the forward-backward efficiency by 28.2% while still leaving plenty of power to strafe side to side.

We are building upon last year's *HydroX* 2.0 vehicle to further develop the software as it has proven to be a reliable, water-tight, and flexible platform for us to add custom electronics and attachments. Our goal with the *HydroX 2.0* was simply to submerge, orient in the correct direction, and navigate through the gate. This year, with the new *High Tide* Vehicle, we are hoping to complete additional challenges including launching the torpedos, dropping objects, contacting the buoy, and surfacing the octagon.

For both vehicles, we are utilizing Qualcomm's Robotics RB5 control computer, coupled with PNI's high precision RM3100 magnetometer, and Invensense's 6-axis IMU to provide a platform for autonomous navigation. Furthermore, we are developing several vision pipelines to further improve our AUV localization accuracy. We aim to incorporate our vision pipelines into our path-planning algorithm to provide a robust framework for future seasons.

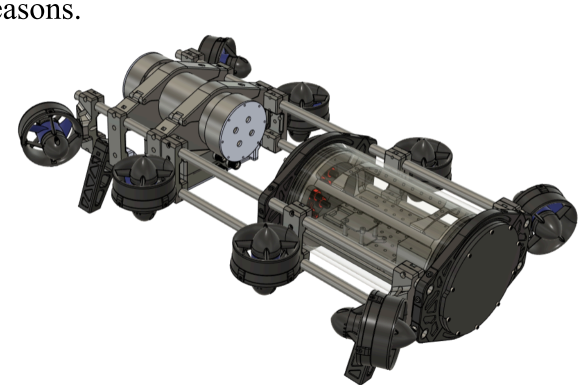

Figure 3: CAD model of our completed High Tide AUV

Design Creativity

Mechanical and CAD

High Tide utilizes a waterproof 6-inch cylindrical acrylic enclosure from Blue Robotics with an acrylic lid on one side and an aluminum plate with feed-throughs 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 to achieve a highly modular and stable structure. 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 can pull out all of the electronics inside the main enclosure 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 temperatures without losing rigidity. We optimally positioned our hardware inside the enclosure for ease of use when plugging in ethernet, power, or other connectors. Figure 2 displays the CAD model of the 3D-printed structure of the enclosure.

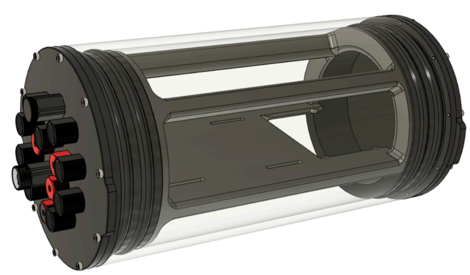

Figure 4: CAD model of the High Tide Vehicle's main enclosure

During experimental testing, we experienced thermal heating as a direct result of the battery and ESC being in the main enclosure. Therefore, we designed and built our own custom T6-6061 aluminum alloy enclosure for the ESCs to maximize thermal conductivity, allowing us to keep the ESCs cool even at high loads. We also designed and built our own battery enclosure out of PVC pipe and custom-machined aluminum end caps to ensure maximum modularity by designing the battery enclosure to be easily swappable; simply loosening two screws allows the mount to be folded up to allow for rapid replacement of the battery.

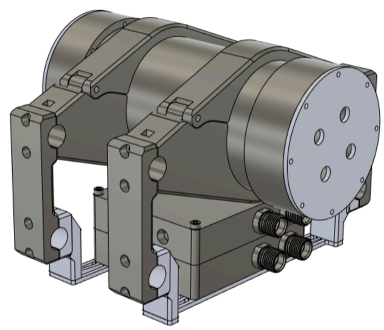

Figure 5: CAD of our custom battery and ESC mounting system. The top is the battery enclosure, the bottom is the ESC enclosure

For our torpedo launcher, we used a bungee-loaded design with a servo-actuated release. The entire release module and dual torpedoes are printed out of ABS for improved underwater performance compared to PLA and to ensure the torpedo is slightly positively buoyant. The torpedo itself has 4 fins with a minimized circular cross-section to reduce unnecessary hydrodynamic drag on the body of the torpedo. Small cutouts in the fins were also added to hold each torpedo individually, preventing them from firing prematurely.

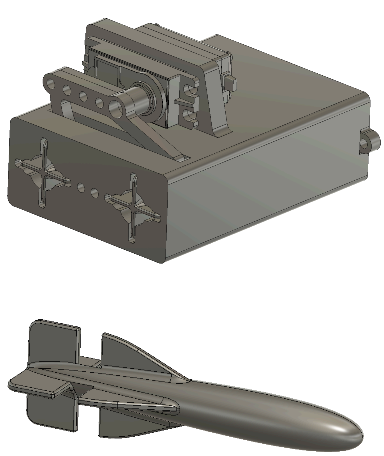

Figure 6: Torpedo launcher and torpedo design. The top image is of the torpedo launcher and the bottom is the torpedo itself.

