# RoboBoat 2021: VantTec Technical Design Report VTec S-III

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***Abstract*—The RoboBoat 2021 competition strategy, developments and improvements on existing systems, and final results are presented in this report. The strategy relied on improving the perception and collision avoidance methods of the USV system to validate through simulations the approaches to the challenges proposed last year. A realistic simulation environment was developed for this purpose, as COVID-19 pandemic made difficult physical development. The electronics system performance achieved during last years proved to not be robust enough, so a complete redesign is proposed. Additionally, a new and more efficient microcontroller unit is chosen for peripheral signal processing of the USV. Simulation results deemed the proposed perception and collision avoidance methods as reliable solutions for the problems at hand. The improved systems enabled a successful completion of almost all challenges.**

***Index Terms*—Unmanned surface vehicle, robotics, autonomy, GNC system, computer vision, artificial intelligence**

## I. COMPETITION STRATEGY

A year has passed since the COVID-19 pandemic started. The global event caused the imposition of strict health regulations by the government, inhibiting team efforts and ruling out physical development or testing for an extended time period.

Progress of the school year and subsequent graduation of several senior members, caused radical changes in team management. These events resulted in difficulties in the establishment of specific goals for the year, leading the team to not being able to maximize efforts on the time available but serving as a learning process for most of the team members.

At the beginning of 2021, the uncertainty of the competition format was an important concern. In addition to the previous issue, access to the Tecnologico de Monterrey facilities was still restricted, not showing clear signs of when or how these restrictions would be reversed. These situations forced the team into planning with a focus on an online scenario but considering the possibility of a physical competition and flexibility on restrictions to enter campus for preparations.

The competition strategy for RoboBoat 2021 improves on the methods developed for the last competition, with a focus on practical implementations validated through realistic simulations and research-based solutions.

Improvements in the electronic system of the boat was of high priority before the pandemic but had not been addressed until this edition. A redesign of the electronic systems of the vehicle was deemed necessary, as robustness in the previous iteration was not guaranteed. The new system still requires validation, as only a few weeks prior to the competition the team was given access to the vehicle and its components.

### *A. Course Approach*

The VTec S-III (Fig. 1) remains the go-to model for two important reasons: it has already been validated through physical experimentation during the last years, and its dynamic model has proved invaluable to create a more realistic approach for the simulations.

The course approach in the 2021 edition is based on improvements made in the software architecture. The creation of a realistic simulation environment was necessary to pave the way for further work, as it enables to develop and test approaches based on simulated sensor readings.

Considerable advances have been achieved in the areas collision avoidance algorithms, perception systems and simulation environments that further validate the approaches. These advances, in conjunction with the aforementioned electronic architecture changes, have the goal of increasing the robustness of the overall system.

The lack of changes in the RoboBoat 2021 challenges meant it was not necessary to make drastic modifications to most algorithms. Instead, the focus was directed into integrating software advances of the different systems into these approaches.

Moreover, a big difference from previous editions is that the perception system now relies only on data generated by the Velodyne VLP-16 Puck. This new approach improves confidence in the completion of challenges as it has several benefits: it is less resource-intensive, increases frame rate, it is more precise as the distances are calculated from lasers, and it has a 360 °field-of-view.

The Mandatory Navigation and Speed Gate challenges remain the most consistent challenges due to the feasible solutions proposed in previous years. These challenges were addressed and solved in previous competitions, so the approach is the same. The main difference this year is the validation given with the new perception system and simulation environment.

Furthermore, the creation of a more robust obstacle avoidance method, in conjunction with the mentioned perception improvements, highly increased the confidence rate on the approaches to the Obstacle Channel and Obstacle Field, as success in these challenges was situational, highly dependent on positions of the obstacles relative to the boat.

The Acoustic Docking challenge only received an improvement in the new perception system. The current solution obtains the positions of the dock frontal corners, necessary for the challenge execution. The rest of the approach remains the same due to a lack of further development on the hydrophone system.

Fig. 1. VTec S-III USV.

The Object Delivery Challenge was not addressed as no new developments were made by the drone sub-team and the nonexistence of gripping mechanisms. The lack of developments was due to COVID complications and a constantly changing, non-friendly API of the drone (DJI Phantom 4 Pro). To further increase progress in this area, creation of a new drone has been considered for future competitions, but is still in a planning phase.

