The Design of an Autonomous Surface Vehicle for the 2018 Maritime RobotX Challenge

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***Abstract*— Creating an autonomous ASV for operations in marine environments presents a unique set of design challenges. This paper provides an overview of the design and development of the University of Michigan's autonomous surface vehicle (ASV) for the 2018 AUVSI Maritime RobotX Challenge. The evolution of the design over the course of the project is outlined in the context of the design strategy and reasoning for design decisions made to address the unique challenges. Detailed descriptions are provided to outline both the physical layout of the vessel as well as the logic used to design the systems on-board to support autonomous functionality. This encompasses vessel design, sensor selection, software architecture, and the logic for completing the competition tasks. The testing of these systems is described as it pertains to design changes, validation and verification (V&V), and ongoing work.**

I. INTRODUCTION

The Maritime RobotX Challenge is held every two years with the purpose of engaging students and industry partners around the Pacific Rim in high level competition to create a fully autonomous unmanned surface vehicle (USV) for the challenging maritime environment. The vehicle also may be used for multi-domain operations such as incorporating unmanned undersea vehicles (UUVs) or unmanned aerial vehicles (UAVs) [1].

The University of Michigan (UM) entered into the challenge for the first time in 2018. The goal of the team of UM students, primarily led by Ph.D. students in the department of Naval Architecture and Marine Engineering, was to incorporate new design ideas and to leverage a background in naval architecture to bring a novel approach to the challenges presented.

Michigan RobotX utilizes the Marine Advanced Research Inc. 16' WAMV-V USV as the base platform for the design. The WAM-V was donated by the AUVSI Foundation after being awarded at the 2017 RobotX Forum in Sydney, Australia. Marine Advanced Research, Inc. designed the WAM-V and the model was introduced in 2014 after being chosen by the Office of Naval Research (ONR) as the sole platform for the RobotX Challenge [2].

The resulting vehicle is a modular and robust platform that is cable of being easily modified to approach new challenges as tasks evolve. The vehicle, shown in Figure 1, is able to be torn down or rebuilt in only one to two hours and can be easily packed into several cases and crates. With a top speed of approximately five knots, the vehicle can navigate quickly and efficiently in a wide range of operational environments.

The remainder of this paper will discuss the design drivers and the final vehicle design that was chosen for the 2018 Maritime RobotX Challenge.

Fig. 1. The University of Michigan autonomous surface vehicle during testing on July 18, 2018 on Strawberry Lake in Michigan, USA.

II. DESIGN STRATEGY

The design strategy of the Michigan RobotX Autonomous Surface Vehicle (ASV) focused on reliability, simplicity, and safety. The WAM-V platform did not arrive until the end of February 2018, which left only eight months to design, construct, and test the vehicle. Michigan fall and winter seasons presented additional limitations on the final date in which the ASV could be tested due to freezing temperatures on the water. Given the significant time constraints, initial design decisions prioritized the ability to deploy the vehicle by the end of May (approximately three months) to maximize test time on the water over the summer. These initial choices were significant factors, and in many cases drove the appearance and functionality of the final product.

The Michigan ASV evolved rapidly to ensure the hardware was working on the water early after the vehicle was delivered. For this reason, commercial off-the-shelf (COTS) products were selected wherever possible to speed up design and installation timelines. This reduced the overall flexibility of the design, but increased the speed at which the design could be implemented. The vehicle was built in a small storage locker due to limited space on campus, which presented a number of spatial constraints in developing the ASV. Additionally, all testing was conducted on Strawberry Lake, located approximately 20 miles North of Ann Arbor. This resulted in a requirement to quickly disassemble and reassemble the vehicle for transportation every time it was to be tested. As a result of these limitations, the vehicle was designed to be simple and modular, by requiring that the ASV be broken down or reassembled within one to two hours, in relatively small spaces, and for all equipment to be easily transported using an enclosed trailer.

This strategy began by designing the top rack. The goal was to ensure that all hardware elements fit above the primary sensor rack to allow for future expansion opportunities below the rack, such as adding autonomous underwater vehicle (AUV) or remotely operated vehicle (ROV) launch and recovery capabilities. The design was simplified and modularized by adding removable cases containing hardware equipment on top of the rack instead of manufacturing complicated rack mounts to go below the payload tray. This proved advantageous for assembly, disassembly, and transport of the ASV. This design choice also allowed for room to be reserved for the later expansion of an ROV or AUV beneath the main sensor tray which would help maintain a low center of gravity. The top rack would also allow a platform to be added to allow an unmanned arial vehicle (UAV) to be added at a later date as well.

