Sailing into the Future: An Autonomous Maritime System for the 2024 RobotX Challenge

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***Abstract* – Team Autonomous Maritime Operations and Robotics Engineering from Lake Superior State University has developed an Autonomous Maritime System for the 2024 RobotX Challenge. The project builds on prior efforts and includes a WAM-V Unmanned Surface Vessel (USV) and an Unmanned Aerial Vehicle (UAV) to complete various tasks autonomously. The USV integrates an upgraded propulsion system, Guidance, Navigation and Control system, and several modular systems for specific missions. The UAV enables autonomous launch and recovery from the USV. This paper outlines the AMS design, integration, and testing, with a focus on maximizing performance at the 2024 RobotX competition.**

Keywords – Autonomous Maritime System (AMS); Unmanned Surface Vessel (USV); Unmanned aerial vehicle (UAV), Launch and recovery (L&R).

I. Introduction

Team AMORE (Autonomous Maritime Operations and Robotics Engineering) is a student-led competition team from Lake Superior State University (LSSU) that competes in various marine robotics competitions, including the Maritime RobotX Challenges and the RoboBoat competitions. Thanks to continuously growing support, AMORE has progressed from an entry-level team to a competitive team that consistently makes it to finals during competitions, placing in the top five most recently during RoboBoat 2024 and Virtual RobotX 2023. AMORE's work has spanned from four engineering senior design projects, a research course, international collaboration with other robotics institutions, and published academic research in both robotics and biology across the North American Great Lakes region [1],[2].

For the 2024 RobotX Challenge, the team is bringing the AMS developed for the 2022 RobotX, which has been substantially improved. The main robots of the AMS are the 16' Wave Adaptive Modular Vessel (WAM-V) USV and an Unmanned Aerial Vehicle (UAV) developed on a Holybro X500 V2 base.

I. Competition Strategy

AMORE developed a competition strategy drawing off of the large amount of work which had been done previously. Instead of developing any new systems, AMORE focused on integrating existing systems, and testing and improving their reliability. At competition, AMORE plans to complete only those tasks that they have reliable systems for, ignoring tasks or parts of tasks which require new technology.

For Task 1, AMORE worked to improve the reliability of an existing communication system for use in the noisy RF environment previously observed in the competition. Tasks 2, 3, and 4, require navigating colored buoy pairs, avoiding certain obstacles in the water and circling others. AMORE focused on integrating existing robust perception to identify colored buoys with a new propulsion system which allows for faster navigation through tasks, and improved stationkeeping accuracy. Also with perception and navigation, AMORE plans to complete the docking in Task 6. Additionally, an upgraded racquetball launcher can be integrated to maximize points on that task.

Tasks 7 and 8 require the UAV to take off from the USV and perform two different tasks. AMORE has a novel method of doing this, and will have its UAV takeoff and land from the USV. However, due to the small size of the existing UAV, it does not have the payload capacity to carry additional systems needed for identification of collection of task elements. Thus AMORE will not complete these tasks beyond takeoff and landing. Finally, Task 5 requires the perception system to identify a blinking colored light pattern. As AMORE have only developed previously developed perception for identifying solid color buoys, this task will be ignored entirely.

II. USV Design Strategy

The WAM-V is a 16-foot long pontoon style vessel with a raised stable platform and a payload of 825 pounds [3]. This versatile platform, seen in figure 1, is designed for coastal seas, can handle many of the surface conditions found on the Great Lakes where AMORE tests it. This has led to the USV's use being expanded beyond competition to be used for collecting data for biological research [2].

Figure 1. WAM-V 16 USV

On the base WAM-V AMORE has added a variety of systems for unmanned operation. These include the Guidance, Navigation, and Control (GNC) system seen in section A. Section B explains the USV motion with a new propulsion system and its control. The perception system in section C, including vision, enables the USV to make decisions based on its surroundings. The communication system (section D) allows monitoring of the USV from shore. There is a safety system outlined in Section E. Finally, there is a modular racquetball launcher developed specially for RobotX, seen in Section F.

A. Guidance, Navigation, and Control

The GNC box is located aboard the payload tray and is responsible for all communication aboard the USV. The GNC box (figure 2) houses the Jetson TX2 computer, a Teensy 4.1 microcontroller integrated with a printed circuit board, and the integrated safety system (Section C). The main function of the GNC box is to act as a management device for all sensors and components aboard the WAM-V. This is achieved using Robotic Operating System (ROS) as middleware to communicate between various sensors and components in software. Using ROS, the low-level controllers aboard the WAM-V have access to vital peripheral data, such as the current GPS location, that can be used to dynamically adjust the propulsion system's output to reach a desired state and respond to changing environmental conditions. This setup allows the WAM-V to achieve accurate and reliable movement, essential for tasks such as navigating complex waterways, performing scientific data collection, and conducting autonomous operations. The overall software architecture developed for the USV can be seen in Fig. 3.

