Design of the USYD Sealions WAM-V Autonomous System for the 2022 RobotX Challenge

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***Abstract*—This paper provides the design of hardware and software systems for The University of Sydney Sealions' WAM-V based Autonomous Surface Vessel (ASV) participating in the 2022 RobotX challenge. This is the second time for The University of Sydney to participate in the International Maritime RobotX challenge after 2018. From the experience in 2018, the new team has updated the control system with new front thrusters for station-keeping, updated the perception system with machine vision cameras, and added a brand-new racquet ball launcher sub-sytem for the find and fling task.**

I. INTRODUCTION

A surge of popularity in Unmanned Surface Vessels (USV) as well as development and interests in robotic and autonomous systems has inevitability led to desire to develop autonomous USVs (ASVs). This has been made easier with advancements in both hardware and software, such as improved Commercial Off-The-Shelf (COTS) sensors and comprehensive software architectures for automation (namely ROS).

The biennial Maritime RobotX Challenge serves to stimulate ASV technology development and practise by providing a space for competition and innovation in a complex and collaborative environment. USYD Sealions is a team from the University of Sydney which has entered the challenge for the purpose of learning, collaborating and contributing to the state of the art in marine autonomy.

USYD Sealions is a team of undergraduate engineering students working on a real-world robotic system for the first time and with assistance of technical staff from the Australian Centre for Field Robotics (ACFR) and faculty staff from the University of Sydney.

II. DESIGN STRATEGY

A. Development Goals

The main goal of USYD Sealions' is to deliver a robust, capable ASV which can operate with many mission profiles in a wide variety of environments. From this perspective, the 2022 RobotX challenge is a critical step forward in this development process. This challenge is the second trial of USYD's WAM-V platform and has been updated from the previous experience and is expected to improve in future iterations .

With this view of the competition, USYD Sealions aims to demonstrate an ASV which can acquit itself well in surface perception, navigation and propulsion while also being readily extensible to other missions in the future.

B. Team Capabilities and Limitations

USYD Sealions was founded in late 2021, and the team started working on the WAM-V system beginning in the second quarter of 2022. At this time, ACFR staff had implemented an operational propulsion and localization solution on the vessel for their own research applications and the 2018 team had laid a good foundation for the software architecture of the systems. It was the student team's task to augment this existing platform for use in the RobotX Challenge. Almost none of the participating students had experience with comparable systems and most had not been involved in projects of such scale, extent, and complexity.

To compensate for these limitations, the team decided to pursue a rapid development process that made the most use of software solutions developed during the Virtual RobotX 2022 competition and focused more on improving the quality of hardware on the system with the technical experience of ACFR staff. This allowed the team to deliver an operational vessel with a good set of functionalities.

C. Task Selection

The tasks presented at the 2022 RobotX Challenge are complex, and varied and thus require a complex and multi-functional vessel to complete them. In view of its limitations in development time and manpower, USYD Sealions elected to eliminate the AUV module limit its mission scope to the fundamentals of the challenge so that it could deliver effective solutions to the majority of tasks.

The team, therefore, decided to focus its resources on effective and reliable surface perception and navigation at the cost of more complex advanced tasks. This philosophy is grounded in the understanding that observing and responding to the surface environment successfully is the most critical aspect of an ASV's functionality.

III. VEHICLE DESIGN

A. Power and Propulsion

The WAM-V's propulsion is delivered by 2 Torqueedo electric outboard thrusters in a differential arrangement. This provides the vessel with abundant thrust and heading control which is adequate for the team's requirements. These thrusters are connected to the WAM-V pontoons via custom flotation pods in place of the factory-standard pods delivered with the vessel. The new pods are more suitable for fine control of the vessel and allow for a mounting method that is better adapted for future ACFR usage of the vessel.

To power the AMS, 2 banks of lithium-ion batteries are attached to the WAM-V. These batteries provide for a mission duration in excess of 4 hours with high-power use.

In regards to station-keeping and stabilisation of the WAM-V, there are two Flipsky motors mounted on each side of the bow. These motors are controlled via CAN by two Flipsky ESCs, located within the power distribution box. Via a control system, the WAM-V is able to respond to the affects of wind and current by manipulating the motors, allowing the vessel to remain still.

