RoboBoat 2020: VantTec Technical Design Report VTec S-III

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Abstract—**The overall strategy, creative new elements, and final results from VantTec for RoboBoat 2020 are presented. The strategy relied on using experience from previous editions to continue working on top of the same platform, the VTec S-III USV, and have a higher focus on the software and scientific segment of the project. A simulation environment was developed to increase the testing time for the algorithms, and became the only source of testing as the COVID-19 pandemic grew. The new creative implementations include improved software architecture, user interface, and algorithms for path-following control, collision avoidance and visual-based guidance. Experimental results show the performance of the new path-following controller. Simulation results demonstrate the capabilities of the proposed solutions for each challenge based on local visual-based guidance and reactive collision avoidance. Finally, embedded systems and UAV mobile application sub-teams increased the performance of both technical aspects of the project, that had not been sufficiently worked on during previous RoboBoat editions.**

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

I. Competition Strategy

Three main characteristics dominate the proposed strategy for RoboBoat 2020: research-based solutions, practicality, and funding management. The latter consideration is due to VantTec's goal of competing in both RoboBoat and RoboSub 2020. This group management decision branched most of the budget toward the underwater vehicle required components and materials, hence the RoboBoat team decided to work with the VTec S-III platform used for RoboBoat 2018 and 2019 editions. In consequence, practicality of the prototype had to remain low-budget, tackling only the development of 3D-printed pieces and new printed circuit boards (PCBs) to improve space efficiency on the inside of the vehicle. However, due to the current COVID-19 pandemic, manufacturing and implementation remain undone, thus mechanics and electronics will not be further addressed in this report. Further work of the VantTec RoboBoat hardware team will appear in the RoboBoat 2020 Systems Engineering Paper.

A. Course Approach

Reusing the VTec S-III USV (Fig. 1) is as a highly reliable approach giving the accumulated research with the platform [1]–[4]. Particularly, the knowledge of a mathematical model is valuable to generate a robust strategy. Taking into account the team's experience, particularly after reaching the finals in the 2019 edition and publishing a paper about some of the technology developed [2], the overall strategy focuses on algorithms to solve all of the competition challenges. However, distribution of time invested in each challenge is not equivalent.

Mandatory Navigation Challenge and Speed Gate have a higher importance than the rest of challenges in the proposed approach. The first reason is due to the requisite of achieving Mandatory Navigation Challenge to take part on the rest of challenges, working as the main filter for teams qualifying to the finals. The task was successfully accomplished in RoboBoat 2019, but the new strategy relies on robustness and research-based justification that the system will be capable to succeed at a higher rate, which the previous solution lacks. The second

Fig. 1. VTec S-III USV.

reason is the similarity between both challenges, as the first stage of Speed Gate can be solved with the same methodology applied to the whole Mandatory Navigation Challenge task. Thus, by achieving a robust Mandatory Navigation Challenge, a robust solution for Speed Gate is feasible.

Likewise, RoboBoat 2019 presented a big step on the team's Obstacle Field task performance. However, the collision avoidance algorithm implemented was not robust, and was designed and implemented only a week before the competition due to delayed hardware delivery. Therefore, following the problem of hitting buoys in the previous edition, an objective this year is a much more robust approach to avoid hitting any obstacle during the challenge and overall navigation.

Moreover, as Acoustic Docking and Object Delivery tasks imply subjects the team has not tackled in past years, two sub-teams were created to focus on both challenges. For Acoustic Docking, this year was going to be the first time the team arrived with a working hydrophone-based solution, but due to the pandemic, the approach has not been validated with field experiments. The strategy in this challenge is to accomplish an acoustic and laser based solution, combining independent sensor data to improve the docking maneuver. The second sub-team topic, Object Delivery, implies cooperation with an unmanned aerial vehicle (UAV), which is something the group has achieved in previous years since the Special Drone Award from RoboBoat 2017 was given. This experience and the fact that significant hardware additions to the USV are been avoided this year, shapes the proposed strategy to deliver the objects only with the UAV. This becomes a challenge of developing visual-based control for the UAV, and work toward the delivery of the necessary objects.

