Autonomous Surface Vessel

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Abstract: The Autonomous Surface Vessel (ASV) capstone project is designed to highlight the increasing amount of technology and growth potential within the marine industry. In combination with the standards set by RoboNation's RoboBoat competition, the Electrical Engineering Department at the US Coast Guard Academy established the ASV project to pursue building and programming an autonomous vessel to compete in the annual challenge. The ASV must be able to autonomously interact with and navigate through an obstacle course consisting of six separate challenges. By designing a system with specific solutions to each challenge, the capstone group developed a concept for the vessel that can accomplish the necessary criteria. An inertial measurement unit (IMU) and global navigation satellite signal (GNSS) sensor provide the input data at a frequency of 5Hz to maintain the ordered headings throughout the navigation channel and obstacle field. A hydrophone detects underwater acoustic signals for the onboard computer to process, which is used to perform the docking sequence. Light detection and ranging (LiDAR) mapping is crucial for the sensing of buoys while transiting, helping to avoid collisions, or straying off course. The use of a camera system and an image detection algorithm allows the ASV to recognize buoys by color and shape, enhancing the vessel's decision-making capability. This is supplemented by a path-finding algorithm run on an external computer from course-wide photographs taken by the group's partner project, the unmanned aerial vehicle (UAV). This external computer communicates the startup protocol and the calculated path with the onboard UDOO Bolt computer via XBee wireless communication protocol while allowing for vessel voyage monitoring throughout the competition.

I. INTRODUCTION

As cars and other vehicles progress with artificial intelligence to be fully autonomous, expect maritime partners to explore the potential benefits of bringing similar technology to vessels to help eliminate human error and minimize safety risks. The Autonomous Surface Vessel capstone project is a continued research and development opportunity highlighting this growth in technology, contained within the Electrical Engineering Department at the US Coast Guard Academy. The main objective of the project is to design, build, and test an autonomous surface vessel that can compete in RoboNation's RoboBoat competition, which consists of six individual challenges including events such as a navigation channel, obstacle field, and speed gate to test vessel capability [1]. The annual competition tests teams on a vessel build and programmed to navigate its way through all six challenges completely autonomous, using any combination of GNSS, image processing, range detection, and other means to complete the tasks. Each year the governing rules set standards for size, weight, and other requirements for safety while allowing freedom for problem-solving. Each challenge is designed with a common maritime evolution in mind, from navigating shipping lanes to cargo offloading or docking to ensure the project generates vessels that could positively impact the development of autonomous vessels for actual use. As such, the project also offers potential future use for Coast Guard statutory missions, conducting search and rescue in risky or low visibility situations, or patrolling coastline for law enforcement, all while requiring no human operator.

The research and development gained from this project have strong potential for future integration with the Coast Guard as the force modernizes. The Coast Guard Research and

Development Center in New London, CT has experimented with using a 29’ RBS-II and autonomous vessel technology to explore the potential in autonomous technology [2]. The group’s work could be utilized in the programming work for this Coast Guard project, building upon the lessons the capstone group has learned regarding sensor suite and autonomous decision-making. The growth of this technology in both the maritime field as a whole and the Coast Guard is likely to keep growing exponentially as it allows for greater risk aversion requiring no crewmembers for unmanned missions in heavy seas or dangerous situations. This increases the Coast Guard’s ability to act in all conditions, while also minimizing the potential for any human error or indecision. The opportunities for autonomy in marine vessels are growing continuously and the research gained from competing in a high-level competition such as RoboBoat can positively influence the Coast Guard’s advancement.

II. BACKGROUND

The project development was previously started to compete in the RoboBoat competition, this is also still the current purpose of the development of this vessel. The RoboBoat competition requires the use of an autonomous vessel to properly maneuver and complete a variety of different skill-based courses. Autonomy is the ability for a vessel, in our case a boat, to be able to drive and perform processes on its own without human interference. Examples of this can be seen in surveillance drones developed by the Air Force or self-driving Tesla cars. The vessel has gone through development with multiple different capstone groups with the main feature that is constant through each year being the vessel’s structural design due to it being found as most suitable and stable for the specifications of the competition and project. This year we decided to start our own codes from scratch mostly due to bits of the previous year’s code not being found completely and cutting the time of trying to understand or reverse engineer how to utilize the code they developed. Hardware used from the previous year's team has been heavily utilized this year as well as continuing to hit all the needs we currently needed to accomplish at this point of the project.

