Technical Design Report for Charybdis

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***Abstract*— With interdisciplinary cooperation between team members, the Kennesaw State University Autonomous Underwater Vehicle Team (KSU AUV) has improved the design of the AUV Charybdis platform and has integrated new functionalities and behaviors for the 2020 RoboSub competition. The motor configuration and control systems of the AUV run parallel with rising paradigms used in aerial drones. This vehicle utilizes a PixHawk flight controller as both a motor controller and gyroscopic sensor. The communications between a dual camera system and the Pixhawk govern the movement of the AUV through a state machine. This paper discusses the 2020 KSU AUV competition strategy and highlights the technical attributes of Charybdis.**

Keywords—autonomy, underwater, vision, machine learning

I. Competition Strategy

A. Preface

The KSU AUV team is a 25-member student organization sponsored by Kennesaw State University which competes yearly in the RoboSub competition in San Diego, CA. For the 2020 competition season, KSU AUV continued to improve on the design of Charybdis, the versatile platform developed during the 2019 season. Our team consists of three major sub-groups - mechanical, electrical, and software - which collaborate to design and integrate the necessary systems required to form a working autonomous architecture. The technical attributes of Charybdis are found in Sections II and III of this report in addition to the hardware and software specifications provided in the appendices.

With the onset of COVID-19 in the spring of 2020, all physical meetings for design work, integration, and testing were suspended for the remainder of the season. In response, the team has instead adopted virtual environments to conduct these proceedings to the greatest extent possible.

B. Competition Strategy

Post RoboSub 2019, the team identified numerous potential improvements to make to the Charybdis platform. Notable examples include an internal wiring overhaul, motor maintenance and replacement, killswitch redesign, overheating mitigation, chassis and fastener corrosion protection, and numerous frame improvements. For the 2020 RoboSub competition, the team identified three primary challenges to pursue:

1. Passing through start gate with spin
2. Surfacing in the octagon
3. Launching a torpedo through a target

To meet these objectives, the team sub-groups focused efforts on improving movement-critical systems from the 2019 season and developing a new torpedo system.

II. Vehicle Design (Novel Aspects)

A. Mechanical Design

1) Outer Structure: The frame of Charybdis from the previous competition season was constructed of 6061-T6 aluminum plates slotted together and fasted using captive nuts. While this design proved affordable, simple to manufacture, and light; several design flaws were revealed with the external frame during the 2019 competition. These problems were addressed for the 2020 season as well as additional minor changes that improved overall accessibility and modularity, including the addition of mount points. The updated Charybdis AUV is shown by the Solidworks rendering in Fig. 1.

The team's focus on community outreach in the current season gained new corporate sponsors for the team but the previous iteration of Charybdis did not have space for sponsor logos. In response, an acrylic plate was to replace most of the aluminum side plate in the 2020 update. This change would also decrease overall vehicle weight. The Solidworks FEA addon was used to confirm that the acrylic substitute would provide enough rigidity for the sub to be lifted and propelled.