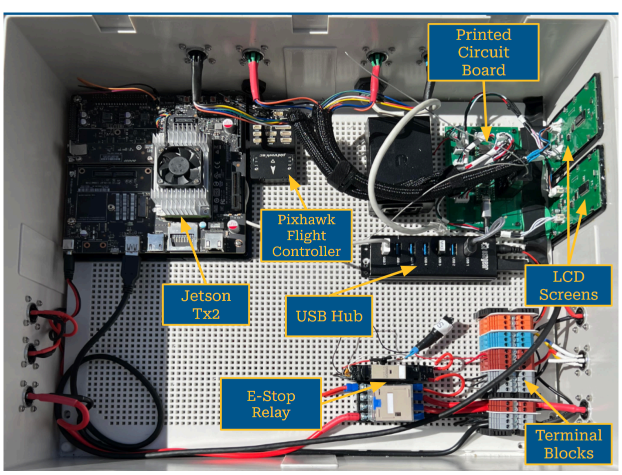

Figure 2. USV GNC Box

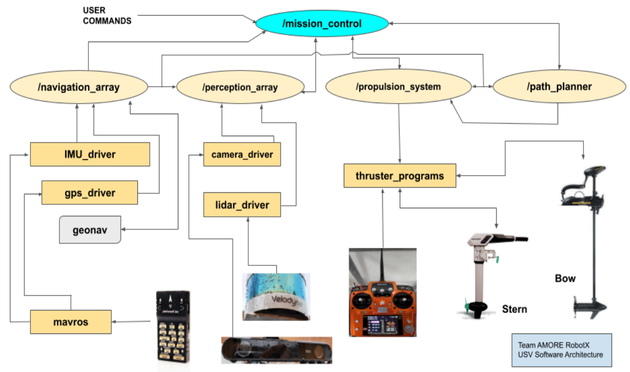

Figure 3. USV Software Architecture

B. Propulsion and Control

The WAM-V's propulsion system, developed as part of a senior project in 2023/24, sought to increase the speed of the WAM-V and allow it to function in larger waves than the previous limited thrusters by integrating new stern thrusters. The previous thrusters were moved forward and integrated as bow thrusters to make the WAM-V fully-actuated while station-keeping, providing more accurate positioning for accurate data collection [2], and for more reliability for completing RobotX tasks such as task 6 (Section F). There are two separate Proportional Integral Derivative (PID) controllers which carry this out. During waypoint navigation a Heading and Speed controller uses only the stern thrusters, Newport trolling motors capable of 490 N each, providing sufficient speed and maneuverability via differential thrust. This conserves power in the smaller bow thruster batteries. For Stationkeeping, the bow thrusters, Minnkota motors producing 245 N, are activated to allow fully-actuated movement, with the stern thrusters' thrust output saturated at 245N to match the bow thrusters'.

a) Heading and Speed

The Heading and Speed controller is a PID controller that utilizes the stern thrusters with differential thrust to navigate over long distances. The bow thrusters are not utilized by this controller, so the vehicle uses differential thrust with the stern thrusters. The parameters governed by the Heading and Speed controller are velocity and heading Given a desired point, the WAM-V will hold its heading to face the point as it navigates. As the WAM-V approaches the point, its velocity decreases to allow for a smooth transition between the Heading and Speed controller and the Station Keeping controller. The maximum velocity allowed for the WAM-V during the use of the Heading and Speed controller is directly proportional to the distance to the point. For both controllers, the output is desired forces T_x, T_y and moment M_z on the vehicle. Since the Heading and Speed controller only uses the stern thrusters, the output of the controller is transformed into thrust for the port and starboard stern thrusters Fx_{SP}, Fx_{SS}.

The free-body diagram of the forces from the thrusters during the use of the Heading and Speed controller is shown in Fig. 4.

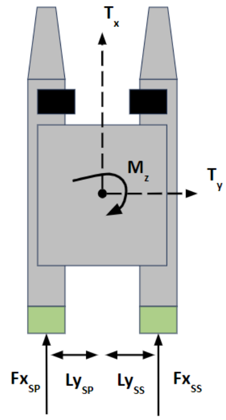

Figure 4. Force Output from Heading and Speed Controller

The derivation of the thruster forces from the desired state for the Station Keeping controller can be found in reference [2].

b) Stationkeeping

The Station Keeping controller is a PID controller that utilizes all four thrusters simultaneously to hold the WAM-V at a desired point. Since the USV utilizes all four thrusters using this controller, the USV is considered over-actuated, which generates the thrusters' output Fx_{SP}, Fx_{SS}, Fy_{BP}, Fy_{BS}. The motions governed by the Station Keeping controller are position and heading . The free-body diagram of the forces from the thrusters during the use of the Station Keeping controller is shown in Fig. 5.

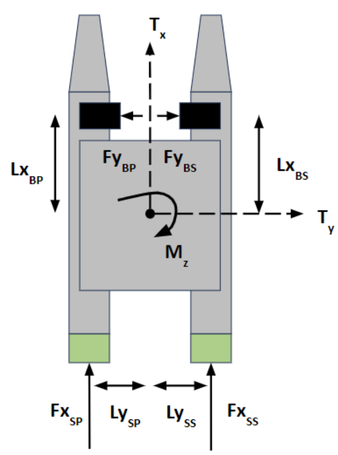

Figure 5. Force Output from Station Keeping Controller

The derivation of the thruster forces from the desired state for the Station Keeping controller can be found in reference [2].

C. Perception

Unlike the rest of the USV systems, the perception system AMORE developed for RobotX 2022 [4] is not unique to the WAM-V but is modular and can be removed and used for the autonomous kayak, most recently for RoboBoat 2024 [5]. It consists of a VLP-16 LiDAR and a Zed 2i stereo camera. The LiDAR is used to detect and localize data within an area in front of the vessel within a ± 45 degree angle of the vessel coordinate frame and a certain distance, which will be re-tuned for the WAM-V at the competition venue. An occupancy grid of the is generated to map the course. This map is an input to the path planner, used to calculate the necessary trajectories and avoid obstacles. Once the objects in front of the USV are mapped, then the stereo camera classifies them. Here the path planner gains information about navigating buoys based on rules defined based on particular missions, such as following general buoy rules or identifying buoy pairs for competition tasks.