The strategy proposes that, by adding robust improvements on the collision avoidance and the perception systems, both validated through realistic simulations, higher confidence on the course approach performance can be guaranteed for RoboBoat 2021.

## II. DESIGN CREATIVITY

### A. *Software Architecture*

The software architecture for this competition is almost the same as the previous approach [1]. The Robot Operating System (ROS) persists as the backbone of the system and has proven to be extremely useful again, as it provides means of working with the Gazebo simulator and RViz, which are essential tools for the competition.

A new package, USV_AVOIDANCE, was added to the software architecture (Fig. 2). This package hosts the collision avoidance node and takes inputs from RB_MISSIONS, data from USV_PERCEPTION and VECTORNAV packages and yields suitable references to USV_CONTROL for the Obstacle Channel and Obstacle Field challenges. For the rest of tasks, it is not used.

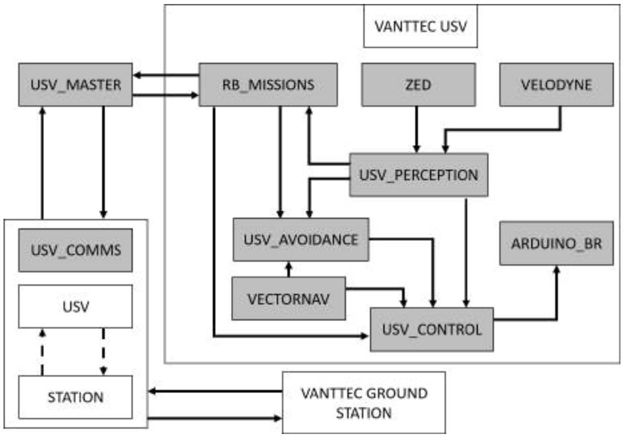

Fig. 2. USV software architecture.

Additional modifications were made to the USV_CONTROL, USV_PERCEPTION and RB_MISSIONS packages, as a result of the improvements made for the perception and collision avoidance methods.

Moreover, changes in the hardware will make the ARDUINO_BR package outdated, being replaced by a package currently in development as now an STM32-based microcontroller interfaces with the T-200 Blue Robotics thrusters.

Due to the fact that simulations are the only source of development, not all the packages in the software architecture were used, leaving only USV_MASTER, RB_MISSIONS, USV_CONTROL, USV_AVOIDANCE and USV_PERCEPTION packages required to run simulations.

### B. Simulation Environment

The last competition strategy relied solely on the use of RViz to validate the challenge algorithms, which was deemed as an acceptable approach due to sudden changes caused by the pandemic. However, means of further validating the methods were still necessary, as physical tests were still not possible, and RViz does not provide infrastructure to simulate sensor data.

The previous factors led to the decision of developing a simulation environment with the next objectives in mind: to validate the past system approach; to prepare for this competition in the case of another online scenario; and to facilitate development for future competitions, as physical testing can be difficult.

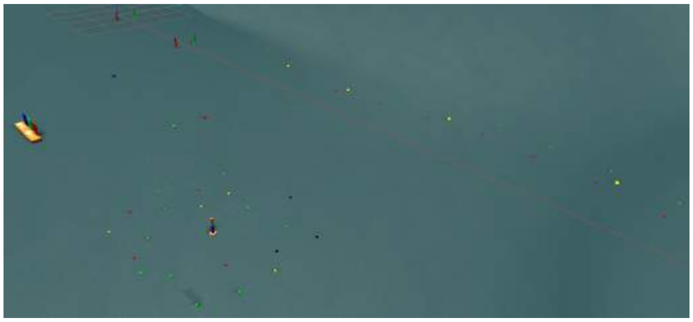

Fig. 3. Gazebo simulation environment.

The first task in the development of the simulation environment was to find similar solutions proposed by the community. Simulators found in [2], [3], [4], [5], [6], [7] proposed attractive approaches, as some could simulate waves, buoyancy, water currents, wind, and a variety of scenarios. However, some of them required the user to fill a complete description of the vehicle to work, which was a lengthy and tedious process as not all aspects of the model were known. In addition, the team was in no need to simulate waves or water and wind currents as the goal was to validate the correct functioning of the already developed algorithms with the improved systems.

