Technical Design Report for Charybdis

Paul J. Pieper
Software
KSU AUV
Douglasville, GA, USA
paulj.pieper@gmail.com

William Wisener
Mechanical
KSU AUV
Tyrone, GA, USA
mtrelife1@gmail.com

Dante Orlando
Electrical
KSU AUV
Atlanta, GA, USA
danteorlando1213@gmail.com

Logan Spencer
Mechanical
KSU AUV
Dunwoody, GA, USA
lspencer9349@gmail.com

***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 2021 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 2021 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 continuation of COVID-19 in the spring of 2021, all physical meetings for design work, integration, and testing were suspended until just recently. In response, the team has adopted virtual environments to conduct these proceedings to the greatest extent possible.

B. Competition Strategy

Post RoboSub 2020, 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 2021 RoboSub competition, the team identified three primary challenges to pursue:

1. Passing through start gate while spinning
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 and Component Housing: The 2021 competition marked the second year using the same hull structure, and internal layout. Charybdis is constructed from 6061-T6 aluminum plates. The plates were cut on a water jet, and slotted together. All of the subs control electronics are housed in a large 8-inch acrylic tube to centrally house the sub's critical controls.. The sub also has four smaller acrylic tubes. Three of the tubes hold the subs 1000mAh batteries. A fourth tube is included to house control circuitry for the auxiliary systems.

Despite the effectiveness of this design, there were still plenty of opportunities for optimizing various systems. One issue was the difficulty our electrical team faced when performing maintenance on the housing components. The complexity of hardware and wiring connections proved challenging to keep organized which led to increased time locating and troubleshooting problems. This process is further discussed in the experimental results section..

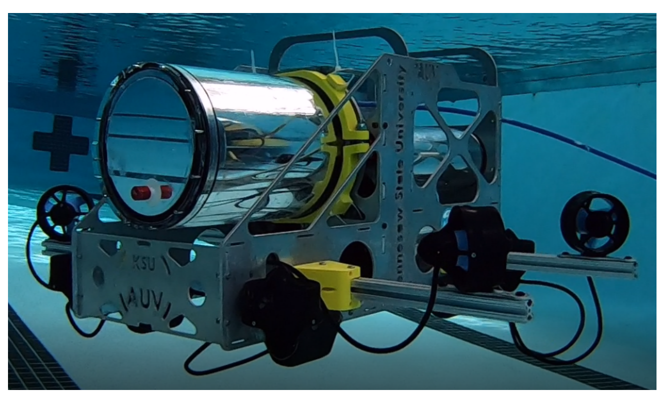

Figure 1. Charybdis in Action

2) Control Electronics Housing: As mentioned, all of Charybdis' control electronics are housed in an eight-inch acrylic tube. This created a mess of wiring that plagued the electrical team. To resolve some of this, two things were done. A new internal layout was designed--again discussed in section__, and all of the electronic routing was reworked.

A common carrier was designed within SolidWorks to house all the control electronics and keep their wiring short. The carrier organizes the port and pin locations for repeatable wire and cable runs. Volume inside the tube was previously taken by excess wire lengths and misplaced components, but having a set path aids in airflow for the processor and ease of maintenance. The housing was FDM 3D printed. This process was chosen because it was fast, inexpensive, and allowed for the level of complexity and this part needed.