D. Communication

To have a strong and reliable connection with the USV on the water, AMORE improved upon the WAM-V's network antenna. For RobotX 2022 an omni-directional Ubiquiti Rocket M5 tuned to 5 GHz was used [4]. To eliminate possible conflicts over bandwidth, Ubiquiti's built in software allows for adaptive bandwidth control. The antenna scans for any signal or noise within its channel width and can show where any high use channels are. During competition, this feature helped solidify communication with the USV and avoided some conflict with other teams' antennas. However, this system, which had previously been used successfully in testing, proved susceptible to conflict from other networks at RobotX 2022. To capitalize on the existing infrastructure and usually reliable network, a stronger narrow beam directional antenna was integrated into the base station to increase the robustness of the network when working near other teams at competitions.

E. Safety

To comply with the RobotX safety guidelines laid out in [5], The USV is equipped with an integrated safety system which shuts off power to the propulsion system. This can be done in one of three ways: by pressing one of the four red E-stop buttons placed around the USV for easy access (figure 6), by pressing the E-stop switch on the USV RC on shore, or automatically when the GNC box loses connection to the RC controller on shore. The last two trigger a remote relay in the GNC box (figure 2).

There is also a light stack indicator on the WAM-V communication mast, which indicates the state of the USV to anyone nearby. There are three lights, green to indicate the USV is autonomous, amber to indicate it is under remote control, and red to indicate it has been emergency stopped.

F. Launcher

RobotX Task 6 requires the USV to dock in one of three bays, and fling racquetballs into one of two holes in the dock [5]. For this task AMORE built took inspiration from the hooded launcher design used in RobotX 2022 [4], but created a new launcher that can rotate in two degrees of freedom rather than one, allowing for complete control in launching. This design, seen in Figure 6, makes the entire assembly lower to the deck of the WAM-V and therefore more controlled when moving.

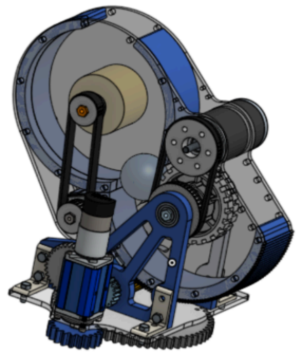

Figure 6. Racquetball Launching Turret

III. UAV DESIGN STRATEGY

The UAV used for RobotX 2024 is the same that was developed for RobotX 2022 [4] and used in creating the novel launch and recovery method [1]. A Holybro x500 v2 kit was chosen since it could be assembled and integrated with a flight controller out of the box. The carbon fiber frame and brushless motors can carry a 1 kilogram payload. With that payload and a 7000 milliamp-hour battery, it has a flight time of 6 minutes, enough time to perform a task while taking off and landing in a controlled manner from the WAM-V [1]. The UAV has its own GNC system (Section A). In case of an emergency landing in the water, the expensive GNC system is contained in a water-tight box, while the Hoybro legs were expanded with a flotation device to allow the UAV to land upright on the water and remain there for human retrieval. At RobotX 2024, tasks involving launching and recovering the UAV from the USV will be a large portion of the points available [5] so a novel launch and recovery system (Section B) was devised and can be mounted to the top of the USV for tasks involving the UAV.

A. Guidance, Navigation, and Control

The 1 kilogram payload of the x500 is nearly entirely taken up by the UAV battery and GNC system. The GNC box contains a Jetson Nano, a Pixhawk 6C, a Pozyx transducer, and an RC receiver. The GNC for the UAV is shown in Fig. 7.

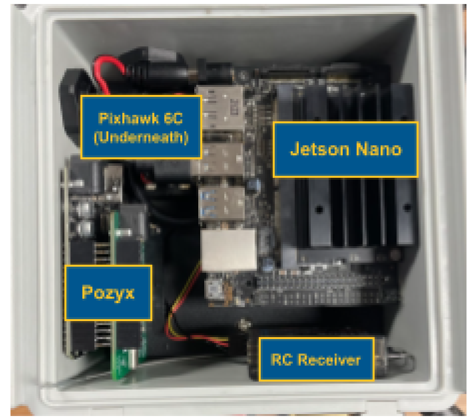

Figure 7. UAV GNC Box [1]

The Jetson Nano runs the high level control software through ROS/C++. The Pixhawk is the flight controller, handling the mid- and low-level control through PX4, using the built-in IMU and enabled GPS antenna. The Nano and Pixhawk communicate via MAVROS. Finally, the Pozyx transducer, which is a shield on an Arduino Uno, reads the transmissions for the LaRP on the WAM-V. The Uno runs a constant low-pass filter to remove noise and calculates the location of the UAV with respect to the WAM-V, sending that information to the high-level controller on the Nano, where it is used in the landing control. The software architecture for the UAV is shown in Fig. 8.

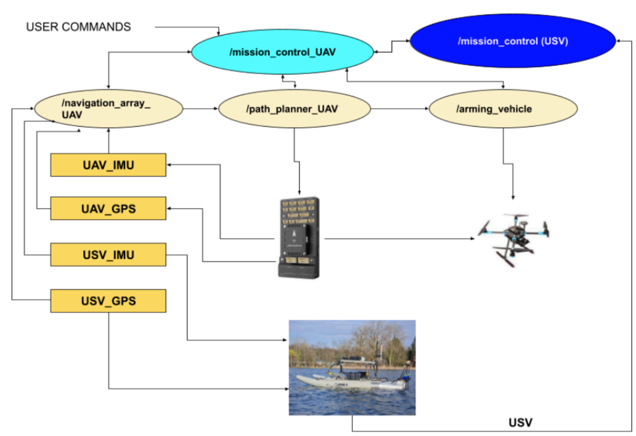

Figure 8. UAV Software Architecture [1]

B. Launch and Recovery

For completing Tasks 7 and 8 at RobotX, a novel method of launching and recovering a UAV from the WAM-V was devised using a Pozyx indoor GPS system to create a local coordinate frame over the USV. This frame is used as a reference by the UAV to land accurately on the WAM-V, independently of lighting conditions which would render standard vision-based landing impossible. The UAV Launch and Recovery Platform (LaRP) consists of a 1 m^2 launch pad raised above the deck of the WAM-V [1].