The top rack was designed from 80/20 which is a modular aluminum system. The advantage of this was that elements can be added, removed, or modified easily with minimal impact on the vehicle. The system also allows for easy installation and removal of sensors, such as the camera, GPS, and LiDAR systems on board, which facilitated quick deployment and recovery.

The design avoided elements that would limit the ability and ease of transport of the vehicle. Specifically, lead-acid batteries were chosen over lithium-ion batteries. This allowed the transportation of the vehicle to be less complicated due to federal and state hazardous material (HAZMAT) requirements, and the overall product was significantly less expensive allowing funds to be freed up to invest in other areas of the vehicle.

In addition to maximizing the vessel's modularization, an underlying design strategy for the ASV was to leverage naval architecture principles to improve the overall design. For example, the decision was made to locate the batteries low on the vessel's vertical plane to decrease the vehicle's center of gravity, and increase stability performance. The shock absorbers connecting the pontoons to the payload tray were tuned using marine dynamics principles to mitigate sensor motions. Resistance calculations were performed to inform thruster and propeller selections. Given the team's unique background in marine design, all design decisions were considered in the context of a vehicle operating in a marine environment to maximize reliability and operational performance.

The software for the vehicle was mainly written in Python and C++. Robot Operating System (ROS) was selected to provide the communication environment for the scripts to run, and act as the backbone of the software system. ROS was selected given its widespread use in the Robotics community, its extensive documentation, and its ability to handle all elements of the operation of the ASV.

III. VEHICLE DESIGN

This section is broken down into three sections: acting, sensing, and reasoning. The acting section describes how the ASV physically acts using information it is provided, and mainly focuses on the hardware used to drive the vehicle. The sensing portion describes how the vehicle perceives the world around it using a multitude of sensors. The reasoning portion describes how the vehicle interprets the sensed information, and transmits appropriate information to the hardware to perform actions.

A. Acting

1) Layout: The Michigan ASV was designed to be modular in order to easily setup and tear down the vehicle. This began with the top rack, shown in Figure 2, which is made of 80-20, a modular aluminum product, with all components fitting inside of Pelican cases which fit inside the rack. Sensors, antennas, and additional components are then added on to the rack easily.

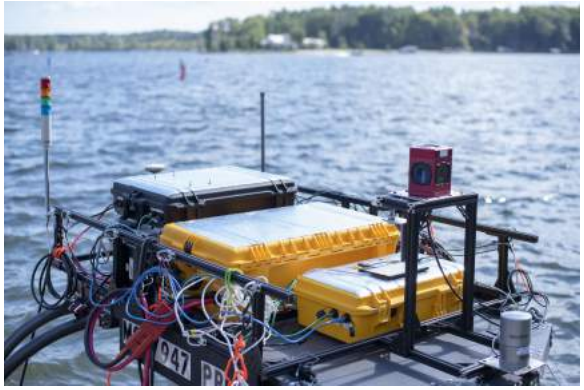

Fig. 2. The top rack of the ASV, constructed of modular aluminum bars with commerical-off-the-shelf components.

The three main cases are separated based on function. Located at the aft end of the rack, the first case contains the primary computer as well as the motor controllers. The middle case contains the primary electrical distribution system, emergency stop system, and the IMU. The forward-most case contains the network interface and additional sensor interfaces. All three cases were designed to be waterproof by incorporating watertight bulkheads for all cable runs and maintaining the integrity of the case so far as possible. All cases were designed to have positive buoyancy individually to ensure that they would float and be able to be retrieved in case of an accident in which they fell off of the vehicle.

The aft-most case contains a high performance computer and power inverter used to provide power to the computer. These electronics output significant heat while operating, which presented a unique challenge to cool the case. To ensure this case remains at operational temperatures, a thermoelectric air cooler was installed in the side of the case. The unit, built by TE Technology, is capable of removing 229 Watts of heat. The unit is IP68 rated, ensuring the case remains waterproof [3]. This was the primary factor in selecting the air cooling system as opposed to fans to vent the case. Cases are also covered in a reflective surface to reduce the impact of the sunlight on heating the cases. Additionally, silica packets were added to the case to prevent moisture in the air from condensing on the electronics. No other cases contain active cooling elements.