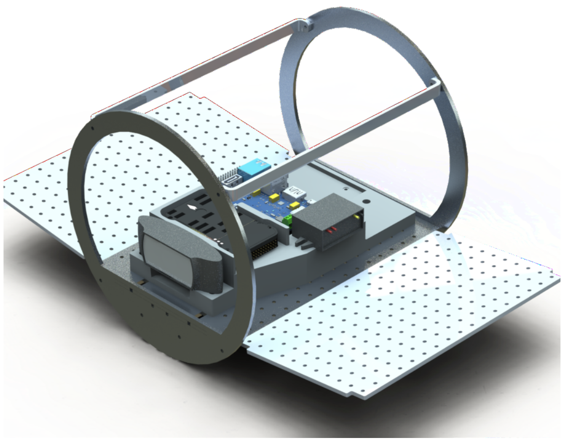

Figure 2. Charybdis Internals Mockup

3) ESC Mounts: The purpose of the mount design was to create a better accessibility to the electronic speed controllers (ESC) avoiding inadequate management of wires when it comes to replacement or disassembly. Having the ESCs' wires clamped by the structure that has a smaller radius than the power and signal wires will prevent the ESCs from being able to move laterally. Additionally, the mounts needed to address the issue with the large amount of heat created by the ESCs when the motors are running. The design allows for proper air flow by the assembly having the ESCs with the least contact with any surface as possible. As well, the structure enables mounting a small size fan on the top of the ESCs to help with cooling.

SolidWorks was used by members of the team to design and analyze the mount structure. Several design iterations were made to achieve the maximum air flow possible and increase ease of assembly. For the ease of manufacture, the mounts were 3D printed. The ESCs were tested in the mounts and design modifications were made to ensure that the ESCs did not loosen cables and that the ESC sits firmly in place.

4) Propulsion: As with in previous years, Charybdis is powered by eight T-200 Blue Robotic Thrusters. The thrusters are laid out in the Blue Robotics vector 6DOF configuration. This gives the sub maximum maneuverability. And by using a standard motor layout, programming motion control becomes easier. This year saw a total replacement of thrusters. The sub had been using the same set of thrusters for the past four competition years. Because there were no travel expenses this season, there was room in the budget to purchase a few new T-200 thrusters, as well as new rotors and stators to replace some that were rusted out as shown in Fig 3.

Figure 3. One of Charybdis' Older T200 Thruster Stators

5*) Torpedo Design:* This season's torpedo project was a continuation from the 2020 competition season. Multiple torpedo designs were considered and were tested thoroughly leveraging the SolidWorks computational fluid dynamics (CFD) simulation package. Each torpedo was run through a series of simulations in an attempt to evaluate the performance of the torpedo before production. The launching mechanism remained the same from the previous year.

After the torpedo was decided upon, further work was required to make the launcher functional. A set of requirements and limitations were placed on the design, the most notable of which required the use of the existing launching mechanism, for it to be fully waterproof, and for a mechanism to be able to apply a linear force of 20 pounds onto a single point. This limited the mechanism to use a waterproof servo with a limited output, thus a gearing needed to be used, as well as a mechanism to translate the rotational motion of the servo to linear motion needed to activate the launcher. The decision was made to make 3D printed gears, and a minimum gear tooth size was determined. Using this, a rack and pinion setup was constructed alongside a mount for the torpedo launcher itself, as well as a 3:1 gearing which was found to give the servo enough torque to meet the requirements defined earlier.

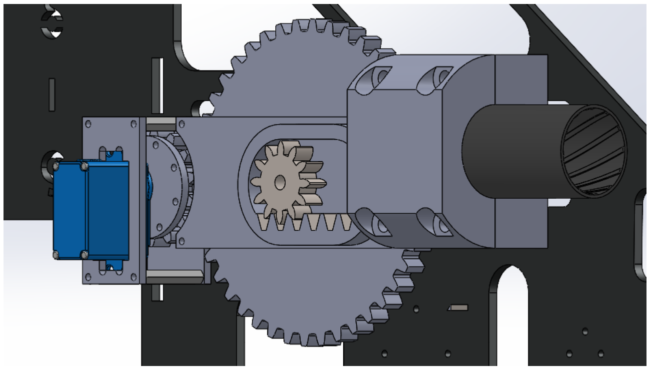

Figure 4. Torpedo Launching Mechanism

B. *Electrical Design*

1) Wiring diagram

A wiring diagram was drawn up to aid the electrical team in troubleshooting electrical issues in Charybdis. This revealed that the interior was still a mystery to most and only well understood by a few members of the electrical team. To fix this problem, a wiring schematic and network block diagram was generated using AutoCAD and Adobe Illustrator that depicts how the sub is wired and how the different components communicate to each other. This allowed for members in different teams and new members to easily grasp an understanding of how the sub works. Using these two software allowed for the creation of a library of components that can be used for future designs of the wiring internals. The wiring diagrams will be kept updated as components are changed, and improvements are made to the sub.