B. Localization

Accurate localization is critical for the functioning of the WAM-V in all environments and usage cases, so the vessel is equipped with a Novatel INS system with differential GPS. This system provides a complete navigational solution to the vessel with accurate heading and a low-drift position fix.

Although SLAM could technically be utilized while on the RobotX 2018 challenge course, future applications for the WAM-V involve offshore activities beyond visual range of reference objects along with operations in built-up areas where GPS data is unreliable and large objects could move unexpectedly. The INS has been chosen for these situations and so serves as a dependable benchmark for the vessel's perception and navigation systems regardless of the availability of stationary landmarks or a consistent GPS signal.

C. Sensors

The team has improved the perception system with a set of new machine vision cameras and an additional HSI camera for the Wildlife React and Report task.

1) LIDAR: Scanning LIDAR is a critical component of the WAM-V's perception system. After an assessment of the team's requirements and means, a single RoboSense RS16 unit was selected to provide the key object detection functionality for the platform. This unit has proved to be capable, reliable, and simple to integrate with the ROS system. The LIDAR is mounted on top of the vessel's perception unit, above the camera array.

2) Imaging: For the visual perception, the maximum object distance and maximum field of view were estimated and three Allied Vision Manta G-235 GigE cameras were chosen. These are 2.35 MP machine vision cameras with gigabit ethernet connectivity. These cameras are chosen as an upgrade to the previous camera system for their bigger sensor size, and a range of functionalities including auto exposure, white balance, color correction, etc. The Ethernet connectivity of these cameras makes them modular, so they can be accessed by any device or computer on the network, also convenient for future computer upgrades. The cameras each have a 140° field of view and are mounted on 60° offsets to deliver a 260° total field of view with 10 degrees of overlap between the frames of adjacent devices.

3) Sensor Mounting: A custom mounting system was designed for the Lidar and the cameras were to be modular and at the same time protect the circuits from water. The three cameras are placed in a 3D-printed enclosure, along with a 5-port network switch, to which the three cameras and the Lidar are connected, and the switch is connected to the router through a single ethernet cable.

The Lidar is held at a 15° slope, so it gets a maximum field of view from its optical center. It is attached to a 3-D printed holder, which is bolted to the lid of the camera housing as seen in 1. The box and all the joints have been sealed with TPU washers and waterproof cable glands were used to avoid water seepage. The lenses are protected with an acrylic sheet to avoid fogging.

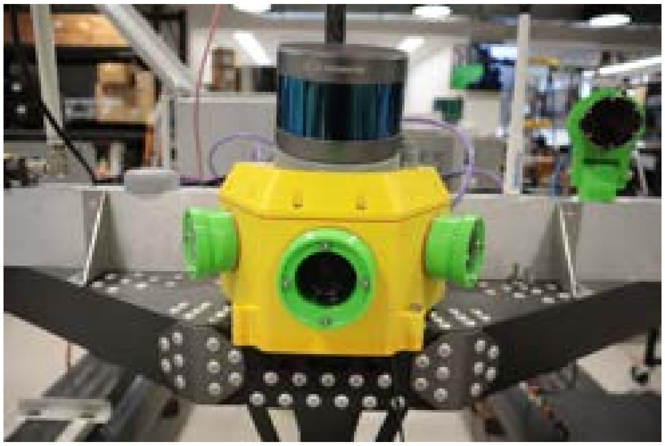

Fig. 1. Sensor Unit, mounting a RoboSense LIDAR and 3 enclosed cameras

4) Future Sensor Hardware: Plans have been proposed by the team to supplement the existing RoboSense RS16 LIDAR with new 32-beam Velodyne LiDAR. This new device would be installed to cover some of the blind spots in the current LIDAR system and to increase the range that the LiDAR is used for. A downside to this upgrade would be the increased processing requirements but this could be dealt with.

Stereo vision systems and smart machine vision imaging options have also been considered for future implementations. The WAM-V available to the team has already been modified by ACFR for use with various acoustic devices, namely multi-beam sonar and USBL units. Time and budget constraints prevented the team from integrating a hydrophone array onto the vessel for the 2022 competition, but this capability is a key part of development plans for future competitions.

In addition to the aforementioned sensor package upgrades, various new sensor technologies are being assessed for extending the capabilities of the WAM-V for research applications. The team is considering the addition of marine radar units and meteorological equipment to supplement the perception and data-collection capabilities of the vessel.