The proposed Gazebo environment relies on the dynamic model of the USV to simulate the vehicle state (position, velocity and orientation); a 3D model of the boat; a LiDAR sensor [8]; a stereo camera [9]; a node to interface the USV repository with Gazebo; a basic lake scenario obtained from [3]; and custom props, such as buoys and markers. These elements proved enough to simulate a realistic stage (Fig. 3) for RoboBoat competitions.

### C. Guidance and Control

The path following controller based on Adaptive Sliding Mode Control (ASMC) strategy and a Line-Of-Sight (LOS) based guidance law developed for RoboBoat 2020 is still used. In [10], the controller was proven to be robust to handle uncertainties, shown by physical experimental results.

### D. Perception

In previous competitions, the perception system main sensor was the ZED stereo camera for object detection and localization. In this year, a new system was developed, outperforming the same functionalities but relying solely on a Velodyne VLP-16 LiDAR sensor and its generated 3D point cloud.

Following an approach similar to [11], the point cloud is pre-processed by filtering out all points outside a 20m side cube, centered in the origin. Then, the point cloud is projected on the XY plane, and organized using an octree data structure, creating a 2D grid space. Each grid or voxel has a dimension of 20x20 cm. Information for each grid is stored in a 2D array of 512x512 elements, using the grid coordinate for indexing. An example of the information stored is the grid coordinate, height, density, and occupancy. It is worth mentioning that the Z axis information was lost with the projection, nevertheless, the point indices are the same as in the original point cloud. This indices are used to access the Z axis information and calculate the height of the points in the grid.

In simulation, noise is not present in the point cloud. However, density information from each grid is used to handle the noise, by ignoring all grids with density fewer than a certain threshold.

The 2D array is then converted into an image using the occupancy data as follows: if the grid is occupied, then the pixel value is 255 (white), otherwise 0 (black) (Fig 4a). The 512x512 pixel occupancy grid image is used to merge adjacent occupied grids in order to identify objects present in various grids (the OpenCV function *findContour* is used for the latter purpose). While iterating through each pixel from each contour, the grids individual information is merged, creating a data object containing the overall information corresponding to the full object. For example, comparing both grids and only preserving the maximum and minimum height and voxel dimension; or calculating the center of the full object by using the center of both voxels.

Finally, classification of the object is done by comparing their height and dimension, with the known sizes of the real objects, in this case the buoys, markers and dock (Fig. 5). If the height is less than 0.5 m it is a buoy, if the object is wider than a meter it is a dock, otherwise it is a marker.

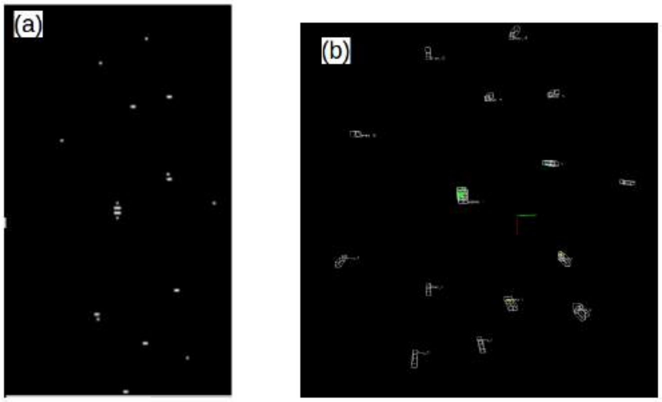

Fig. 4. Grid Image. (a) Occupancy Grid Image example (b) Point cloud with voxels occupancy

### E. Collision Avoidance

Two collision avoidance methods are the result of the efforts made to improve the performance achieved during the last competition. The first one is the Velocity Obstacles (VO) method that started development during the second half of 2020, and the second one is an MPC-based collision avoidance method developed during the first half of 2021. The latter method was developed because the expected performance was not met by Velocity Obstacles, as the execution of the method was situational, and therefore not a robust solution.

*1) Velocity Obstacles:* The VO method [12] accounts for static and dynamic obstacles, but the current implementation considers only static obstacles. The method relies on the state of the system (position, orientation and velocity) and the position and size of the obstacle. The technique works at the same level as the LOS guidance law, and is considered reactive, as it overrides the LOS references with suitable avoidance velocities and orientations only when colliding velocities are detected.

