Development of an Autonomous Maritime System for the 2022 RobotX Challenge

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***Abstract*—As the field of mobile robotics continues to expand, new solutions to previously "unsolvable" problems occur more and more frequently. The RobotX Maritime Challenge helps students find unique answers to these problems by having them design and develop an Autonomous Maritime System (AMS) capable of completing several challenging autonomous tasks. Team Autonomous Maritime Operations and Robotics Engineering (AMORE) has developed an AMS for the 2022 Maritime RobotX Challenge that is composed of an unmanned surface vehicle (USV) and an unmanned aerial vehicle (UAV). The USV can be operated in remote control or autonomous control modes. It can autonomously localize and classify various maritime markers, while autonomously navigating through a disturbed environment using a combination of station-keeping and wayfinding controls. The UAV is designed to share data with the USV, thus expanding the capabilities of the AMS. This paper will provide an overview of the team's design strategy, AMS design, and experimental results completed prior to the 2022 Maritime RobotX Challenge.**

I. Introduction

Team AMORE (Autonomous Maritime Operations and Robotics Engineering) is a 2022 Maritime RobotX team composed of undergraduate students from Lake Superior State University (LSSU). The team started in August of 2021 as an engineering senior design project and expanded to include a student-led club. In addition to the club, a second senior design project and a research methods class were started in August of 2022 to continue work on the project. The 2022 Maritime RobotX Challenge is the first of many to come for LSSU RobotX Team AMORE.

To compete in the Challenge, the team is developing an unmanned surface vehicle (USV) using a 16' Wave Adaptive Modular Vessel (WAM-V). This WAM-V is produced by Marine Advanced Robotics, Inc. and was awarded to the team by Robonation [1]. Team AMORE's USV can be seen in Fig. 1.

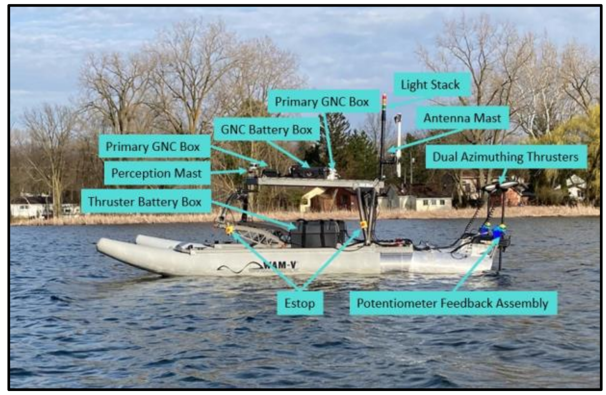

Fig 1. Team AMORE's WAM-V on the water during Spring 2022 testing.

In addition to the USV, the team is developing the control systems for a X500 V2 Holybro unmanned aerial vehicle (UAV). These two vehicles, which will work in tandem to complete tasks during the competition, form AMORE's Autonomous Maritime System (AMS). This paper will provide details about Team AMORE's design strategy, vehicle design, system testing, and experimental results.

II. Design Strategy

Team AMORE's approach to the 2022 Maritime RobotX Challenge involves designing an AMS that has baseline functionality in all competition areas. This approach favors reliability over complexity and robustness over capability. For example, the team has dedicated large amounts of time to testing the USV's station-keeping and wayfinding control capabilities. Although the concepts used are not extremely complex, the team is dedicated to ensuring that the USV can reliably navigate through a set of given waypoints. The strategy of focussing on baseline functionality is ideal since the team has only had the vehicle for just over one year and has not been able to dedicate substantial time or financial resources to advanced systems. This design strategy also results in a simple and dependable USV that will make it easier to implement more advanced features in the future.

The current AMS reflects the baseline functionality design strategy in a few areas. First, the AMS relies on off-the-shelf products to address challenging problems. For example, the USV has two Minn Kota 12V PowerDrive trolling motors that have a 360° azimuth range. This feature of the thrusters readily allowed the team to achieve the baseline goal of having a fully-actuated USV under the assumption of a two-dimensional working environment. Another example of this is the use of the X500 V2 Holybro UAV. By buying a pre-developed quadcopter frame instead of designing a unique frame or investigating alternative UAV options, the UAV meets baseline requirements without unneeded complexity. Second, the AMS relies on software that uses commonly accepted approaches to tasks. For example, the USV currently uses a proportional-integral-derivative (PID) dual-azimuthing station-keeping controller to maintain heading and position and to navigate through waypoints. The team has started to develop and simulate a more complex control scheme that involves having long-range, mid-range, and short-range controllers that use different drive configurations (Ackermann, differential, and dual-azimuthing); however, this strategy has not been fully implemented yet since the team has been focused on testing the baseline controller instead.

To make design decisions that accurately reflect Team AMORE's design strategy, a couple of methods are used. The first of these methods is called a Pugh Analysis. In this kind of analysis, different solutions are numerically compared based on a set of criteria. Each of these criteria are assigned a weight based on their importance. The tasks are also weighted based on how well they meet the criteria. Simple multiplication and addition are then used to determine which of the decisions is best. When deciding which systems and components to use on the AMS, the decision often relies heavily on criteria such as functionality and price. The second of these methods is design reviews with professors. The first design review, which was held in November 2021, was used to receive feedback from four different engineering faculty members regarding propulsion, control, safety, sensors, software, and miscellaneous hardware. The second design review, which was held in March 2022, was used to receive feedback from three engineering faculty members regarding how to test the functionality of the USV. Based on the result of this review, an extensive series of tests were generated to check the USV performance.

