Design and Development of an Autonomous Kayak for the 2023 Roboboat Competition

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***Abstract*—As the field of maritime robotics continues to expand, new challenges in autonomy appear. To help facilitate the discovery of solutions to autonomy challenges in the maritime domain, high school and college students have the opportunity to participate in a competition called Roboboat. This competition requires teams to build an autonomous surface vehicle capable of completing several challenging autonomous tasks, such as navigating buoy channels, avoiding obstacles, docking, and delivering projectiles to a floating target. Team AMORE has chosen to develop a vessel for Roboboat using a kayak as the base platform. This vessel has two fixed thrusters mounted parallel to the kayak keel and one bow mount thruster mounted perpendicular to the keel. The control system implemented allows the vehicle to switch between under-actuated and fully-actuated control based on the current vehicle task. While the autonomous kayak has many unique components, it also reuses several systems previously developed for a larger unmanned surface vehicle. This paper will provide an overview of the team's competition goals, autonomous surface vessel design, and testing strategy.**

I. Introduction

Team Autonomous Maritime Operations and Robotics Engineering (AMORE) is a multidisciplinary group of undergraduate students from Lake Superior State University (LSSU). The team was founded in August 2021 with the intent to develop an Unmanned Surface Vehicle (USV) using a Wave Adaptive Modular Vessel (WAM-V) platform for the 2022 Maritime RobotX Challenge [1]. After participating in this competition, the team began making plans for future involvement in events hosted by Robonation. The goal of competing in Roboboat 2023 was a natural fit for the team since it provides unique challenges while simultaneously allowing integration of several elements that were already used on the WAM-V USV developed for RobotX.

To compete in Roboboat 2023, Team AMORE is responsible for the design and implementation of an autonomous surface vehicle (ASV) that is capable of performing autonomous tasks in the maritime domain. This paper will provide details about the team's competition goals, ASV design, and testing strategy for Roboboat 2023.

II. Competition Goals

Having already participated in the 2022 Maritime RobotX Challenge, Team AMORE's primary competition goal is to complete tasks that are similar to the challenges encountered at RobotX [2]. This goal allows task specific code and systems to be recycled for Roboboat, which minimizes the amount of time required for new software development while maximizing the time devoted to the testing stage of development. Table 1 shows which Roboboat tasks align with the tasks experienced at RobotX.

Table I

Roboboat tasks that are comparable to RobotX tasks [2],[3]

Roboboat task	RobotX task
Task 1: Navigate the Panama Canal	Dynamic Navigation Demonstration
Task 2: Magellan's Route / Count the Manatees & Jellyfish	*Task 3:* Follow the Path
Task 3: Beaching & Inspecting Turtle Nests	*Task 6:* Detect and Dock
Task 4: Northern Passage Challenge	*Task 2:* Entrance and Exit Gates
Task 6: Feed the Fish	*Task 7:* Find and Fling

In addition to the five tasks listed in Table 1, the team also has the goal of completing Task 8 – Explore the Coral Reef. Although this task is not related to RobotX, it can be completed using the systems developed for the other tasks.

The final vehicle design described in Section III of this paper complements the competition goal of completing Task 1-4, 6, and 8 as its layout was intentionally designed to successfully reuse the systems that were developed for RobotX [1]. This includes the Guidance, Navigation, and Control system, safety management setup, vision system, and ball launching device. Although each of these systems could be optimized for Roboboat, incorporating previously developed systems helps increase reliability while decreasing system complexity. In addition, it ensures that the design remains modular.

To successfully complete Tasks 1-4, 6, and 8, Team AMORE will implement the competition strategy illustrated in Figure 1. This strategy breaks down the final goal into manageable steps to help ensure success. As noted in the figure, GPS waypoints will be relied on during the beginning of the competition. While GPS waypoints are not able to account for complex dynamic situations, they have proved to be a reliable method for piloting a WAM-V USV in previous tests [1]. In addition, GPS waypoint following can be implemented quickly since it has been used in the past. This will allow the team to spend more time on the course, collecting valuable data. Although GPS waypoints will be heavily relied on in the beginning of the competition, the strategy eventually transitions to utilizing the vision system.