Furthermore, the strategy for Obstacle Channel initially relied on learning first from the known challenges from previous competitions, and use that learning to think of solutions for this new task. This decision led to work on the Obstacle Channel after the rest of the challenges were achieved. As development progressed, the strategy became to use the same principles learned from Mandatory Navigation Channel, Speed Gate, and Obstacle Field, and adapt them into the Obstacle Channel environment. Finally, simulation of the challenges became a significant part of the strategy, especially after the pandemic started.

Therefore, the strategy proposes that by working with a known platform, improving and adding robustness to previous approaches, spending considerable time on simulation, and designating sub-teams for specific technical challenges, achieving a better performance than previous years is feasible at the RoboBoat 2020 edition.

II. Design Creativity

A. *Software Architecture*

Since 2019, Robot Operating System (ROS) has been the backbone of the software architecture. This year, the whole system was redefined and it now integrates different ROS custom packages (Fig. 2).

USV_COMMS is the package in charge of enabling communications between the boat and the ground station. It is done through radio-frequency modules. With this, the ground station is able to tell the USV when to start or kill the system. The desired course to take (alpha, beta, charlie), and the desired competition challenge can be commanded. Also, through this package, the USV general feedback is sent back to the ground station.

USV_MASTER controls the course planning and execution. It receives directives from the ground station through USV_COMMS to execute a given challenge from the RB_MISSIONS package. The RB_MISSIONS package is where the Mandatory Navigation Challenge, Speed Gate, Obstacle Field, Obstacle Channel, and Acoustic Docking task solution scripts are located.

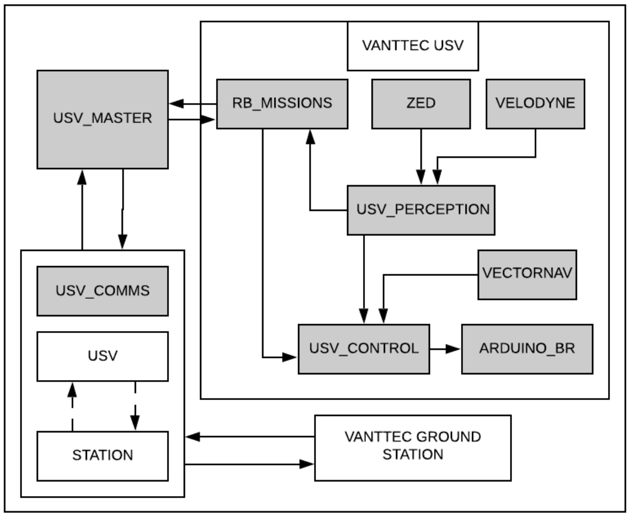

Fig. 2. Software architecture.

The ARDUINO_BR is a package that uses rosserial [5] to interface with the T-200 thrusters. It is subscribed to USV_CONTROL to receive the desired motor PWM signal.

There are three sensor packages used in the system. The VECTORNAV package allows the USV to interface with VectorNav IMU/INS sensors. Likewise, the VELODYNE package is a ROS wrapper for the Velodyne LIDARs. Finally, the ZED package is a ROS wrapper for the Stereolabs ZED Camera.

The USV_CONTROL and USV_PERCEPTION packages were created to handle the real world interaction of the USV. The USV_PERCEPTION package is used to detect and map obstacles using data from the VELODYNE and ZED packages. This data then goes as input to the visual-based guidance systems from RB_MISSIONS. The USV_CONTROL package includes the designed algorithm to achieve path-following control, and uses the speed and positional data from the VECTORNAV package as feedback. The USV_CONTROL package additionally receives data from USV_PERCEPTION for the collision avoidance methodology.

The main problems with the 2019 software architecture were the inefficient communications between the ground station and the boat, and the lack of readability and comprehension of the code. The communications were a major problem as the ground station was not aware of the USV state. The lack of comprehension of the code was also a major problem as very few members of the team understood the system. This lead to the necessity to create full-duplex communications between the boat and the ground station, and coding standards. The current software architecture allows more understandability of the USV processes.

B. Guidance and Control

By using a previously identified model [3], a class of backstepping controller similar to a proportional derivative controller was designed and implemented at RoboBoat 2019 [4] to achieve heading, and was adapted for GPS navigation. Although the algorithm successfully navigated the USV through waypoints and challenges, it is not the most efficient or robust control strategy. Another issue arising from the 2019 edition was the lack of performance against environmental disturbances, as the USV was easily carried away by wind gust. Thus, research was performed to design and implement a path-following controller based on adaptive sliding mode control (ASMC) and a time-varying look-ahead distance line-of-sight (LOS) guidance law [6]. Hence, a robust performance while navigating between waypoints is expected, which could improve the motion of the USV between and inside challenges. In addition, artificial intelligence-based methods were also experimented [7].