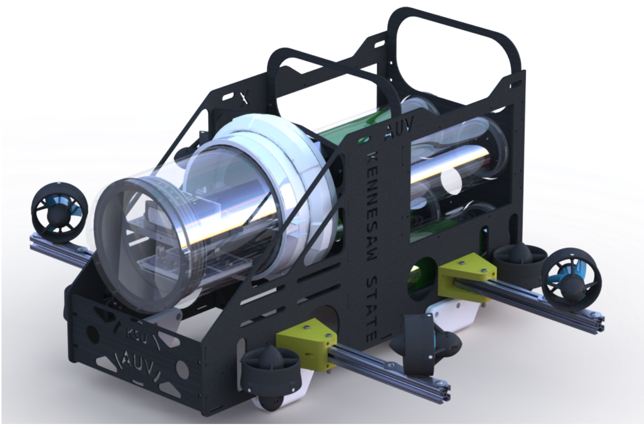

Figure 1: 2020 Charybdis CAD Design

2) Housing: All of Charybdis' electronics are housed in five different clear acrylic tubes manufactured by Blue Robotics. The major electronics—such as the Pixhawk and the Jetson—are housed in 8 in. diameter tube mounted in a cantilevered fashion on the front of the sub. The batteries are housed in three 4 in. acrylic tubes with a fourth 4 in. tube for later expansion. This is the same setup used in the previous competition season. In that season, it was shown that while the unloaded sub had a center of buoyancy near the sub's geometric center, the weight of the batteries outweighs the electronics. This shifted the sub's loaded center off gravity backwards which caused an upwards list in the sub. To combat this, ballast weight was to be added to the front of the sub.

The inner structure of the primary tube, shown in Fig. 2, consists of a tiered shelving system designed to allow easy and stable access to electronics and to keep components from shifting with movement. Manufactured from waterjet-cut 6062-T6 aluminum sheets, the units are lightweight and allow for the physical separation of components, especially important for electronics such as the ESCs.

Figure 2: Charybdis Internals Mockup

3) Propulsion: Propulsion is provided by eight T-200 Blue Robotic Thrusters. During the previous competition season the team switched to powering the thrusters using EMAX electronic speed controllers (ESC) located in the forward acrylic tube. At that year's competition, connectivity issues arose where the sub was unable to control some of the motors.

This season, the EMAX ESCs again were used. To ensure that the same issues did not arise, the ESCs were torture tested using the apparatus in Fig 2. The testing found that the ESC produced dangerous amounts of heat when the motors were run continuously for 15 minutes. This was most likely the source of the communication errors. To deal with dissipating this heat, the ESCs were moved to the rear of the acrylic tube and were thermally coupled to the aluminum frame.

4) Torpedo Design: The team elected to use externally propelled 3D printed torpedoes for their mechanical simplicity and ease of production. The population came from a self-contained, compressed air shell launcher produced by TAGinn. This decision allowed the team to focus on the geometry of the torpedo and not the launching. The goal of the torpedo design was to minimize drag and induce spin to increase stability. Several designs were generated by different members of the team. Each of the designs were subjected to tests within the Solidworks FEA package. The simulations found the drag coefficients, centers of lift, and induced torque. The design that performed best in these preliminary tests was further subjected to parametric studies. The parametric studies—again using the Solidworks CFD package—were performed on the torpedo, altering dimensions across a certain range and recording the effects on the criteria mentioned above. The chosen geometry is shown in Fig 3.

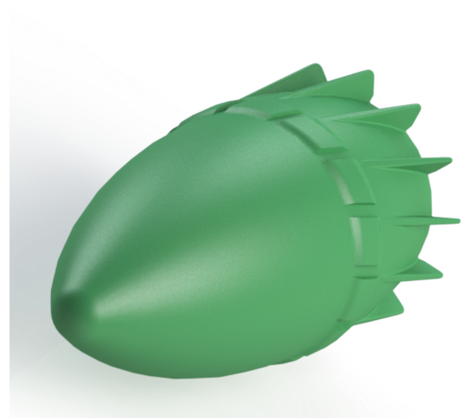

Figure 3: 2020 Torpedo Design

B. *Electrical Design*

1) External Electronics: The connections between sub electronics are shown in Fig. 4. Charybdis utilizes eight BlueRobotics thrusters for maneuverability. Eight electronic speed controllers (ESC) control and regulate the speed of the thrusters. The ESCs receive instructions by pulse width modulation from the PixHawk and give us the ability to control the rotational speed and direction of the thrust.

