Design of a Robust Autonomous Maritime System for RobotX 2024 and Beyond

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***Abstract*—The Maritime RobotX Challenge presents a series of interconnected tasks involving perception, navigation, and interaction performed by an Autonomous Maritime System, a set of multi-domain vehicles centered around the operation of a large surface vehicle. For the 2024 challenge, a system was developed with a primary objective of robust surface vehicle navigation and communication between the vehicles and ground station.**

I. INTRODUCTION

The Maritime RobotX Challenge promotes the development of Autonomous Maritime Systems (AMS) centered around a large autonomous surface vehicle (ASV), specifically built on an OPT WAM-V 16 chassis. Previous challenges have included collaborative autonomous underwater vehicles. In 2024, the challenge incorporates a companion unmanned aerial vehicle (UAV). It is uncommon for teams to be able to successfully complete all tasks, and many of the winners have platforms that have been built over many years. In order to demonstrate competence across all tasks, it is important to have a stable platform upon which new task-specific components can be added.

Past entries from Georgia Tech (GT) have often been individual instances with teams composed of different people, resulting in completely independent architectures between competitions. Due to unexpected hardware limitations encountered by the GT team in RobotX 2022, the upcoming entry consists of significant hardware upgrades. However, as a result of an emphasis in training, the creation of knowledge bases, and continuity of development through multiple maritime systems projects, the latest iteration of the system inherits the positive design aspects from the previous AMS and other vehicles.

The design of an AMS involves a considerable trade space, as there is an individual trade space for each vehicle as well as that for the system of systems itself. With the specifics of the challenge changing between iterations with full rules released close to competition dates, it is important that the AMS is built on a flexible and robust framework. The overall design philosophy of the latest iteration is for adaptability built on a strong foundation, so that missions can be quickly defined, created, and tested.

The System Implementation was redirected to a modular approach for vehicle architecture, with a focus on robustness, redundancy, and simplicity. Each system is divided into four primary subsystems: communication, power, propulsion, and software. These subsystems were managed by designated teams to enable parallel development while maintaining safety as a critical factor in both design and procedures.

II. COMPETITION STRATEGY

The competition strategy concentrated on creating a reliable and adaptable system capable of handling multiple tasks in changing environmental conditions. Given the complexity of the RobotX competition, this approach prioritized autonomous navigation and object detection performance, which are crucial for most tasks. Navigation was prioritized to ensure accurate path planning and obstacle avoidance, while robust computer vision processed the large amounts of visual guidance across the course. The performance of these two core functions was essential to demonstrate the capabilities of both the USV and UAV.

Fig. 1. The starboard OAK-D stereo camera.

For object detection and classification, both vehicles were equipped with cameras and LiDAR to classify buoys, platforms, and other objects. The computer vision algorithms were trained to recognize colors and shapes under varying light conditions, while the control system enabled precise approaches to targets such as the light tower, floating platforms, and helipads.

To maintain system reliability, the design was intentionally simplified by dividing the system into smaller subsystems. Core functions like object detection and navigation were centralized in the main computer and microcontroller, while smaller tasks, such as controlling auxiliary systems like the light tower and voltage alerts, were handled by additional microcontrollers. This approach, aided by ROS2 and micro-ROS, minimized risks from overly complex programming and facilitated easier integration of secondary tasks.

Flexibility was also considered, allowing adjustments based on team expertise and performance. The redundancy in the sensors was designed to make sure that critical tasks can be completed even in the event of a subsystem failure. This adaptability maintains consistent performance throughout the competition and allows the vehicles approach all tasks effectively.

III. DESIGN STRATEGY

The design integrates the WAM-V, UAV, and base station into a system-of-systems architecture. Each component is designed to emphasize redundancy and reliability under competitive conditions. The surface vehicle and UAV communicate through Wi-Fi, allowing each vehicle to maintain autonomy while collaborating through information sharing, which is crucial for task completion during the competition.

A. *The Autonomous Surface Vehicle*

The current system presents a significant upgrade from previous versions. Key modifications include implementing new motors, upgrading the main computer, and transitioning to more reliable communication hardware. These improvements required the redesign of the control and navigation algorithms and the WAM-V's power distribution system.

Motor power on the WAM-V is derived from two Torqueedo 26-104 batteries. DC-DC Buck converters provide regulated power from one of these batteries for the various computing systems on the WAM-V.

The surface vehicle is equipped with three stereo vision cameras and a 3D LIDAR, enhancing sensing capabilities from multiple angles. Two outboard motors were selected for their ability to provide sufficient power during challenging conditions, such as wind stress and water currents. Each motor operates with a dedicated battery, allowing for easier monitoring and management of power distribution during operation.