To complement the robust path-following controller, a methodology to increase robustness in challenges is also proposed. This methodology improves previous year work [2] by diverging from only implementing a type of visual-servoing in the vessel, and adding coordinate transformations to increase robustness into the guidance of the vehicle. The creativity rises when, at the moment of detecting a pair of obstacles (gate), the USV creates a new reference frame. Thus, a local reference of the challenge can be used to increase the level of task knowledge, which is then used to solve the challenge in turn. This is mostly convenient for Mandatory Navigation Challenge and Speed Gate, as the new reference frame can be used to ensure the USV follows a straight line to find the second stage of each challenge (e.g. second gate or blue buoy). One expected improvement here is, that even if wind gust perturbs the vessel, the knowledge of the reference frame can assist the USV into returning to the main path and find the second stage easier than with the previous method. Another benefit to the Speed Gate is the simplicity in returning, as the origin of the new reference frame is also the point where the USV should return. Finally, the reference frame approach is also applied to the Acoustic Docking challenge, to accomplish a straight trajectory at the moment of docking, and to the Obstacle Channel to maintain a reference for the overall challenge.

C. Perception and Collision Avoidance

Same as in RoboBoat 2019, the perception system for the USV is made up of 2 sensors: a ZED stereo camera and a Velodyne VLP-16 LiDAR. The ZED RGB image is used mainly for buoy and marker detection, using the costume trained Convolutional Neural Network Yolo-Tiny 3 [8], and its stereo point cloud is used separately to calculate distance to the detected buoys. The LiDAR point cloud is used for obstacle detection in general, benefiting from the 360° field of view.

In the case of the Mandatory Navigation Challenge and Speed Gate Challenge, the colored buoys are detected and located using the ZED image and point cloud. This detection methodology was demonstrated during RoboBoat 2019, and it is not modified due to it's reliable and high speed results from testing in preparation for RoboBoat 2020.

A new collision avoidance methodology was developed specially for the solution of the Obstacle Field challenge. This static collision avoidance algorithm is based on an improved Velocity Obstacle method [9], which means it does not require global environment mapping, relying only on reactive avoidance. This makes it suitable for low computing and power budgets while running in real-time. The objects detected using the VLP-16 point cloud are given as input for the collision avoidance and guidance of the USV. This methodology has been tested and verified in simulation as physical experiments are off limits at this time.

The VLP-16 point cloud is used in its laser-scan format to aid in resolving the acoustic docking challenge. The point cloud is first filtered, then clustered for object detection. Once an object of acceptable dimensions and geometry of the docking platform is identified, the laser scan line is extracted and used in the acoustic docking solution explained in detail in the Acoustic Docking subsection of Section III.

D. Acoustic Signal Detection

The Acoustic Docking challenge requires a sensor array that is capable of detecting the position of an acoustic pinger relative to the USV position. Therefore, a three hydrophone array was designed to accomplish this goal.

The array is connected to a custom made amplification circuit, which has some improvements compared to last year's circuit. First, a higher input impedance was selected, to avoid the signal distortion. Second, a filter phase (low pass) was added to eliminate noise coming from the thrusters. For high frequency noises, a digital filter was proposed. The expected output of the circuit is one hydrophone signal with a 2.5V maximum amplitude and low impedance, so that it can be ready for Analog to Digital conversion (ADC). Three equal circuits are expected, one for each of the three hydrophones.

For signal processing, the STM32F103x8 microcontroller (MCU) is used. The signals are read from the ADC integrated in the MCU, and processed to obtain the angle of the pinger in respect to the USV current position. Then, the data is fed to the control system via I2C communication, where the data is used to set a waypoint for the boat to perform an automated docking.

FreeRTOS was implemented to be able to add other applications to the MCU in the future given the wide range of capabilities it has. A real time operating system (RTOS) allows for a better management of the resources of the MCU given the hard and soft time constrains. This is of vital importance as the docking task requires a precise location of the pinger at all times. After the pandemic, in-water experiments to validate the proposed system capability of detecting the pinger relative position are expected.