2) Propulsion: The boat is propelled primarily by two Minn Kota RT-80 EM motors. These motors, shown in Figure 3, each produce 80 lbs of thrust at full power [4]. The motors came stock with a two-bladed propellers; however, after testing the propellers, a significant amount of cavitation was observed. Cavitation leads to poor efficiency, degraded performance, and long-term degradation of the propeller. To combat cavitation, three-bladed propellers were sourced and installed on the motors. In order to speed up the design process, a commercially available propeller was selected, though ideally a propeller would have been designed and tested specifically for this vehicle. The new propellers reduced the observed cavitation and increased the efficiency of the motors by 20%. This resulted in less consumed power, higher thrust, and an increased the top speed of the vehicle.

The motors are powered by 24 VDC. As the largest power consumer on board the vessel, the main electrical distribution system was set to 24 VDC to match the requirements of the motors. Under normal use, a simple potentiometer controls the motors which is operated manually. To be compatible with the autonomy system this controller was replaced by an Arduino Mega 2560, sending a pulse width modulation (PWM) signal through an R-C circuit to the motor control unit that was provided by the manufacturer. The R-C circuit was introduced to minimize time-delays from the controller to the motors, and smooth the signal sent to the motors.

Fig. 3. The motors, shown in the out-of-water configuration which allows the vehicle to be brought into shallow areas without damaging the propellers.

The motors are attached to the transom stern via a hinged aluminum bracket. The hinged design allows the motors to be pulled up out of the water for the initial deployment of the ASV in shallow water environments such as at a boat ramp or on a beach. The motors are fixed facing forwards to maximize forward speed, and thus cannot provide directed thrust. It was initially hypothesized that eliminating directed thrust would reduce maneuverability; so the decision was made to install additional lateral thrusters. Yaw motions are generated by providing differential thrust to the two aft motors, while vessel sway motions are provided using the lateral thrusters. Preliminary testing showed excellent maneuverability over a range of speeds, even in adverse environmental conditions.

To assist in the docking task, allow for enhanced station keeping, and improve overall maneuverability, the design decision was made to install lateral thrusters to enable pure sway movement. It was decided to size the thrusters to enable lateral movements in 10kts of wind, at a forward operating speed of 1 knot, in currents of 1 knot. In order to determine the size requirements of the lateral thrusters, geometric measurements from the WAM-V were used to calculate projected areas both above and below the waterline at relative wind and current headings of 10° increments over a full 360° range. These projected areas were then combined with estimated drag coefficients for the various shapes represented on the vehicle, to determine the total drag force on the vessel at each corresponding heading increment. Using these calculations, a polar plot was created to visualize the maximum force required to be overcome, shown in Figure 4.

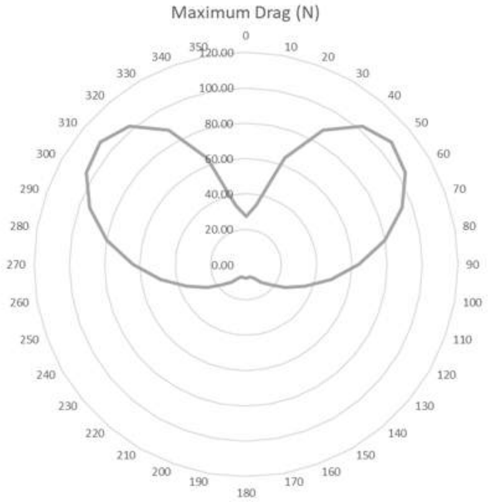

Fig. 4. A polar plot displaying the required thrust from lateral motors given the relative heading of the ASV.

Using the results of the polar plot it was determined that the lateral thrusters would need to provide at least 14.4 lbf (64 N) of pure lateral thrust, and thus were sized to be much larger to account for errors in the estimation, and enable increased flexibility in operations. Four Blue Robotics T200 thrusters were selected as the lateral thrusters. These electric thrusters are specially designed for marine use, and their compact size results in low drag when the vessel is underway and they are not in use. These thrusters are powered from a 12V DC circuit on-board, and each provide a thrust of up to 7.8 lbf, for a total lateral thrust force of 31.2lbf [5]. Additionally, these thrusters are able to be operated in forward and reverse, providing thrust in both lateral directions. The thrusters are controlled from four independent electronic speed controllers (ESCs) which require PWM signals for control. The PWM signals are provided by the same installed Arduino Mega 2560 that controls the main forward thrusters, which interfaces with ROS via a serial connection to the master computer.