III. OBJECTIVE

In the Coast Guard, it is possible to see a shift to autonomous vessels in completing specific mission tasks [2]. Many of the solutions found for the RoboBoat competition offer the ability to be beneficial to the Coast Guard. The group’s image detection software could be repurposed to provide Search and Rescue (SAR) capabilities, being used to spot capsized vessels and Persons in the Water (PIWs). LiDAR offers potential use for autonomous transiting of traffic channels and navigation in low or zero visibility, significantly reducing the risk of collision. LiDAR also offers the potential to be beneficial to Aids to Navigation servicing, allowing for precise navigation near buoys and the shoal water or obstructions they often mark. The opportunity to expand the capstone research and development work to the Coast Guard offers countless potential innovations, many of which could be accomplished with the necessary resources to improve the Coast Guard’s mission success.

To simulate a multitude of scenarios, we based our project goals that would determine the success of the ASV off the RoboBoat 2021 competition. This simulates real-life objectives that are demanded by both the Coast Guard and the maritime industry [1]. The goals that must be met for the competition are being able to navigate within a navigable channel, obstacle avoidance, obstacle fields, timed trials, acoustic docking, and object delivery. Using these goals, we defined our system requirements. These include having an onboard computer and controller, integrating computer vision with an onboard camera, integrating an onboard GNSS, and designing a landing platform for an aerial vehicle to land on safely. Because much of the physical aspects of the ASV have been designed and built from previous years, there are no other resource constraints other than a few electronic hardware items, such as monitors and external storage devices, for the ASV’s on-board computer. The schedule for meeting specific goals are: creating a system diagram by mid-September, creating a controller for the vessel by the end of September, integrating the controller and integrating an RC controller by mid-October, testing in the pool in late October, integrating GNSS, and allowing waypoint to waypoint maneuverability mid-November, test in the Thames late November/early December, integrate computer vision and LiDAR mid-January, integrate path-finding with waypoint maneuverability mid-February, implementation of acoustic sound receiver mid-March, all other necessary steps to make the ASV fully autonomous for the RoboBoat Competition, final presentation in April.

IV. SYSTEM DESIGN

For the vessel's design, we decided to use the same model used by last year's capstone group. This design is a catamaran-style hull, meaning it has two separate hulls with one rigid body holding the whole structure together. A catamaran vessel is best for our use because it is one of the most stable designs and allows for a wide body for sensor payload. Minimizing the rolling and pitching of the vessel is also essential as we want to use our sensors in the most stable environment possible. As unpredicted motion increases, it becomes harder for the sensors to interpret the world around them. The large beam of a catamaran vessel can also maximize the space for a UAV to land. Finally, the vessel's structure will include a watertight box to house all sensitive electronics. This box will give easy access when working with the vessel but will ensure no water damage will occur to the electronics. With this current design of the vessel, we will have no problem achieving the size and weight standards.

This vessel will make use of two Blue Robotics T-200 thrusters with an accompanying pair of 14.8V batteries. These batteries exclusively provide power to our thrusters and have inline thermal circuit breakers to prevent an excessive current draw. Also, in line with the battery circuit are relays. These relays are triggered by an external onboard switch to manually cut all power to the thrusters. Each T-200 thruster will require its own Electronic Speed Controller (ESC) to be properly operated. No rudder will be included in this design, we will use differential thrust to have full maneuverability of this vessel. Differential thrust is a method in which different forces from the center of the vessel are created to create a net force in a particular direction. This removes the need for a rudder and allows more maneuverability than a rudder would potentially allow as this method can rotate the vessel in place.