Further PVC arms extend out from the center of the LaRP, which hold four acoustic transmitters at varying heights. These four transmitters form the local 3D coordinate system with which the UAV to localize with respect to the WAM-V. Finally, safety nets were installed between the arms to catch the UAV if it failed to properly take off or tipped off the edge of the platform when landing [1].

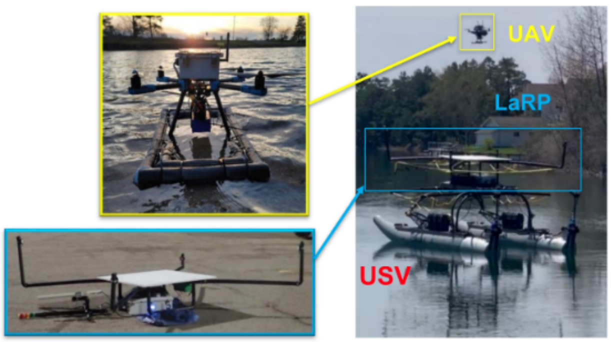

Figure 9. LaRP [1]

IV. TESTING STRATEGY

To ensure that the WAM-V was prepared for the competition, a rigorous testing phase was undertaken for the main components of the WAM-V. The propulsion system, control system, and UAV system were all recent additions to the WAM-V, and they are critical to the success of the overall AMS during the competition, so they were the main focus for testing.

A. Propulsion

To ensure that the propulsion system would be competitive for the competition, rigorous testing on land was undergone to determine the thrust values for each thruster at varying signals. This data was vital for the implementation of the thrust allocation through the Teensy microcontroller. Once the range of values was determined, a bollard pull test was conducted for each thrust signal to build a reference table that would be used for the implementation of the low-level controllers. Results from the Bollard pull test can be found in Appendix **B.1.**

B. Control

Due to a new propulsion system being implemented with two additional thrusters mounted on the bow, the control system required modification to ensure its functionality for the competition. The first step to testing the controllers was the validation of their functionality through the use of Gazebo and Virtual RobotX (VRX). Gazebo is an open-source simulation software for robotics [7]. VRX is an open-source simulation environment tool for Gazebo used to test autonomous maritime robotic solutions [7]. VRX models realistic environmental conditions, such as wind and current, that the WAM-V could face when operating. This tool was used to ensure that both the Heading and Speed controller and the Station Keeping controller would respond to changes in the desired state similar to scenarios seen during competition. The results from the validation signaled that a four-thruster configuration would be viable for the Station Keeping controller. The next step for testing the control system was by performing water testing. The WAM-V was given a mission consisting of multiple waypoints that it had to navigate to. This test was conducted for both controllers individually. The controllers were then tuned based on the amount of error from the desired state until they were deemed acceptable. This criteria and the results of the tests can be found in Appendix **B.2**. Once both controllers functioned as expected, code was written to implement the switching of controllers during an autonomous mission. The WAM-V was given a mission consisting of various waypoints that it would navigate to using the Heading and Speed controller. Once the WAM-V had reached within 10m of the desired point, the control system would switch from using the Heading and Speed Controller to using the Station Keeping controller. Figure 10 shows the results of an autonomous mission utilizing both controllers.

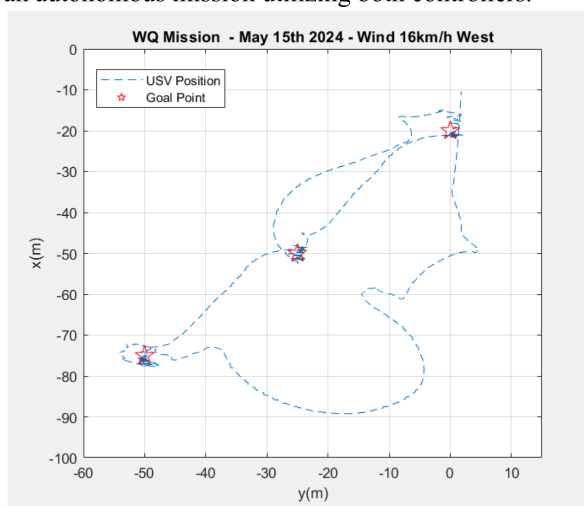

Figure 10. USV mission using both controllers

C. UAV

To ensure the safe recovery of the UAV during the autonomous launch and recovery sequence, rigorous testing was undertaken to validate the system. The first step of testing was validating the landing and recovery sequence through the use of Matlab, a programming platform for computational mathematics. A dynamic model was created for both the USV and UAV. Using the dynamic models, the low-level controllers were developed to control the UAV and USV individually. The landing and recovery sequence was then run using a predetermined path for the USV and a set of waypoints for the UAV. The UAV would head to the location of the USV once it had reached all predetermined waypoints. The UAV was able to land on the USV, validating the developed controls. The MATLAB simulation of the Launch and Recovery sequence is shown in Figure 11.