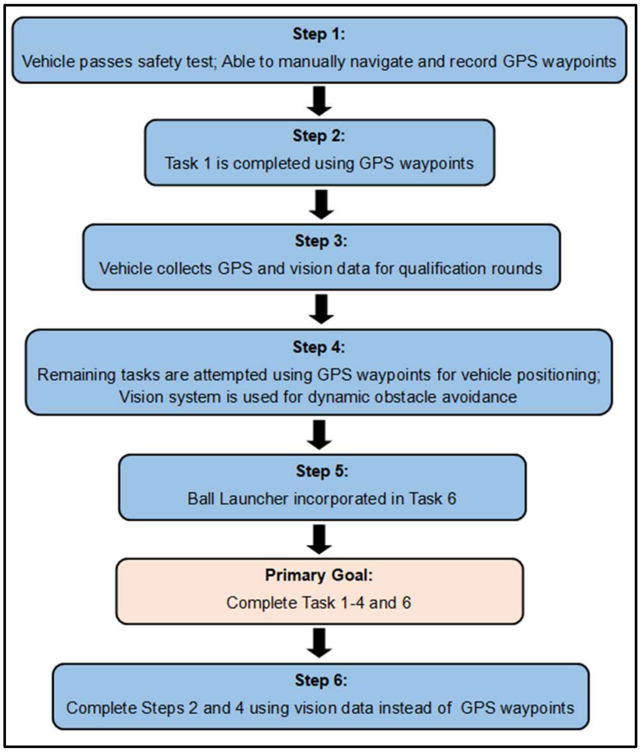

Fig 1. Team AMORE's Roboboat competition strategy.

This strategy was developed based on the observation that the teams at the 2022 Maritime RobotX Challenge who relied on vision systems often took longer to complete the Dynamic Navigation Challenge but performed better in Semi-Finals and Finals. The strategy detailed in Figure 1 accounts for this by increasing time on the challenge course while simultaneously developing the vision system for use in Semi-Finals and Finals. This strategy balances complexity and reliability by systematically increasing complexity after good results have been reliably achieved in fundamental areas.

III. AUTONOMOUS SURFACE VEHICLE DESIGN

Team AMORE's primary design goal for Roboboat 2023 is to produce an ASV that is able to implement the competition strategy discussed in Section II of this paper. Based on the tasks specified in the competition strategy, the most important components that require development are (A) a vehicle platform, (B) a propulsion system, (C) a guidance, navigation, and control (GNC) system, (D) a vision system, and (E) a ball launcher.

The design strategy followed when developing these components has two main aspects. First, the design should be modular. Whenever possible, systems from the existing WAM-V USV used for RobotX should be incorporated into the new design. Second, the design should be kept simple. Rather than spending excessive time trying to optimize the vehicle design, off the shelf components and elemental engineering principles should be used so that more time can be dedicated to testing. In addition to these two primary design criteria, cost and weight should be minimized and thrust should be maximized. In the following sections, detailed descriptions of how this design strategy was applied in the development of the ASV for Roboboat 2023 will be given.

A. *Platform*

To effectively implement the competition strategy discussed in Section II, the development of an ASV that is large enough to hold systems that were originally designed for a much larger vessel was required[1]. Although redesign of some components, such as the GNC system, was initially considered to reduce weight and size, the team determined that this would greatly increase design complexity and the risk for vehicle malfunction without appreciably benefiting vehicle design. In addition, incorporating previously developed systems without modification helped ensure that the design remained modular and could be easily installed on either the WAM-V USV or the smaller ASV.

For the vessel to be large enough and have sufficient stability, a suitable base platform had to be chosen. Several options were considered for this platform including a PVC pontoon boat, a polystyrene pontoon boat, a polystyrene monohull, a pre-purchased child's kayak, and a pre-purchased RC hull. To determine the optimal platform, a Pugh analysis[2] was performed. This analysis, which included cost, size, weight, payload, manufacturing simplicity, drag, transportability, and aesthetic factors, indicated that a child's kayak was the best option. Information about the specific kayak model selected can be found in Appendix A.

