# Development of the TopCat Uncrewed Surface Vessel for the Maritime RobotX Challenge 2022

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***Abstract*—The RobotX competition, and its companion Virtual RobotX (VRX) are a way to foster the community of innovators in the maritime autonomy, allowing teams of dedicated students to compete against each other in an obstacle course with Uncrewed Surface Vessels (USVs).**

**The problem facing this competition, are various tasks and how to solve them. All the tasks make use of control, computer vision, and/ or communication, at a minimum. As well as these aspects there are task specific developments that need both hardware and software including Uncrewed Aerial Vehicle (UAV), and hyperspectral camera-based tasks.**

**During development for these tasks the team found the best way to test the various algorithms needed was to use a digital twin, which can be represented by VRX and by extension, an in-house simulation developed from this base.**

**The results of this development show new advancements in control, object registration and classification, acoustic beacon localization, path planning, and mission planning, with some of these tasks needing newly developed hardware.**

**These development tasks show that testing algorithms and getting them to run on a real-life vessel is harder than a simulation.**

## I. INTRODUCTION

The need for Uncrewed Surface Vessels (USVs) is greater than ever. Their ability to traverse dangerous waters autonomously is an ability that is vastly sought after by both military and merchant marine organizations around the world. To expand on this research, the Centre for Defence Engineering Research and Training (CDERT) have recruited a dedicated team of Flinders University students to further develop a readily available platform, Wave Adaptive Modular Vessel (WAM-V), named TopCat.

The structure of this paper comprises a detailed discussion of our design strategy, a vessel description, vessel implementation for each competition task, discussion of results from the testing performed to date, and finally, future work to be conducted on the vessel.

### *A. Literature Review*

There are many different challenges that arise when delving into the development of autonomous maritime robots. To offer a test environment and framework for development, the Maritime RobotX Competition was founded from a partnership between RoboNation and the United States Office of Naval Research [1]. Some of the main challenges include object and obstacle detection and localization, vehicle path planning and navigation, and underwater sound source localization. A typical method of object detection and classification that has been used by many teams in previous challenges was to interpret and fuse data from both camera and lidar. Lidar data was used to localize the objects relative to the vessel, which allowed teams to region of interest image processing to isolate objects in a subsection of the camera view [2], [3], [4] [5]. For path planning and navigational tasks many teams relied on the use of grid maps and an A* path search algorithm [2], [4] [5]. An alternate approach making use of Delaunay triangulation was detailed in [6]. The underwater sound source localization challenge was primarily approached using a Multilateration technique [7], using an array of piezoelectric hydrophones. Some teams used larger arrays of hydrophones, allowing for more accurate localization with a static vessel [2], [4], while other teams used fewer hydrophones and relied on a moving vessel to obtain sufficient location information [8], [9].

With many different hardware and software systems being used in one vessel, there comes a need to make them interact cohesively and coherently. There are a range of different middleware implementations – software that acts as an interface between hardware and operating systems, and higher level applications and software, particularly in distributed systems [10] - that are used in robotics; Player Project [11], CLARAty [12], MSRS [13], and Miro [14] to name a few. Another solution is the Robotics Operating System (ROS), and open-source framework for working with robots [15]. The ROS design structure allows for very modular code by breaking up different components of the system into separate packages and nodes, that all share information using what is known as ROS topics. The general premise of a ROS topic is that some components of the software publish information in what is effectively a “notice board”, that other components subscribe to. This allows for easy sharing of data or information between many separate sections of the code. ROS has been used with effectiveness in previous RobotX competitions [5], [16] and was used as a key component of the Virtual RobotX (VRX) Competition in 2022 [17].

The need for prototyping and system design testing is essential in the development of any robotics system. This is especially true for distributed systems with several complex subsystems. Fortunately, ROS integrates with the robotics simulation environment known as Gazebo [18]. This combination of software was used for the VRX simulation from

[19], which aimed to simulate a complex maritime environment. There are drawbacks to using simulated environments for testing subsystems, such as a lack of noise in sensor data, and a lack of fidelity in virtual objects compared to real life objects [16]. In any case, a simulated environment offers many opportunities for prototyping and testing systems that can be prohibitive if done with real systems, either due to time or financial constraints – one can test the effectiveness of expensive equipment without needing to purchase it first.

## II. DESIGN STRATEGY

TopCat has been used for competing in multiple iterations of the RobotX challenge since 2014 as well as a research platform for CDERT's activities, and as such the vessel design has gone through multiple iterations to improve and augment the vehicle's capabilities. To accommodate these changes, the vessel was designed from the onset to be future-proof and to allow interoperability of sensor systems with other platforms that CDERT operates.

Enabling future proofing and interoperability in the electronic hardware involved using standardized communication buses such as ethernet to connect all the instrumentation systems through switches back to the central computing system. Controller Area Network (CAN) buses were additionally employed to connect the actuators and battery systems back to the central computing system. Two CAN buses are employed, one for starboard, the other for port, such that if one fails, the vessel is still able to drive back with one motor/battery/steering system combination. The TopCat system was also developed with the implementation of a single common microcontroller shield design that is reused for the Operator Control Station, the custom-made motor Kill-board units and the Core-board shields used in the host electronics box.

In addition to the above design choices for the electronic system, the software was also designed to be modular. To this end, the Robotic Operating System (ROS) has been used to develop TopCat's software architecture. This makes it relatively simple to replace ROS nodes with updates or application specific drivers as sensors are swapped out for other sensors. For example, the initial path planning component could generate straight line segments to build navigable paths, just to test out dependent components. This was then upgraded to an algorithm that allows for more efficient curved paths without having to redesign the entire architecture. It also allowed for the easy regression to the old algorithm for validation and comparison purposes.