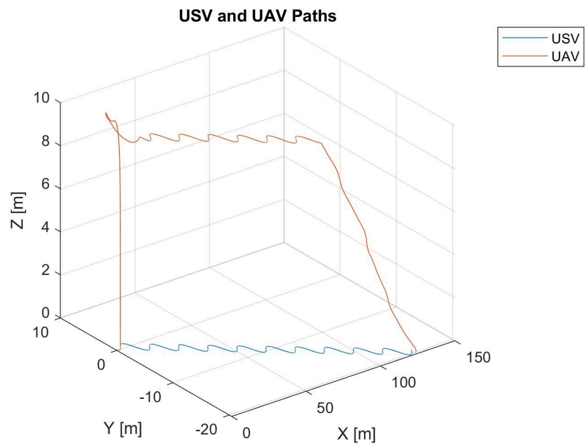

Figure 11. MATLAB simulation of UAV takeoff and slow landing on the USV

The next step was to simulate the launch and recovery sequence through a 3D simulation. The simulation software Gazebo was used to model the UAV and validate the waypoint navigation software that was developed [7]. Multiple waypoints were given to the UAV, which it would then navigate to. It would then initiate the landing sequence once it had reached the final waypoint. With the results of the simulation validating the functionality of the controller, the next step was to test the UAV landing capabilities onto the landing platform on land. The platform was placed at ground level separate from the WAM-V. The code that was validated through simulation was run and modified during the testing. The UAV was recovered by the WAM-V 90% of the time during ground testing through 27 trials. The results of the ground level tests can be seen in Figure 12 with the yellow outline symbolizing the landing platform.

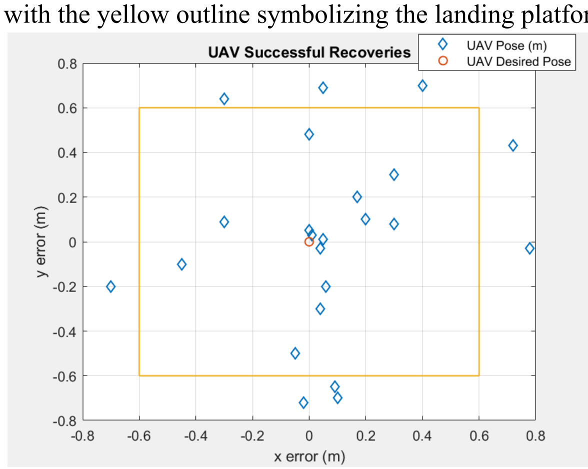

Figure 12. Landing of the UAV on the LaRP

With the validation of the system during the ground level tests, the landing and recovery sequence was then tested with the WAM-V on the water. The test consisted of giving the drone various waypoints to navigate to after launching from the WAM-V. The UAV would land onboard the WAM-V landing platform once it had reached all of the waypoints. The UAV was recovered 100% of the time through 2 trials. The full data from these tests can be found in Appendix **B.3.**

V. CONCLUSION

AMORE's AMS showcases advancements in maritime robotics, focusing on system integration and reliability for the 2024 RobotX Challenge. Testing of the AMS confirms the systems reliability for competition tasks such as obstacle avoidance and launch and recovery of a UAV from a USV. This work positions the team for success in RobotX and shows some of the broad applications of marine robotics in the real world.

VI. ACKNOWLEDGEMENTS

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In addition, the team would like to thank the LSSU School of Engineering and Technology for providing laboratory space, equipment, and software; and to all the faculty for providing ongoing technical expertise and encouragement. We would like to specially thank our faculty advisor Dr. Edoardo Sarda for unending support, motivation, and patience; and finally to our friends, family, and community for all their various support.

VII. REFERENCES

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APPENDIX

Appendix A
Component List

Component	Vendor	Model/ Type	Specs	Custom/ Purchased	Cost	Year of Purchase	Reasoning
WAM-V	Marine Advanced Robotics	WAM-V16		Purchased		2021	Needed for competition
Stern Thruster (x2)	Newport	NT300	3HP, 1300W https://newportvessels.com/products/nt300-electric-outboard-motor	Purchased	$999 each	2023	Upgraded stern thrusters, more powerful than previous. Were significantly modified for autonomous operation. Acquired through grant.
Bow Thruster (x2)	MinnKota	Powerdrive V2	55 lb thrust https://minnkota.johnsonoutdoors.com/powerdrive	Purchased	$750 each	2021	Original stern thrusters repurposed to bow. Were significantly modified for autonomous operation.
LiDar	Velodyne	VLP-16	https://store.clearpathrobotics.com/puck	Donated	$4,000	2021	Donated by Robonation
Main Computer	Nvidia	Jetson Tx2 Developer Kit	https://www.nvidia.com/jetson-tx2/	Donated	$500	2021	Donated by Robonation
Camera	Stereolabs	Zed 2i	https://www.stereolabs.com/zed-2i	Purchased	$569	2021	Chosen for senior project. Polarized lens for glare reduction.
Bow Battery (x2)	Advanced Auto	AGM Battery	12V	Purchased	$513 total	2021	Favorable battery capacity.
Stern Battery (x2)	Newport	Lithium Battery	36V 30AH https://newportvessels.com	Purchased	$799 each	2023	Favorable battery capacity. Acquired through grant.