One challenge of using a kayak for the ASV base platform is that supporting infrastructure is needed to fasten components to the kayak deck[3]. This infrastructure must support the electronics while maintaining vehicle stability. To keep the center of gravity as low as possible, the batteries are housed in watertight containers mounted directly to the kayak deck. Above the batteries, the GNC box is mounted to a marine grade plywood deck. This added elevation diminishes the hazard of water damaging the sensitive electronics housed in the box. Finally, the racquetball launcher is secured near the bow of the kayak in order to remain under the three-foot height constraint [3]. A GoPro mount will also be secured in the bow to fulfill Roboboat requirements [3].

[1] The platform used for RobotX was the WAM-V 16 produced by Marine Advanced Robotics. This platform is 16 ft. long, 8 ft. wide, and weighs 450 lbs [5]. In contrast, Roboboat specifies that the ASV must be no more than 6 ft. long, 3 ft. wide, and 140 lbs [3].

[2] A Pugh analysis is a decision-making metric that ranks solutions based on how well they satisfy a series of weighted criteria.

[3] The kayak model selected requires the user to sit on the top surface of the vessel when piloting it. This means that it does not have an enclosed space like a traditional kayak. For the remainder of the paper, the terminology "kayak deck" will be used to refer to the top surface that the user sits on.

B. Propulsion

In addition to the platform, a propulsion system was another baseline requirement for the ASV. Although it would have been advantageous to use the existing WAM-V USV propulsion configuration[4] to increase the modularity of the design, the system was not adequate for mounting on the smaller kayak. Because of this, other configurations were considered instead. These configurations are summarized below in Table 2.

Table II

PROPULSION CONFIGURATIONS CONSIDERED FOR THE ASV.

Configuration	Specifications
Differential drive	Two fixed thrusters mounted parallel to the keel of the vehicle
Differential drive with rudders	Rudders added to the differential drive configuration to direct thrust
Differential drive with bow thruster	Bow thruster mounted perpendicular to the keel in addition to differential drive thrusters
Omnidirectional	Four thrusters mounted at ±45° angle from the keel

One important factor in the propulsion system selection process was whether the configuration resulted in an under-actuated, fully-actuated, or over-actuated system. The ideal system would be fully-actuated since this would allow the controller used for the WAM-V USV to be adapted for the ASV with minimal changes. Ultimately, a differential drive configuration with a bow thruster was selected for the propulsion system. This choice was made based on the configuration's simplicity, fully-actuated status, and minimized cost and weight. This layout can be visualized in Figure 3 where T_p and T_s represent the thrust force from the differential drive motors and T_b represents the thrust from the bow motor. The thrusters used to implement this design are Hawk Hobby Underwater Thrusters. Additional information about the propulsion system components can be found in Appendix A.

C. Guidance, Navigation, and Control System

To provide the necessary control for the ASV, a robust GNC system was implemented. This system includes mechanical and electrical components in addition to the control software necessary for vehicle movement. The following sections will provide details about these aspects of the system.

[4] The existing WAM-V USV propulsion configuration consists of two independently controlled azimuthing Minn Kota trolling motors mounted to the back of the pontoons [1].

I. Mechanical and Electrical

The mechanical and electrical components of the ASV's GNC system are the same as those used on the WAM-V USV [1]. As mentioned in Section III – A, this decision was made to increase vehicle modularity and reduce system complexity. Since the 2022 Maritime RobotX Challenge, several updates have been made to the components used including an additional onboard computer and ethernet switch. The current GNC layout is shown in Figure 2.