Two hinged brackets were created to mount the T200s, one of which was mounted to each pontoon near amidships. The brackets enable the thrusters to be oriented transversely, and extend below the keel line to prevent the flow of water from interfering with the hulls. As these brackets are hinged, the thrusters can be lifted out of the water in shallow waters, and for launch and recovery of the vessel. Each of these bracket has two thrusters installed. To enable movement in pure sway, the thruster mounts were located at the approximate center of buoyancy of the WAM-V effectively decoupling any yaw movements from sway. Upon testing the setup, it was clear that the additional resistance of the rear mounted motors was still leading to yaw motions, so the mounts were shifted forward until the yaw was effectively nullified.

Two independent PID controllers were designed and implemented to control the linear and angular velocities of the WAM-V, respectively. It was determined that these two parameters would be best to implement controllers on due to the ease of integration into the ROS Navigation package. This package provides the path planning, used to prescribe the required linear and angular velocity setpoints for which the PIDs require. The control layout is shown in Figure 5.

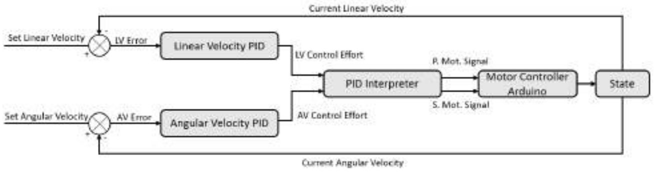

Fig. 5. The layout of the PID control system.

TABLE I

THE TUNED PID VALUES.

PID Parameter	Linear Velocity PID	Angular Velocity PID
K_p	450.0	450.0
K_I	30.0	200.0
K_D	15.0	10.0

The outputs of each PID is fed into a PID interpreter, which takes the control efforts from each PID and converts those to signals to send to the port and starboard motors. The PID interpreter contains the logic for how to prioritize each control effort. It was decided that the angular velocity should be prioritized over the linear velocity, to ensure proper heading control, and good path following characteristics, while potentially sacrificing speed. The output of the PID interpreter yields signals to pass the to the Motor controller Arduino to control the port and starboard motors. These signals are then used to determine the WAM-Vs state, in terms of the both the current linear and angular velocities, which are then fed back to the beginning of the control loop. The linear and angular velocity data is provided by the on board inertial measurement unit (IMU).

The PIDs were tested and tuned, and satisfactory system behaviors were observed using the parameters shown in Table I.

3) Electrical: As mentioned in the previous section, the main electrical distribution is a 24 VDC system. The vehicle is powered by four 105Ah 12V AGM Dual Purpose lead acid batteries. There are two banks of two batteries each wired in series to bring the bank to 24 VDC, with the banks then tied together in parallel in order to extend the time that the unit can run. Additional systems on board require 48 VDC, 12 VDC, and 5 VDC. There are DC-DC power converters to step down or step up the voltage as necessary for these systems.

The main on-board computer runs on 120 VAC, which is supplied by a 1000W power inverter located next to the PC in one of the cases. Ideally, the PC would have run directly off the DC circuit, since the individual components in the computer are running off DC power and it is well known that transforming from DC to AC and then back to DC is inefficient. However, in the time allotted to get the ASV initially built and on the water, finding a DC power supply compatible with the computer was not feasible, and the high performance computer was selected to allow for high processing power.

In case of emergency, there is an emergency stop system on board that will cut power to all systems except for the status light. The emergency stop system hardware consists of two mounted push-button kill-switches connected to a central COTS console as well as a COTS remote kill-switch controller. The central console is powered by a 12 VDC independent battery and supplies 24 VDC to a contactor switch, also pulled from a separate small battery, which turns on or off power to the rest of the boat. The central console software determines whether a kill-switch has been activated from any of the three switches. The remote kill-switch operates over a 900MHz radio connection with the central console.

All power cables on board were designed to handle extreme power surges from the batteries and assume a 25% safety factor, in addition to safety factors recommended by the American Boat and Yacht Council. The main batteries are wired using 2/0 gauge marine grade cable, with all breakouts from the main bus wired with 6 gauge marine grade cable. Individual sensors are wired based on manufacturer recommendations. All cable-ways are fused to protect the cables, and additional fuses are set based on sensor limitations.