2) 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 the ability to control the rotational speed and direction of the thrust.

3) Power Distribution: Five lithium polymer batteries power the sub's motors, onboard computer, and sensors. Power distribution is managed through the kill switches that were designed for sending power to the rest of the electrical system. The kill switches also manage the power distribution of the sub through acting as a way of killing all power to the sub via a switch located at the back of the sub.

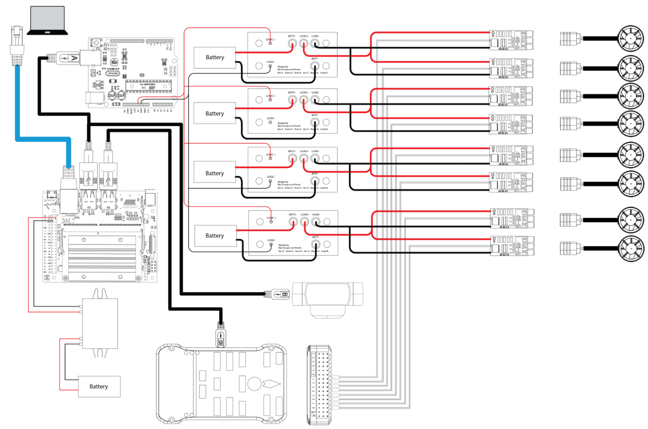

Figure 4. Electrical System Overview

4) Kill Switch (KS) Redesign: For the third iteration it was a modified version of the 2020 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. The design was created in EaglePCB software to layout the original design and then optimized trace widths and thicknesses for their respective applications. In addition to trace width modification it was also designed to the physical geometry of the board to be directly attached to the chassis of the chamber along with bringing all of the existing components closer together.

5) Hydrophones: The RESON TC4013 are the hydrophones that were chosen for detecting the varying frequencies found in competition. These frequencies during competition would act as way markers for the sub for targets for the torpedo and for the gates that the sub would have to go through.. The hydrophone was put into a pool and the hydrophone was hooked up to an oscilloscope and the pinger was switched on in the pool at a set frequency to test the hydrophone's capabilities from a set range. For the first frequency the pinger produced was its default of 20kHz, then it was tested later at 35kHz. Once the pinger was switched on and producing the frequency desired, the hydrophone would pick up the frequency of the pinger from the edge of the pool (about 25'') and record the wave frequency from the pinger to the oscilloscope.

6) Pinger: The JW Fishers MFP-1 Pinger was the device being used to test out how the Teledyne hydrophone would operate when exposed to different frequencies that would be found in competition. The pinger would only output one specified frequency at a time, but the design of the pinger itself would allow for manual switching of the pinger's frequencies through the switches located in the interior of the pinger itself. This would allow for the testing of multiple frequencies and see how the hydrophones would pick them up.

7) Filter: For how the sub will detect certain frequencies and ignore irrelevant ones, IC filters were chosen. There are three important modes on these ICs: low-pass, high-pass, and band-pass. These modes will allow for the sub to pinpoint frequencies based upon a predetermined frequency that was given from the Robo-sub's competition rules. The mode that is needed to focus on these specified frequencies produced by the pingers in the pool at competition would be the band-pass mode.The bandpass mode on the IC filter would allow the sub to focus on frequencies found in competition (25kHz, 35kHz, etc.) and filter out any frequency that is above or below the set frequency from the pinger in the pool. To allow the filter to be able to switch to different frequencies found in the different stages of competition, the plan was making an IC circuit that would have multiple ICs and capacitors that would be focused onto a single frequency (I.e: 25kHz) and then would be able to switch to a different frequency to focus on for that stage's frequency. All the IC filters will be tied together in parallel to allow the simulation of the band-pass filter for the multiple frequencies that would be expected in competition.

8) Amplifier Circuit: The amplifier circuit was designed to allow for the sub to amplify the frequencies trying to be detected through the IC filters. How this would be done in the design was the filters all being connected to a series of capacitors to help with the amplification of the signals passing through the IC filters. This would theoretically help with the software of the sub to get clear signals of the frequencies and prevent the sub getting confused about where or what signals it is receiving.