The method accounts for collisions by creating a Collision Cone, which represents a set of colliding velocities for a given obstacle. Avoidance can be performed by choosing velocities outside of the cone, respecting certain physical limits. The same approach applies for multiple obstacles.

*2) MPC-Based Collision Avoidance:* To improve the collision avoidance performance of the system achieved so far, a new approach based on Model

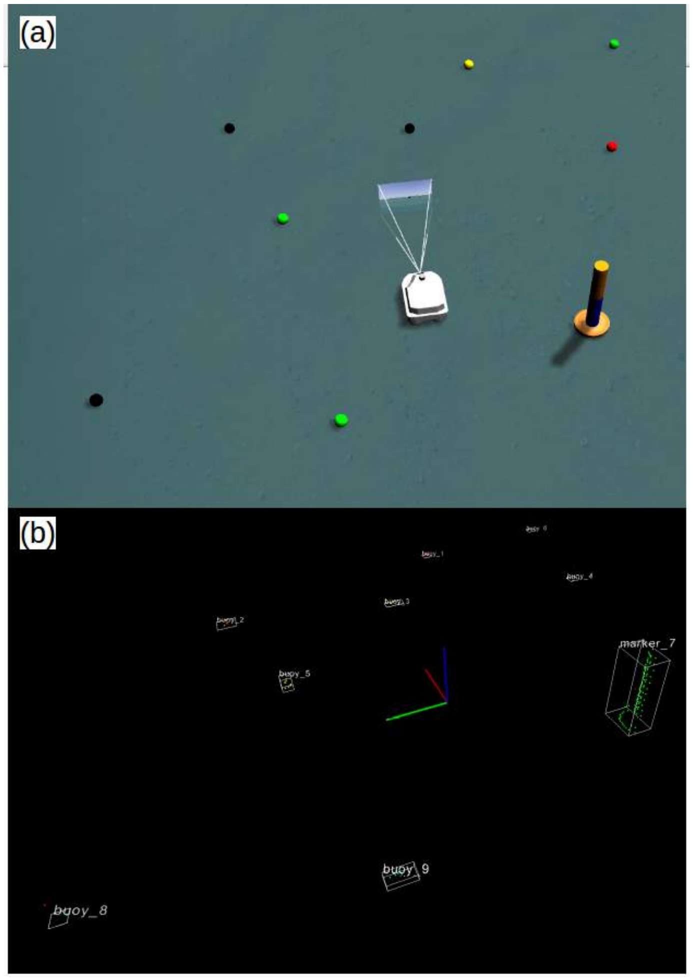

Fig. 5. Demo of the Perception System. (a) Gazebo World with Objects (b) Point cloud with detections from the gazebo world in (a)

Predictive Control (MPC) was developed. This new strategy requires knowledge of the system state (position, orientation, and velocity), the obstacle characteristics (position and radius), and the desired path to follow. When the collision avoidance strategy is used, it replaces the LOS guidance law, and sends the desired surge speed and yaw references to the ASMC low-level controller.

The MPC-based collision avoidance method uses a kinematic model to predict and optimize the performance of the USV along the path. A cost function is applied to minimize the cross-tracking error and avoid the obstacles. The cost function weights the distance from the USV to the path (to remain near the path), the difference between the path orientation and the USV orientation (to favor moving in the path direction), and the distance from the USV to each obstacle. The distance from the USV to each obstacle is computed by first acquiring the position difference between the USV and the obstacle, and then subtracting the detected object radius and a safety distance.

### *F. Acoustic Signal Detection*

The main improvement made for the acoustic signal detection is the development of an algorithm capable of calculating the source signal location of the ALP-365 pinger, in relation to the array of hydrophones (Appendix A). The approach was developed in MATLAB, by using a Direction of Arrival (DOA) algorithm [13], which uses a spatial-spectrum scan function to process the frequency response from the hydrophones and calculate the angle at which the signal is located. Currently, this algorithm only works for 2D scenarios, and only using two hydrophones. The algorithm still requires extensive improvements, as it is still in an early stage of development and not ready to be implemented in the simulations.