B. Sensing

The ASV was designed to collect data from all sides of the vehicle in order to maximize the vessel's environmental perception. The main sensors on board include one camera, two LiDARs, two GPSs, an IMU, and three hydrophones. A summary of the sensors is shown in Table II.

TABLE II
THE SENSOR SYSTEMS ONBOARD THE MICHIGAN ASV.

Modality	Manufacturer	Model	Quantity
Camera Imagery	FLIR	Ladybug 3	1
LiDAR Points	Velodyne	HDL-32E	2
INS	Advanced Navigation	Spatial Dual	1
Hydrophones	Teledyne	TC4013	3

1) Camera: The ASV is equipped with an FLIR Ladybug 3 camera for image recognition. The Ladybug 3 is capable of sensing with 360° views of the vehicle [6]. The camera is mounted as the tallest point on the vehicle to allow for unobstructed views around it. The camera is powered and interfaces with the main computer via a Firewire 1394 cable. An open source ROS driver was modified to interface with the camera sensors. The Ladybug 3 contains five horizontal-facing cameras, with one pointing straight ahead. The combined images of the five cameras include overlap between each camera. The view from the cameras, showing overlap, can be seen in Figure 6.

Fig. 6. The view from the Ladybug3 Camera System.

2) LiDAR: The ASV is equipped with two Velodyne HDL-32E LiDAR systems. The LiDARs are mounted on the centerline of the vehicle at the forward and aft ends of the sensor rack. This gives them a clear field of view in front of and behind the vehicle, with overlaps on the port and starboard sides. The LiDARs are powered by 12 VDC and are interface with the computer via an ethernet connection. The LiDARs have a +10° to -30° vertical field of view, with full 360° horizonal coverage. The sytem has a range of approximately 100 meters [7]. An open source ROS driver was modified to work with the LiDARs, and the LiDARs were calibrated to stitch their point clouds together. There are cases located between the two LiDARs which prevent inter-LiDAR interference.

3) Inertial Navigation: An inertial navigation system (INS) was purchased to provide global positioning system (GPS) data and also contains an inertial measurement unit (IMU). The INS system is the Advanced Navigation Spatial Dual.

The system features dual GPS receivers which allows the system to determine the vehicle's heading in addition to its position. The IMU provides the velocities and accelerations of the vehicle in all six degrees of freedom. While utilizing RTK, the system has a horizontal position accuracy of 0.8 cm. The system has a velocity accuracy of 0.007 m/s and heading accuracy of 0.1° [8].

A ROS driver was provided by the manufacturer to interface with the device.

4) Hydrophones: In order to detect the active beacons, the system utilizes three Teledyne RESON TC4013 hydrophones arranged in a planar array in the shape of an L. The hydrophone in the center was deemed the reference and placed a uniform distance from both of the other hydrophones. This distance was less than half the minimum wavelength (18.75 mm) of all possible beacon frequencies to ensure it did not have spatial aliasing [9]. The signal is first amplified using PA-4 hydrophone preamplifiers from Aquarian Audio. Then a NI 9223 analog-to-digital (AD) converter is used to send digital signals to a NI 9040 cRIO. A band pass filter is used to remove any frequencies that fall out of the range of the beacon frequencies, which could exist as a result of operating the motors and thrusters, or due to ambient noise in the environment. The remaining signals are processed using a fast fourier transform (FFT), implemented in the FPGA of the cRIO.

The magnitude of the FFT allows identification of the beacon signal and also to extract the phase. Using the phase differences between the reference and the other two hydrophones, the relative heading of the acoustic source can be determined.

C. Reasoning

The ultimate goal of the ASV is to perform tasks that are set forth by the organizers of the Maritime RobotX Challenge. Rather than explicitly formulating a specific strategy for each task, the tasks were restructured to be represented as a sequence of simpler goals. In this way, the ASV was designed to complete tasks by populating and traversing a first-in first-out (FIFO) queue of goals. These goals build off the core capabilities of the ASV, which in turn operate off the data streams provided by the sensors. The software was designed to leverage as many existing ROS libraries and packages as possible.

1) Data Preparation: On a basic level, each sensor transmits some type of message to the ASV's central computer. For example, the camera sends messages representing the images that are observed at some given time. Before using any of these messages, they are time-stamped and assigned the appropriate sensor identifier. The time-stamping enables time-synchronization across multiple messages and reduces the potential of non-deterministic errors.