III. Unmanned Surface Vehicle Design

Team AMORE is designing a USV using the 16' WAM-V platform. The USV design consists of a propulsion system, a Guidance, Navigation, and Control (GNC) system, a safety system, and a racquetball launcher. USV top-level and mid-level system architecture diagrams showing the interactions between these different elements are shown in Fig. 2 and Fig. 3, respectively. The remainder of this section will provide details on the mechanical, electrical, and software components of each of these systems.

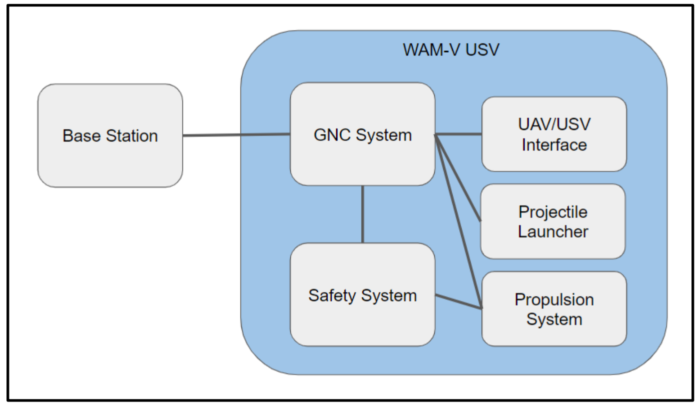

Fig 2. The top-level system architecture for the USV includes the GNC System, Safety System, UAV/USV interface, Propulsion System, and Projectile launcher. The GNC System will also interact with a Graphical User Interface.

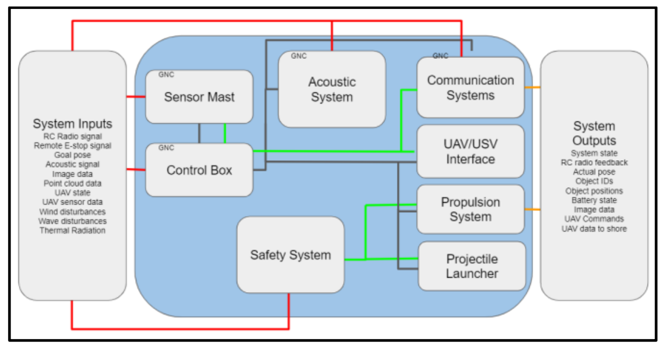

Fig 3. The mid-level system architecture for the USV includes more details about the interactions between different systems. It also provides information about expected inputs and outputs. The red lines represent USV system input, green lines represent electrical power transfer, black lines represent control data, and orange lines represent USV system output.

A. Propulsion System

Team AMORE's propulsion system is composed of two 12V Minn Kota PowerDrive trolling motors. These motors are rated for outputting 55 lbs of thrust and have a full 360° range of motion. In their stock configuration, the trolling motors are controlled using a foot pedal. To integrate them on the USV, the foot pedals were replaced with Arduino-based Teensy 3.6 microcontrollers which output pulse width modulation (PWM) signals that control the angle and magnitude of the motor's thrust. In order to attain closed-loop control of the thrust angle, angular feedback is obtained using a multi-turn potentiometer. This potentiometer is housed in a 3D printed assembly and is connected to the thruster shaft using gears. The thrusters are mounted to the back of the buoyancy pods using custom aluminum mounting brackets. Finally, each motor is powered by a 12V AGM battery. Fig. 4 shows one of the thrusters mounted on the WAM-V with its potentiometer assembly.

Fig 4. The USV's propulsion system includes 12V Minn Kota PowerDrive thrusters, 3D printed potentiometer assemblies, and custom aluminum mounting brackets.

Propulsion is a critical element in the USV's design since it is needed to complete the competition's Dynamic Navigation Challenge [2]. This challenge, which requires navigation through a set of channel markers, is a mandatory requirement for entering into the Autonomy Challenge course [2]. Because of the importance of this system, Team AMORE considered several other propulsion configurations before deciding to use dual-azimuthing thrusters. These configurations included twin stationary thrusters, twin stationary thrusters with a third stationary sway thruster, and twin stationary thrusters with a third azimuthing thruster. Using a Pugh Analysis that factored in elements such as cost, USV maneuverability, and design complexity, it was found that having dual-azimuthing thrusters was the ideal option. In addition, Team AMORE compared the use of 12V thrusters with 24V thrusters. Although 24V thrusters would be more effective, 12V thrusters were chosen because of their adequacy and price given the team's limited budget. A static analysis that uses a dynamic model of the USV [3] and accounts for disturbances expected at the Sydney International Regatta Centre was run using MATLAB. The expected disturbances were found by examining average wind conditions at the Regatta Centre. This analysis confirmed that the 12V thrusters would be sufficient for the competition.

B. Guidance, Navigation, and Control System

The USV's Guidance, Navigation, and Control System includes all of the vehicle's electronic boxes, processors, sensors, and communications. It also includes the vision subsystem and the acoustics subsystem.

I. Guidance, Navigation, and Control Box

The GNC system's hardware is housed in the following boxes, located on the top tray of the WAM-V: Primary GNC Box, Interface Box, Inertial Measurement Unit (IMU) Box, and GNC Battery Box.