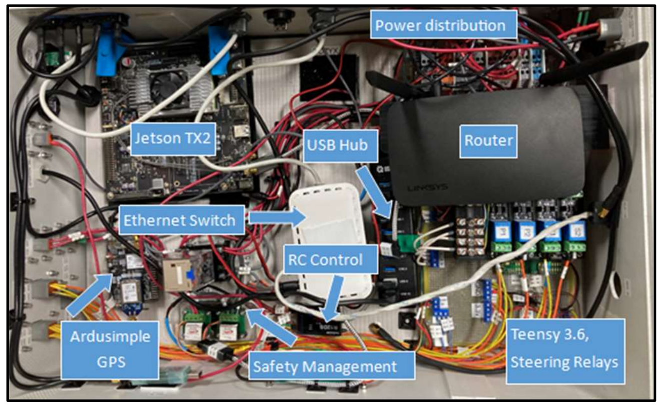

Fig 2. The Primary GNC Box holds the majority of the electronics onboard the WAM-V USV.

II. Control Software

Although the hardware components of the ASV are integral to meeting the team's competition goals, another vital area is the control software. Without this software, the vehicle is unable to complete tasks autonomously. Because the propulsion system on the ASV differs from the configuration used for the WAM-V USV (see Section III – B), the control software implemented must be adjusted. Given an ASV with three thrusters mounted as shown in Figure 3, the control software can switch between an under-actuated configuration using only two thrusters and a fully-actuated system using all three thrusters. The under-actuated configuration is used for navigating from one task to another and the fully-actuated configuration is used for precise pose control when attempting a task. The equations and theory behind each of these control schemes is described below[5].

To design and test both the under-actuated and fully-actuated controllers, the dynamic model shown in Equation 1 was used.

$$M\dot{v} + C(v)v + D(v)v = \tau + \tau_d \qquad (1)$$

In this equation, M is the mass and inertia matrix, including rigid body and added mass; v is the ASV velocity vector; C is the centripetal matrix, including rigid body and added mass; D is the drag matrix; $\tau = [T_x\ T_y\ M_z]^T$ is the control output vector which is represented by forces in the x and y direction and moments about the z direction; and τ_d is the

[5] The control theory discussed assumes that the boat exists in a 2-Dimensional environment.

disturbance vector, including wind, surface current, and wave disturbance. The parentheses indicate the dependencies of the various elements (e.g. $D(v)$ indicates that the drag is dependent on the ASV velocity, v).

For the under-actuated differential thrust configuration, no output thrust can be generated in the body fixed y direction. The ASV state error must therefore be decomposed into position error e_{xy} (Equation 4) and heading error e_ψ (Equation 6). The position error e_{xy} is the Euclidean distance between the x and y components of the ASV state error, e_x and e_y, which are shown in Equations 2 and 3. These components are calculated by taking the difference between desired position (x_d,y_d) and actual position (x,y).

$$e_x = x_d - x \tag{2}$$

$$e_y = y_d - y \tag{3}$$

$$e_{xy} = \sqrt{e_x^2 + e_y^2} \tag{4}$$

The heading error e_ψ is calculated using the constraint that the ASV desired heading ψ_d should always be tangent to the ASV desired position x_d and y_d as shown in Equation 5.

$$\psi_d = arctan\left(\frac{y_d - y}{x_d - x}\right) \tag{5}$$

$$e_\psi = \psi_d - \psi \tag{6}$$

Using these error values, a position only PID control law is formulated as shown in Equations 7 through 9.

$$T_x = K_P e_{xy} + K_D \frac{d(e_{xy})}{dt} + K_I \int_0^t e_{xy}\, dt \tag{7}$$

$$T_y = 0 \tag{8}$$

$$M_z = K_P e_\psi + K_D \frac{d(e_\psi)}{dt} + K_I \int_0^t e_\psi\, dt \tag{9}$$

In these equations K_P, K_D, and K_I are the proportional, derivative, and integral gains respectively. The error values are dependent on time, t. The results of these equations are then used to calculate the output thrust by solving the system of equations shown in Equations 10 and 11.

$$T_x = T_p + T_s \tag{10}$$

$$M_z = \frac{(T_p + T_s)B}{2} \tag{11}$$

In these equations, T_s is starboard thrust, T_p is port thrust, and B is the distance between port and starboard thrusters.