The software subsystem is divided into sensing and control functions. An environmental map is generated and continuously updated with obstacle data, enabling effective path planning for the vehicle. The software is based on ROS2 and micro-ROS, which are essential for managing autonomy tasks.

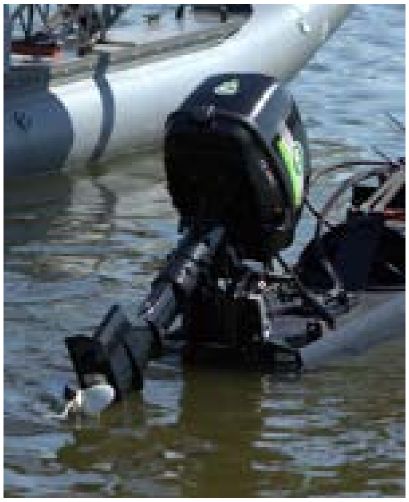

Fig. 2. One of two upgraded outboard motors (prior to propeller guard installation) in a stowed configuration. Note that this photo was taken before the completion of the yaw mechanisms.

As previously mentioned, the sensing subsystem updates the maps based on sensor inputs and obstacle detection, with a focus on sensor fusion and point cloud stitching from the cameras and LIDAR. This information feeds into the path-planning algorithm, which generates a navigational path for the control system to interpret and guide the WAM-V effectively. The control consists of a line-following strategy for the two rear motors [references]. Additionally, a yaw angle control mechanism simplifies navigation and adds to station-keeping capabilities.

B. *The Unmanned Aerial Vehicle*

The UAV selection and design strategy was heavily influenced by the tasks designated to be completed solely by an aerial vehicle, which are the UAV replenishment and Search and Report tasks. The UAV replenishment task requires a UAV to launch from the WAM-V, locate a platform containing colored tins, collect a colored tin, and then deposit the tin on another platform before returning to land on the WAM-V, and

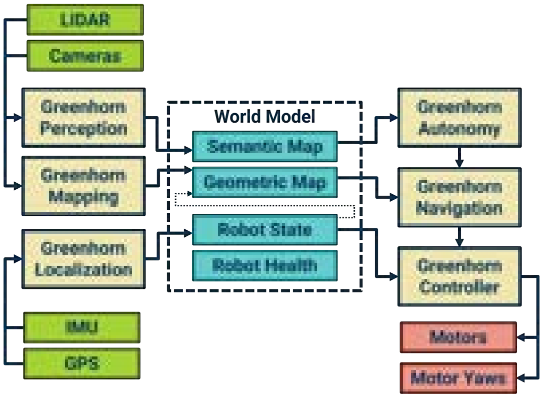

Fig. 3. Software subsystem architecture.

Fig. 4. The UAV in flight during testing.

the Search and Report task requires a UAV to takeoff from a platform and search a field for two letter markers, report the location of the markers, and then return and land on the launch platform. The UAV replenishment task required that the UAV must be light enough to be carried by the WAM-V, and other additional constraints that had to be adhered to was that the UAV must have the ability to float on water, be able to operate in varying weather conditions and have a maximum takeoff weight of 55lbs.

To accomplish these tasks while adhering to the aforementioned constraint, it was deemed necessary for the UAV to weigh less than 10lbs and have a width of 22 - 18 inches, to be able to conveniently fit on the WAM-V and have an endurance of 20mins while lifting a camera payload. Then we iteratively select an appropriate combination of frame, propellers, batteries, sensors and electrical components that could meet these requirements.

1) UAV Subsystem Selection: To meet the above requirements, the four-rotor Holybro X500-V2 carbon-fiber frame was selected as the frame of choice because it is significantly lighter and stronger than the six-rotor plastic configuration used in the last competition. This frame configuration also provided enough room to house the sensors and other electrical components.

Next, we select the motor and propeller combination that could provide sufficient thrust to lift the estimated takeoff weight of the UAV. A motor specification that influenced this ability is its Kv rating, which specified the number of rotations per minute a motor will spin per volt provided. This typically ranges between 800 – 2000 Kv. Higher Kv motors produce less torque but will spin faster than lower Kv motors, but lower Kv motors have more torque to turning larger propellers making them suitable for the current application. After careful consideration and market survey, four Holybro 920 Kv motors, each paired with 1045 Propellers were selected as our propulsion elements of choice. The maximum current draw expected from each motor is 18A, as such we select four 20A electronic speed controllers to be connected to each motor to deliver timed electric signals to control its rotation.