From our in-pool testing, we found that the torpedo was able to launch ~2 feet in a straight line with a <5° deviation from the initial trajectory. This is in large part because of the torpedo's fins which ensure the torpedo's center of pressure is behind its center of gravity, resulting in a stable trajectory.

Communication

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 over time. Additionally, we incorporated waterproof connectors and gasket face seals to ensure reliable operation around wet environments.

Figure 7: 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). Last year, we designed a kill switch that disconnected the PWM signals from the RB5 to the ESCs. However this year, we decided to change the design as cutting off PWM signals is not the most effective way of disabling the thrusters. Instead, we opted for a design that shuts off the ESCs' power provided by the battery.

The new design utilizes an external magnet affixed outside the AUV and the second component comprises a compact printed circuit board (PCB) housing two magnetic reed switches and two connectors; this allows for the killswitch to activate by pulling off the magnet outside the enclosure. The new killswitch is connected directly to the battery's power and carries it over to the ESCs. The power is carried through the source and drain channels of 4 parallel P-MOSFETs (*CSD2540Q3T*) as shown in Figure 9. The gate channel of the MOSFETs is connected to the battery in series with 1 kΩ resistors and parallel to the source channel of an N-MOSFET (*RU1J002YNTCL*). The drain channel of the N-MOSFET is connected to ground and the gate channel is connected to the battery as well as the 2-pin JST-GH connector which goes to the magnetic reed switch. When the reed switch is <u>open</u> (when the magnet is pulled away), the N-MOSFET is closed as its gate channel is held at around 2.8 V; no current can flow through the N-MOSFET. In turn, the voltage at the gate channels of the P-MOSFETs will be around 16 V. Thus, the intended purpose was to prevent current from flowing from the battery to the ESCs in order to make the thrusters unable to operate. When the reed switch is <u>closed</u> (when the magnet is attached to the enclosure), the voltage at the gate channel of the N-MOSFET will drop down to 0 V since the gate channel will be directly connected to the ground; as a result, the gate channel of the P-MOSFETs will be at 0 V as well since the current from the battery will flow through the N-MOSFET to ground instead of the gate channel. Thus, the P-MOSFETs will allow current to flow from the battery to the ESCs and the thrusters are able to function.

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 by JLC PCB.

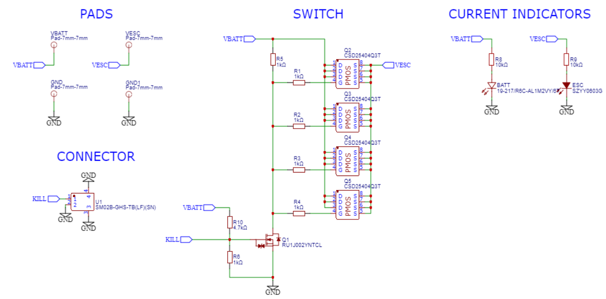

Figure 8: Kill Switch Schematic

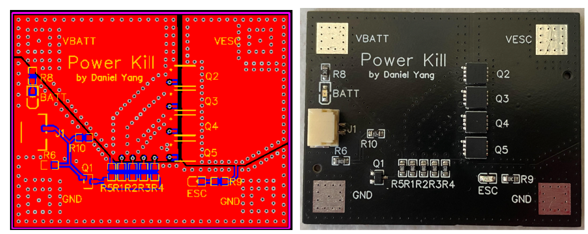

Figure 9: Kill Switch PCB layout and fabrication

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

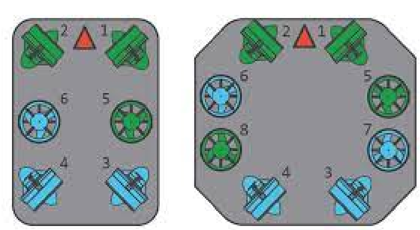

Figure 10: 2021 (Left) and xfc2023 (Right) thruster orientation

On our HydroX 2.0 vehicle, we angled 4 thrusters towards the centerline instead of straight forward to allow the robot to move in the x-y plane (using strafing) without physically rotating. Due 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 *Qualcomm* Robotics RB5 Platform controls all the ESCs and the thrusters for autonomous movement. The RB5 communicates with the ESCs using the DSHOT protocol which unlike traditional PWM protocol allows motor telemetry data to be received from the ESCs as well. The message then travels from the main enclosure to the ESC enclosure via CANBUS, a protocol used in cars that allows signals to be sent and received between multiple devices all connected to only 4 wires.