Most ROS packages used in the TopCat system belong to one of four categories: sensors, processors, planners, or actuators. As seen in Figure 1, sensor packages act as simple drivers and interfaces between the ROS environment and the physical sensor. Processor packages read in data from one or more sensors (or other processors), to create useful information from the given data. Planner packages take in this processed data and use it to determine what course of action should be taken by the system. Finally, actuator packages listen to the actions of the planner packages and interact with the physical systems (i.e., thrusters) to complete these actions. It is important to note that some packages can be combinations of these basic types, for example the control system package is a combination of a processor, planner, and actuator all in one.

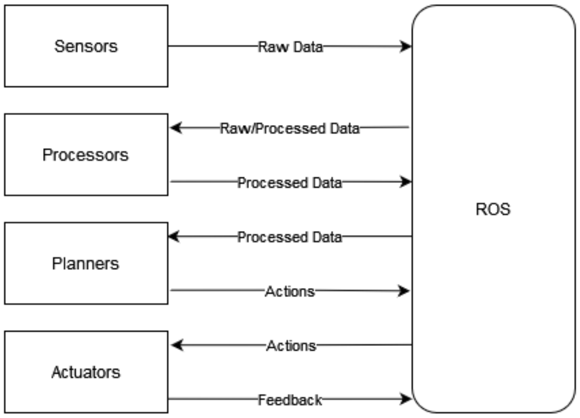

*Figure 1: Different types of Robot operating System (ROS) packages and their relevant information flows, using the four categories; sensors, processors, planners, and actuators.*

In designing TopCat to meet the RobotX tasks requirements, it was fitted out with a mixture of active and passive sensors. These include hydrophones, lidar, radar, cameras, GPS, IMU, and wind speed sensors. Due to the range of sensors installed, efficiency of coverage was optimized to maintain maximum coverage in the forward and side views, whilst preventing crosstalk and occlusion, this can be seen in Figure 2.

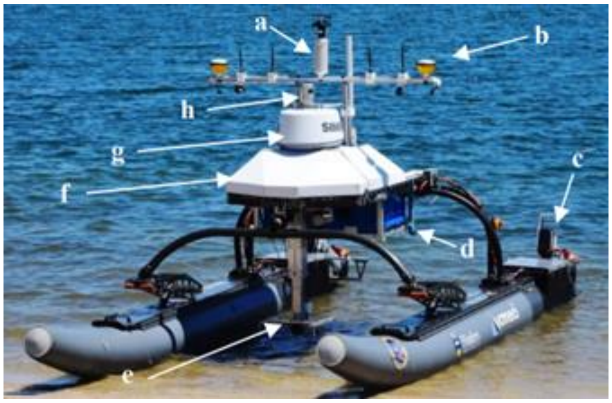

*Figure 2: Overview of TopCat's hardware platform*

| Key: | |
|---|---|
| a: Central Mast | e: Deployer |
| b: Sensor and comms array, including cameras | f: Computing and electronics |
| c: Propulsion system | g: Marine radar |
| d: Battery system | h: Velodyne lidar |

All exposed electrical and electronics systems and their corresponding connectors are IP67 (ingress protection 67) or higher. All equipment below IP67 is enclosed in watertight containers and additionally protected by a weather resistant platform cover. In addition, this equipment has been mounted using maritime grade G316 stainless steel bolts and nylon-insert lock nut to protect against corrosion and vibration.

## III. SYSTEM OVERVIEW

### *A. Sensors*

While most of the sensors on TopCat are identical to previous iterations, there have been a few changes, such as the revised camera mounts, the sensor fusion algorithms, a new control system, communication firmware and the visual indicator system. The vehicles sensors include the following:

Additionally, several proprioceptive senses are used, tracking temperature, voltage, current and other similar properties. This allows the vehicle operator to monitor the health of the vehicle.

#### *1)* Hydrophones

As with most piezoelectric sensors, there is the matter of instrumentation, or rather how the sensor will be used. The Teledyne Marine hydrophone TC4013 sensors are interfaced via a BNC cable. The BNC cable introduces some capacitance to the sensor. Due to the nature of the piezoelectric, the lower the frequency the higher the impedance of the signal. This essentially means that to use the hydrophones, since the band of consideration, 25khz – 40khz is so wide, there will need to be impedance matching in the acoustic data acquisition system used for the pinger detect solution.

#### *2)* Lidar

A Velodyne HDL-32 volumetric lidar. This is a long-range lidar system with 32 beams that are swept in a concentric pattern, capable of detecting objects at up to 100 meters, the sensor has a rated range accuracy of +/- 20mm. This sensor is the primary object detection and tracking sensor for the TopCat platform.

#### *3)* Radar

A long range Simrad 4G maritime navigation radar. This is a dual-channel Frequency Modulated Continuous Wave (FMCW) unit capable of simultaneous ranging up to 50 meters and up to 36 nautical miles. The custom-built ROS radar driver allows individual control of each channel's parameters including gain, range and rejection mode allowing each channel to be individually setup for an observation or tracking task.

#### *4) Camera (Microsoft LifeCam)*

The two cameras are interfaced with the host electronics box via USB, with a resolution of 1920 x 1080 pixels and a framerate of 10Hz. The cameras are rigidly mounted on the sensor superstructure near the GPS antennas for accurate pose estimation of the camera system. The feed is processed to recognize colour blocks and sequences for docking and navigational tasks.

#### *5)* GPS (Dual-Antenna Trimble BX982 GPS system)

The survey-grade GPS system provides both position and heading estimate using cross correlation between antenna signals. As the GPS system does not use a magnetic compass to determine heading, it is not susceptible to magnetic inclination or declination or interference from electrical sources [20]. A real-time kinematic correction source produces sub-centimeter position accuracy required for survey tasks. A Microstrain Attitude Heading Reference System (AHRS) is fused with information from the GPS to produce a pose and velocity estimate for the vehicle, providing pitch, acceleration, and angular rate information. with information from the GPS to produce a pose and velocity estimate for the vehicle, providing pitch, acceleration, and angular rate information.