With the motors, propellers and speed controllers selected, we then calculate the estimated current required to conveniently power all components for a sustained amount of time, and based on this, a 30C 5000mAh 4S lipo battery was selected.

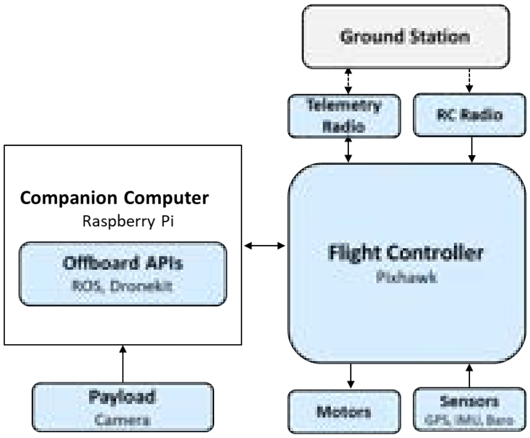

Fig. 5. UAV Architecture.

Other sensors and components attached to the UAV include a GPS, telemetry link for two way communication between the ground station and the UAV, a Pixhawk flight controller and a Raspberry Pi.

2) UAV Software Architecture: The software architecture adopted for the UAV follows a two-tier configuration. A Pixhawk flight controller running on the open-source Ardupilot flight stack for low-level stability and control and a Raspberry Pi companion computer running on Ubuntu 22.04 responsible for high level autonomy and offboard control. The companion computer interfaces with the flight controller using both ROS 2 middleware and the Dronekit API to implement a state machine that governs the task execution.

IV. TESTING STRATEGY

The testing strategy involved a combination of simulation and in-water testing to ensure a thorough evaluation of the components and subsystems of each system. During the development of propulsion electronics, the software teams utilized Virtuoso, a simulation software developed by the lab, to test and refine the algorithms. This dual approach allowed for the early identification of potential issues before real-world deployment.

The test related to sensor fusion was on stitching data from multiple sensors to recognize objects from different perspectives, identify anomalies and reduce overlapping errors. Control systems were tested in both clear conditions and in the presence of obstacles. The communication systems were evaluated for range and reliability, particularly in terms of data sharing between the vehicles and the ground station. Additionally, UAV tasks are tested using printed markers on land to simulate the tasks competition scenarios.

Virtuoso facilitated the simulation of several system elements, including cameras, LIDAR, GPS and motors, while incorporating obstacles into the virtual environment, and in parallel, In-water testing played a crucial role in evaluating system performance in real-world conditions. These tests focused on identifying buoys and navigating along a defined path, accounting for environmental factors such as varying light conditions and water flow, which could affect the vehicle's course. Power components and battery withstood the tasks endurance as designed. As physical integration progressed, regular in-water tests were scheduled almost every weekend leading up to the competition.

Potential risks identified during testing include communication delays between the boat and ground station when sharing data during autonomous operations. To mitigate these risks, the team upgraded to long-range Wi-Fi equipment and a faster processing computer to improve communication reliability and processing speed. Continuous data collection during these tests allowed post-mission analysis, helping debug errors in decision-making and identify sensor processing challenges under real-world conditions.

A. *Simulation*

Simulation testing was performed to show proof of validity for new autonomy concepts. The VRX environment presented in [**VRX**] was used for simulation and the default vehicle was modified to match the propulsion and sensor configuration of the real vehicle.

B. *Dry Testing*

Dry tests were performed out of water before any ”wet” test. These tests are necessary to show that all critical systems, in particular those related to safety, function as expected. Dry tests were also used to develop and refine test procedures and checklists. As dry tests were performed both in lab and in the field, they allowed for team members to become comfortable with procedures before testing in uncertain field environments.

C. *Field Testing*

Field tests were performed at Sweetwater Creek State Park located 30 minutes east of Georgia Tech's main campus. This location provided easy access to the water, a dock for performing in water tests, and a suitable variety of conditions. The lake at Sweetwater Creek State Park is sufficiently large that on windy days controller robustness to disturbance could be tested.

V. COMPETITION STRATEGY

A. *Perception*

The integration of LiDAR and camera data is essential for robust obstacle detection, object identification and autonomous navigation of the WAM-V. A geometric grid map is created to register the location of obstacles. To accurately populate the map, point cloud data from the LiDAR and three cameras are fused together for data noise reduction and to provide richer contextual information. The depth data from the stereo cameras are combined with the color data from the RGB cameras to produce a point cloud that stores color information. LiDAR compensates for inaccuracies in depth perception from stereo cameras, while cameras provide contextual information such as the color of the buoys. The fused data is further processed by applying Euclidean clustering to group obstacles and implementing grid-based downsampling to allow efficient real-time computing.