5) Hyper Spectral Imaging: OpenHSI's Hyper Spectral Imaging camera provided by Robonation is used for the wildlife encounter task and is simulated by three same appearance boards reflecting different radiance data. The team mounted the HSI camera at the front section of the boat (as seen in figure 2 and retrieved reflectance data through the Arena SDK and Python OpenHSI packages to get the hyperspectral reflectance of the boards to classify the wildlife type. After the successful implementation of the data mining technique to classify the encounter type, we plan the best path following task requirements to approach the designed target.

Fig. 2. HSI Camera Mounted on the WAM-V

D. Computation

The computational requirements of the current vessel are sufficiently low that a single industrial PC is capable of processing the collected information from the sensor arrays and controlling the vessel. Future development, particularly the addition of acoustic arrays or more cameras may require this PC to be supplemented with additional computers for pre-processing some or all of the collected data.

All electronic equipment that is not IP-rated is stored along with the computer in a central instrument box. Cooling of this box is handled via conduction to the outside air, which is sufficient for the small number of efficient devices contained within.

E. Software

1) Operational Architecture: The control software for our WAMV is running within a ROS enabled Docker container, hosted on an onboard industrial PC running Debian 9. Low level control of sensors and actuators is handled by the host operating system, and communicated into the Docker container using the Lightweight Communications and Marshalling (LCM) [3] protocol.

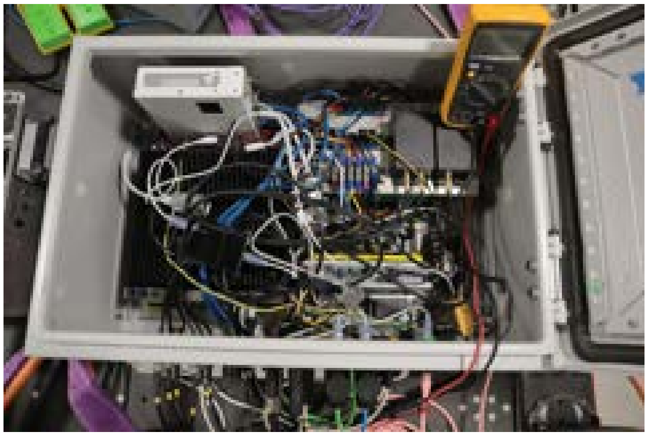

Fig. 3. Enclosure for the Computer and the Electronics

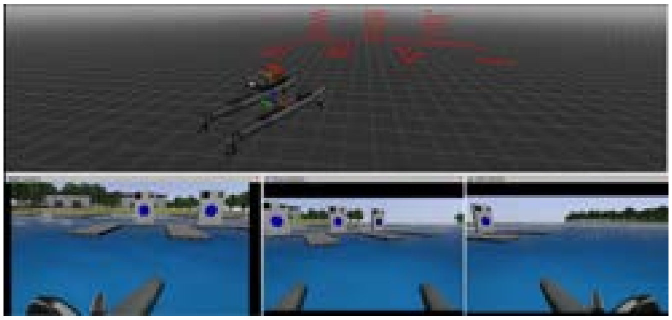

Fig. 4. Perception System in the Simulation

LCM was chosen for our low level control as it enables us to utilise existing ACFR solutions for sensor and actuator interfaces. Higher level functionality is carried out in ROS so that some of the main control functions programmed for the Virtual RobotX event may be used again for this year's competition.

Containing our main control functions within a Docker Image made it significantly easier to develop and test our software solution remotely, without physical access to the WAMV, by running the Docker Image as a Dev container in Visual Studio Code, with simulated sensor inputs.

2) Simulation: The simulation was a key part of the software development as testing opportunities were sparse. We used a simulation developed designed for the Virtual Maritime RobotX Challenge) [1]. This simulation allowed us to prototype and test all of our high-level functionality without physical access to the WAMV. This includes camera vision and lidar as well as our GPS and IMU.

F. Perception

The perception solution developed for the AMS is implemented with a combination of existing ROS and OpenCV tools with custom-developed python scripts for fusion and operation.

1) LIDAR Processing: The LIDAR data is received as a point-cloud ROS message, courtesy of ROS drivers provided by RoboSense for use with the RS16 unit. This point cloud is then pre-processed with the pointcloud_to_laserscan ROS package to produce a 2D laser scan with points represented by bearing and range values.