#### *6)* Inertial Measurement Unit (IMU)

The 3DM-GX2™ Inertial Measurement Unit and Vertical Gyro is used to provide angular and linear acceleration, velocity, and orientation data to the control system at a data rate ranging from 1-250Hz [21]. This information is used to inform the control system for navigational and location tracking decisions, along with platform stabilization [21]. The IMU was interfaced with the system using a RS232 Serial to Universal Serial Bus (USB) adaptor.

#### *7)* Wind Sensor

The WindSonic wind speed sensor by Gill Instruments is utilized to assist the control system in making decisions regarding the direction and strength of the propulsion to reach set objectives [21]. The wind sensor is mounted on top of the visual indicator system to allow uninterrupted/unhindered readings, critical for navigational and pathfinding tasks.

### *B. Platform Base*

#### *1)* Batteries and Propulsion

The battery system on board TopCat comprises of two main batteries and a set of preliminary auxiliary batteries.

The preliminary battery system consists of two 12V lead acid gel cell batteries connected in series to provide 24V to the low-level electronics on board whilst the main system is off. The RFD900X radio system is powered with these batteries and allows for communication between the base station and TopCat, which is required to power the main batteries.

Two sets of Kokam Li-Ion batteries are the main power supply, distributing power to the motors, sensors, and electronics on board. The system has redundancy measures, allowing the vehicle to operate on one battery if required. Each of the Kokam batteries power each side of the motors and can be directly isolated using the isolation switches.

Finally, there are a series of small batteries required for the handheld remote e-stop and tele-operation remotes, and a lithium iron phosphate battery used to power the base station.

The propulsion system is provided by two Torqeedo Cruise 2R electric outboard motors. Due to the high-risk nature of the spinning propellors, there are fail-safe mechanisms in place including isolation switches for each motor and the e-stop system. There is a mechanical relay system that disconnects the power supply from the motors when the safety mechanisms are engaged.

#### *2)* Communications

TopCat uses three communication buses, Ethernet, USB, and CAN bus. Communication with the battery and engine modules is across CAN while sensors are connected via a combination of Ethernet and USB. USB devices are directly connected to the host computer through a USB hub. An onboard Ethernet switch maintains network communications on the boat, with a direct line of communication to the shore via a 5Ghz long range antenna. Two independent CAN buses, one port side and one starboard side, are interfaced via the core board microcontroller into the USB communication ports within the host computer, this can be seen in Figure 3.

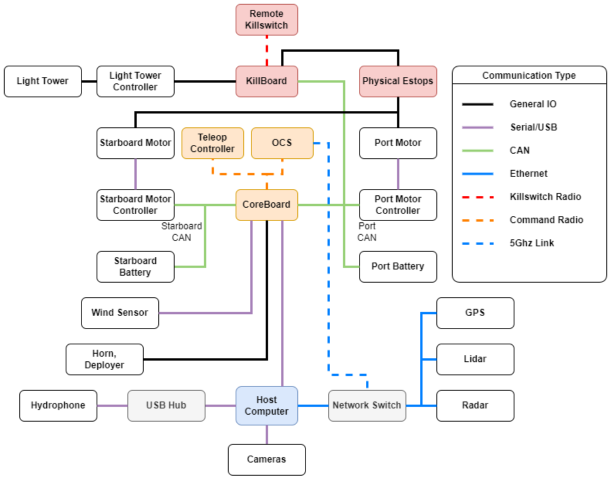

*Figure 3: TopCat Communication Diagram, with a legend describing the type of communication used, as well as their connected sensors, actuators, batteries, and microcontrollers.*

Communication channels from vessel to shore were selected based on legal and operational requirements. For teleoperation and remote kill switch communications, two 900MHz radio modem nets were selected. Australia and the USA both permit use within the 900MHz Industrial Scientific Medical (ISM) band, though Australia's ISM frequency allocation is smaller than that of the USA. Therefore, the radio modems are compliant with both USA and Australian regulations. These radios were tested with a spectrum analyzer and found to be within the expected frequency range.

For data transfer and high bandwidth communications a point-to-point 5GhZ Wi-Fi link was used. This system uses two Ubiquiti Rocket M5 modems with an omni-directional antenna on TopCat, and a directed antenna for the Operator Control Station. The system can be configured for use around the world and is set up to meet both USA and Australian standards.

#### *3)* Computer System

The key design criteria outlined for the current computer system in relation to the 2016 iteration of the competition was additional required processing power, ability to interface with on-board electronics, as well as effective methods of cooling the computer system. From the given requirements, the solution was a custom-built metal computer case, integrating a custom heatsink to displace the thermal output to the outer case, acting as both a defence to external entities and a heatsink. This design continues to carefully isolate the CPU electrically whilst ensuring mechanical loading and thermal throttling was mitigated. The computer system is an i7-6700 CPU, operating on a mini ITX motherboard with 16GB of RAM with a 1TB SSD. Additional space was left for the later addition of GPU/CPU boards or extra storage drives.

## IV. PREVIOUS WORK ON TOPCAT

### *A. Lessons from Previous Competitions*

The maritime environment is extremely challenging for all parts of an autonomous surface vessel. From the ability of the electronics to withstand environmental effects, such as mechanical forces and weather, to the robustness of perception algorithms to reliability operate in varying lighting conditions and floating, non-static, objects. All these issues can only be resolved with copious amounts of testing and refinement. All components need to be validated on the vehicle but testing on the vehicle can be challenging due to logistical complications and the potential consequences of failure. This leads into multi-layered testing plan that makes significant use of simulation for functional testing, to offline testing by processing recorded data, to open loop online testing, finishing with closed loop online testing.