The Primary GNC Box is the largest of the boxes and holds the majority of the electronics. Major components included in the box are the Jetson TX2, Ardusimple GPS, Pozyx GPS, WiFi Router, RC receiver, and Teensy 3.6 microcontroller. The Jetson is the primary processor and is responsible for control of the USV. The Ardusimple GPS is used for localizing the boat outdoors while the Pozyx GPS is used to localize the boat in an indoor environment. The Pozyx GPS is especially important for testing during the winter as ice prevents outdoor testing. Fig. 5 shows the contents of the Primary GNC Box.

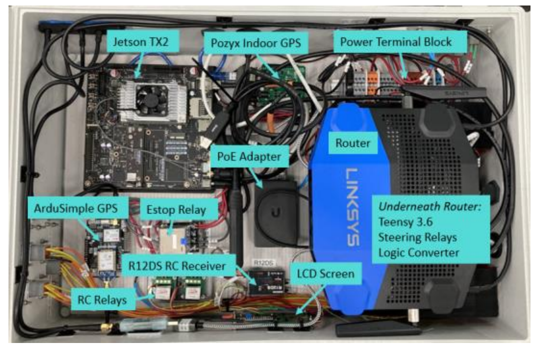

Fig 5. The Primary GNC Box holds the majority of the electronics onboard the USV.

The Interface Box is a smaller box that houses the LiDAR interface unit and a compass. This box is used in addition to the Primary GNC Box since it waterproofs the entrance and exit of wires without having to use bulkhead connectors. This is especially important for housing the LiDAR interface box since the team does not want to modify its cord. It is also ideal since it allows the compass to be separated from other electronic devices that might have affected its readings. The compass uses a magnetic field to provide heading information, and is used as a failsafe in case of IMU failure.

The IMU Box contains a Sparton AHRS-M2. Unlike the other boxes, the IMU Box is attached to the bottom of the USV's payload tray. This design is implemented to prevent electronic interference with the IMU readings by placing the payload tray of the USV between the IMU and the majority of the other components.

Finally, the GNC Battery Box is used to power all of the necessary electronics. Two 12V Sealed Lead Acid batteries are connected in series to power the entire GNC system. In addition to outputting 24V, DC/DC converters are also included within the box so that it can output 5V and 12V. Since most of the electronics require 5V and 12V power sources, using a 24V configuration prevents reduced performance when the batteries are drained. A CAD drawing showing the layout of the GNC Battery Box can be seen below in Fig. 6..

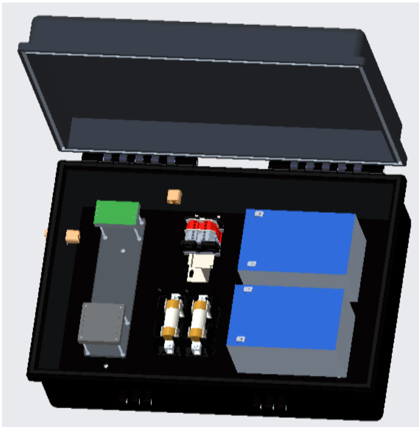

Fig 6. CAD drawing showing the layout of the GNC Battery Box.

II. Antenna Mast

In addition to the different GNC Boxes, an antenna mast is also mounted to the WAM-V's top tray. This antenna mast is important because the placement of the antennas helps prevent the USV from losing connection. The mast is constructed using PVC pipe, which allows the wires to be routed through the mast. A PVC solution was chosen because of its cost, weight, machinability, and insulative properties. The PVC pipe is held to the top tray using a pin, allowing the mast to be easily removed for transit.

The mast has a distinctive shape with two arms extending out to form a *t* and a third arm protruding outwards and then upwards. The arms of the *t* hold all of the component antennas. This includes two Linksys antennas, two Ardusimple antennas, and an RF modem antenna. The third arm supports the Ubiquiti antenna which is used for long range wi-fi communications. The antennas are placed at a distance that is greater than 1/4th of their respective wavelengths to reduce interference [4]. Finally, on the top of the antenna mast is the lightstack. This placement ensures that there is a 360° view of the light stack at all times as required by the challenge rules [2]. The CAD drawing of the antenna mast can be seen below in Fig. 7.

Fig 7. The USV has an Antenna mast located on its top tray. This mast also supports the lightstack. .

III. Vision Subsystem

The USV's vision subsystem (Fig. 8) is composed of a ZED 2i Stereo Camera and a 16-beam Velodyne LiDAR Puck (VLP-16). These sensors are attached to a custom mount that attaches to the top tray of the WAM-V. The mount allows for independent pitch control of both sensors. The data obtained from these sensors allows the USV to recognize and localize objects. This capability is used in tasks two, three, five, six and seven in the Maritime RobotX Competition [2].

Fig 8. The vision system implemented on the USV is composed of a ZED 2i Stereo Camera and Velodyne VLP-16 LiDAR.

All of the vision sensors on the USV communicate through Robotic Operating System (ROS). ROS allows communication between multiple platforms as long as each component is on the same network and is able to send and receive information from other processors.

To implement object recognition, a package called Darknet YOLOv3 is being used. This package allows for direct access to the information already in ROS. This simplifies the transfer of data to the whole system. Publishers and subscribers are then set up to analyze the objects seen and to filter through the outputs of the object recognition package. This package also allows for collection of images that can be compiled into a library. This is necessary so that the sensors can accurately report buoys and other obstacles that will be found in the Challenge course. These libraries are also easily transferable once they are created, so they can be run on the UAV and the USV. An example of Darknet YOLOv3 being used to detect a buoy can be seen below in Fig. 9.