E. UAV

For the UAV challenge, an android app was developed for the USV and UAV communication. The UAV model is a DJI Phantom 4, and the android app was developed with the DJI public (software development kit) SDK [10]. The system can be used with any android phone with an Android operating system with at least version 4.4. The user interface offers a manual mode controller, with the essential actions to pilot the UAV.

The user is able to launch, set way-points in a Google Maps environment for a specific route, and create a geofence. The map and geofence intentions are to indicate in every flight moment the current position of the UAV and delimit the motion space, respectively. In addition, the user interface offers a recording and shooting mode for UAV camera, with the purpose of having a visualization of the navigation path.

Furthermore, the use of DJI SDK virtual sticks allows for an autonomous control of the drone. These sticks emulate what a real controller would do, and their values can be set via code, or in by the camera view as in this approach. The camera-view can be used to detect an object and accurately control the drone to complete the UAV segment of the Object Delivery Challenge. Due to the COVID-19 pandemic, no experiments exist to validate this approach.

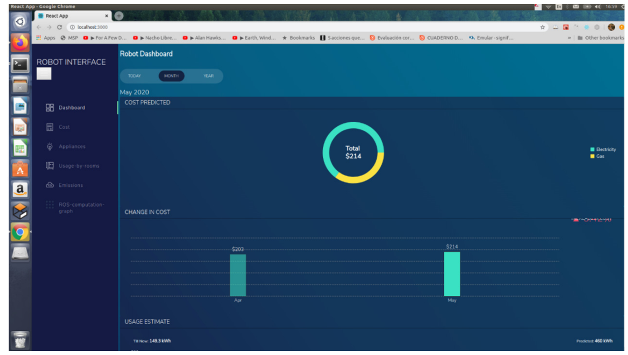

Fig. 3. Fusion Charts API, for deploying information.

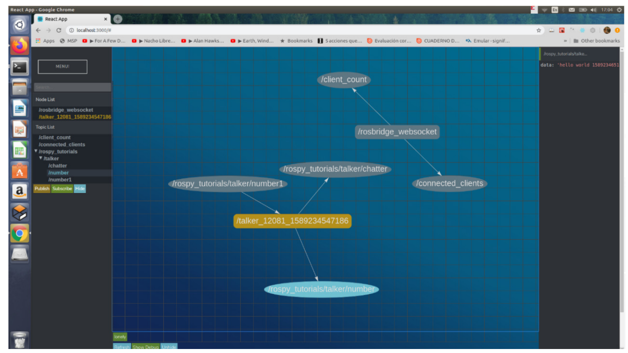

Fig. 4. Rqt-graph interface, for sending ROS commands.

F. Graphic User Interface

To improve the USV state visualization and increase the operating practicality, a Graphic User Interface (GUI) was developed. To create this interface, React.js [11] was used, which is a JavaScript library for building user interfaces in an easy and fast way. With a ROS package for JavaScript, establishing communications with a web-browser is possible.

The GUI prototype gets information from rosbridge ROS package [12]. Fig. 3 depicts an advanced API called Fusion Charts [13], which deploys information of the USV. Fig. 4 shows the rqt-graph from the system, and allows it to interact with ROS publishers and subscribers. Hence, it becomes easier than last year to operate the VTec S-III. Likewise, in contrast to previous years, a monitoring system was implemented with this GUI.

G. Simulation Environment

To reduce the time spent debugging software at field experiments, a simulation environment was proposed. The necessity to have a simulator increased as the pandemic started, and became a great solution to continue working on the USV autonomy. The simulation environment is proposed to create a digital twin of the VTec S-III using the mathematical model [3], and simulating the INS feedback data, and stereo camera, LiDAR and hydrophone detection outputs. The simulation runs in a ROS environment parallel to the VTec S-III software architecture, with Rviz visualization. Hence, it is possible to recreate the RoboBoat challenges, simulate how the USV would detect and locate the observable obstacles, and test the algorithms. In addition, another benefit of the digital twin is the ability it brings to recreate experiments using logged information.