### *B. Visual Indicator System*

The visual indicator system was used to illustrate the state of the vessel, i.e., E-Stops active, tele-operation, or autonomous mode. The display was constructed with a strip of RBG LEDs wrapped around a polyvinyl chloride (PVC) pipe, seen in 4, and controlled by a Freetronics LeoStick. The firmware was updated to integrate with the software revisions and change colour in sync with the change in state from the kill board.

*Figure 4: The Visual Indicator System, constructed from a weatherproof RGB light strip wrapped around a housing, hosting the electronics, allowing a wind sensor to be mounted on the top of the beacon.*

### *C. Control System*

Planning and control in maritime environments is a challenging task. The RobotX challenge required autonomous platforms to perceive their environment, detect and classify objects, infer relationships, and build plans based on this world model. From this the USV had to choose the actions to be performed, including localization of pingers, deployment of marsupial systems, and launching of projectiles.

The complexities of hydrodynamics, combined with confounding environmental effects such as wind and wave action, prevented a single simple solution being found. Simple guidance to a goal pose can be used, but vehicle side loads would result in a curved path being followed, potentially resulting in collision with obstacles. For this reason, the TopCat vehicle used paths constructed from transect line and curve primitives. This allowed the vehicle to clearly identify and correct for the vehicles transverse error while following the path to its goal pose.

Control is used performed using a monte-carlo optimization algorithm that searched through possible future trajectories to find one that most closely matched the desired path. This allowed a highly complex control model to implemented, including added mass, coriolis and wind effects.

### D. *Actuator Control Module (ACM) Firmware*

The TopCat USV had multiple communication systems used to connect between system actuators, radio communications and ROS topics. At the core of this system was the Core Board, a microcontroller system that connected RF teleop, CAN messages and ROS communications. Together these boards had the following functions:

Communicate with the teleoperation system using MAVLINK messages over the 900MHz radio link,

Communicate with the Kokam batteries using CAN,

Communicate with the Actuators using CAN,

Communicate with the higher-level autonomy package using ROS topics,

Control low-level functions including deployer operation and battery switching

Information logged to the autonomy system includes battery voltage and temperature, max and min cell voltages, battery currents, motor speed, temperature, and current draw. The autonomy system can control battery state, motor actuation, and deployer raise and lowering using ROS topics.

A second board with a modified firmware called the *kill board* was tasked with:

Control of motor isolation relays,

Control of the vehicle status light.

The core and kill boards implemented a state machine, moving between *linkloss*, *stop*, *manual* and *auto* modes under the control of their respective remotes as shown in Figure 5.

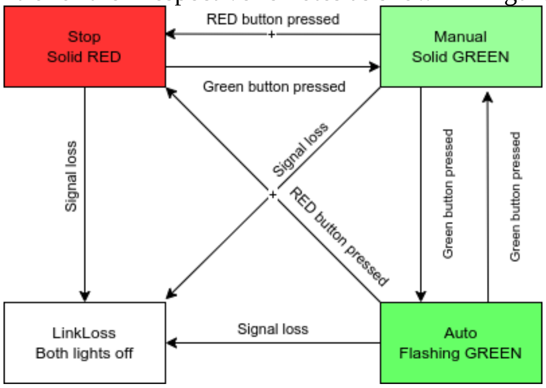

*Figure 5: A functional block diagram showing the radio communications between the e-stop remote, operator control station, and the remote control used for TopCat.*

### E. *Object Recognition and Classification*

To have our USV navigate its environment, it requires access to a live feed of surrounding features given from a robust estimation of its location. A constantly updated map of the surrounding environment extracted from on-board sensors as well as vessel navigation data ensures that safe operation of the USV will occur.

With the amount of features present surrounding the USV at any given time navigating waterways, one such issue that must be considered is the environment the USV is operating within. As objects within the operating environment (buoys, docking stations etc.) not being static, subject to drifting with the current, the solution requires a robust data association process to ensure consistent mapping and identification of current location in relation to other objects. To comply with international maritime regulations, identification of surface features is crucial, being able to identify and distinguish between various types of navigation markers.

To operate within a GPS-denied environment, the object localization system produces both an estimate of an object's position and the vessels. This is referred to as a Simultaneous Localization and Mapping system (SLAM) [6].

For the conditions, the FastSLAM algorithm was determined to be the most suitable option to solve these problems. It maintains a feature-based map, describing identified objects by type and location. In a sparsely populated environment, this solution provides a memory-efficient representation, lending itself to maintenance of the object classifications. Using a FastSLAM solution provides a stronger solution to the data solution problem compared to other SLAM algorithms.

The SLAM algorithm is implemented using the Point Cloud Library (PCL) [22], [23]. The first stage of the mapping system is performed through the Object Detection node, aiming to segment objects of interest from point cloud measurement data provided by the lidar.

From a new point cloud measurement, unwanted data returned from features beyond the shoreline must first be removed by the Object Detection node. This is performed through defining a polygon that encloses the USV's operating field, using a point-in-polygon algorithm [24] to remove points beyond the shoreline. The water's surface creates additional sources of unwanted data, with disturbances on the surface producing additional data points. As the average point cloud intensity values from these disturbances is a lower average intensity value than the values of those from physical features, these points are filtered out based on a minimum intensity threshold.

Following removal of unwanted data, features of interest are separated using a point clustering algorithm based on distance thresholding. Bounding box representations of the segmented clusters are constructed and published as a list of landmark-measurements to the SLAM node and used to update the current map.

An Iterative Closest Point (ICP) algorithm [25] is used to perform classification of complex 3D shapes, comparing point cloud clusters to local template models. The algorithm iteratively attempts to match point cloud clusters to the template, searching for unique key-point features in the point cloud cluster. This results in a best-fit score and a transformation matrix describing the estimated orientation of the observed feature.