The laser scan is then converted into an occupancy grid format, with cells storing the probability of occupancy, ranging from 0 to 100. Unknown cells are represented with -1. Successive hits on a particular cell increase that cell's probability value up to its maximum. The probability of cells measured to be empty is decreased over successive scans. Cells are considered empty when an object is detected behind the cell or no returns are observed from that cell when it is within the LIDAR's field of view and detection range envelope.

This mapping methodology was chosen for the robust handling of spurious data, such as false positives or negatives as well as moving objects in the water. These false positives and negatives are anticipated in a marine environment due to random reflection and scattering of laser pulses off ripples in the water. By requiring multiple scans for LIDAR returns to significantly influence the occupancy grid, interference from these transient noise sources is mitigated.

2) *Image Processing:*

a) Data Collection: Image data is continually collected by ROS from all 3 cameras at a frame rate of 10 fps and stored as OpenCV image messages. These images are processed only on request from the various image processing functions in order to reduce the computation requirements for image-based perception. All images are converted into the HSV colour space before processing them for content.

b) Buoys: A color mask-based approach is taken for buoy identification. Masks are generated for all possible colours of buoys which the vessel is expected to encounter during a run on the course. Contours are then generated from the image within a given Region of Interest (RoI). The contours are filtered by size and shape to classify the object within the RoI.

c) Light Buoy: Identifying the displayed colour of a light buoy is completed in a similar way to determining the colour of docking symbols. A white mask is used to detect the buoy's frame, and the shape and colour of the LED panel is confirmed by contours.

To determine the colour sequence being displayed by the Light Buoy is handled by a progressively-filled buffer of size 3. Each change in panel colour triggers a new entry in the buffer, and an extended blank period (i.e. end of sequence or missed readings) resets the buffer to ensure the code is collected properly.

In order to ensure that subsequent colour detections are correct, after the first reading only a restricted RoI around the panel's position is processed for colour identification.

3) Sensor Fusion: Sensor fusion begins from the occupancy grid, where K-means clustering with a distance threshold is used to group occupied cells into representations of objects. These objects are filtered by size to provide an initial guess of their classification. Small objects (radius < 1.2 meters) are classified as buoys, larger objects are classified as docks, and very large clusters are classified as land. A list of object ID, position, type and confidence values is maintained by an object server for future reference.

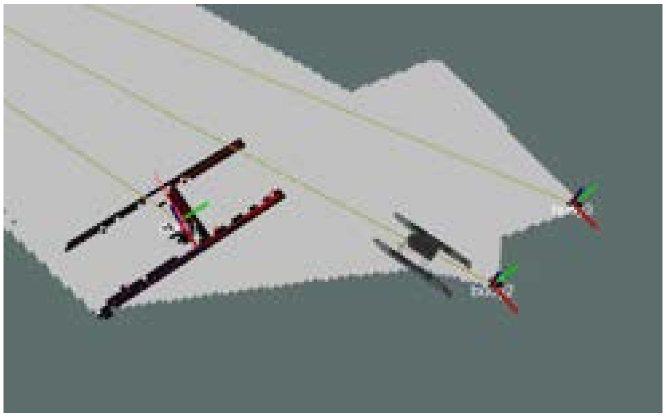

Fig. 5. Perception of Dock and buoys

For buoys, each detection triggers the image-based buoy classification routines, providing a bearing that the routine converts into the required RoI. With the classification returned, the confidence value attributed to it is range-dependent, with closer values resulting in higher confidence. If the new confidence value is greater than the previous, the classification will be overwritten to reflect a better result.

The light buoy is a special case, where a process is continuously running when classification is required. This process is activated and deactivated as necessary to conserve computing resources. Whilst activated, the process will actively seek to detect the buoy and report its state. Once the state is determined, it and buoy classification are returned to the object server.

For docks, which have already been detected by their size, a rectangular rotated bounding box is fitted to the dock to determine its orientation. From this, the dock entry locations can be determined along with the locations from which the docking symbols should be captured and determined. Once the vessel arrives at these positions, the symbol detection routines are called to produce a classification.

4) Resultant Data: The object server periodically publishes the object list for most other processes (chiefly the mission planner) to leverage for their operation. High-level decisions are made based on the vessel's state and the object list.