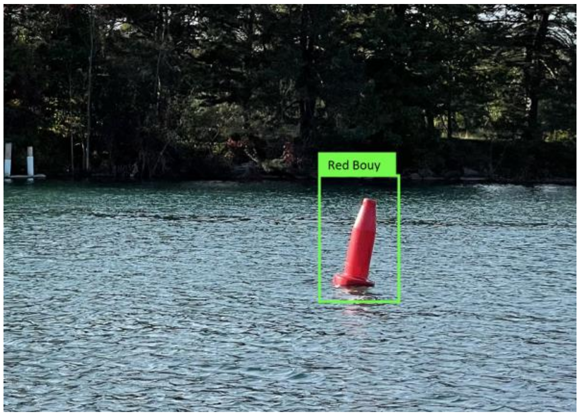

Fig 9. Darknet YOLOv3 object recognition software is used to find objects such as buoys.

In addition to identifying objects, it is also imperative that the vision system can localize these objects. Both the ZED2i and the VLP-16 can be used to calculate the distance to an object. The ZED2i calculates depth using a disparity map. The VLP-16 calculates depth by calculating the amount of time it takes for its emitted laser beams to reflect back to the sensor. When used in tandem with object recognition, the type and position of an object can be obtained. This pairing allows the USV to detect and respond to objects.

IV. Acoustics Subsystem

In order to successfully complete task two of the competition, an acoustics system is required [2]. Team AMORE's acoustics system is designed to locate underwater beacons using a Short Baseline system [5]. In this configuration, three hydrophones are placed on the USV. The first two will be used to determine if underwater sound is coming from quadrants I and IV or from quadrants II and III. The amplitude of the signal detected by the third hydrophone will be used to determine if the USV is moving towards the source or away from it. This setup can be seen in Fig. 10.

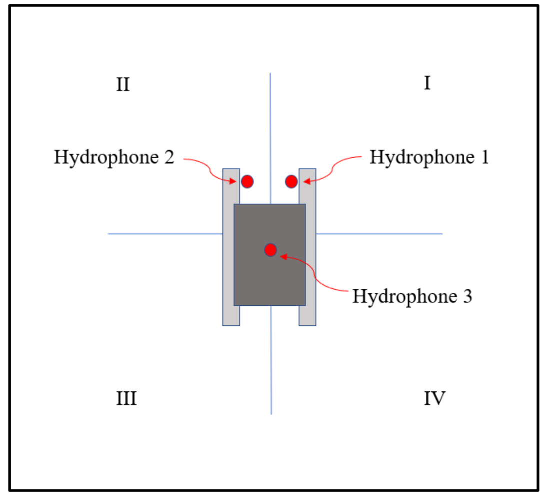

Fig 10. The acoustics system implemented on the boat will have three hydrophones. Two for determining direction and one for determining amplitude. The Roman Numerals I-IV represent the quadrants that a noise could originate from.

The three hydrophone setup was chosen since it reduced the number of hydrophones that needed to be implemented while retaining a good level of precision. In addition, while using four hydrophones enabled the system to determine which individual quadrant the acoustic ping was coming from, it also would result in discontinuities on each of the quadrant boundaries. For example, if the ping was coming near the border of quadrant I and IV, the code might switch between telling the USV that the sound was in front of it and behind it. This would create a challenging control environment.

The hydrophones used on the USV were made by the team by taking a piezoelectric crystal and encasing it in Urethane. In addition, a pre-amplifier PCB was designed in to reduce the impact of noise on the signal[1]. This PCB was also surrounded by Urethane. Once passed through the pre-amplifier, the acoustic signal is received by a processor running Labview[2].

V. Control Software

Team AMORE's software solution is currently executed on a Jetson TX2 and a Teensy 3.6 microcontroller. The Jetson TX2 runs most of the autonomous control software while the Teensy 3.6 controls the Minn Kota thrusters. These two processors communicate using ROS. Control is based on Remote Control (RC) input when in manual mode and Jetson TX2 input when in autonomous mode.

Currently, the script running on the Teensy 3.6 monitors the status of a switch on the RC to decide whether to perform in autonomous or RC manual mode. When operating in RC mode, the Teensy 3.6 monitors the position of the joysticks on the RC controller. It then uses this information to drive the USV in a differential-thrust configuration. This

[1] The pre-amplifier PCB was designed by Mario Miranda in collaboration with Team AMORE members

[2] The Labview code used for processing the acoustics signals was developed by Mario Miranda during his education at Florida Atlantic University.

configuration was chosen for ease of driving. In autonomous control mode, the Teensy 3.6 subscribes to the thruster speed and angle topics published by the Jetson TX2 and relays this information to the thrusters. As previously discussed, a potentiometer provides closed-loop control for thruster angle. A Pulse Width Modulation (PWM) signal is sent directly to the motor controller on the thrusters to achieve the desired propeller rotational speed. To identify the relationship between thrust output and PWM input, Team AMORE performed a Bollard Pull test. In this test, PWM signals are sent to the Minn Kota thrusters and then the corresponding thrust amount is recorded. Force is measured by securing the USV to a load sensor. After the data points are collected, a line of best fit is found to relate the output thrust (T_x) to percent throttle ($\%T$). The results of the Bollard Pull Test can be seen in Equation 1 and Fig. 11 respectively.