The T-200 thruster is a marine Brushless DC (BLDC) Motor. The ESCs that control these BLDC motors use Pulse Width Modulation (PWM) values to output a thrust. Our design has two ways of supplying these PWM values to the ESCs: manually through a handheld radio transmitter or sent by our onboard computer. As one of the design parameters requires a manual control method, we utilize a radio transmitter with two joysticks to control each thruster. This radio transmitter communicates with a receiver onboard the vessel to send the values to the ESCs. To write the values from our onboard computer, it utilizes the digital pinouts of an Arduino to send the PWM values. A multiplexer is used to determine where the PWM signal is read from to the ECS's. A toggle switch on the radio transmitter can remotely control the multiplexer to change the input to the ESCs between the computer or the reviver. This design not only gives us the ability to take full control of the vessel with the flip of a switch but do so in a manner where the ESCs are constantly receiving a signal which prevents the thrusters from initializing over again.

Onboard, there is only one small compact computer to perform all the autonomous operations needed, the UDOO Bolt. The UDOO is a standalone computer with an integrated Arduino Leonardo and is powered by its own power bank onboard the vessel. This power supply is responsible for powering all other electronics and sensors onboard. Our design makes use of both the UDOO and the Arduino Leonardo. The Arduino has digital pins that are used to communicate directly with the ESCs to control the thrusters. Because the Arduino interacts with the ESCs, it will contain the PD controller that will determine the proper PWM values needed to steer a specific heading. It also is connected to the IMU, as that data is needed for the PD Controller. All other information will be processed on the UDOO Bolt. The UDOO bolt will take in information from the various sensors onboard the vessel and compute the desired heading to steer and speed to travel. This information will be sent to the Arduino to be put into the controller that will maneuver the vessel in the desired fashion.

The design incorporates a PD controller as it will allow the vessel to autonomously and continuously correct itself to achieve the desired state. The UDOO sends a base-speed and desired heading to Arduino. The PD controller alters that base speed to turn to the desired heading. When the vessel is at the proper heading, the vessel adjusts to travel at the base speed. The Proportional portion of the controller will create a correction for the vessel that is proportional to how far off it is from its desired heading compared to its current heading. The Derivative term will track the rate of change in heading as the vessel corrects itself to match the desired heading. Together the controller can quickly track a heading in a controlled manner. The IMU sensor gives the vessel its current relative heading, and as this is needed by the PD controller to compare to the desired heading, it will be the only sensor interfacing directly with the Arduino.

The UDOO Bolt is responsible for supplying the Arduino with a heading and speed to travel. To provide a general direction for the vessel to follow, a local map is created and used in conjunction with

GNSS. This map is created by an image taken by the UAV group where is sent to a separate computer. This separate computer makes use of a pathfinding algorithm and creates track lines and waypoints on a local map. This local map is then sent wirelessly to the UDOO Bolt. Once the vessel identifies where its GNSS coordinates are on the local map, it can identify the latitude and longitude positions of the waypoints. All this information allows the vessel to determine what heading is required of the vessel to travel to meet the waypoint and stay on the track line. The distance from the waypoint can determine the base speed needed to travel. Every time the vessel takes a GNSS fix, the UDOO Bolt can compare its position to the waypoint and send a desired heading and base speed to the Arduino.

For more fine-tuned maneuverability, specifically obstacle avoidance and channel navigation, our design would not be able to rely on GNSS alone. Our vessel will instead also make use of a LiDAR and camera to sense the outside environment. A LiDAR sensor can determine where objects are and how far they are away from the vessel, plotting it in the two-dimensional plane. A camera will be able to determine what these objects are through image processing. By determining the color of a buoy or obstacle, the camera will identify what the object is and how it must be navigated. Using the LiDAR and Camera together will give the UDOO Bolt enough information to properly alter the desired heading and base speed to properly navigate the obstacle

The acoustic docking challenge will be completed with the hydrophone and LiDAR sensor. There will be hydrophones attached to the middle of the boat that will all send information to the code that will use beamforming, a process that finds the angle of a transmitter by receiving a signal at multiple locations. Once the vessel knows where the signal is transmitted, which also identifies the docking station, the vessel uses LiDAR to safely transit into the dock without hitting the dock or any other object.