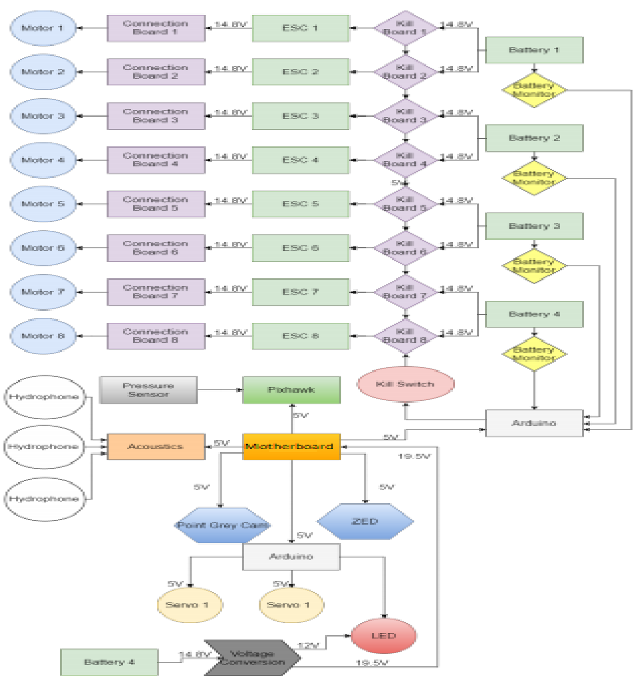

Figure 4: Electrical System Overview

2) Power Distribution: Five lithium polymer batteries power the sub's motors, onboard computer, and sensors. Power distribution is managed through custom

3) Killswitch (KS) Redesign: For the third iteration we modified the 2018 KS board. Still using the same components as last year (optocoupler, resistors, and MOSFETs), the main focus was placed on pinpointing the cause for failure from the second iteration where the traces would overheat after extended run times. To do this we utilized EaglePCB software to layout the original design and then optimized trace widths and thicknesses for their respective applications. In addition to trace width modification we also designed the physical geometry of our board to be directly attached to the chassis of the chamber along with bringing all of the existing components closer together.

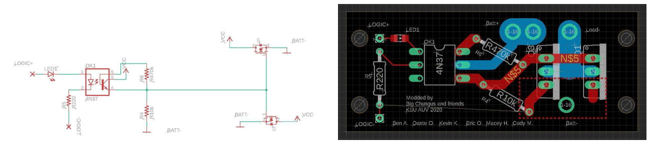

Figure 5. Schematic and Board View Renderings of KS MK3

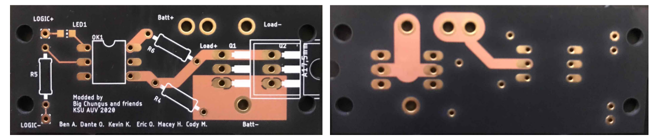

Figure 6. Manufactured Osh Park Boards

4) Temperature Monitoring: From pool testing, it was evident that the heat generated by both the NVIDIA Jetson and the eight ESCs after extended use was in excess of their respective operating temperatures. In addition to the native temperature monitoring of the Jetson, thermistors have been integrated into the main electronics housing to monitor ESC and ambient temperatures.

5) Water Detection Cutoff: After a flood event that occurred last year and the loss of many of our on board electronics, the discussion of a system that would shutoff power when a leak was detected was developed. We initially looked into such moisture sensors like the DHT11 temperature and humidity sensor but ultimately settled with the Blue Robotics leak sensors and probes that would send a signal to our main computer that would result in a KS shut off state.

6) Battery Current Monitoring: With the addition of new sensors and systems it has become important to determine not only how much of our battery power is used during operation but at what rate of consumption too. We decided that a differential op amp circuit would be the best approach for this. From this circuit we would be able to collect real time data as to how much current was being drawn and examine it after each run.

C. *Software Design*

1) Hardware: After using the Nvidia Jetson Nano last year, we decided to swap up to a more powerful computer. In comes the Nvidia Jetson TX2. The TX2 has twice the core count as the Jetson Nano had and is on the newer Pascal microarchitecture compared to the Nano which runs off Maxwell. This allows us two to three times the performance output while maintaining a small, compact, and relatively lightweight platform.

2) Architecture: The software architecture of Charybdis is based on the Robot Operating System (ROS), which provides a message-passing system and networking capabilities, among other functions [5]. The packages we created were designed to take advantage of ROS and the open-source libraries that use it, including SMACH, MavROS, and rosserial.