For the fully-actuated thrust configuration shown in Figure 3, the position and heading of the ASV can be controlled simultaneously. The PID position and heading control law in vector form is shown in Equation 12.

$$\tau = K_P \varepsilon + K_D \frac{d(\varepsilon)}{dt} + K_I \int_0^t \varepsilon\, dt \tag{12}$$

In this equation, $\varepsilon = \eta_d - \eta$ is the ASV state error and is calculated as the difference between the desired ASV state $\eta_d = [x_d\ y_d\ \psi_d]^T$, which is the output of the path planner, and the actual ASV state with respect to world $\eta = [x\ y\ \psi]^T$ which is obtained via sensor feedback. Given the control output $\tau = [T_x\ T_y\ M_z]^T$ obtained from Equation 12 and the distances to the ASV center of rotation l_y, l_x shown in Figure 3, thrusts for the starboard thruster (T_s), port thruster (T_p) and bow thruster (T_b) can be calculated using Equation 13.

$$\begin{bmatrix} T_s \\ T_p \\ T_b \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \\ -l_y & l_y & l_x \end{bmatrix}^{-1} \begin{bmatrix} T_x \\ T_y \\ M_z \end{bmatrix} \tag{13}$$

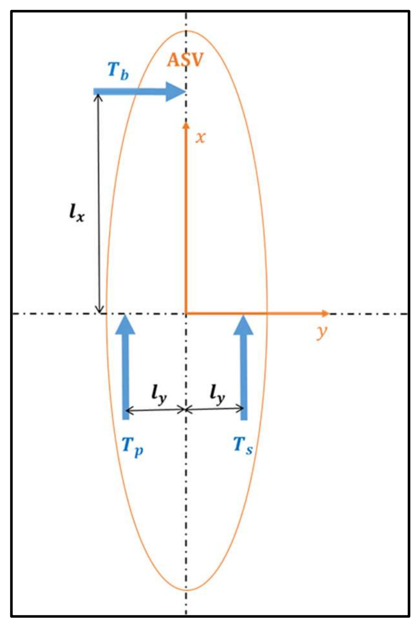

Fig 3. ASV layout showing two differential thrusters and a single bow mount thruster.

D. *Vision System*

As mentioned in Section II of this paper, the competition strategy requires the use of an onboard vision system. This vision system consists of a VLP-16 LiDAR and a ZED 2i stereo camera. These are the same components used for the WAM-V USV vision system [1]. More information about these components can be found in Appendix A.

The LiDAR will be used to create an occupancy grid and to localize known objects reported from the camera. The LiDAR will be using a single beam laser to map the course, leaving blind spots between 135° and -135° and for areas that are within a radius of one meter from the platform's frame[6]. Basic filtering will also be applied to ensure valid points are being recognized. Figure 4 shows the output of the LiDAR's laserscan topic before filtering and partitioning of the points has occurred.

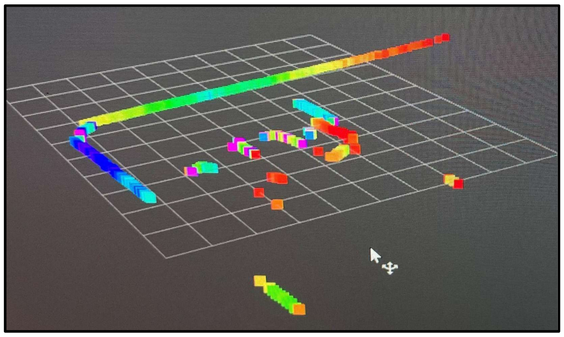

Fig 4. 2D laserscan map created from the VLP-16

The ZED 2i camera will be responsible for two primary tasks in the competition. The first task is object detection and the second is object localization. First, for object detection, the competition has many obstacles and key objects that need to be identified [3]. The ZED 2i creates image streams, as shown in Figure 5, that will be used to run basic image processing scripts for object recognition. The scripts will be written in C++ and will be processed using opencv libraries and functions.