Classification is achieved by associating one or more finite Bayesian filters with each identified object [6]. Each of these filters instantiate a set of possible values, for the given property and recursively estimate the probability of each value. These probabilities are generated by the pertinent sensor processing algorithm by supplying the defined set to the algorithm and the algorithm returning the probability of each element in the set.

The map is published as a list of objects, with each object containing a unique identifier, position, as well as zero or more identifying parameters such as type, colour, or shape. This was performed due to the expectation that the environment will be sparsely populated.

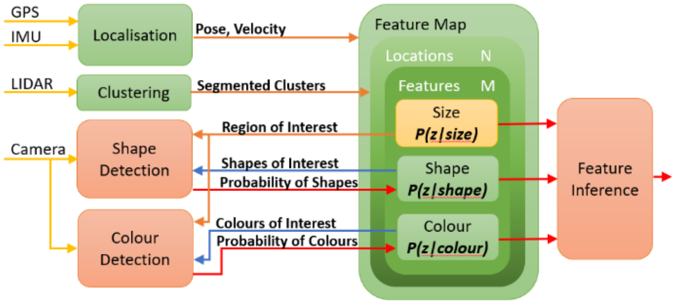

*Figure 6: Functional block diagram showing the Simultaneous Localization and Mapping System*

The vehicle uses two primary sensors for localization, the BX982 Dual antenna GPS, and a Microstrain AHRS. Each sensor provides capabilities that the other does not. The GPS produces absolute positioning and velocity estimates and, due to the positions of its antennas, heading and roll information, but only heading angular rate. The AHRS produces acceleration and angular rate in all axes, but the heading reference is produced by a magnetometer which is susceptible to interference. By combining information from both sensors, an improved position and velocity reference can be achieved.

To perform fusion, GPS data is first pre-processed by wamv_spatial, a custom ROS package. This converts from the GPS' geodetic coordinate system into a locally flat projected coordinate centered on a datum point. The GPS' heading and roll estimate is then used to project the position and velocity estimates to the center of the vehicle. The resulting estimates are then fused with the AHRS data by the robot localization [26] package to produce the final odometry estimate. This estimate combines linear and angular velocity with pose allowing a single topic to be used as the basis of

### *F. 2022 Additions*

### *1) Steering Upgrade*

In the 2014 competition the outboard motors were initially rigidly mounted. Steering was then added to each thruster in 2016 by linear actuators attached to the tiller steering link arm. This allowed the motors to be tipped up when desired without any interference to the steering mechanism. The steering mechanism, however, experienced binding between the linear actuator and the steering linkage and was inherently limited in the steering angles achievable. To overcome these limitations a new steering system, seen in Figure 7, was developed utilizing a high torque servo connected directly to the head of the Torqeedo motor via a toothed pulley system. The ±45° provided by the servo is converted, via a 2:1 pulley system, to ±22.5° of steering angle, although this can be increased via a firmware update to the servo to provide ±67.5° of steering angle well beyond the capabilities of the previous system. Almost all the housing is 3D printed using PLA sealed with a primer and painted to limit UV degradation. To facilitate the tipping of the outboards the housing is retained to the pivot arm using Delrin arms bolted to remainder of the housing which is pressed against the rear face of the outboard by longitudinal bolts.

*Figure 7: Steering module using a toothed pulley system controlled by a servo.*

### *1)* Shrouds

The RobotX 2022 competition required the addition of propeller shrouds on the vessel as a safety feature. As the Torqeedo motors currently installed on the boat are no longer in production, it was difficult to source appropriate propeller shrouds. Therefore, custom-made shrouds were designed and manufactured in-house at Flinders University. The overall design of the shroud is inspired by the propeller guards offered by Torqeedo [27]. An absence of accurate Computer Assisted Drawing (CAD) models of the motors meant measurements of the motors needed to be taken. This was done through scanning the motor and 3D printing prototypes to ensure the shroud accurately fitted the motor. After analyzing various options, the final design comprised of a separate rolled aluminum tube that would be screwed onto an internal PVC bracket. The shroud was manufactured with water and corrosion resistance in mind using 316 stainless steel or aluminum components, as shown in Figure 8.

*Figure 8: A custom manufactured shroud installed on Torqeedo thrusters, inspired by the manufacturers design.*

A visual inspection was made to monitor for any obstructions to motor movement and function and to confirm the rigidity of the shroud installation, however, in-water testing of the thruster with the shroud is yet to be conducted.

### *2) E-Stop* System Improvements

Four mechanical E-Stops are required on TopCat for it to pass the safety regulations of the competition. Due to the age of the previous E-Stops, it was decided that they would be replaced and four new IP67 E-Stops would be installed onto the vessel. The old e-stop mount had the issue of fasteners that were difficult to access, and thus the decision was made to redesign the old mounting system. The new design focused on making the nuts and bolts more accessible and included a new face plate, made of acetal, used to make the new E-Stops more readily changeable in the future. This was done by mounting the e-stop onto the plate instead of directly onto the bracket. An emphasis on corrosion resistant fasteners was also made in this area, therefore the fastener material was G316 stainless steel.

The new e-stops are IDEM e-stops designed for surface mount and rated for IP67. M20 cable glands were used on the e-stops to better seal and protect the connections from the environment. The new front e-stops are connected in series, as seen in Figure 9, with the aft e-stops to the electrical box. All new e-stops have been installed and were confirmed to be in a functional state.

The e-Stops were mounted using maritime grade G316 stainless steel bolts, to protect against degradation due to weather, and held together with nylon-insert lock nut to protect the connection against vibrations.