C. Computer and Software Design

1) Hardware: After using the Nvidia Jetson Nano last year, the decision was made to swap up to a more powerful on-board computer. The Nvidia TX2 was used as an upgrade, for both its technological advancements as well as our familiarity with Nvidia's platform. 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 for two to three times the performance output while maintaining a small, compact, and relatively lightweight platform. The result is a direct increase in responsiveness with our OpenCV-based approach as well as faster processing of larger, high-definition visual input.

Leveraging two Logitech C920 HD Pro webcams, Charybdis is able to take high-resolution images of its surroundings that can be cleaned up via software filters. By passing higher resolution images through the convoluted neural network, it can use them for object and task identification, measurement approximation, and real-time targeting.

2) Software 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, ROS Serial, OpenCV, and Tensorflow. Figure 5 shows the high-level overview of Charybdis and signal direction.

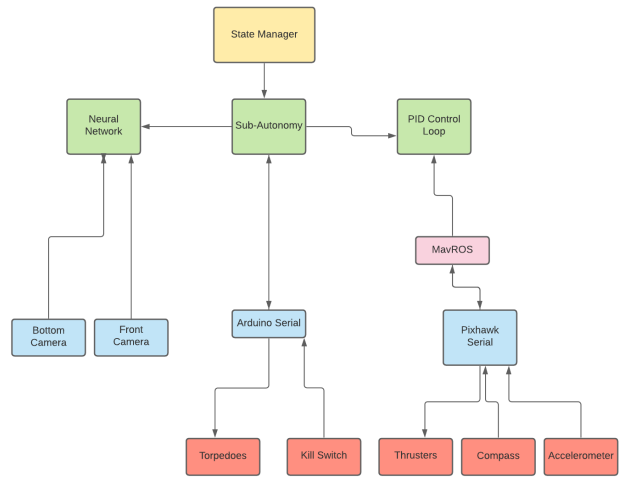

Figure 5. Software Architecture

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, the use of machine-learning based object detection was deemed more effective than the creation of hand-crafted detection algorithms. The decision was made 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 this application while still performing well on the TX2 hardware. After taking a snapshot using one of the two cameras, the state machine will hand off the image to OpenCV in order to run some filters to better enhance the image. These filters include: Color Correction, Contrast Stretching, Histogram Stretching, Histogram Equalization, Whitebalacing, and Edge Detection via Canny Filter. Figure 6 is an example of one of the filters used. This improves the neural network's ability to correctly identify objects by over 30% when compared to non-filtered images based on test results.

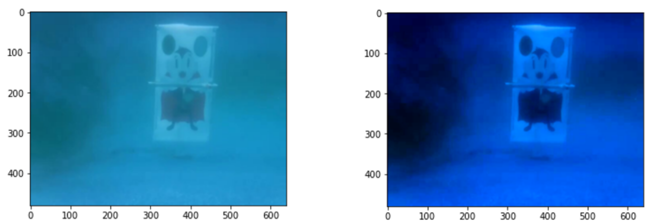

Figure 6. Contrast Stretching Filter

Once the network visualizes the detections, Charybdis can perform movements based on that information. The Neural Network takes 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]. This allows for a plug-n-play format, in which we can both operate effectively while afforded some level of flexibility

6) Arduino Auxiliary Control: Controlling external mechanisms on the sub requires an external interface, which has been implemented through an Arduino over serial communication. The Arduino facilitates the ability to send commands to the torpedo launcher and manipulator while also monitoring 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 the software design process and improved the speed of implementation for 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.

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.

B. Design of the Internals

The design of the interior was a complicated problem. It had been "solved" several times, but while each design looked great in CAD, the solutions proved too complicated or cluttered in real life.