Static coordinate frame transformations were defined between rigidly connected components, and all coordinate frames follow the standard defined by ROS REP 105. Dynamic coordinate frame transformations, such as the one between the ASV and Earth, are updated continuously during operation. Since each sensor is assigned a unique identifier and a local coordinate frame, sensor messages may be transformed into different coordinate frames as required [10].

2) Core Capabilities: A host of core capabilities were developed for the Michigan ASV, including localization, mapping, object recognition, and navigation.

Localization is the process by which the ASV determines its location with respect to its environment. Many localization procedures rely heavily on odometry estimates of the mobile robot, and the most common source of these estimates is wheel encoders. Since this solution is not applicable to the ASV, the odometry is instead estimated from a combination of information from the IMU, GPS, and LiDARs. The sensor fusion and localization is performed within ROS utilizing an unscented Kalman filter to produce the ASV's state estimate and covariance [11].

Mapping is the process by which the ASV constructs and updates a map of its surrounding environment, which is particularly important for path planning when the navigation goal is outside of sensor range. The ASV's mapping procedure utilizes the point cloud messages provided by the bow and stern LiDARs. The point clouds from two sensors were fused together to form a single composite point cloud, centered on the ASV's base link. This point cloud is filtered to remove any points that collide with the ASV itself. This point cloud is processed and used as an input to a simultaneous localization and mapping (SLAM) procedure within ROS [12]. The resulting map is saved and served in real time.

Object recognition is performed on camera images using the You Only Look Once (YOLO) Detection System [13]. Training images were labeled to develop a custom prediction model that focused on recognizing obstacles, buoys, and docking symbols. The custom model provides two outputs: one specifying the object and the other specifying the object's color. This approach was deemed to be simpler and more robust than predicting the colored object as a single outcome. When the camera recognizes an object while the ASV is under operation, the LiDARs then provide an estimate of the object's location. At this point, an "East-North-Up" coordinate frame for the object is created and its transformation is defined with respect to the map of the ASV's environment.

Navigation is performed within ROS utilizing the ASV's localization, mapping, and coordinate frame transformations. For each navigation goal, global and local path planning are performed, and velocity commands are sent to the PID controllers.

3) Task Completion Strategies: With the exclusion of the straight-line qualification, all tasks were developed with the intention of developing an initial map while operating under remote control in order to simplify the path planning requirements of the vehicle for the first year of competition. In addition, each task was designed to begin with a start pose and conclude with an end pose, followed by station keeping. This is done to ensure predictable operation as well as to facilitate the integration of multiple tasks.

The first capability developed was to ensure qualification via the straight line test. For this, the ASV does not utilize a prebuilt map, and operates on a simple sequence of goals. These goals are:

1) Navigate to start pose: between start buoys, 3 meters behind the line, with orientation vector pointing through the gate and perpendicular to the vector from the green buoy starboard and red buoy to port
2) Begin movement, traveling in a straight line until the exit gate can be seen. Sends angular velocity to 0 and linear velocity max. Once the exit gate is observed, push two waypoints into the navigation stack: one in front of the exit gate, and one on the far side - which will be the end pose.
3) Complete the Navigation goals set at the end of step 2 and station keep.

Task 1: Entrance and exit gates. Parameters defined for this task are the buoys to be circled, a dictionary of the orientation to circle buoys in, default gate, max speed. Using the map developed by RC, an initial pose is set behind the middle gate. The goal sequence is as follows:

1) Navigate to start pose: between middle gate, 3 meters behind the line, with orientation vector pointing through the gate
2) Identify the entrance gate using hydrophones with thrusters turned off if necessary (should they be interfering with the acoustic signals). The hydrophones return a relative heading to the signal source, split into three regions, which correspond to the three gates. The default behaviour, if the vehicle is unsuccessful at determining a gate from the hydrophones, is to choose the middle gate as the entrance.
3) Push a waypoint on the other side of the entry gate, and a waypoint between and behind the buoys, and face the buoys.
4) Navigate to waypoints in queue. Upon reaching final pose, push waypoints to circle the intended buoy in the appropriate direction, and a final waypoint/pose to the current location.
5) Identify the exit gate following the same logic as in Step 2, drive to gate 2, stopping 3 meters before it. Then drive through the exit gate and hold station.