*Figure 9: The redesigned e-stop mount, showing a three-piece modular design, this decision was made as it allows easy replacements of damaged parts.*

### 3) Acoustic Beacon Localization

A new solution was developed for TopCat's underwater acoustic sensing capability, seen in Figure 10, in place of the original FPGA solution developed for the 2014/2016 iterations, as the old system had a critical flaw in acquisition processing time. An ADLink USB 2405 Analog to Digital acquisition device, was used, a 24-bit Sigma-Delta ADC with built-in anti-aliasing filter which uses four channel simultaneous sampling analog input, up to 128kS/s.

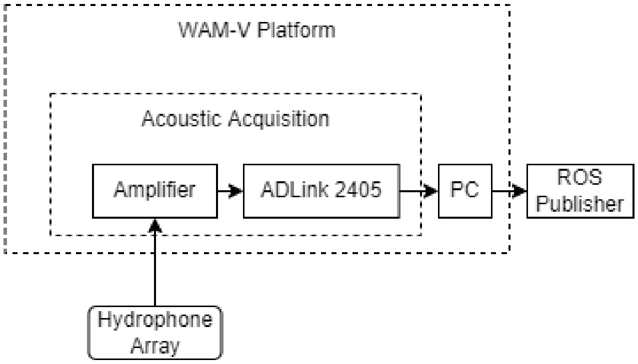

*Figure 10: An overview of the system with the Amplifier board and ADLink 2405 mounted on TopCat using the Linux based on-board computer for transmitting converted data using a Robot Operating System (ROS) Publisher.*

This new ADLink USB 2405 based audio acquisition solution, incorporates an amplification stage with signal conditioning as well as other signal processing techniques [28] can detect a pinger, similar in specification to the one used in the RobotX 2022 Team Handbook [29], to be detected from a range of 10 meters. This data is obtained through a ROS interface, designed to calculate the Time Difference of Arrival (TDOA) between the signals of interest. These TDOA's are then fed into a particle filter ROS node, allowing TopCat to locate the most probable source of the acoustic beacon ping, due to the algorithm's efficiency at sea [30], being resistant to echoes and reverberations.

### 4) Path Planning

Given a method of locating and identifying objects, and a method of propelling TopCat around its environment, what was needed was a method of navigating the vessel around obstacles and through appropriate checkpoints.

The design of the path planning system was based on a triangulation method adapted from [6]. It started by collating a list of obstacles, as in the computer vision system, then assigning a start and end goal pose (combination of position and bearing). A Delaunay triangulation of the obstacles and the start and goal poses was then generated. From this triangulation the midpoints of the edges connecting the obstacles as navigable points was taken (checking for a sufficiently large distance between them to drive the vessel). A Dijkstra shortest path algorithm was then applied to navigate from the start pose, through the triangulation midpoints, to the goal pose. At this point the system had a path comprised of straight-line segments connecting a list of poses. The final step was to do straight line projections from start poses to later poses to check if it were possible to reduce the number of intermediate steps.

### 5) *Mission Planning*

Mission planning is an essential component of the overall software design of the TopCat system. It acts as the synthesising section of all other parts of the system, taking in processed sensor data and deciding what course of action should be taken to complete a given goal. The mission planning in TopCat has two main components: the decision components and the action component, as seen in Figure 11.

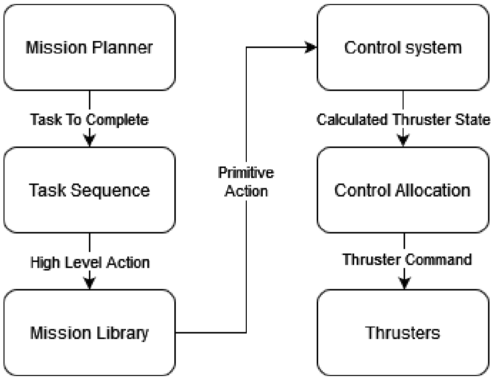

*Figure 11: Structure of the Mission Planning system, showing the flow of logic from the mission planner through to the thrusters. This however, does not detail the feedback delivered in the control system.*

The decision component of the mission planning, as the name suggests, is what takes in information about the current surroundings and inferred state of the world to decide what TopCat should be doing at any given point in time. The decision component makes use of a high-level state-machine behaviour, generating actions that should be taken to progress from one state to another. For example, when a task is begun, TopCat would require an information gathering state. For this, the mission planner would generate a “scouting” action that would move the vessel to point the cameras at nearby obstacles. The mission planner would then continuously keep checking if the action has been sufficiently completed before moving to another state, such as a navigation state.

The action component of the mission planning system is what takes the high-level actions generated by the decision component and turns them into simple actuator functions. The TopCat system has two tiers to this part of the mission planner. Firstly, a high-level mission library that has tasks such as “approach buoy” or “navigate through gate” that generate a set of lower level “primitive” actions which are sent to the next tier. The second tier of the action component of the mission “planner” is the control system, which has a library of “primitive” actions that are then sent as messages directly to the thrusters.

## V. RESULTS

### A. Simulator

To test and prototype many of the software components for the competition a Gazebo 11 simulation [31] was set up using the course from the 2022 VRX competition [19]. Once this was operational, interfaces for both the simulated and real world WAM-Vs were used to integrate with the main processing packages, an image of the simulated TopCat can be seen in Figure 12. The key benefit of the simulated environment was that it allowed for effective prototyping and development of essential components of the vessel’s software without having to pack up and transport TopCat to a suitable testing location.

Simulation allows testing that is difficult to perform in a real-world environment, for example repeating a test multiple times with similar initial conditions allows investigation into the statistical distribution of the result. For testing the variability of a system, a control system task was repeated thirty times, with the vehicle returned to the origin with each iteration. This allowed a mean and variance of the result to be estimated.

*Figure 12: Simulated TopCat in Gazebo 11. The vehicle model and environment are based on the Virtual RobotX (VRX) package [19] combined with assets from TopCat’s CAD design. The vehicle model has been extended with custom wind and thruster models.*

Although a simulated environment is effective for prototyping, real-world data is often noisier and more unstable. To deal with this, test data was gathered from the real vessel using the ROSbag functionality. This data collection was useful for testing the different sensor data processing algorithms, in real world scenarios, without having to repeatedly take the vessel out every time.