Motion Sensors	Holybro	Pixhawk 6C Flight Controller	IMU, Compass, GPS https://holybro.com/products/pixhawk-6c	Purchased	$319	2022	Familiarity with Pixhawk flight controllers
Drone RC Controller	Radiolink	AT10 II	1 km range https://www.amazon.com/Radiolink-Transmitter	Purchased	$158	2022	Easy to integrate with GNC system
Drone Flight Controller	Holybro	Pixhawk 6C Flight Controller	IMU, Compass, GPS https://holybro.com/products/pixhawk-6c	Purchased	$475	2022	Familiarity with Pixhawk flight controllers
Drone Computer	Nvidia	Jetson Nano	https://www.nvidia.com/jetson-nano	Purchased	$209	2022	Familiarity with Nvidia Jetson products
WAM-V RC Controller	Radiolink	AT10	1 km range https://www.amazon.com/Radiolink-Transmitter	Purchased	$157.99	2021	Easy to integrate with GNC system
Drone Frame	Holybro	X500 V2	https://holybro.com/products/x500-v2-kits	Purchased	$575	2023	Affordable and easy to configure. Purchased ARF kit.
Indoor GPS	PoZYX	Creator Kit	10 cm accuracy https://www.pozyx.io/creator-one-kit	Purchased	$1,412	2021	Acquired for indoor pool testing, repurposed for drone landing platform
Vision Processor	Nvidia	Jetson Tx2 Developer Kit	https://www.nvidia.com/jetson-tx2/	Purchased	$500	2022	Purchased to process data from the vision system. Did not want to overwhelm the main computer.

GNC Connectors (x20)	CNLINKO	LP20	https://www.cnlinko.com/Products/137	Purchased	$309		Waterproof connectors for the system. IP68 rated.
Open-Source Software	ROS	Noetic	http://wiki.ros.org/noetic	Download	Free	2021	Familiarity of ROS from coursework
Algorithms	Team AMORE			Developed	Free	2021	Developed by Team AMORE as part of senior project
Vision	Team AMORE			Developed	Free	2022	Developed by Team AMORE as part of senior project
Localization and Mapping	Team AMORE			Developed	Free	2022	Developed by Team AMORE as part of senior project
Autonomy	Team AMORE			Developed	Free	2022	Developed by Team AMORE as part of senior project
Teleoperation	Team AMORE			Developed	Free	2021	Developed by Team AMORE as part of senior project
Bow Motor Controllers	RoboteQ	LDC1430	https://www.roboteq.com/fdc-mdc-family/mdc1460	Donated	Free		Used to control Minn Kota bow thrusters. Ease of use and 120A limit
Stern Motor Controllers	Newport	NK300 Board		Purchased	$8.45		Proprietary controller required for operation

Appendix B
Test Data

1. Propulsion

Various tests were conducted to ensure the functionality of the propulsion system in preparation for the 2024 Maritime RobotX Competition. The most important test for the propulsion system was the Bollard pull test. This test was conducted by attaching towlines to a point in the middle of the pontoons. The towline is then connected to the measuring end of a tension dynamometer, a device used to measure tension. A VEVOR Digital Crane Scale was used for this test. The VEVOR Crane Scale is shown in figure B.1

Figure B.1 Scale used to measure tension in towline

The other end of the dynamometer was secured to an anchoring point via a rope. For this test, the leg of a metal dock was used to anchor the dynamometer. Once the USV was secured, each set of thrusters was tested to determine a force equation that fit the force output data. This involved running a set percentage of the total throttle and reading the force reading from the scale. The equations would be used to normalize the forces output by the thrusters so that the more powerful set of thrusters would be scaled down to perform to the same level as the weakest pair of thrusters. The results of the Bollard pull test are shown in Figure B.2 and B.3.

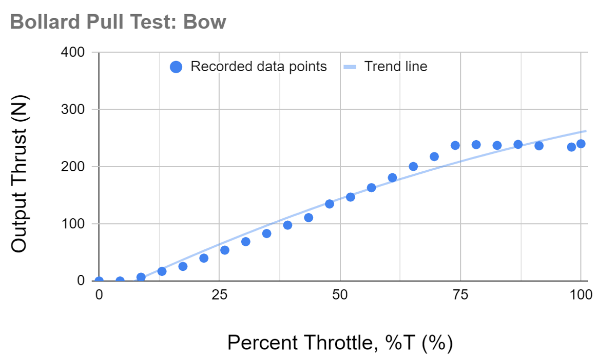

Figure B.2 Result of Bollard pull test for the bow thrusters

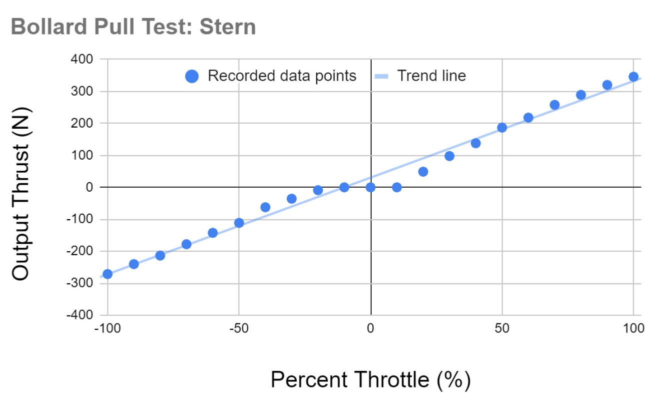

Figure B.3 Result of Bollard pull test for the stern thrusters

2. Control

In order for the control system of the USV to be considered proficient, each low-level controller had to meet a set of criterion developed by the advisor of the team based on the prior system.

The set of criterion were as follows:

- Heading and Speed Controller
  - The velocity of the USV must reach within ± 0.2 m/s of the desired velocity for a period of 3 minutes.
  - The heading of the USV must reach within ± 10 degrees of the desired heading for a period of 3 minutes.
  - The readings must be taken from the onboard compass and GPS.
- Station-Keeping Controller
  - The heading of the USV must stay within ± 10 degrees of the desired heading for a period of 5 minutes.
  - The position of the USV must stay within ± 1 m of the desired position for a period of 5 minutes.
  - The readings must be taken from the onboard compass and GPS

The tests were conducted by executing a mission using each control individually. For the Heading and Speed controller, a waypoint was given to the USV. The data from the GPS and compass were collected during the operation and were analyzed to ensure the compliance with the criterion.The MATLAB figures from testing is shown in Figure B.4.