The AMS also needs to navigate through gates marked by colored buoys and interpret RGB light sequences from towers. Object recognition is done by employing three cameras, covering a combined horizontal field of view of 285 degrees. The RGB images from the OAK-D cameras are combined into a panoramic image using homographic transformation. This combined image is then processed through a YOLOv8 model, custom-trained using advanced deep learning framework to accurately recognize buoys, light towers, and other objects. The identified objects are stored in a semantic map, which is continuously updated to reflect the dynamic nature of the environment.

B. *Controls*

Controls are an important enabler of autonomous behaviors. Given the emphasize on guidance, navigation, and control, considerable effort and thought was put into the development of controllers. The overall controller is split into a path following controller and a station-keeping controller. In the dual aft-facing motor configuration the vehicle can be considered underactuated. That is to say, for a 3D model (surge, sway, and yaw), only two of the states are actuated. The motors easily provide effort in the surge and yaw axes, but cannot provide any effort in the sway axis. Fortunately, this is a fairly common issue on surface vehicles. A line of sight control strategy was adopted from [**fossen˙underactuated**]. This controller was highly effective when combined with the WAM-V dynamic model estimated in [**wamv˙dynamics**].

Underactuated station-keeping is a hard problem and most solutions do not provide consistent station-keeping and instead maintain a region of states near the desired states. This problem was addressed by introducing a motor yawing mechanism thus making the vehicle fully actuated. This mechanism rotates the motors off of the directly aft-facing default which reduces the maximum surge thrust. For this reason, the rotated configuration was only used when station-keeping was

Fig. 6. The WAM-V undergoing field testing at Sweetwater Creek State Park

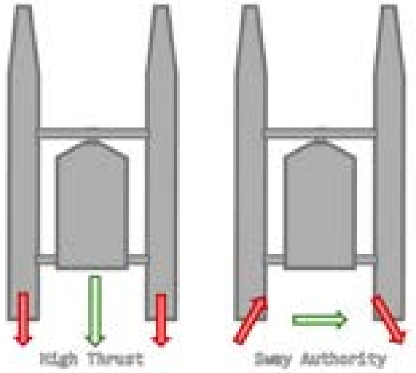

Fig. 7. The two motor configurations used during path following and station-keeping respectively.

absolutely necessary. The controller for this configuration was a combination of one PID controller for each state.

C. Autonomy

The autonomy subsystem is structured so that new tasks can be easily added and existing tasks can be modified without affecting others. The overall autonomy for RobotX 2024 was implemented as a state machine operating on a ”main” ROS node. This node manages an individual run of tasks (qualification, semi-final, etc.) in a simple state machine built up from the various individual task classes. These task classes provide their own internal state machine to manage the progress through the task. All task state machines also provide feedback and a result which allows the the high-level state machine to make decisions on when a task should be abandoned and how to proceed once it is completed.

Each task specific class inherits from a base Task class which provides functionality for a number of key capabilities. This includes preprepared ROS actions for the aforementioned the control algorithms that provide path following and station-keeping. As the competition strategy heavily emphasized guidance, navigation, and control, most task-specific state machines primarily operated through these actions. Additional actions such as code-reading and circling allowed more unique tasks to operate. Because tasks are composed of a series of repeated actions, this structure is easily extended to new tasks.

D. Task Prioritization

Except for Situational Awareness & Reporting (task 1), which extents on the entire competition and holds the highest priority, task prioritization was based on tasks involving autonomous navigation and object detection performance, arranged from lower to higher difficulty. Another factor in prioritizing tasks was the likelihood of scoring all available points, constrained by the hardware developed for the ASV before the competition deadline.

Besides task 1, Scan the Code (Task 5) involves most of the competition and was given high priority. Significant effort was invested in developing the capability to process the light tower data sequence displayed in the wide camera view.

Follow the Path and Wildlife Encounter present the greatest challenge, requiring a combination of perception, control, and autonomy. These tasks were prioritized because they help develop the skills necessary for completing the remaining competition tasks.

Dock and Deliver was deprioritized for later attempts, as the vehicle is capable of station keeping, but lacks an integrated ball shooter. Similarly, the ASV does not include a hydrophone for the Entrance or Exit Gates. Nevertheless, even without these elements, the team will still seek to complete these assignments with the highest possible score.