III. Experimental Results

In this section, experimental results of the proposed strategy are presented. The challenges solutions, following the proposed strategy, were in development or debugging phases when the quarantine began. Therefore, no in-water results are presented

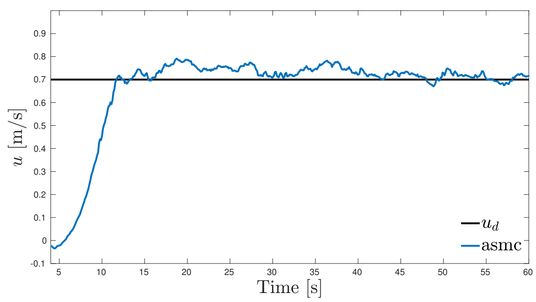

Fig. 5. Speed control.

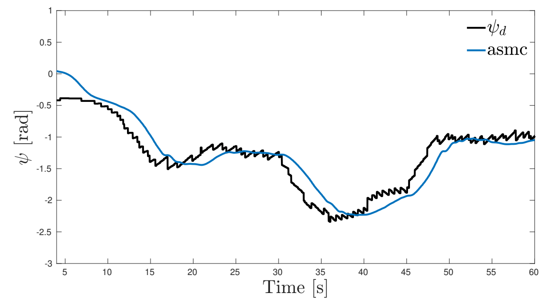

Fig. 6. Heading control.

for the challenges, as either no logged information exists, or the challenges were not ready to be tested. However, results from field experiments for the path-following control system are presented, and simulation results of the successful challenges are reported as well.

A. Path-Following Control

Field experiments were performed to validate the path-following controller [6], after extensive simulation testing the first part of the fall semester. Fig. 5 shows the USV response to a speed reference of 0.7 m/s. Including a speed controller is a new addition for RoboBoat 2020, as previous years only selected a desired thrust to advance as a percentage of the maximum thrust. The controller shows the capability of reaching the speed set-point smoothly, and it is relevant to point the accomplished robustness as the USV carries a payload of 20% of its mass during the experiment. Equally noticeable is the heading response in Fig. 6, which tracks the variable desired heading. Finally, Fig. 7 depicts the path-following performance of the cascaded system while pursuing a zig-zag path. The payload has several effects on the USV, changing plenty of the dynamics such as the overall mass, center of mass/gravity, drag, and moment of inertial. Thus, the desired robustness is adhered to the proposed course strategy.

B. Mandatory Navigation Challenge

The recently-developed simulation environment was used to test the robustness of the proposed approach for the Mandatory Navigation Challenge, the trajectory is shown in Fig. 8. Here, both sets of gates are located in the same formation as the competition rules dictate. The interesting fact

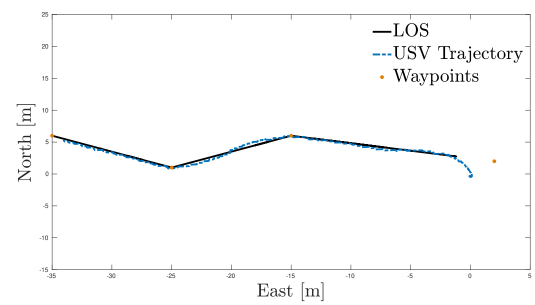

Fig. 7. Path-following control.

that demonstrates the robustness of the approach is the initial heading and position of the USV. At RoboBoat 2019, the VTec S-III had to start at the center of the first gate to be able to compute the desired heading. More importantly, it was easy for the vehicle to lose track of the straight path and difficult to find the second set of buoys if the USV entered to the first set of gates diagonally. With this approach, although the vessel starts facing diagonally toward the entrance, the trajectory is robust enough to maneuver into a straight-line path perpendicular to the first gate. This solution only requires the detection and positioning of the first two buoys, and has no penalty while finding the second set of buoys to finish the challenge.