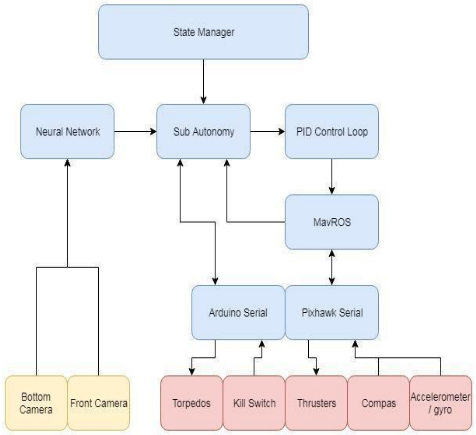

Figure 5: Software Architecture

3) High-level Control: High-level decisions about what Charybdis should do are made in a state machine implemented in SMACH, a ROS package that defines a state machine structure. [6]. Each state performs a competition task or part of a task: for example, to get through the gate, Charybdis passes through up to seven different states. One is the start state, four (implemented as a smaller state machine) combine to form a search pattern, one tracks the gate once it has been detected, and one passes through the gate once Charybdis is close to it. The implementation of the other tasks is architecturally similar. SMACH allows us to create complex state machines.

4) Vision: Video input is received from two USB cameras, one forward-facing and one downward-facing, and sent to the object detection algorithm via ROS. Due to the visual noise, variability in environment, and other factors, we deemed the use of machine-learning based object detection more effective than the creation of hand-crafted detection algorithms. We chose to use the SSD (Single Shot Detector) architecture with MobileNet, implemented in Tensorflow, because of its availability and performance - while not perfect, SSD is accurate enough for our needs while still performing well on our limited hardware.

Once the network visualizes the detections, we can perform movements based on that information. We take two points from the field of view: one provided by the SSD and one provided by the center of the camera. The program calculates the error between the two points and processes the error through a PID control loop, then outputs an RC value published to MavROS.

5) MavROS: MavROS, a ROS wrapper for the Pixhawk's MavLink software, serves as an all-in-one package to control movement of the submarine by publishing virtual RC controller values to the Pixhawk flight controller. [7]. We used the Pixhawk because the open source community which developed Ardusub has created custom firmware for controlling AUVs that is easily wrapped with MavLink and MavROS for communication [8].

6) Arduino Auxiliary Control: Controlling external mechanisms on the sub requires an external interface, which we implemented through an Arduino over serial communication. The Arduino allows us to send commands to the torpedo launcher and manipulator and monitors the sub's killswitch to keep it aware of its current state.

7) Simulation: This year, we decided that due to the challenges that Covid-19 provided, that a way to test Charybdis' states and functions prior to an in-person test would be crucial. Thus we decided to use Software-in-the-Loop with Ardusub, using MavROS to send communications. This allows us to get a visual simulation running of Charybdis and to test functions and states before executing them on the physical sub in water. This has streamlined our software design process and improved how quickly we can implement new behaviors.
The physics in the simulation accurately models an underwater environment rather well using Ardusub. However, it isn't a perfect 1-to-1 recreation of how it handles Charybdis' physics directly. This introduces a small but noticeable amount of error between the simulation and actual physical tests with Charybdis. That being said, these fluctuations are minor and easily corrected once in-person tests are performed and software is adjusted.

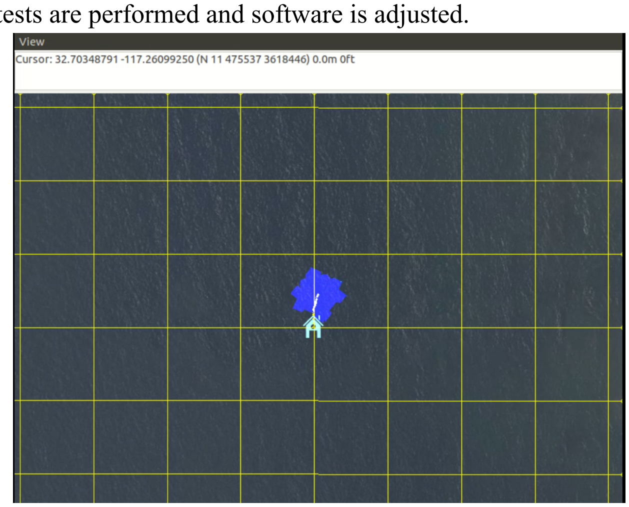

Figure XXX. Charybdis Simulation.