The occupancy grid is used by the path planning software as its primary reference information. This allows for very fine detail to be provided to the path planner while streamlining data processing for other functions which do not require this resolution.

G. *Control and Guidance*

The WAM-V is a differential drive vehicle. The platform has an option to use either a Pure Pursuit Controller [2] or a non-linear guidance law controller, depending on the application. Each one uses a list of waypoint to go to as it target. With pure pursuit, the AMS will chase each waypoint to within a specified margin of error before chasing its next waypoint.

Another method was a non-linear guidance law controller [4]. The algorithm works by setting a virtual target point at the intersection of a user-defined circle around the USV, and the straight line connecting the two way-points.

Each of these methods output a course message containing a desired speed and angle. A PID controller is used to match the angle and speed to the given course command.

H. *Planning*

Mission planning is done primarily using a state machine of a ROS package called SMACH [5]. For each task there will be a series of states that the robot must traverse to complete its task. SMACH was used because it has a variety of useful features that extend a normal state machine. Firstly SMACH has a Visualization tool implemented, where the current state can be visualized and observed. This is helpful when debugging and inquiring about the actions of the platform. Secondly, it allows for the nesting of tasks and modification, such as allowing the implementation of state machines inside state machines. This is especially useful for the finals and semifinals where the course is a combination of tasks rather than just individual tasks.

I. *Safety*

Safety was a key concern for the team throughout development and care was taken to ensure that each subsystem included fail-safe features and would not interfere with the safety features of other subsystems on the vessel.
The vessel is equipped with 4 emergency stop buttons around its perimeter, which immediately cut power to all the actuators on the vessel. This emergency stop system includes a relay that can be triggered from software in ROS and a custom-built wireless emergency stop unit developed by the team. The wireless emergency stop operates using the LoRa protocol and allows for the vessel to be shut down safely from over 300m away. This quoted range is the furthest separation tested by the team while beyond the line of sight and is far below the true capabilities of the equipment.

To ensure battery safety on the WAM-V a QR code was affixed to the top of both battery units, linking to a battery safety data sheet that outlines how to correctly and safely use, store and transport the batteries. Additionally, records of battery discharges are kept to analyze the life of the battery.

IV. EXPERIMENTAL RESULTS

A. *Lab Testing*

Lab testing was critical in validating the low-level functionality of the various components of the AMS. Each software subsystem and hardware device was function tested before integration with any other system.
Lab testing proved particularly important for the Torqueedo thrusters, which plagued the team with teething problems as multiple bugs were identified and fixed. The cameras were calibrated using checkerboard calibration methods to calculate the intrinsic and extrinsic parameters.

B. *Simulation*

With the limited field tests available to the team, it proved imperative to retain an accurate and comprehensive simulation environment. In order to improve the simulation's accuracy and to tune it for the real-world operation of the vessel, data was recorded from the field tests to be for configuring the simulator.

C. *Field Testing*

Field testing of the AMS was completed in various stages throughout development. This testing was primarily to inform and validate the outcomes of simulation testing.
The vessel's propulsion and navigation systems were tested on 3 days in the latter months of the development period. This main testing occurred in Chowder Bay in Sydney's north and proved that the vessel could follow a commanded course and deliver the required level of control and reliability.

Other smaller-scale tests were also conducted for parts like the front camera box allowing for testing without getting the whole boat in the water. The perception systems were field tested separately using test targets built by the team. These field tests were chiefly designed to validate the performance of the cameras in varied lighting conditions. The ability for the cameras to reliably identify an object in the frame by color is a lynch-pin for the system so field tests for this were prioritized.

Fig. 6. The WAM-V on field test day 2, flotation pods detached

V. PLATFORM ASSESSMENT AND FUTURE DEVELOPMENT

1) Current Capabilities: USYD Sealions believes that the current AMS system to be delivered for the 2022 RobotX challenge is a capable surface vessel that can acquit itself well and provides a suitable platform for future development. Its perception, propulsion, and autonomy all stand to be upgraded and supplemented for research and competition in the coming years.
The vessel's reliability is judged to be adequate for competition but not for a long-duration mission.

2) Development Paths: Future competitions and research will require many upgrades and alterations to the current vessel to improve and extend its capabilities.

Fig. 7. Testing of the camera module with small floats

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