### *G. Embedded Systems*

In previous years, an Arduino Nano was used as the electric control unit (ECU) for signal processing and motor handling of the boat. To improve the reliability and precision of the microcontroller unit (MCU), the previous device was replaced by a STM32F405RG unit that provides more computing capacity, has better sampling precision, larger memory banks, and a Controller Area Network (CAN) bus interface [14]. The new MCU runs on a Real-Time Operating System (RTOS) that provides the ability of having multiple tasks with automatic resource management on a single core [15]. This system enables the employment of the functions developed for motor control and signal processing, fulfilling hard time constraints required for better performance of the microcontroller. The CAN Bus 2.0b (also known as ”Extended CAN”) was determined to be a better option for data transfer between the Jetson TX2 and the STM32F405RG MCU, with each device acting as a node. The main reason came from how the data frames, depicted in [16], have a unique identifier that can be used to prioritize the frames by the information each one holds. For example, the data packet for motor control needs a higher priority compared to the data from the hydrophones. Altogether, the implementation of this communication protocol in conjunction with RTOS, gives the embedded systems an allowance for further expansion while also accomplishing the real-time operation desired. RTOS permits not only to have more precision while sampling with the sensors, but also provides a modular design, which allows to eliminate dependencies between components.

### *H. Electronics*

The transition from the Arduino Nano to the STM32, as was previously mentioned, required a new PCB design due to the microcontrollers physical differences. A decision was made to take advantage of this need and further improve the reliability of the electronics from past iterations of the boat system. In order to unify team efforts, a standardized electronics system was proposed, one that can be used in several projects, such as the USV and the UUV. With this approach, a common codebase can be used, where only some small adaptations are needed depending on the situation.

To begin with, several design flaws were identified in the previous electronics system, which made the earlier iteration of the USV extremely unreliable. These problems included a scattered and poorly organized electronics inside the shell of the boat, which complicated debugging and accessibility. Furthermore, the failure in performance of the Arduino Nano during competition triggered subsequent faults in the USV electronics.

To account for these flaws, the main focus during the new design process was to make the electronic system as robust as possible, reducing the points of failure, and simplifying the amount of manual wiring that had to be made, by distributing power to the motors controllers via the PCB. Consequently, the electronics inside the hull were compacted, saving on weight and power usage.

With the new design, the power distribution and control can be contained in a 3 inch x 3 inch area, which solves the packaging issues. This new design also features thruster failure prevention with the inclusion of current sensors and automotive fuses on each motor controller power input, preventing damage to the main battery or other electronics in case of a major over-current event. The data collected from these sensors is sent to the Jetson for logging and analysis so that it can later be used to identify any unusual amount of current drain, these motors can be replaced or repaired in order to prevent a critical failure. In order to reduce the amount of batteries used inside the hull, several switching power supplies were used. With these, the number of batteries was reduced from five (three of which were heavy lead acid batteries), to two high energy density *LiPo* batteries. A new modular system was developed to ensure that this new PCB design can be used in any future projects, allowing for the expansion of the capabilities on the board. With these changes, the new PCB design can be used for both RoboBoat and RoboSub. A render of the final design can be seen in Fig. 6.

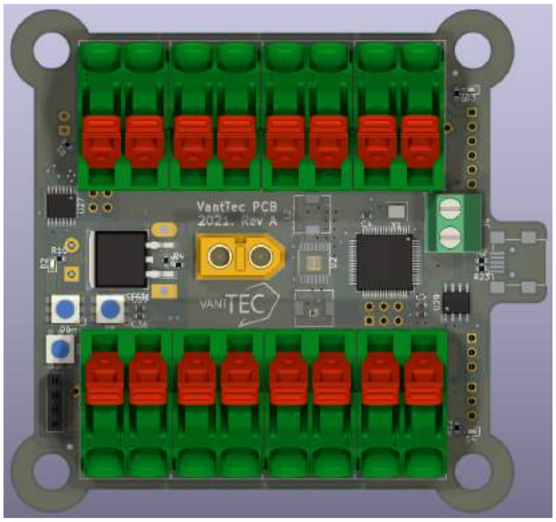

Fig. 6. New PCB Design.

## III. EXPERIMENTAL RESULTS

In this section, evidence and validation of the proposed course approach is presented. The Gazebo simulation environment was used to test all of the challenges with the aforementioned LiDAR-based perception and the collision avoidance system.