Task 2: Obstacle avoidance. Before beginning this task, the WAM-V will be driven around the course under remote control to map obstacles and course as well as set boundaries. The parameters defined for this task are the entry corner, max speed, negative reward profile for obstacles, and a costmap. The goal sequence is as follows:

1) Push in starting waypoint (near entry corner), push in end waypoint/pose (deduced from entry corner).
2) A route will be planned between the waypoints to avoid any obstacles identified in the original map using the costmap.
3) The vehicle will navigate the path.

The waypoints set at this point are the goals of the navigation stack, which performs local/global path planning.

Task 3: Find totems. Before beginning this task, the WAM-V will be driven around the course under remote control to map obstacles and course as well as set boundaries. The parameters for this task are target buoys (order implied). The goal sequence is as follows:

1) From the map developed from remote control, objects will be identified.
2) Waypoint goals will be set. From the stating pose, the vehicle will send waypoints to navigate to each buoy and around each buoy in the correct directions.
3) The vehicle will then set the end pose back where it started and work through the queue of waypoints.

Task 4: Scan the code. Before beginning this task, the WAM-V will be driven around the course under remote control to map obstacles and course as well as set boundaries. The parameter defined for this task is the light default sequence. The goal sequence is as follows:

1) The vehicle will identify the light bar buoy and set a waypoint relative to the screen.
2) Waypoint goals will be set: start pose, near light buoy, posed in front of screen, end pose.
3) Using the region of interest to identify the screen, the vehicle will record the image sequence with camera, filter color in region, check for a match. The color sequence will be reported back to the operator control station.

Task 5: Docking. The parameter for this task is the symbol of the day. The goal sequence is as follows:

1) The vehicle will identify the dock symbols of the day and identify the correct dock
2) A waypoint will be set just in front of the target dock and then once again just inside the dock.
3) The PID mode will be changed to incorporate the lateral thrusters.
4) The vehicle will move into the dock and hold station.
5) The vehicle will back out of the dock and return to the start point.

No other tasks were attempted in the sake of time and complexity.

IV. EXPERIMENTAL RESULTS

The University of Michigan WAM-V underwent multiple phases of testing, including component level tests, software tests, vehicle bench tests, and full scale deployments of the vehicle.

A. Component Testing

After the WAM-V platform arrived in February, the initial design began with propulsion and electrical distribution. Once a motor was selected, we did a component level test of that motor in a water tank in March in order to determine the electrical load of the motor. This test was performed at the University of Michigan's Marine Hydrodynamics Laboratory, and is shown in Figure 7. The results showed that the motor drew 12 Amps at full throttle with a 24VDC electrical supply. This was significantly lower than expected.

Fig. 7. The WAM-V motor being tested in March, 2018 at the University of Michigan Marine Hydrodynamics Laboratory.

The initial electrical distribution system was sized based on the expected load of the motors, sensors, and computer, with the motors and computer being the most significant loads. These early bench tests allowed us to appropriately size the equipment. A heavy safety factor was added to all of the cabling and allowed room for motor expansion.

Additional tests were conducted including analyzing the motor's acoustic frequency in order to determine if the motor may interfere with picking up the acoustic signal from the underwater beacons.

B. Software Testing

Throughout the eight months of software development, the software team worked to test new packages as soon as possible. The initial level of testing was to ensure that drivers for the various sensors were functioning. This testing was to simply connect the various sensors to the computer system individually to ensure that the data could be read in and utilized.

During the first full scale vehicle deployment that included the on board sensors, and during all later vehicle deployments, bag files of the sensor data were collected. The bag files contained all of the data streams running through ROS during the duration of the recording, and essentially contained a snapshot of what the vehicle software was doing at a given moment. These bag files could be played back to test new software packages without returning to the lake or the full vehicle.

C. Bench Tests

Over the course of the vehicle deployments, several major systems failed, including communication, emergency stop, motor control, and sensor drivers. To prevent wasted time and resources during a full scale deployment from new code being added to the vehicle, prior to each full scale deployment the code base was locked down and a bench test was conducted in the workshop.

During the bench testing, the vehicle was fully assembled on a stand. The full operator station was setup and all major components were tested in the workshop to ensure that they were functioning prior to the vehicle being packed up and taken to the lake. During these bench tests, problems were often identified and could be fixed prior to arrival at the lake. This saved time and resources on the lake.