III. Experimental Results

A. In-Pool Testing

Our pool testing focused on verifying that the elements of the sub worked correctly, specifically the updated frame, wiring, and neural network architecture. While limited testing was conducted in both the fall and early spring semesters, our primary testing period was cut short by the onset of COVID-19. In response to this unprecedented challenge, the software team developed a novel simulation environment during the summer to virtually test novel project aspects prior to commissioning as discussed in Section II.C.7.

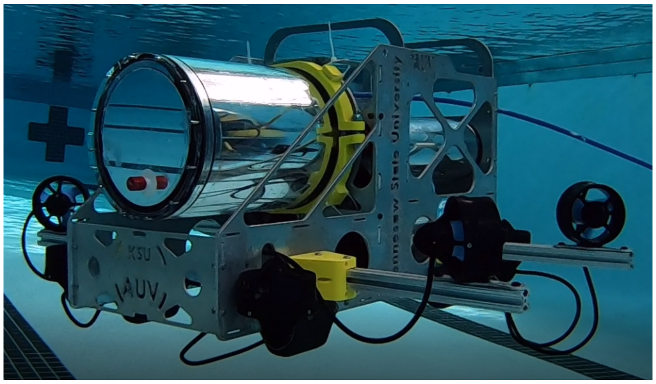

Figure 8: Charybdis performing functional checks

B. Motor Testing

At the start of the season, the team's eight T-200 Blue Robotics Thrusters were nearing the end of their lifespans so the team considered using another brand of thrusters as replacements. Few underwater thrusters are available given budgetary constraints, so it would require modifying an off-the-shelf brushless motor by adding a propeller and a shroud. The submerged testing apparatus, shown in Fig. XXX, was used to compare brushless motor alternatives to the T-200 thruster in thrust output as well as power draw.

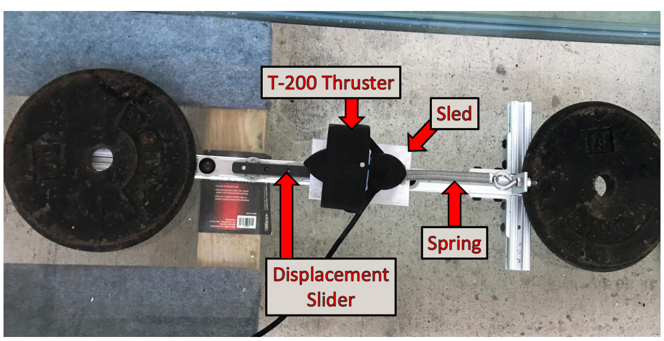

Figure XXX. Motor Testing Apparatus

The apparatus uses a spring with a known spring coefficient and a marker. The motors were slowly powered up until they reached a high yet stable RPM. The motors were left at this speed for 15 minutes to torture test the motor and ESC and then were slowly shut off. The distance that the motor pushed the marker was recorded and the motors' thrust was computed using this distance and the k-factor of the spring.

After a series of tests on the T-200, it was determined that the EMAX ESC was heating up to a dangerous level after the 15 minutes of continuous run time. This prompted concerns about the ESC during sustained operation which led to additional thermal testing.

C. ESC Thermal Testing

Because the employed EMAX ESCs are designed for RC helicopters with natural air convection, it became a point of interest to investigate their thermal dissipation under extended operation in an enclosed space after an ESC temperature of 209 °F was recorded during a 10 minute endurance test.