A Gazebo world encompassing all of the challenges, except for the object delivery, was built to represent the lake at Daytona Beach, Florida (Fig. 3). The world was built based on information provided in the official ’2021 Rules & Task Description’ document [17], and considering a real scenario.

Fig. 7. Mandatory Navigation Challenge.

### A. *Mandatory Navigation Challenge*

Fig. 7 shows the Mandatory Navigation challenge on a lake. Here, a set of green and red markers were added to represent the gates of the challenge. The dimensions of the markers, the width of each gate and the distance between them correspond to ones established in the competition rules.

With this setup, the Mandatory Navigation challenge was the first to be solved. The robustness of the approach was validated last year, so testing with the new perception system took focus. In the simulation, the USV starts close to the center of the first gate, and was able to cross it and navigate to the end of the challenge by identifying the tall objects as markers, as shown in the competition video.

### B. *Obstacle Channel*

The Obstacle Challenge (Fig. 8) was built considering the proposition given in the competition rules. A set of 10 gates made of red and green buoys were placed consecutively, with a separation of 7 m between each one, and having a width of 3 m. In addition, four larger yellow buoys were positioned at certain places to obstruct the USV path and to test the avoiding capabilities of the system. The simulation tests showed successful results in the challenge algorithm, the perception system, by identifying all of the buoys, and in the MPC-based collision avoidance performance, being able to avoid the four obstacles.

### C. *Obstacle Field*

A setup of 21 total buoys of different colors, placed at random positions around a central marker was built for the Obstacle Field challenge (Fig. 9). This scenario is meant to test the capability of the perception system to identify and differentiate the markers from the buoys, in addition to assessing the performance of the collision avoidance method, presenting multiple smaller obstacles. The simulation demonstrates the USV finding the middle marker without difficulties, breaching inside the obstacle field, circumnavigating the marker and exiting the field through the same opening, all while avoiding buoys in the path.

### D. *Speed Gate*

The Speed Gate (Fig. 10) challenge setup was built with a red and a green buoy that serve as a gate with a width of 3 m, and with a third blue buoy found 70 m perpendicular to the gate. The solution follows the same principle as the mandatory navigation, heading in a perpendicular path in relation to gates until it finds the middle buoy, then returning to the original position. The simulation shows the USV crossing the gate, and following a straight line perpendicular to the gate itself. After a few seconds, the boat was able to identify the third buoy, and started to circumnavigate it to return to the gate.

### E. *Acoustic Docking*

The Dock shown in Fig. 11 was simulated with a rectangular prism, with the top symbols represented as colored boxes.

Improvement in acoustic docking came with the successful identification of the dock (Fig. 12) and of the two front corners required for the algorithm. However, further validation of the final approach is still required, as a suitable way to simulate the pinger signal and the hydrophone array was not found, keeping the solution the same as the one proposed last year in RViz.

## IV. CONCLUSIONS

A new strategy for the RoboBoat 2021 is presented. Evidently, this strategy takes focus on software aspects, mainly in the realistic and practical simulation environment developed and its use for testing. Improvements on the perception system and the collision avoidance methods were developed. As the COVID-19 pandemic remained a latent threat for health well-being, simulations became the

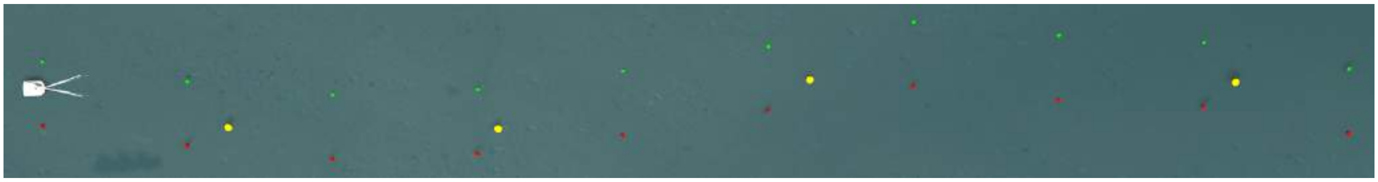

Fig. 8. Obstacle Channel Challenge.