$$T_x = -6.58 + 0.905(\%T) - 0.00252(\%T)^2 \qquad (1)$$

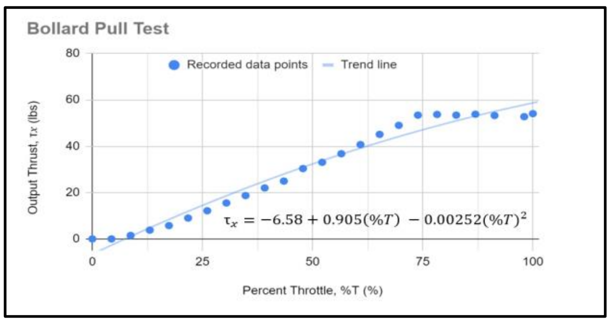

Fig 11. Bollard Pull Test Data.

The Jetson TX2 contains the ROS drivers for the USV sensors and runs the majority of the software necessary for autonomous operations. The Jetson TX2 software solution developed by Team AMORE is split into the following executable scripts: mission_control, path_planner, navigation_array, perception_array, and propulsion_system. Each executable was written in C++ programming language. Although ROS allows users to code in C++ or Python, C++ has a faster execution time than Python. On the other hand, Python is more user-friendly when prototyping because each edit to a script can be wrote out during execution instead of having to shutdown the system and recompile the executable. C++ was used over Python primarily due to the familiarity of the programmers on Team AMORE.

Mission_control acts as a state machine and oversees the USV. It determines the operational states of the other executables using operator input and given competition parameters. Path_planner acts according to the mission set in mission_control by publishing goal poses for the USV to navigate to. Path_planner is also responsible for telling propulsion_system which type of controller to use dependent on the range to the next goal pose. Different controller types used by Team AMORE include dual-azimuthing station-keeping, differential wayfinding, and Ackermann cruise control. Navigation_array interfaces with the sensor drivers and translates the USV pose to a local North-East-Down (NED) frame. Perception_array interfaces with the ZED 2i and the VLP-16 to provide object detection and localization. Propulsion_system uses the goal pose for the USV to perform all the necessary calculations to determine the thruster outputs needed to reach that goal. Dependent on which controller type is declared to be used by the path_planner, propulsion_system performs the necessary control allocation. A diagram of the USV autonomous software architecture can be seen in Fig. 12.

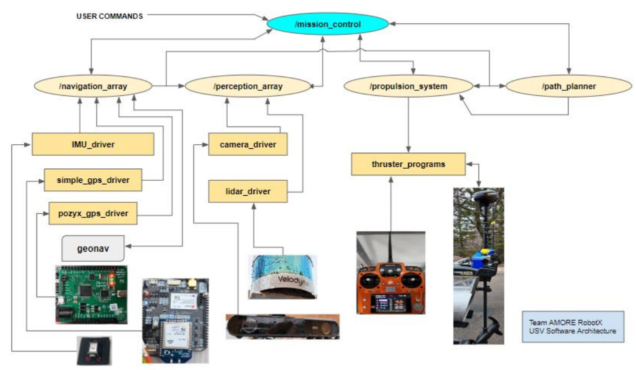

Fig 12. Autonomous software architecture implemented on the USV.

Station-keeping calculations are performed by propulsion_system. To station-keep, position and heading must be controlled. This is represented by three variables, position in x, position in y, and heading ψ. Propulsion_system uses PID Theory to control the pose of the vehicle represented by Equation 1.

$$\eta = \begin{bmatrix} x \\ y \\ \psi \end{bmatrix} \qquad (1)$$

By PID Theory, the controllers use the error, ε, between the USV pose, η, and the goal pose, η_d, to compute an amount of "effort" to achieve that goal. The error is calculated using Equation 2.

$$\varepsilon = \eta_d - \eta \qquad (2)$$

The "effort" can be calculated using PID Theory in Equation 3.

$$\tau = K_P \varepsilon + K_D \frac{d(\varepsilon)}{dt} + K_I \int_0^t \varepsilon dt \qquad (3)$$

In Equation 3, the K_j values are gain constants for the proportional, derivative, and integral terms. To control these three variables, system identification and math are used to solve the control allocation problem of an over-actuated system. To begin the control allocation problem, the relationship between the forces in the x and y directions at each thruster are solved for using the computed "efforts" to correct the USV pose. This relationship is shown in Equation 4.

$$\tau = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -l_{y_p} & l_{x_p} & -l_{y_s} & l_{x_s} \end{bmatrix} \begin{bmatrix} F_{x_p} \\ F_{y_p} \\ F_{x_s} \\ F_{y_s} \end{bmatrix} \quad (4)$$

C. Safety System

In compliance with the rules laid out by the Maritime RobotX Challenge [2], the USV is equipped with numerous safety systems including emergency stops, a light stack, and overcurrent protection. Emergency stops can be triggered in one of three ways. The first is pushing one of the large red buttons located on any corner of the boat. The second method is flipping a switch on the remote control transmitter. The third method is losing remote control capabilities or power to the AMS's control systems.

The light stack located on the highest point of the USV notifies surrounding vessels of the vehicle's control status. A green light indicates the AMS is being autonomously operated, a yellow light indicates remote control by a human operator, and a red light indicates an emergency stop. Overcurrent protection was implemented by using appropriately sized fuses on the batteries powering the electronics and circuit breakers on the thruster circuits.