To better understand how components would fit in person, the mechanical team decided to subvert the traditional use of computer aided design, and instead, implemented "cardboard aided design". The created mock-ups of the sheet metal front tube racks. This was done by cutting sheets of cardboard, and laying out scale models of the computer components. The team produced four competing ideas to find traits that would benefit the sub: an improved, removable, version of the current rack, a trifold design, a "T" shaped design, and an "I" shaped design. The cardboard mockups were given to the electrical team to get feedback on what traits work and what traits hinder

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

[1] A. Graves, A. Hagle, C. McDermitt, C. Meier, E. Neleski, B.Sailor "*Technical Design Report for Via Maris*," RoboNation, https://robonation.org/sites/default/files/Kennesaw_TDR_RS18.pdf [Accessed on July 1, 2019]

[2] A. Cheng, H. Evans, J. Gragg, A. Graves, A. Hagle, C. Meier, J. Nguessan, V. Nguyen, B. Sailor. "Design rationale for Leviathan autonomous underwater vehicle." RoboNation, http://robonation.org/sites/default/files/RS17_KennesawState_Paper.pdf

[Accessed on May 15, 2021]

[3] W. Liu, D. Anguelov, D. Erhan, C. Szegedy, S. Reed, C. Fu, A. C. Berg. "SSD: Single Shot MultiBox Detector." arXiv. Dec. 2016, https://arxiv.org/pdf/1512.02325.pdf [Accessed on June 3, 2021]

[4] A. G. Howard, M. Zhu, B. Chen, D. Kalenichenko, W. Wang, T. Weyand, M. Andreetto, H. Adam. "MobileNets: Efficient Convolutional Neural Networks for Mobile Vision Applications." arXiv. Apr. 2017, https://arxiv.org/pdf/1704.04861 [Accessed on June 1, 2021]

[5] "ROS Melodic Morenia." wiki.ros.org, 2020, http://wiki.ros.org/melodic [Accessed on 8 July, 2020]

[6] "smach - ROS Wiki", wiki.ros.org, 2020, http://wiki.ros.org/smach [Accessed on 17 June, 2021]

[7] "mavros - ROS Wiki", Wiki.ros.org, 2020, http://wiki.ros.org/mavros [Accessed on 15 March, 2021]

[8] "Overview ArduSub GitBook", BlueRobotics, 2017, https://www.ardusub.com/ [Accessed on 19 June, 2017]

[9] R. Panez. "Simplified method for obtaining navigational information from hydrophone arrays". University of Florida, 2004, https://www.mil.ufl.edu/publications/thes_diss/Rolando_Panez_thesis.pdf [Accessed on 5 January, 2021]

[10] "rosserial - ROS Wiki", Wiki.ros.org, 2020, http://wiki.ros.org/rosserial_arduino [Accessed on 19 June, 2021]

[11] "LT1097 - Low Cost, Low Power Precision Op-Amp", Linear Technology Corporation, https://www.analog.com/media/en/technical-documentation/data-sheets/1097fas.pdf [Accessed on March 25, 2021]

[12] "RESON TC4013 - hydrophone", Teledyne Marine, http://www.teledynemarine.com/reson-tc4013?ProductLineID=48 [Accessed on March 30, 2021]

[13] "MID-FREQUENCY PINGERS", JW Fishers, http://www.jwfishers.com/products/pingers-mid.html [Accessed on April 25, 2021]

Appendix A: 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	Teledyne Marine	RESON TC4013	N/A	$1500
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)	32			
HW/SW expertise ratio	2 HW : 1 SW			
Testing time: simulation	2 hrs.			
Testing time: in-water	15 hrs.			

Appendix B. Community Outreach

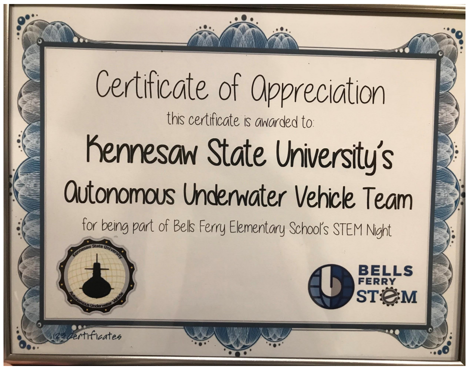

Figure 7. Bells Ferry Certificate of Appreciation

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."