The RB5 is equipped with the *Sony* IMX577-AACK Sensor Module and *OMNIVISION*'s OV9282 used for image processing. The RB5 is connected to a MS5837 depth sensor which is able to measure up to at most 30 bar (300m depth); the RB5 is also connected to an RM3100 magnetometer and Invensense's 6-axis IMU to obtain the Robosub's heading, acceleration and velocity.

All of the sub's telemetry is able to be communicated using Ethernet via a wired tether to a computer outside the submarine 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 500 Mbps.

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 sub 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 a large safety margin as well as a high power density, meaning it can 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

The vision processing system and ESCs all have independent software stacks running on them, which are controlled by *Qualcomm's Robotics RB5 Development Platform.* 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. Furthermore, 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 of the physics properties associated with the 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.

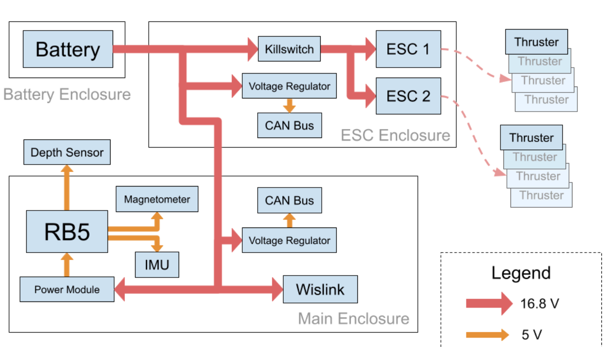

Figure 11: Electronic Power Distribution diagram

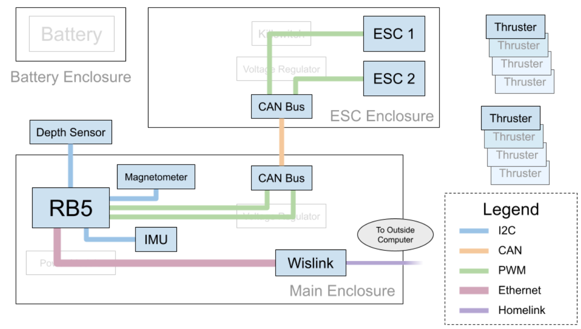

Figure 12: Electronic Communications diagram

Experimental Results

Debugging PCB Board

After we fabricated the new PCB board, we discovered that there was a severe issue with it. The killswitch won't turn off even if the magnetic reed switch is open. In order to debug the board, we used an oscilloscope and a multimeter to probe several points on the board to see if each component works properly. We checked if each wire has the intended current and voltage when the reed switch is open and closed. After probing around, we found two issues: the drain and source channels of the P-MOSFET are switched and the P-MOSFET opens when the voltage between the source and gate channel is zero. Since the drain and source channels were switched, the P-MOSFET was not able to fully close the connection between the battery and the ESCs. However, even if the drain and source channels weren't switched, the killswitch would have worked opposite than what we intended. We didn't catch these two issues since we neglected to test the layout in a simulation. In the future, we plan to always simulate the layout before manufacturing the PCB.

Acknowledgments

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Appendix A

Components	Vendor	Model/Type	Specs	Number	Status
Frame	ePlastics	ePlastics Cut Enclosure	Acrylic	1	Installed
Waterproof Housing	Blue Robotics	6" diameter acrylic with end caps	Acrylic	1	Installed
Thruster	Blue Robotics	T200		4	Installed
Motor Control	Hobbywind	60A 4-in-1	60A / 6S/ 4 Ch	3	Installed
Propellers	Blue Robotics	T200		4	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, CAN				Installed
External Comm Network	1Gbit Ethernet, WiFi				Installed
Ethernet Current Converter	Qualcomm	QCA7005 chip	QFN 68 pins	2 (1 on each end)	Installed
Compass / Magnetometer	PNI	RM3100	± 1100 µT	1	Installed
IMU	Multiple	Included on RB5	3-axis accelerometer w/ gyroscope	5	Installed
Vision	Qualcomm	Mounted on RB5	4K, 30 FPS	2	Installed
Algorithms: Vision	OpenCV				Planning
Algorithms: Localization and Mapping	SLAM				Planning
Algorithms:	PX4, ROS2				Used throughout

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Thruster	Blue Robotics	T200		4	Installed
Motor Control	Hobbywind	60A 4-in-1	60A / 6S/ 4 Ch	3	Installed
Autonomy	OpenCV				season
Open Source Software	Yocto, Ubuntu, C++, Python, JavaScriptC, ROS2				All programs Used throughout the season
Schematic/Fritzing Software	Fritzing, EasyEDA Pro, LTspice				All programs Used throughout season
CAD software	Solidworks, Fusion 360				All programs Used throughout season
Expertise Ratio	5 Mechanical 1 Electrical 3 Software				In use
Team Size	9				In use
Underwater Testing Simulation	Gazebo				Used Throughout Season
Water Test Time	50 hrs				