D. Racquetball Launcher

Competition task seven, "Find and Fling," requires the delivery of four projectiles to a designated target. Team AMORE approached this task by developing a vision-based adjustable launcher using the USV's Zed2i to correct the orientation of the launcher depending on the outcome of each shot. The exact dimensions of the target for task seven are unknown, so the launcher is designed to reach various heights using different angles and velocities depending on the situation..

The design of the launcher mechanism is modeled after a single-driven hooded shooter. The system consists of a linear actuator, a revolver-style projectile magazine, and a belt-driven shooter wheel. The hooded launcher was chosen due to the efficiency of the launcher type. As time was of concern, the launcher was designed to be as simple to manufacture and maintain as possible. The linear actuator is used to pivot the launcher to the correct orientation based on the feedback received from the vision system. The linear actuator pivots the hood about the shooting wheel, such that the hood maintains a constant distance from the wheel, regardless of angle. The launch angle is able to be determined through readings from a potentiometer connected to a gear on the bottom of the launcher. The projectile magazine stores four racquetballs and is designed to have a fifth, empty slot that is used as a buffer. The magazine is connected to a linear actuator, which tilts the whole launcher. Fig. 13 shows the CAD of the projectile launcher prototype.

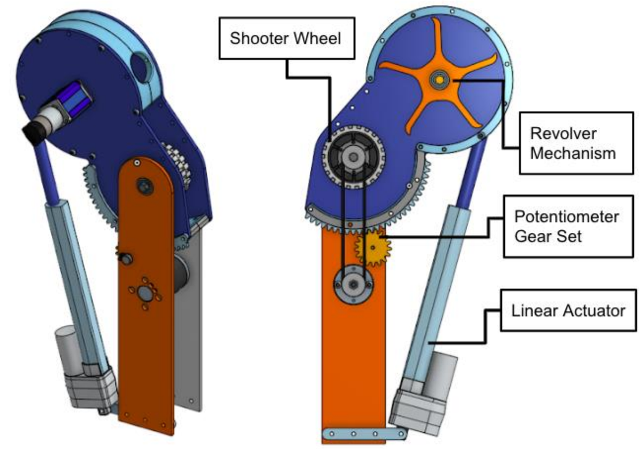

Fig 13. Side views of the racquetball launcher CAD

The USV's Zed2i camera is used to adjust the launcher between shots based on where the previous shot hit relative to the target. As the USV approaches the floating dock, the camera detects the target and begins tracking the racquetball once one has been launched. Based on where the ball hits the target, the furthest z value is compared to the target hole, then adjustments are made to the orientation of the launcher if the shot is not successful.

Projectile simulations done on-board the USV are used to give an initial estimation of what speeds and angles will be needed to reach the target. These simulations make use of the distance, *d*, and height, *h*, to the target detected by the Zed2i, the angle reported by the potentiometer, θ, and the shooting wheel's angular velocity recorded by the encoder. This data is fed into Equation 6, which returns the needed shooting velocity to reach the target, *V*, given the current angle and force of gravity, *g*.

$$V = \frac{d\sqrt{g}}{\sqrt{2}cos(\theta) * \sqrt{d * tan(\theta) - h}} \quad (6)$$

Upon receiving an updated distance and height to target, the launcher will adjust both the wheel velocity and the launch angle simultaneously, all the while running the simulation, until the simulated launch hits the target. In this way the time between the camera's data and the time of launch will be minimized. Upon detecting a failed shot, an adjustment factor will be added to the simulation, to increase its accuracy.

IV. Unmanned Aerial Vehicle Design

Team AMORE has designed a UAV using the X500 V2 Holybro platform. This UAV is used to complete tasks four, eight, and nine in the competition [2]. This section will provide details on the current design plan.

In the current design, the Holybro x500 drone kit will carry a Hyperspectral Camera and an Mp4 Video Camera. These sensors will allow the UAV to perform basic object recognition and localization tasks in addition to classifying objects using hyperspectral imaging. These capabilities enable scouting and mapping of areas from an aerial point of view. The sensors communicate using ROS, which is important since it allows the USV to access vision information from the UAV. In addition to these sensors, the drone kit carries a Pixhawk 6C and a Raspberry Pi 4. The Raspberry Pi functions as a companion computer that connects to the USV using the USV's wi-fi network. It is used to receive commands from and send updates to the USV. The companion computer is also used to process images received from the hyperspectral camera, identify competition objects, and relay the locations of those objects to the USV.

V. BASE STATION

To interact with the AMS, a base station with a Graphical User Interface (GUI) is used. It also receives an AMS heartbeat message. This base station is used to meet the requirement of task 1 in the Challenge [2]. This GUI will show the current objective of the AMS, the USV's mode, which objects are being detected by the vision system, speed and heading of the USV and UAV, GPS location of the USV and UAV, and battery level for the thrusters, GNC system, and UAV.

The Base Station uses ROS Workspace in the Qt Creator software for the GUI. The ROS Workspace in Qt Creator connects data available in ROS to an output such as a Liquid Crystal Display (LCD) or a text box. To do this, the QT class in ROS is used.