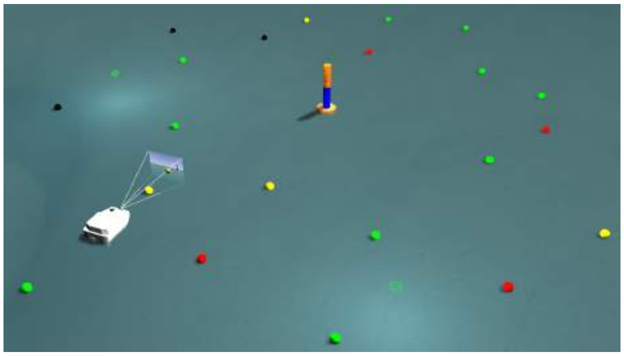

Fig. 9. Obstacle Field.

Fig. 10. Speed Gate.

only means to validate the improved algorithms. The simulation results showed the perception and collision avoidance systems capabilities to improve the overall system performance. In the end, the Mandatory Navigation, Speed Gate, Obstacle Channel and Obstacle Field challenges approaches were validated, as successful simulations were obtained. Further improvements on the Acoustic Docking and Object Delivery challenges require additional work, but so far, the system has been validated through simulations to be capable of successfully solving most of the competition tasks.

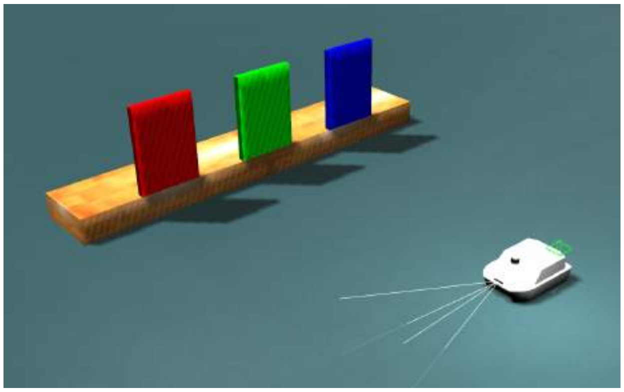

Fig. 11. Acoustic Docking.

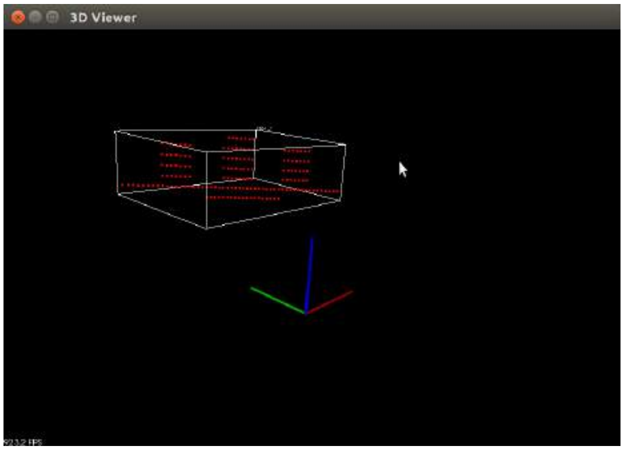

Fig. 12. Dock identification.

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## APPENDIX A: COMPONENT SPECIFICATIONS

See Table I.

## APPENDIX B: OUTREACH ACTIVITIES

### A. *Conexion Tec*

Conexion TEC is an event organized by Tecnologico de Monterrey School of Science and Engineering which highlights the best engineering projects from each semester. VantTec participated with the technology developed for RoboBoat in both semesters.

https://www.facebook.com/conexiontec/

### B. *El Camino del Ingeniero*

El Camino del Ingeniero is a conference that formed part of bigger movement called WOMXN UP, organized by the highschool robotics team FRC 6200 - XRams. Female team members of VantTec participated, sharing their trajectory in STEM, with the objective of empowering women and inviting them to seek STEM-related careers.

https://www.facebook.com/xrams6200/

### C. *Evolve*

Evolve is an event that supports the career decision-making process for students, organized by the Student Society of Mechatronic Engineers. Our president and RoboBoat project lead shared the team's trajectory and history, with a QA session at the end.

https://www.instagram.com/saimt.mty/

### D. *IMT FAQs*

An Ask Me Anything session with high school seniors and undecided major freshmen interested in pursuing Mechatronics Engineering studies to clarify doubts on higher education.