A thermal test was conducted to determine the effect of an EMAX ESC under load in a sealed acrylic tube similar to those used on Charybdis. Two MF52-type thermistors were installed in the tube approximately 5 in. apart. One was directly mounted to the ESC and the other was centered in the tube to measure ambient temperature. Using a potentiometer, the current was set to around 16 A for the time interval [0:00, 9:10]. From time [9:11, 14:50], power was cut and heat was allowed to dissipate. Data collected from the ESC (blue) and ambient (orange) thermistors are given in Figure 7. A maximum ESC temperature of 154.8 °F was recorded, which presents the need for additional heat dissipation methods (i.e. heat sinks, fans, etc.), the increase of contact-to-atmosphere surface area, or the placement of limits on ESC power consumption via software. This experimental methodology will be replicated in the 2021 season to include the NVIDIA Jetson, which has been found to be especially susceptible to overheating in the enclosed sub housing.

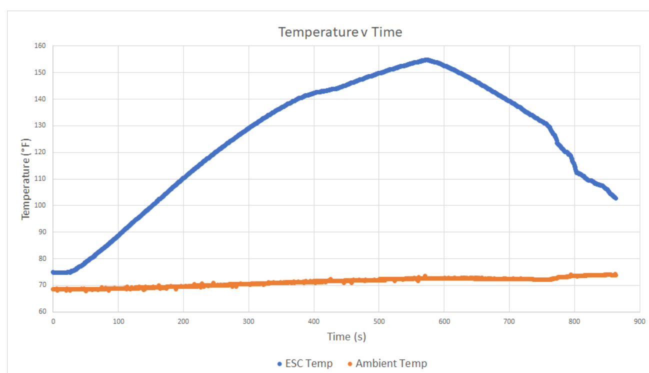

Figure 7. ESC Temperature vs Time Data Plot

IV. Acknowledgments

The team would like to thank Dr. Kevin McFall for acting as our faculty advisor, all our engineering and technology professors for their instruction, the KSU Student Activities Board Advisory Committee, the KSU Alumni Association, and all of our generous sponsors that helped make the Charybdis platform a reality.

V. References

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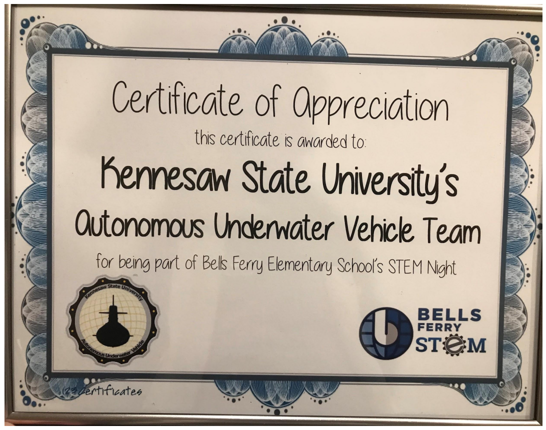
Appendix A: Expectations

Subjective Measures			
	Maximum Points	Expected Points	Points Scored
Utility of team website	50	50	
Technical Merit (from journal paper)	150	150	
Written Style (from journal paper)	50	50	
Capability for Autonomous Behavior (static judging)	100	100	
Creativity in System Design (static judging)	100	100	
Team Uniform (static judging)	10	10	
Team Video	50	50	
Pre-Qualifying Video	100	100	
Discretionary points (static judging)	40	40	
Total	650	650	
Performance Measures			
	Maximum Points		
Weight	See Table 1 / Vehicle	38	
Marker/Torpedo over weight or size by <10%	minus 500 / marker	0	
Gate: Pass through	100	100	
Gate: Maintain fixed heading	150	150	
Gate: Coin Flip	300	300	
Gate: Pass through 60% section	200	0	
Gate: Pass through 40% section	400	400	
Gate: Style	+100 (8x max)	100	
Collect Pickup: Crucifix, Garlic	400 / object	0	
Follow the "Path" (2 total)	100 / segment	200	
Slay Vampires: Any, Called	300, 600	600	
Drop Garlic: Open, Closed	700, 1000 / marker (2 + pickup)	0	
Drop Garlic: Move Arm	400	0	
Stake through Heart: Open Oval, Cover Oval, Sm Heart	800, 1000, 1200 / torpedo (max 2)	1600	
Stake through Heart: Move lever	400	0	
Stake through Heart: Bonus - Cover Oval, Sm Heart	500	0	
Expose to Sunlight: Surface in Area	1000	1000	
Expose to Sunlight: Surface with object	400 / object	0	
Expose to Sunlight: Open coffin	400	0	
Expose to Sunlight: Drop Pickup	200 / object (Crucifix only)	0	
Random Pinger first task	500	0	
Random Pinger second task	1500	0	
Inter-vehicle Communication	1000	0	
Finish the mission with T minutes (whole + fractional)	Tx100	800	