The heartbeat message is constructed using data transferred from the UAV and the USV over the AMS network. It also uses time and date data from the base station. Once the necessary data is collected, the heartbeat is then sent through a hard-wired connection (RJ-45) to the Technical Director's Network. This message is sent using the Transmission Control Protocol (TCP) by making use of the sys/socket internet protocol library, the netinet/in internet address library, and the arpa/inet internet operations library. The message is based on the competition guidelines and is different for each task, however, it is always initiated with a '$' character and terminated with a '*' and XOR checksum.

VI. EXPERIMENTAL RESULTS

In the development of the AMS, Team AMORE has performed hours of testing in simulation and on the water. This section will explain the team's testing procedure and the results that have been obtained.

A. Testing Procedure

Team AMORE has three primary methods for testing the AMS: Simulation, Indoor Testing, and Outdoor Testing. Each of these methods have pros and cons associated with them.

I. Simulation

When developing the AMS, one of the first testing methods employed by Team AMORE is simulations. The simulations are used to test code for functionality. Tests used to fine-tune the code are then performed on the water. The primary simulation environment used is Gazebo, which was used in the 2022 Virtual RobotX (VRX) Competition. Since Gazebo is a physics simulator that can simulate various competition environments, it is ideal for testing new code. This allows code to be debugged before deploying the AMS on the water. The code developed for Gazebo cannot be directly transferred to the physical AMS though and requires some modifications before being used on the USV. Another use of simulations in the development of the AMS involves the use of MATLAB software to test the design of the controllers. The simulation results for the station-keeping (Close-Range) PID Controller are shown in Fig. 14 and the results for the Path-Following (Mid-Range) PID Controller are shown in Fig. 15. Combining both Gazebo and MATLAB testing, Team AMORE has spent over 100 hours in testing the AMS after all of the code was developed.

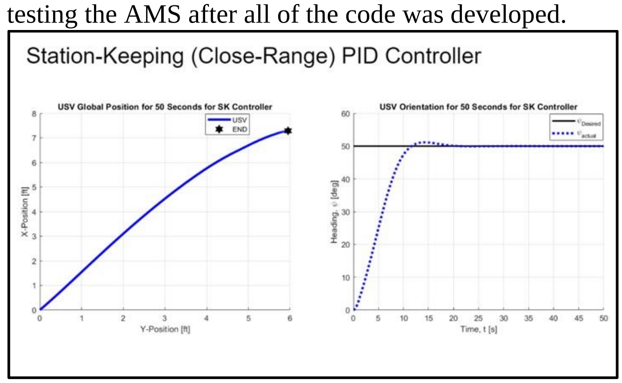

Fig 14. Station-Keeping PID Controller

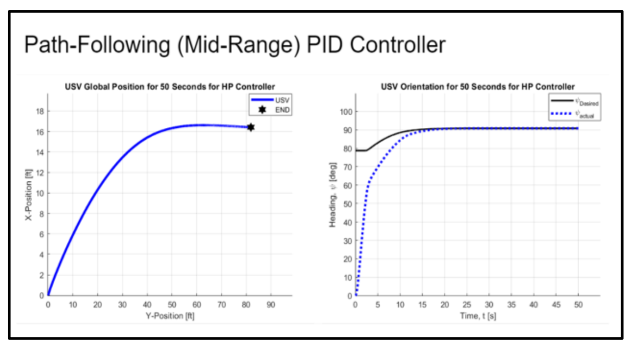

Fig 15. Station-Keeping PID Controller

II. Indoor Testing

Another primary testing environment for Team AMORE is Lake Superior State University's indoor swimming pool. Since the team's location in the Upper Peninsula of Michigan means that there is ice on the water for nearly half of the year, indoor testing is imperative. So far, the pool has been used to test RC control, and autonomous station-keeping. It was also used to gather data from the Bollard Pull test (Fig. 11).

Because the pool is not large, testing is limited in scope in this environment. In addition, being indoors prevents the use of the ArduSimple GPS. Instead, the Pozyx GPS is used in the pool area since it uses tags with fixed locations to calculate the USV position instead of satellites. The team has spent around 30 hours testing the USV in the pool.

III. Outdoor Testing

Team AMORE's final testing location is in the outdoors. Situated near three of the five Great Lakes in the United States, the team has many options for outdoor testing. Extensive testing of USV station-keeping and wayfinding functionality has been done on the water. The team has spent around 70 hours testing the AMS outdoors.

B. Results

Since station-keeping and wayfinding capabilities are necessary for multiple Challenge tasks, a significant amount of time is dedicated to testing them. Fig. 16 - Fig. 19 show the results of an outdoor station-keeping test. Fig. 16 and 18 show the ability of the USV to navigate to a specified pose. The discontinuities in Fig. 18 are due to the discontinuity between 0 and 2π. Fig. 17 and 19 show that error in position and heading decrease as sample number increases. This means that the USV is getting closer to the desired pose.

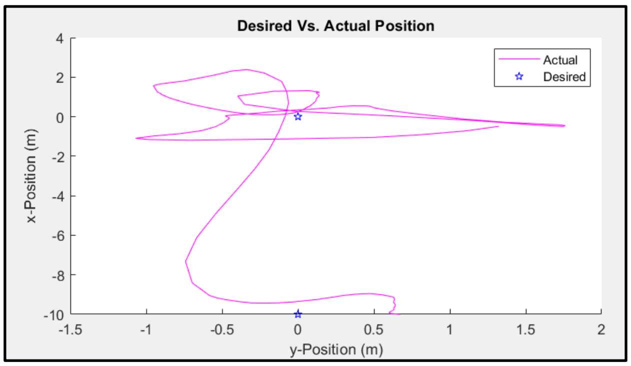

Fig 16. When the USV is given a pose to station-keep at, it first navigates to that location and then attempts to hold its position. This figure shows the desired position as a blue star and the USV x and y location as a pink line.