Overall, the combination of having an accurate simulation environment and having captured and stored some data from real life scenarios was essential for effective development of the software capabilities of the vessel.

### B. VRX

Virtual RobotX is a purely online simulation-based competition. In 2021, Team Australis$^2$ entered this competition for the second time. VRX’ simulation-based nature allows teams to concentrate on the development of effective and reliable autonomy solutions. For Team Australis$^2$, this was an opportunity to train a new cohort of robotics software developers, giving them experience in working in a team environment towards a common goal. The team learned techniques ranging from task allocation, software development with ROS, and Developer Operations - leveraging the power of modern source control systems to maintain, test, and merge codebases from multiple developers.

Team Australis$^2$ finished in seventh place overall, and third in the “Channel Navigation, Acoustic Beacon Localization and Obstacle Avoidance” task. However, the most important result was a chance for the team to work together to develop an autonomy solution under strict time pressure.

### C. Control System

In Figure 13, the transverse error from the start of the maneuver is shown. The control system was started with the vehicle between 5.8 to 6.5m from the transect line. Convergence to the transect line occurred within ten to fifteen seconds on all trials, with the maneuver complete in a mean time of 31.5 seconds. The final line-following control system behavior after convergence showed a mean transverse error of 0.13m, with a standard deviation of 0.11m

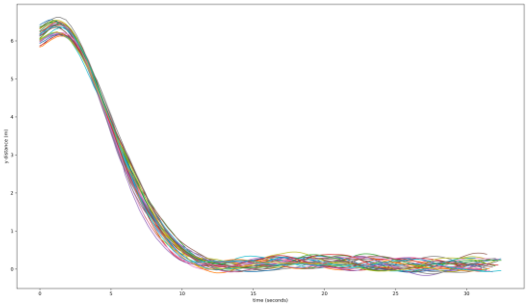

*Figure 13: Graph of control system transect error in simulated environment. A total of thirty trials are shown, with a mean line following error of 0.13m.*

## VI. DISCUSSION

TopCat is currently used for the RobotX competition and for research applications within Flinders University. Both require flexibility in mechanical, electrical, and software design elements to allow effective development and use by current and future teams. Key aims of this year's team, and for the future upkeep of TopCat, are effective documentation, modularity in designs, and easier maintainability of components. In the future, the Flinders teams plan to upgrade the vessel to include the addition of lateral thrusters, refit of the electrical system, UAV landing platform, UAV battery replenishment, UAV code, a mounted and functional air cannon (with a targeting system), and a control system for the sonar deployer.

### *A. Lateral Thrusters*

The addition of forward mounted lateral thrusters to TopCat was proposed to help stabilize movement especially when being pushed sideways by wind. A mounting concept was created this year ready for prototyping, as shown in Figure 14. The design allows the thruster position to be changed in the vertical and horizontal direction by making use of aluminum profiles and T-slot nuts and screws. The design also utilizes existing mounting points on the TopCat platform to minimize permanent modifications on the vessel. Initially the design used Blue Robotics T200 thrusters, however, after reconsiderations in thruster power, the T500 thrusters were selected. Unfortunately, as the T500 only entered production in Sept 2022, they could not be sourced in time for the competition. Lateral course control will therefore be handled using the vectored rear propulsion thrusters.

*Figure 14: A computer assisted drawing of front thruster mount design, with a BlueROV thruster attached to the aluminum extrusion.*

### *B. Uncrewed Aerial Vehicle:*

The Swellpro SplashDrone 4 was selected as the Uncrewed Aerial Vehicle (UAV). This drone is fully waterproof and able to survive full immersion in water and then take off from the water. It is fitted with a pan-tilt camera and an external servo, both of which are waterproof. The drone's remote controller can communicate via Wi-Fi to TopCat's host computer, allowing for packages of information to be sent between the drone and TopCat via the remote. Although the communication protocol was developed and implemented, errors were found in the provided software development kit (SDK) documentation that caused additional problems to occur when attempts were made to communicate with the drone. Eventually, the SDK errors were resolved enabling instruction and data packages to be sent to the drone and queued upon acknowledgment of communication. The drone would then execute the queued commands in the order they had been received. From testing, it was found that the drone was successfully able to return GPS information as well as display a visual feed through the camera to the host computer. Further errors with the protocol, including moving the pan-tilt camera and displacing the drone laterally or vertically by a set amount are as yet unresolved, making it unviable to use the drone in time for the 2022 competition. Work will be continued to resolve these problems.

Additional work was carried out to process the drone's live video stream to detect the landing pad targets. The use of the Hough circle transform, and the rectangle transform allowed successful detection of the concentric circles within the landing square as shown in Figure 15 (a). A machine learning approach combining the use of a feature detector and convolutional neural network (CNN) algorithm was also used to successfully detect the R and the N logos as shown in Figure 14(b)