https://www.instagram.com/saimt.mty/

## APPENDIX C: EMBEDDED SYSTEM OVERVIEW

See Fig. 13

TABLE I
COMPONENT SPECIFICATIONS

| **Component** | **Vendor** | **Model/Type** | **Specs** | **Cost** |
|---|---|---|---|---|
| ASV Hull | VantTec | VTec S-III | Fiberglass | NN |
| Propulsion | Blue Robotics | T200 | http://docs.bluerobotics.com/thrusters/t200/ | NN |
| Power System | Blue Robotics | Lithium-Ion Battery | http://docs.bluerobotics.com/batteries/ | NN |
| Motor Controller | Blue Robotics | Basic ESC R2 | https://www.bluerobotics.com/store/retired/besc30-r2/ | NN |
| SBC | NVIDIA | Jetson TX2 | https://developer.nvidia.com/embedded/buy/jetson-tx2 | NN |
| MCU | STMicroelectronics | STM32F405RG | https://www.st.com/en/microcontrollers-microprocessors/stm32f405rg | NN |
| Teleoperation | FrSky | Taranis X9D Plus | https://www.frsky-rc.com/product/taranis-x9d-plus-2/ | NN |
| Teleoperation | FrSky | X8R | https://www.frsky-rc.com/product/x8r/ | NN |
| IMU | VectorNav Technologies | VN-300 | https://www.vectornav.com/products/vn-200 | NN |
| Camera | Stereolabs | ZED Camera | https://www.stereolabs.com/zed/ | NN |
| Hydrophone | Telodyne | TC4013 | http://www.teledynemarine.com/reson-tc4013 | NN |
| Hydrophone | Aquarian | H1C | https://www.aquarianaudio.com/h1c-hydrophone.html | NN |
| CAN transceiver | Waveshare | SN65HVD230 | https://www.waveshare.com/sn65hvd230-can-board | NN |
| RF Modules | Digi | XTend | https://www.digi.com/products/networking/gateways/xtend-900mhz-rf-modems | NN |
| LiDAR | Velodyne Lidar | VLP-16 | https://velodynelidar.com/vlp-16.html | NN |

| | |
|---|---|
| Algorithms | Internal development. Adaptive sliding mode based control, line-of-sight based guidance, model predictive control based collision avoidance |
| Vision | Point Cloud Library, OpenCV |
| Localization and Mapping | Internal Development. Based on reference frames and 3D computer vision. |
| Team Size | 23 members |
| Expertise Ratio | 1:1 |
| Testing time: simulation | 9 months |
| Testing time: in water | 0 months |
| Inter-vehicle communication | NN |
| Programming | ROS, Python 2.7, C++ and MATLAB/Simulink |

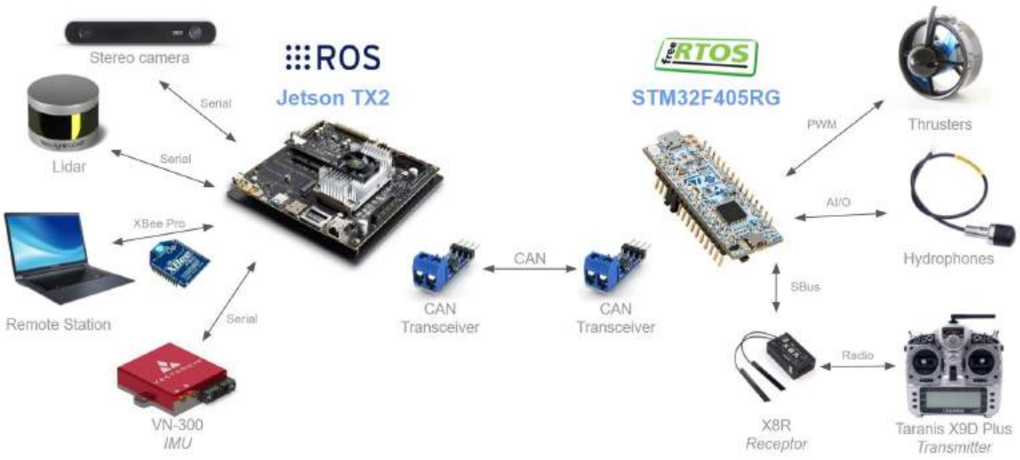

Fig. 13. System Overview.