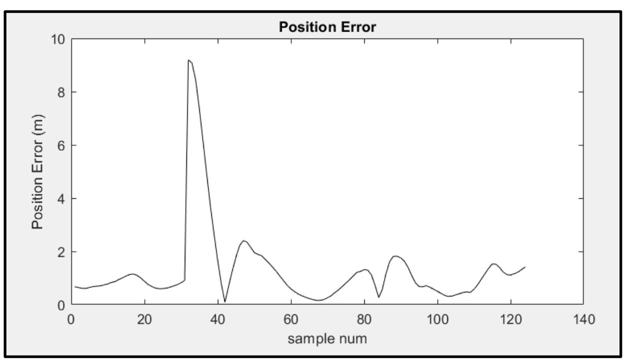

Fig 17. As the USV navigates to a specific pose, error in position should decrease. This means that the magnitude of the error signal should decrease as the sample number increases. .

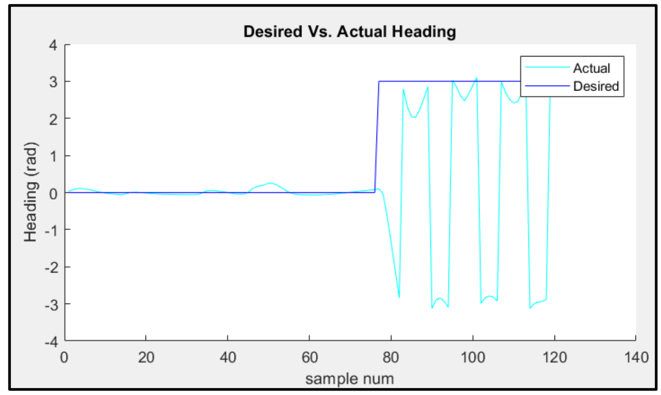

Fig 18. Once the USV has navigated to a given position, it will also try to hold a desired angle. This figure shows the desired angle as a dark blue line and the actual angle as a light blue line.

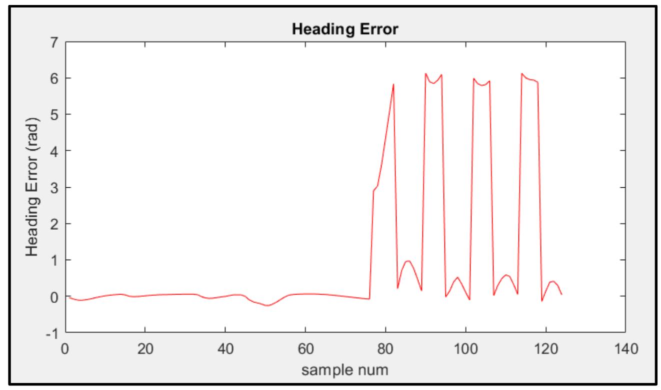

Fig 19. As the USV navigates to a specific pose, error in heading should decrease. This means that the magnitude of the error signal should decrease as the sample number increases.

Fig. 20 shows the results of a wayfinding test. In this test, the USV is given waypoints in the shape of a figure eight. The USV must navigate to each point before continuing to the next point.

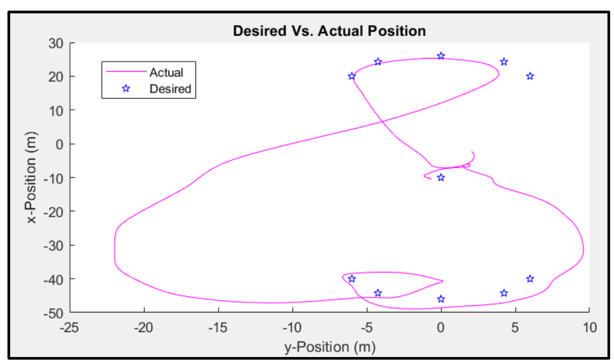

Fig 20. In waypoint following the USV must attempt to navigate through a series of waypoints. The waypoints are marked as blue stars and the actual USV path is represented as a pink line.

VII. Conclusion

Team AMORE has developed an Unmanned Surface Vehicle (USV) and Unmanned Aerial Vehicle (UAV) capable of competing in the 2022 Maritime RobotX Challenge. The team is incredibly excited to participate in the competition and looks forward to future competitions. In the future the team would like to upgrade the propulsion system so that the vehicle is capable of operating in more extreme conditions. The team would also like to update the control software so that it uses long-range, mid-range, and short-range controllers that implement different drive configurations. Finally, the team would like to continue partnership with the Center for Freshwater Research and Education (CFRE) and the Fisheries and Wildlife program for future research opportunities.

VIII. Acknowledgements

Team AMORE would like to thank the Sault Tribe of Chippewa Indians and all other sponsors of our project. Without their support, this project would not have been possible. In addition, we would like to thank Dr. Edoardo Sarda for his continuous support and for challenging us to pursue excellence in our work. We would also like to thank Mario Miranda and Dr. Travis Moscicki for their technical insights and for taking the time to teach us. Finally, we would like to thank our school, community, and families for supporting us on this journey.

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