C. Speed Gate

As with the Mandatory Navigation Challenge, the robustness is clearly shown in Fig. 9. A similar diagonal-to-the-path initial heading and position is used to test the challenge in simulation. The USV follows a perpendicular straight-line path after passing through the gates, and as the buoy to circle is seen and is approached, three waypoints are created to go around it. Then, the origin of the

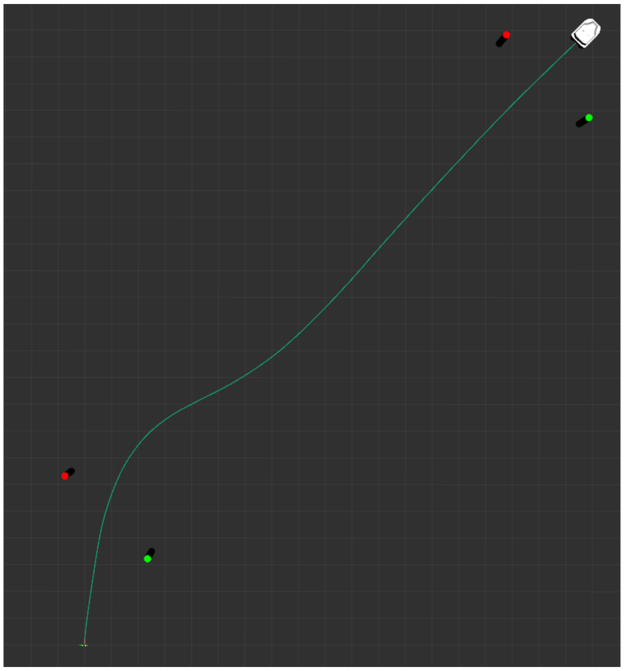

Fig. 8. Mandatory Navigation Challenge.

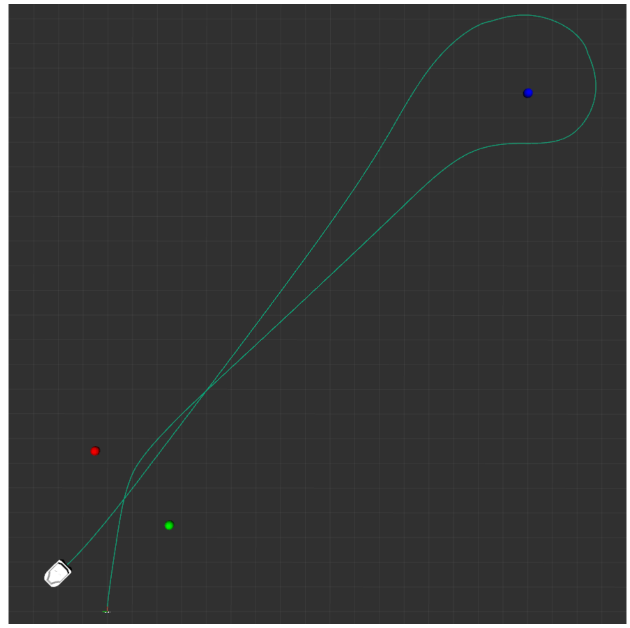

Fig. 9. Speed Gate.

new reference frame is used as a return point so that the challenge is completed. Both Speed Gate and Mandatory Navigation Challenge were in a debugging process before the pandemic, achieving in-water maneuvering through the entrance gates, but more experiments are needed to validate that the next path would be perpendicular using the sensor data (stereo camera/LiDAR), and that the USV successfully achieves circling the third buoy and returning to the entrance during Speed Gate.

D. Obstacle Field

The Obstacle Field solution takes two inputs. The first input, is an array of for waypoints, three strategically placed waypoints around the center marker of the obstacle field and a fourth waypoint to exit the field. The second input are the objects around the USV detected using the LiDAR point cloud. A path from the USV position to the first waypoint is traced. The collision avoidance methodology presented above is used to dodge obstacles in case one is detected on the desired path. After reaching the first waypoint, the process is repeated until the last waypoint, outside the obstacle field, is reached. Fig. 10 shows a simulation experiment of the presented solution, demonstrating successful obstacle avoidance, challenge completion and robust behavior. This approach was developed and tested in simulation and is yet to be validated in field experiments.