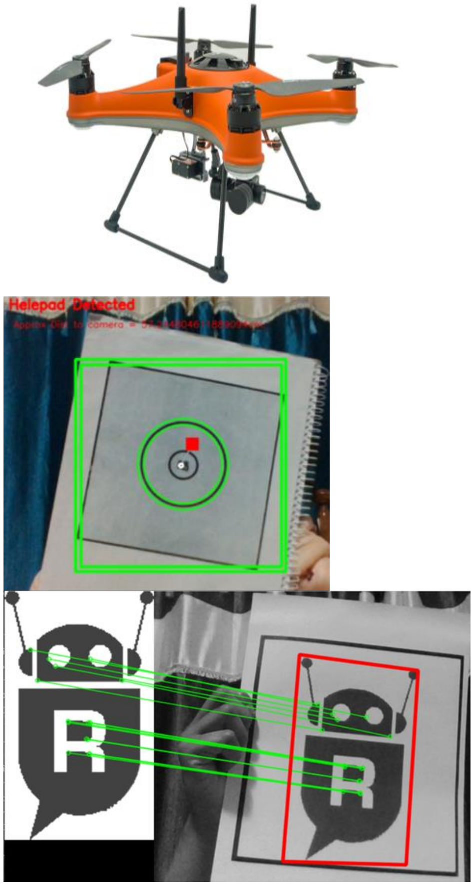

*Figure 15: (a) Left– SplashDrone 4, (b) - Middle -Use of Hough Circle Transform and Rectangle transform to detect the concentric circles within the square landing pad. (c) – Right - Use of feature detection to detect the 'R' logo and then classify it using a CNN classifier. (Images courtesy of Deepthi Paul)*

### *C. Hyperspectral Camera*

In order to complete the Wildlife Encounter task, a hyperspectral camera is required to detect the special paints used to make the wildlife symbols placed on the horizontal floating platforms. Given that the symbols could only be observed from above, the hyperspectral camera would need to be mounted on a UAV. For this purpose, a pushbroom type hyperspectral camera, OpenHSI, donated by Sydney Photonics, was selected, particularly as it came packaged in a waterproof housing and is within the drone's payload capacity. The OpenHSI camera {Mao, 2022 #308} is able to record spectral components in the range 430nm to 900 nm with 529 bands.

A Python script was developed to capture data from the camera as it was scanned along a test scene, simulating the motion of the drone flying past the scene. For the test, 10 blue square boards painted with five distinctive pigments were used as the target objects. These boards were placed in an outdoor environment. The objects look similar and are very hard to discriminate by human eye or by a normal colour camera. The distinct spectral signature of each object depends on the painting pigment which is used to paint the objects. The test image contains 1000 lines, each line scan contains 439 pixels, the number of recorded bands is 529, and the number of bits per pixel per band is 12 bits; hence the image size is 439x1000x529x2 bits. A ground truth of the test scene was established by manually segmenting each panel in the scanned image. This was repeated multiple times to form a training set which was then used to train a CNN classifier. The classifier was then tested using separate scans of the test scene.

The OpenHSI scan of a sample image of ten test samples is shown in Figure 16 (left). The result of the CNN classifier is shown in Figure 16 (right). Although the classifier can discriminate between the targets, more work needs to be done to assess how well it works with different lighting conditions. Given the problems encountered with drone, it will not be possible to deploy the hyperspectral camera in the 2022 competiton, however further research will be continued on developing the classifier further by CDERT members.

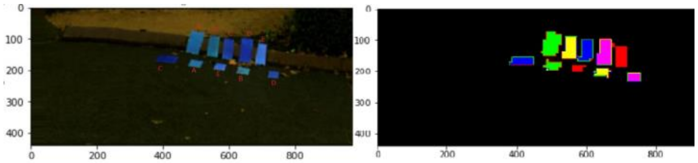

*Figure 16: Left - Recorded scene visualization using OpenHSI camera of various painted surfaces (Symbols A – Watercolour painting, B – Gouache painting, C - Acrylic painting, D - Blue ink painting, E – Oil painting), Right – Result of using CNN classifier.*

### D. *Pneumatic Racquetball Launcher*

A pneumatic racquetball launcher was developed for the Find and Fling task. This task requires a targeting system capable of identifying a designated colour and delivering four balls into two square holes. In 2022, a concept mechanical prototype comprising the pneumatic launcher components was developed as shown in Figure 17 [30]. Further work still needs to be done on developing the gimbaling system and the computer vision-based targeting system that allows the launcher to lock –on to the target despite movements of the vessel.

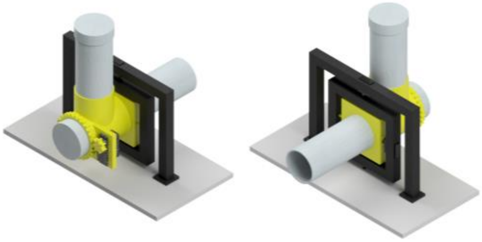

*Figure 17: Pneumatic Launcher designed for the find and fling task [32]*

## VII. CONCLUSION

The main findings of development on TopCat for the 2022 competition are that designing for modularity and using a digital twin for development is critical.

This is evidenced by the ease of upgradability during the development process of TopCat, as well as the results from control system simulations and lessons learned from VRX in the results section.

The uncertainties from this development strategy, however, is that a simulation is not reality, and the complex way the hardware and software interact are not accurately represented in this simulation.

The explanation for the findings of these developments to still be relevant is that, yes, there are uncertainties in the simulation in regard to the software and hardware interaction, it is the development of the algorithm that is more difficult to undertake when compared to instrumentation and creating firmware.

The implications of these findings show that developing for a large platform can be difficult as the number of field test days are always far too small, forcing the majority of development to be on a simulated USV. Future experiments of course, would be to test algorithms on a digital twin, and then validate the results in a field test.

## VIII. ACKNOWLEDGEMENTS

The team would formally like to acknowledge the great support, both financial and in-kind, provided by our major sponsor Thales Australia. We are also thankful to Flinders University for providing technical assistance, facilities, and financial support towards logistics. Additionally, we want to recognise our other sponsors for their generous financial contribution to our project: the Australian Submarine Corporation ASC, REDARC, Flinders University Society of Engineers (FUSE), the Institute of Electrical and Electronic Engineering (IEEE – South Australian Section), and SAGE Group. Finally, the support and advice provided by our academic staff, Prof. Karl Sammut, Assoc. Prof. Russell Brinkworth, Dr. Jonathan Wheare, and Dr. Andrew Lammas, has been invaluable in enabling us to advance this far in the competition.

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