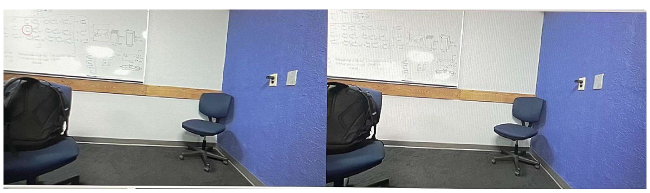

Fig 5. Stitched Camera feed from ZED 2i Driver

Second, for object localization a depth map created by the ZED 2i drivers will be used. Using the right and left camera feeds of Figure 5, an example depth map is shown in Figure 6. The depth map has parameters that can be set to establish a baseline for the minimum and maximum depth. The minimum and maximum depth for Figure 6 is 0 and 10 meters respectively. The inaccuracies seen in the image will be filtered out of calculations.

Fig 6. Depth map created from ZED 2i Driver

E. Racquetball Launcher

Roboboat Task 6 requires the delivery of racquetball projectiles into a floating target [3]. To complete this task, Team AMORE is using the vision-based adjustable launcher developed for RobotX Task 7 [1],[2],[4]. The launcher accurately delivers projectiles to targets of varying sizes and locations by using feedback from the vehicle's ZED 2i camera [1],[4]. The projectile's exit trajectory can be adjusted between 5° and 80° from the water surface to facilitate the delivery of the projectiles.

The launching mechanism is a single-driven hooded shooter as seen in Figure 7. It consists of a belt-driven shooting wheel and a revolving magazine. The hood is attached to a linear actuator at the back of the magazine which raises and lowers to adjust the exit trajectory angle. This angle is measured by a potentiometer which is geared to the edge of the hood [1],[4]. The launcher is controlled by an Arduino Teensy [4]. Design decisions were based on simplicity, ease of manufacturing, and the use of parts already available.

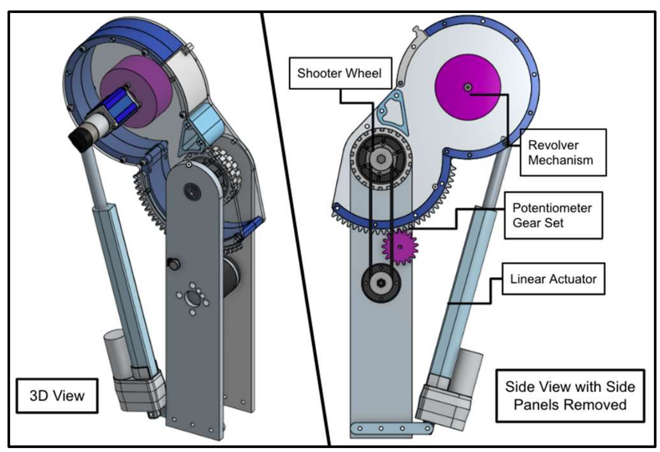

Fig 7. Labeled CAD design of the launcher design

The projectile motion equation onboard the Teensy (Equation 14) calculates a trajectory angle θ based on estimated horizontal distance d and vertical distance h to the

[6] The vehicle coordinate frame is oriented so that 0° is along an axis extending from the front of the vehicle.

target as determined by the Zed2i, and using an experimentally determined exit velocity of 16.4 meters per second [4].

$$V = \frac{d\sqrt{g}}{\sqrt{2}cos\,(\theta_0)\ \cdot \sqrt{d \cdot tan\,(\theta_0)\ - h}} \tag{14}$$

To launch, the ASV must line up with the target and maintain its heading. Once in place, the ASV sends the h and d data to the Teensy, and the launcher makes its first shot. The ASV then uses the Zed2i to determine if the projectile was on target. If not, it sends a correcting vertical distance α which the Teensy uses to calculate a new angle as seen in Equation 15 [4].

$$V = \frac{d\sqrt{g}}{\sqrt{2}cos\,(\theta_1)\ \cdot \sqrt{d \cdot tan\,(\theta_1)\ - (h+\alpha)}} \tag{15}$$

The launcher was tested in lab by shooting at the vertical target from RobotX [2] at three distances (d): 3.45 meters, 5.58 meters, and 8.48 meters. At 3.45 meters and 5.58 meters, the launcher overshot the target and at 8.45 meters the launcher undershot the target [4]. Corrections were performed until the target was hit. The result was a nominal accuracy of ±0.11 meters [4].