This design makes use of a variety of sensors that examine the outside world to compute a heading and speed that will navigate the vessel autonomously. This technology not only can be used to meet the goals of the RoboBoat competition but can be expanded upon to be used to conduct Coast Guard missions. Autonomous technology like this can replace the need for physical people to make up Coast Guard Cutters, allowing the Coast Guard to significantly increase their assets.

V. RESULTS

The performance of the ASV can be broken down into three separate phases: float tank testing, pool testing, and testing in the Thames River. Each of these testing locations allowed for different parameters to be evaluated with increasing levels of risk and quality of data collected. Before each testing evolution, the group determined a testing procedure to follow, along with testing the scenario in the Simulink Model when applicable. Doing this allowed us to best predict how the vessel would act in the water, thus mitigating some risk when it was time to test.

The first major test we completed was in the float tank in the Naval Architecture wing of McAllister Hall. This location allowed us to initially test the watertight integrity of the box housing our onboard electronics, confirm positive buoyancy of the vessel, evaluate the strength of the thrusters in a controlled environment, and evaluate the first iteration of our heading controller in a stationary state. After testing the ability for the ASV to switch in and out of remote/autonomously controlled modes, we tested the heading controller. In this first heading controller test, we evaluated the response of the system to a 90-degree change in the desired heading. For instance, if the ASV was initially facing 000 degrees relative to the initialization of the IMU, it would correct its course to 090 or 270. The graphical results of this test can be found in Figure 1.

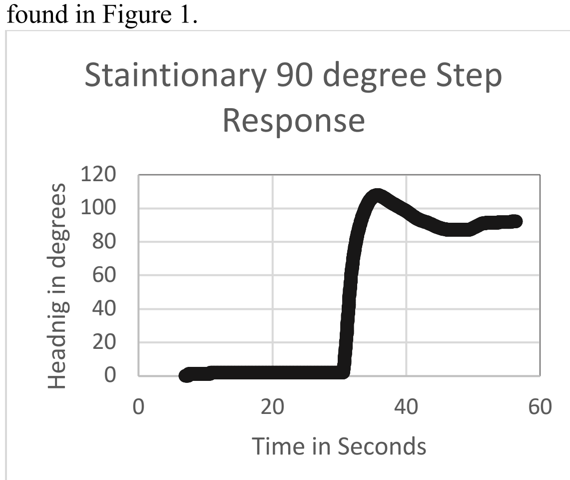

Figure 1: Stationary Heading Controller Test

In this test, our controller was able to achieve a 90-degree change in heading with a 5.8 second rise time and an approximately 10% overshoot of our target value. During this test, the ASV experienced an additional overcorrection caused by this overshoot, which can be noted in the oscillation after 30 seconds before settling at 90 degrees after about 15 seconds. The results of this test were consistent with what our model produced as seen in Figure 2.

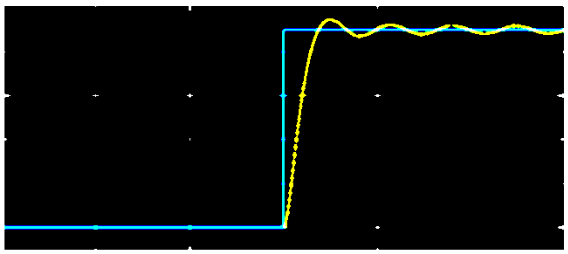

Figure 2: Simulink Stationary Heading Control

The successful results of our stationary test allowed for further testing to be completed in the pool. The pool allowed for greater data quality as the ASV could be evaluated in executing various maneuvers in both remote and autonomous control states. The pool was the first location we were able to test the responsiveness of the remote controller and ensure we would have the ability to regain control of the system if the autonomous mode malfunctioned. The results of the initial controller design in the pool also produced promising results in terms of the direction we hope to move with this project. This test consisted of the ASV proceeding in a user-defined forward direction under remote control and then turning 90 degrees to starboard once the autonomous heading controller was activated. The results of this test can be found in Figure 3.