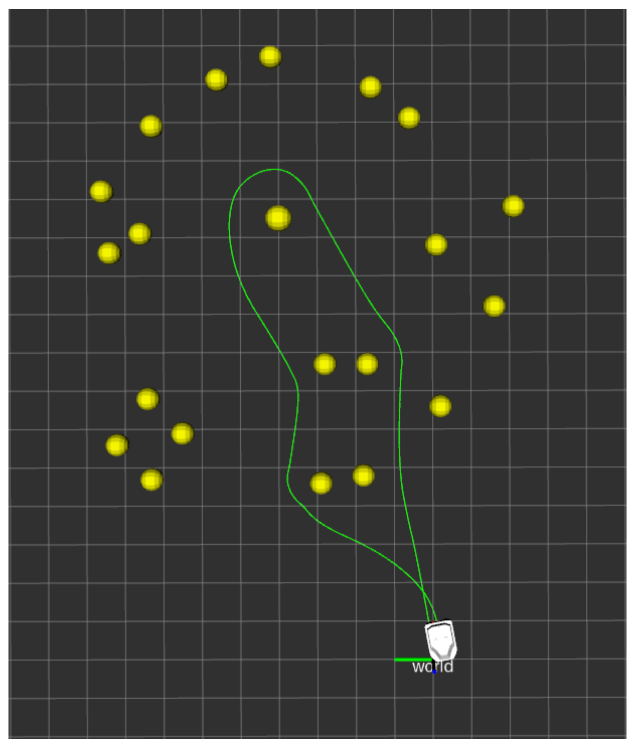

Fig. 10. Obstacle Field.

E. Acoustic Docking

The Acoustic Docking solution was developed in simulation during the pandemic, so no field experiments exist using this approach. For this challenge, the LiDAR and hydrophone data were simulated as if all of the perception strategies are feasible. The simulation makes the assumption that the hydrophone array is capable of returning the angle between the pinger and the USV. Moreover, the second perception input for this method is to detect the dock itself using the laser scan data. Thus, the USV knows the direction toward the pinger, and the two points where the dock begins and ends (both extremes of a line). After this, using trigonometry and algebra, the imaginary line between the USV and the pinger, and the line representing the front border of the dock are intersected to find the location of the pinger. Then, the location of the pinger is set as the origin of a new reference frame, which is used to generate a waypoint perpendicular to the dock. This waypoint assists the docking maneuver of the USV, allowing to create a straight line between the first waypoint and the dock, thus achieving dock as shown in Fig. 11.

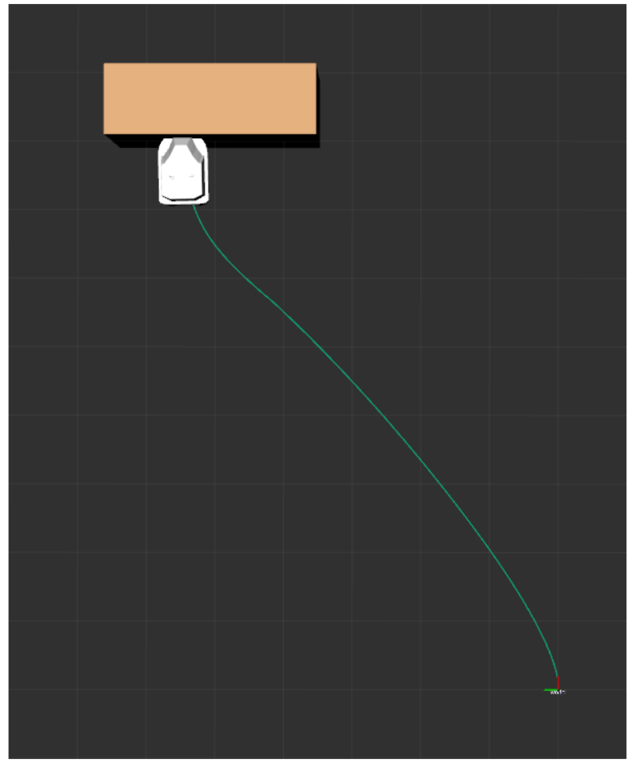

Fig. 11. Acoustic Docking.

F. Obstacle Channel

The Obstacle Channel (Fig. 12) solution strategy was developed only in simulation, so no field experiments exist on this approach. For this challenge, LiDAR data was also simulated as in the previous solutions. From the LiDAR detected objects, the closest pair of objects are considered to create the new reference frame. The system gets an array of obstacles and then segmentates the array considering buoys that are laterally separated. If there is more than one buoy in each segment, the buoys with the largest distance between them are considered a gate. Next, the system places a waypoint in the middle of each gate, creating an array of all the waypoints. Afterwards, the array of waypoints is arranged from the closest to the farthest values to the gate reference frame. Through the path-following controller and collision avoidance strategies, the USV maneuvers through the channel. Once a gate waypoint is reached, a new LiDAR detected objects array is generated to refresh the obstacles map using the maximum sensor range. Finally, the process of generating new gates per waypoint reached is repeated until no more obstacles are detected, assuming the channel ends.