IV. Testing Strategy

While a good design that has been logically thought out and implemented is crucial to completing the competition strategy shown in Figure 1, the best designs may fail if adequate testing is not performed. Based on the nature of the tasks specified in the competition strategy and the requirements of Roboboat, the most important tests involve (A) vehicle safety, (B) vehicle seaworthiness, (C) remote control (RC) mode, (D) under-actuated differential drive control (See Section III – C.I), (E) fully-actuated control (See Section III – C.I), (F) vision capability, and (G) ball launching capability [3].

While testing on the water in conditions similar to those that will be encountered at the competition is ideal, the team's testing strategy is constrained by the winter weather conditions experienced in the Upper Peninsula of Michigan. Since ice typically prevents lake access through April, the team will utilize the pool facilities at LSSU for most of the testing. The indoor pool will require the use of the indoor GPS utilized during the WAM-V USV testing [1]. More information about this GPS unit can be found in Appendix A. In addition, Gazebo, the simulator used for Virtual RobotX (VRX) competitions, will be used to validate controller outputs.

The most important test, which is required for access to the competition courses, is the safety test performed on land. This test validates that power is immediately disconnected from all actuators when an E-stop is pressed on the ASV or RC controller, or when connection is lost with the vehicle [3]. The second crucial test is to assess the seaworthiness of the ASV to ensure that any electrical systems will not become submerged during normal operation.

The third, fourth, and fifth test involve the control of the ASV. Successful control of the ASV is fundamental for completing the desired tasks. RC functionality will first be tested on land. After this scenario has been validated, RC control will be used to drive the vehicle in a controlled aquatic environment. Autonomous control of the ASV will also first be tested on land so that the thrust outputs can be validated before attempting to navigate in the water. This will be done by setting waypoints in a parking lot and then moving the vehicle by hand while observing the outputs. After this has been done, autonomous control will be tested in the water by setting a series of waypoints for the vehicle to navigate through. Rosbag will be used to collect data during these tests and Matlab will be used to analyze the results.

The vision and ball launcher systems will be primarily validated at the competition, however, if time permits the vision system will be tested on buoys that the team has purchased. In addition, while the ball launcher has been tested independently of the ASV, tests will be performed to validate that it interfaces correctly with the vehicle. This will be done by attempting to launch racquetballs while the vehicle is stationkeeping.

V. Conclusion

. Team AMORE has developed an ASV for competition in Roboboat 2023. The ASV was created using a kayak as a base platform and includes many systems previously developed for a RobotX WAM-V USV. The team is excited to participate in Roboboat and is looking forward to using the ASV at the competition.

VI. Acknowledgements

Team AMORE would like to thank the Sault Tribe of Chippewa Indians, LSSU Center for Freshwater Research and Education, and all the other individuals and businesses who have supported us. Without their support, this project would not have been possible. In addition, we would like to thank Dr. Edoardo Sarda and the entire School of Engineering and Technology for their continuous support and for challenging us to pursue excellence in our work. Finally, we would like to thank our school, community, and families for supporting us on this journey.