D. Full Scale Vehicle Deployments

The Michigan WAM-V was tested full-scale at Strawberry Lake in Michigan for the first time on June 4, 2018. During this initial test, the remote control capabilities of the vessel were tested. The power system was still not totally completed, and no sensors were tested. The test proved that the vehicle could be controlled by remote control, and also showed the importance of having a robust emergency stop system. The initial vehicle is shown in Figure 8.

During the initial test, the team was excited to get the vehicle out on the water and did not test the functionality of the emergency stop system prior to the vehicle leaving the dock. During the initial remote control test, the vehicle lost communication with the operator base station and failed with one motor on and one motor off. This resulted in the vehicle doing uncontrolled circles. The remote control emergency stop system failed to activate, and the local emergency stop buttons on the pontoons failed to stop the vehicle either. In order to shut down the vehicle, a rider in the chase boat jumped onto the pontoon of the moving platform and removed a power cable to stop the vehicle. After towing the WAM-V back to the dock, it was found that the antenna for the remote emergency stop had come unplugged. A programming issue in the logic board proved to be responsible for the failure of the local emergency stop buttons. These lessons were valuable to learn early on, and resulted in a re-design of the emergency stop system to ensure these failures would not occur again.

Fig. 8. The WAM-V's first test in the water on June 4, 2018 at Strawberry Lake, Michigan.

The WAM-V was later tested again once in July, once in August, once in September, four times in October, and once in November for a total of nine full scale trials. During the full scale testing, the vehicle suffered major failures that resulted in not being able to continue the test on four occasions. These failures were primarily software related, however on one occasion a short circuit in the wiring caused one of the motor controllers to fail. The software related issues were identified, and dealt with accordingly, while the short circuit issue led to increasing the robustness of the completed wiring, and in some cases redesigns of circuitry.

During the tests in which the vehicle was functional, a number of aspects were tested, namely: vehicle controllability, sensor data, and communications. An additional in-water test was conducted to tune the PID controllers, and test the resulting vessel functionality.

To test vehicle maneuverability, the vehicle was controlled using a joystick to determine the turn radius, top forward speed, and lateral speed using the thrusters. The top forward speed was found to be approximately 5 knots with no wind and a calm lake. The WAM-V's ability to hold position was also tested in the presence of a current, approximately 1 foot waves, and sustained 15 knot winds. Speed and position data was recorded from the INS.

Buoys identical to those used in the RobotX competition were purchased and placed on a mock course in order to collect data of the objects for LiDAR and camera data sets. The buoys and LiDARs were used for object detection tasks, and the recorded data was used to test the vessel's ability to generate a map of its environment. Additionally, images of the buoys captured by the cameras were used as data sets to train the image recognition capabilities. The sets of red and green channel buoys were later used to test the ability of the vehicle to autonomously demonstrate control, as will be demonstrated in the straight line task at the start of the RobotX Competition.

In addition to testing and collecting data for obstacle avoidance, data was also collected for use in the docking task. The vision targets (red, blue, and green triangles, squares, and cruciforms) were printed to the appropriate specifications and were placed on a frame manufactured out of PVC to represent the dock used in the competition (Figure 9. The vessel was maneuvered around the dock setup to capture LiDAR and camera data from the target. Additionally, the vessel's maneuverability was tested within the docking bay, with the ability to station keep.

Fig. 9. The PVC dock used to test the docking task maneuverability and image recognition.

Throughout testing, as system weaknesses were identified, many systems were upgraded to adjust and improve the robustness of the vehicle. One primary weakness was the short operating window with the single power bank. This was a simple solution as a second battery bank was added to double the operating time. The vehicle can now operate for approximately four hours on the water. The communication system was also updated by upgrading the wireless radios and antennas from a 2.4 GHz spectrum to a 5 GHz spectrum. This increased the reliability, data transfer rates, and bandwidth between the vehicle and the operator control station, enabling better functionality of a number of the onboard systems.

Although a significant amount of testing was performed over the course of the project, the significant time constraints left a number of tests yet to be performed. However, the data collected in previous tests enables the team to continue building software capabilities without the presence of the vessel itself. The ability to continue work with recorded data, and without the presence of the vessel, enables the team to continue making improvements to the platform, and make the best use of qualifying and pre-competition time to make final improvements to the systems.

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