In the tasks involving the UAV, Search and Report was prioritized and enhanced based on the performance in the last competition, with the intention of improving results this time. The Replenishment task was prioritized as the second most important. However, an attempt to perform Replenishment in the water will be made during the competition.

VI. FUTURE WORK

Further work will emphasize the more complex aspects of autonomy and cooperation between agents. With the WAM-V as a (fairly) stable platform for integrating new ideas, expanding into the operation of multiple agents is feasible. The lab recently acquired 4 BlueBoat USVs which are much smaller and more easily transported. The autonomy stack developed for RobotX 2024 will be used for proof-of-concept testing as a more cooperative stack is developed for the BlueBoats.

Another area of future work will be into improving the collaboration and coordination between the UAV and WAM-V. The UAV offers an aerial perspective which no surface vehicle can achieve. The WAM-V will be updated to use the UAV as an asset for collecting unique perspective data in order to aid in more advanced navigation.

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APPENDIX A
COMPONENT LIST

Component	Vendor	Model/Type	Specs	Custom/Purchased	Cost	Year of Purchase
Waterproof Connectors	Mouser	M12 Code A + L	5, 8 and 12 pin modes and their cables	$1,537.98	2024	
Propulsion	Elco Motor Yachts	EP-5 Outboard Motors	Long Shaft Remote Throttle	Purchased	$9450.00	2024
Power System	Torqueedo	Power 26-104		Purchased	N/A	2016
Motor Controls	Teensy	Teensy 4.1	Teensy 4.1 Specs	Purchase	$31.50	2023
CPU	Dell	Precision 3280 Compact Workstation	32 GB: 2 x 16 GB, 512 GB, RTX A2000	Purchased	$1,889.00	2024
Teleoperation	Doodle Labs	Doodle Wearable Mesh Rider	900 + 2.4 GHz; 2.4 GHz	Purchased	$7,050.00	2024
Compass	ArduSimple	ArduSimple RTK	Compass Specs	Donated	$619	2020
Inertial Measurement Unit (IMU)	LORD MicroStrain	3DM-GX3-25	IMU Specs	Purchased	$2640	2017
Camera	Luxonis	IMX370	OAK-D W Pro PoE	Purchased	$1797.00	2024
Vision	OpenCV, YOLOv8					
Open Source Software	Python, C++, ROS2, micro-ROS					

APPENDIX B
ELECTRICAL CIRCUITS

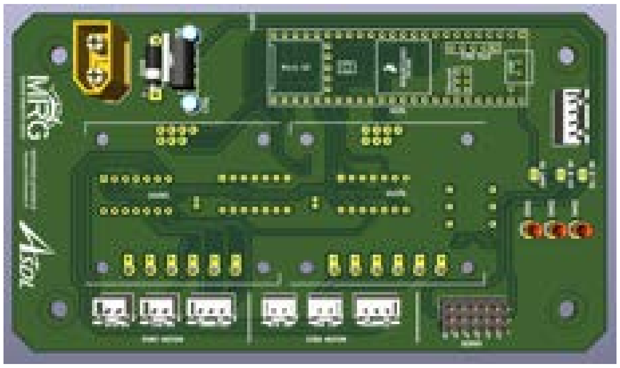

Fig. 8. Custom Motor controller PCB. Implements WigWag control of Elco EP-5 motors through digital potentiometers.

Fig. 9. Custom Buck Converter PCB. Regulates battery voltage to supply WAM-V's network switch

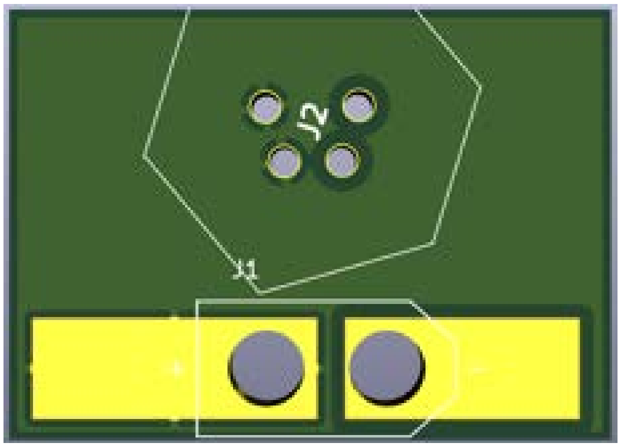

Fig. 10. Custom M12 Amphenol to XT60 PCB. Used to allow for waterproof regulated power to enter main computer box.