Appendix B: Component Specifications

Component	Vendor	Model/Type	Specs	Cost (if new)
Buoyancy Control	N/A			
Frame	KSU AUV	Custom	30in x 36(motors out)in x 18in	$880
Waterproof Housing	Blue Robotics		1 in8 and 4 4in Enclosures	$972
Waterproof Connectors	Blue Robotics	red/black penetrators	N/A	$96
Thrusters	Blue Robotics	T200		N/A
Motor Control		EMAX Formula Series BLHeli	45A	$140
High Level Control	Amazon	Pixhawk 3		N/A
Actuators	N/A			
Propellers	Blue Robotics		N/A	N/A
Battery	HobbyKing	Multistar	10000mAh, 4S	N/A
Converter	N/A			
Regulator	Amazon	KNACRO	AC/DC to DC 20W Converter	$11.20
Embedded System	Nvidia	Jetson Nano	Quad-core ARM Cortex-A57 MPCore processor (1.43 GHz)	$99
Internal Comm Network	N/A	N/A	USB cables	N/A
External Comm Interface	Blue Robotics		Ethernet tether cable	N/A
Programming Language 1	Python			
Programming Language 2	C++			
Compass	Amazon	Pixhawk 3		N/A
Inertial Measurement Unit (IMU)	Amazon	Pixhawk 3		N/A
Doppler Velocity Log (DVL)	N/A			
Camera(s)	Logitech	C930E and C270	C930E: 1080p/30 FPS, 90° FOV C720: 720p /30 FPS, 60° FOV	N/A
Hydrophones	N/A			
Manipulator	N/A			
Algorithms: vision	Tensorflow	SSD MobileNet v2	N/A	$0
Algorithms: acoustics	N/A			
Algorithms: localization and mapping	N/A			
Algorithms: autonomy	KSU AUV	Custom	N/A	$0
Open source software	ArduSub, Ubuntu, ROS, MavROS, OpenCV, SMACH, Tensorflow,			
Team size (number of people)	25			
HW/SW expertise ratio	2 HW : 1 SW			
Testing time: simulation	2 hrs.			
Testing time: in-water	15 hrs.			

Appendix C. Community Outreach



Community outreach is an essential component to the underlying mission of the KSU AUV Team. We believe that using Charybdis as a learning platform for members of the community of all ages is one of its most valuable possible utilities. Not only does an AUV provide a tangible interface to real-world engineering practices, but it provides a medium through which our experienced team members may reach out to the community. As such, our STEM Outreach Sub-team regularly attends local STEM nights at schools as well community events to enhance interest in engineering and science in general.

Veronica Killingsworth

2019-2020 President

Bells Ferry Elementary STEM Day

"What I really enjoy about STEM outreach for girls is that it's something I never had when I was younger. I really want to be able to encourage girls that they can do it."

William Davis
2020-2021 President
Clay Elementary STEM Night
"I think that showing the students what engineering looks like really opened their eyes. I mean, who wouldn't want to see a working sub as a kid!"

Grayson McMichael
2020 Safety Officer
Makers Fair
"Presenting for our team at the Makers Fair was such a rewarding experience. Introducing kids to a new kind of engineering project and seeing their faces light up at the possibilities reminds me of why I chose engineering."