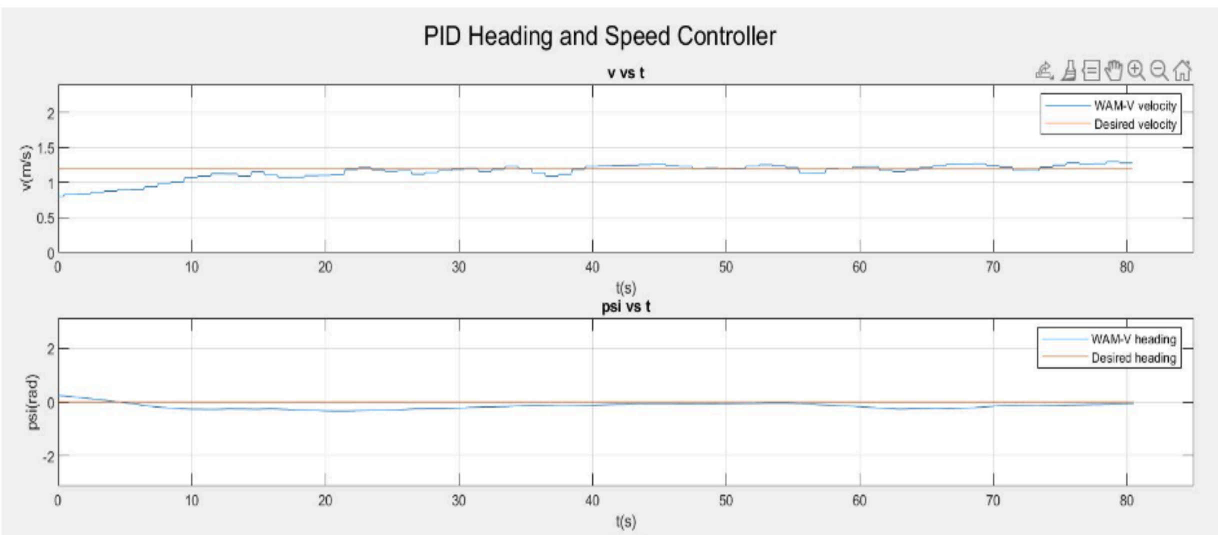

Figure B.4 Result of test using Heading and Speed controller

For the Station-keeping controller, a mission consisting of multiple waypoints was given to the USV. The USV had to navigate to each point using the Heading and Speed controller. Once it was within the range of 10m of a point, the USV would switch to using the Station-keeping controller. The USV would hold its position and heading at the desired point for a period of 5 minutes before it traveled to the next point. The GPS and compass data was collected during the mission and analyzed to ensure the adherence to each criterion. The results of the position-keeping portion of the test can be seen in Figure B.5.

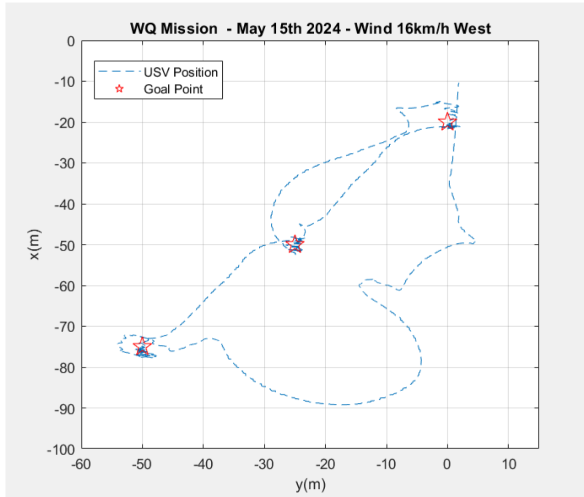

Figure B.5. Result of Water Quality Mission

3. UAV

Due to the limited amount of spare parts for the UAV, it was crucial that the Landing and Recovery sequence almost guaranteed the successful recovery of the UAV on the USV. A successful recovery is determined by if the drone landed on the platform or was caught in the netting during landing. Any other outcome was deemed a failure. To test the landing and recovery sequence, a MATLAB program was created that modeled the UAV and USV. Using the dynamic model of each system, the controller was developed for the UAV. With a functioning controller for the UAV, the USV was given a predetermined path while the UAV would launch from the USV and navigate to a set of waypoints. Multiple tests were run until the controller was properly tuned. Figure B.6 shows the successful recovery of the UAV by the USV.

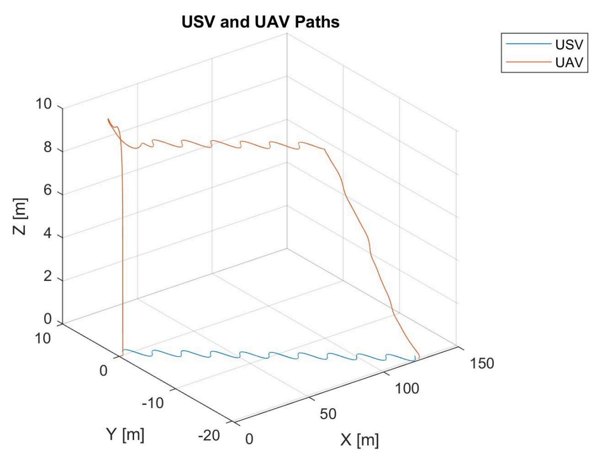

Figure B.6. Result of the MATLAB simulation of the Landing and Recovery sequence

Once the controller was developed in MATLAB, it was simulated using Gazebo to give a visual representation of the behavior of the UAV. Following the simulations, a landing platform consisting of four indoor GPS modules was constructed. The UAV would triangulate its position using the four GPS modules by using a GPS transducer [1]. The Launch and Recovery sequence was tested using only the UAV and landing platform. The landing platform was placed on the ground for the initial tests. The results of a trial of the stationary platform testing is shown in figure B.7.