VII. REFERENCES

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VIII. APPENDIX A

Component	Vendor	Model/Type/PN	Specs	Custom/Purchased	Cost	Year of Purchase
ASV platform	**N/A**	**N/A**	**N/A**	**Custom**	**N/A**	**N/A**
Kayak Hull	Walmart	90154	Kayak	COTS	1 x $104 ea.	2023
GNC Platform	N/A	N/A	N/A	Custom	N/A	2023
Propulsion	**N/A**	N/A	**N/A**	**Custom**	**N/A**	**N/A**
Thruster	Amazon	2022070401	HAWK HOBBY	COTS	3 x $109 ea.	2023
ESC	Amazon	AISN B08FTFM7C6	ZTW Shark	COTS	2 x $44 ea.	2023
Thruster Mounts	Amazon	2088889090	HAWK HOBBY	COTS	3 x $20 ea.	2023
GNC Battery Box	**N/A**	**N/A**	**N/A**	**Custom**	**N/A**	**N/A**
Enclosure	Harbor Freight	4800	Weatherproof Case	COTS	1 x $65 ea.	2022
5V DC/DC Converters	Amazon	N/A	5V DC/DC	COTS	1 x $15.99 ea.	2022
12V DC/DC Converters	Amazon	N/A	12V DC/DC	COTS	1 x $18.88 ea.	2022
GNC Batteries	DigiKey	PC12-12F2	GNC Batteries	COTS	2 x $57 ea.	2022
Fuse Block	AutomationDirect	JM60060-2CR	Fuse Block	COTS	1 x $54 ea.	2022
12V Fuse	AutomationDirect	JDL20	12V Fuse	COTS	1 x $19 ea.	2022
5V Fuse	AutomationDirect	JDL6	5V Fuse	COTS	1 x $19 ea.	2022
Power Switch	Anchor Express	6006	Power Switch	COTS	1 x $24 ea.	2022
GNC Box	**N/A**	**N/A**	**N/A**	**Custom**	**N/A**	**N/A**
Enclosure	PolyCase	WQ-77	Weatherproof Case	COTS	1 x $150 ea.	2022
LCD	Amazon	I2C LCD 2004	LCD	COTS	1 x $13 ea.	2022
Jetson TX2	Walmart	TX2	Jetson	COTS	2 x $980 ea.	2022
Teensy 3.6	SparkFun	N/A	Teensy	COTS	1 x $30 ea.	2022
RC Controller	Robot Shop	AT10ll	RC	COTS	1 x $140 ea.	2022
Outdoor GPS	Ardusimple	AS-STARTKIT-LR-L1L2-EUHS-00	Outdoor GPS	COTS	1 x $752 ea.	2022
Indoor GPS	Pozyx	N/A	Poxyx	COTS	1 x $1350 ea.	2022
Wi-Fi Router	Walmart	Table III E5350	Router	COTS	1 x $26 ea.	2022
RF Modem	DigiKey	ZULU-DONGLE	Modem	COTS	1 x $80 ea.	2022
Vision System	**N/A**	**N/A**	**N/A**	**Custom**	**N/A**	**N/A**
Camera	Stereo Labs	Zed2i	Zed2i	COTS	1 x $549 ea.	2022
LIDAR	Velodyne	VLP-16	Velodyne	COTS	1 x $4000 ea.	2022
Racquetball Launcher	**N/A**	**N/A**	**N/A**	**Custom**	**N/A**	**N/A**
Enclosure	Amazon	N/A	Weatherproof case	COTS	1 x $39.59 ea.	2022
Linear actuator	Firgelli Automations	FA-35-12-9-P	Linear Actuator	COTS	1 x $137.95 ea.	2022
CIM motor	VexRobotics		CIM	COTS	1 x $29.99	2022
Reduction Gear Motor	Andymark	am-4252	Gear motor	COTS	1 x $0	2022
Teensy 4.1	Digikey	DEV-20360	Teensy 4.1	COTS	1 x $41.88	2022
Potentiometer	Amazon	PDB181-E420	N/A	COTS	1 x $0	Unknown
HiGrip Wheel	Andymark	N/A	Wheel	COTS	1 x $8.00 ea.	2022
Miscellaneous	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Ubiquiti Antenna	FAU Donation	AMO-2G13	Antenna	COTS	1 x $245.00 ea.	2021
Rocket M5 BaseStation	FAU Donation	ROCKETM5	Base station	COTS	1 x $89	2021