IV. Conclusions

A new strategy for the RoboBoat 2020 competition is presented. The strategy involves a major focus on the software and mathematical aspects of the project, including new creative implementations on software architecture and user interface. Likewise, algorithms for path-following control, collision avoidance, and local visual-based guidance were designed and implemented. Experimental results show the performance and advantages of the proposed controller, which would have been used in the competition for GPS waypoint navigation between challenges, and motion inside challenges. A simulation environment was developed to increase the testing time of algorithms. As the COVID-19 pandemic increased globally, the algorithms could only be tested in simulation. Simulation results demonstrate the capabilities of the proposed task solutions. Results show the proposed course approach is feasible, as all of the challenges involving only the USV were successfully solved.

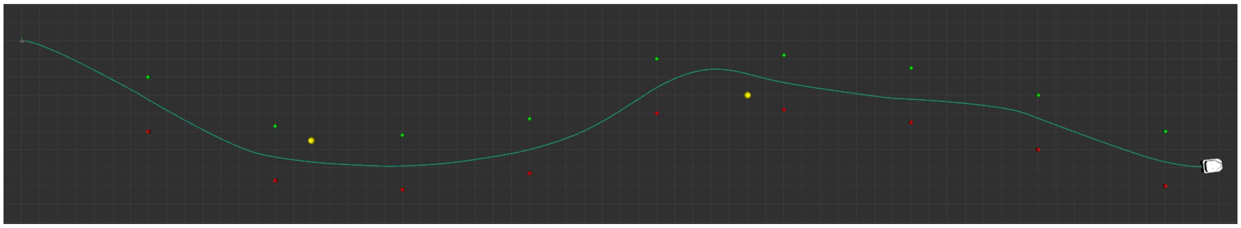

Fig. 12. Obstacle Channel.

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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's 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. Global AI on Tour MTY

Microsoft Student Partners organized this event to promote technologies related to artificial intelligence (AI). VantTec gave a virtual talk during this event, showcasing the history of the group and the AI applications for autonomous systems.

http://globalaimty.net/

C. Expo Manufactura

In partnership with sponsor ifm efector, a mobile robot was developed to demonstrate the capabilities of ifm efector sensors. This robot was showcased at the Expo Manufactura 2020, serving as a platform to attract clients and teach curious students at the Expo.

https://expomanufactura.com.mx/

D. INCmty

INCmty is the largest festival of entrepreneurship in Latin America, based in Monterrey, Mexico. In November, VantTec took part representing the university's School of Science and Engineering.

https://incmty.com/

E. Rice University GCURS

Rice University organizes the Golf Coast Undergraduate Research Symposium, which allows young researchers to present their work, meet Rice faculty, and receive valuable feedback. VantTec members gave presentations on the work developed by the group.

https://gcurs.rice.edu/

F. COMRob 2019

Congreso Mexicano de Robotica (Mexican Congress in Robotics), or COMRob, is an academic conference about the developments in robotics around the country. Two research papers were published about the work done by VantTec for the RoboBoat competitions. Both research presentations had an audience with a high composition of young undergraduate students.

http://comrob.org/2019/

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 controls	Blue Robotics	Basic ESC R2	https://www.bluerobotics.com/store/retired/besc30-r2/	NN
CPU	NVIDIA	Jetson TX2	https://developer.nvidia.com/embedded/buy/jetson-tx2	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
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
Aerial vehicle	DJI	Phantom 4 Pro	https://www.dji.com/phantom-4-pro	NN

Algorithms	Internal development. Adaptive sliding mode based control, line-of-sight based guidance, velocity obstacle based collision avoidance.
Vision	Darknet, YOLO, OpenCV.
Localization and Mapping	Internal Development. Based on reference frames and 3D computer vision.
Team Size	17 members
Expertise Ratio	1:1
Testing time: simulation	9 months
Testing time: in water	3 months
Inter-vehicle communication	Bluetooth(UAV-station) and RF (USV-station)
Programming	ROS, Python 2.7, C++, MATLAB/Simulink, Arduino, Java