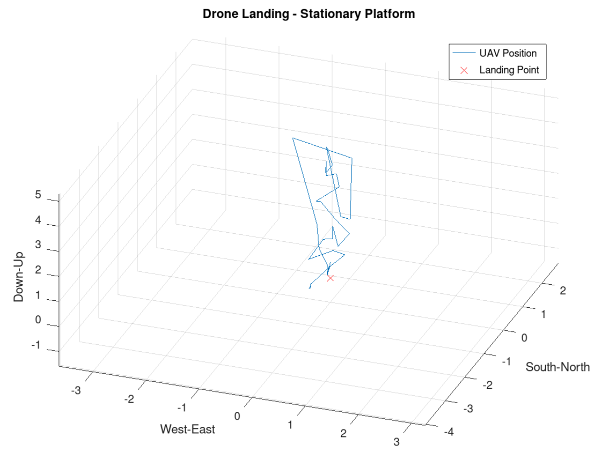

Figure B.7 Launch and Recovery sequence of UAV on stationary platform [1]

The results of the stationary platform landing are shown in Table A.1.

TABLE A.1 - PERCENTAGE OF RECOVERIES ON LARP ON GROUND [1]

Trials	Recoveries	Board	Net
15	73.3%	63.6%	36.4%

The next stage of testing was to place the landing platform on top of the USV. The same landing and recovery sequence was run with the USV on a trailer on land. The setup for this test is shown in Figure B.8.

Figure B.8 Landing and Recovery sequence testing on land [1]

The testing was conducted in the same manner as with just the landing platform. The results of a test run is shown in Figure B.9.

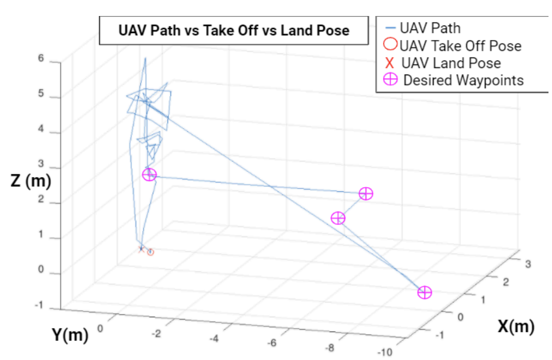

Figure B.9 Results from a test run of the Landing and Recovery Sequence with the USV on land [1]

The results of this testing is shown in Table A.2.

TABLE A.2- PERCENTAGE OF RECOVERIES ON THE USV ON GROUND [1]

Trials	Recoveries	Board	Net
10	90%	70%	20%

With the results of this round of testing deemed as successful, the Landing and Recovery sequence was tested with the USV on the water. The USV was set into the water with its motors shut off. The USV drifted while the UAV underwent its Launch and Recovery Sequence. The results of a test run are shown in Figure B.10 and B.11.

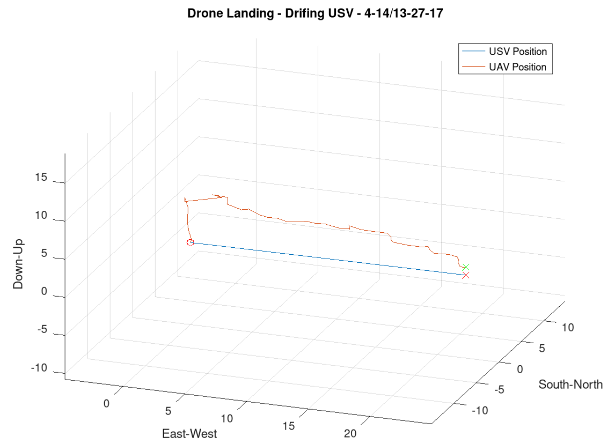

Figure B.10 3D Plot of the USV and UAV path during the Launch and Recovery sequence [1]

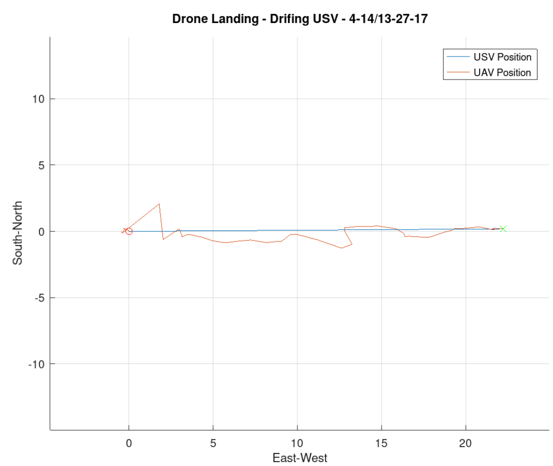

Figure B.11 2D Plot of the USV and UAV path during the Launch and Recovery sequence [1]

The results of every trial of the Launch and Recovery sequence is shown in Table A.3.

TABLE A.3 - PERCENTAGE OF RECOVERIES ON LARP ON WATER TESTING [1]

Trials	Recoveries	Board	Net
2	100%	50%	50%

After each phase of testing the Launch and Recovery sequence, it was determined that it was performing to the standards required for the 2024 Maritime RobotX Challenge. The UAV was able to land in conditions with wind up to 14 mph and rain, so the UAV was considered to be ready for the competition.