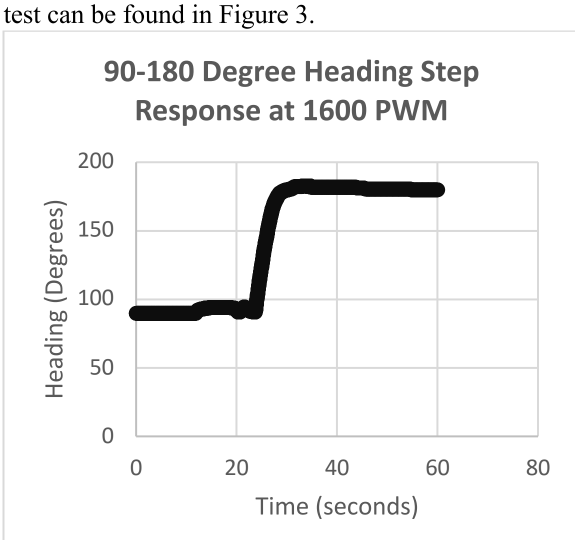

Figure 3: Moving Controller Test at 1600 PWM

In this test, we experienced an identical rise time of about 6 seconds and a comparatively better percent overshoot of about 5%. For the sake of this test, we chose a forward speed of 1600 PWM which is considered the “slow” speed for our ASV and is optimal for handling. Also like the case of the stationary test, this test aligned well with our model, which can be found in Figure 4.

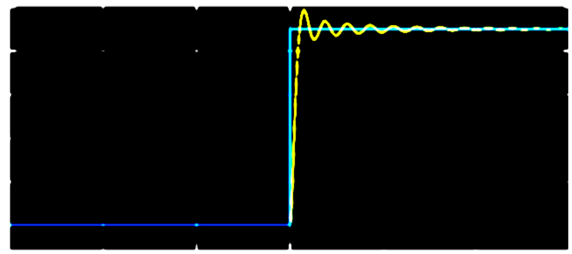

Figure 4: Simulink “Slow” Course Change

The float tank and pool tests have allowed for further testing on the Thames River to be conducted. The significant change from previous tests here is the implementation of an onboard GNSS to allow the ASV to track defined waypoints and follow a “box pattern.” The vessel was programmed to navigate itself to the next point in a continuous loop until stopped by the controller. Follow-on work will consist of refining the accuracy of course corrections completed by the ASV while shrinking the window around the waypoint to get the vessel to navigate more precisely in preparation for the competition. Figure 5 shows the ASV completing two complete loops in the box pattern.

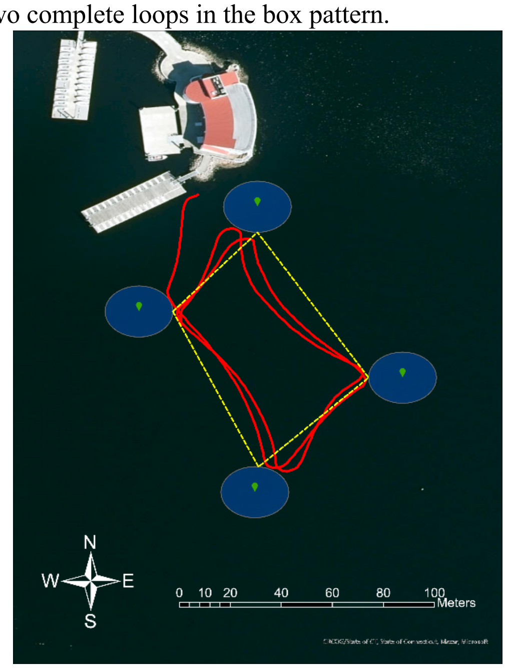

Figure 5: Thames River Box Test

For this test, a 10-meter threshold was put around the waypoints. When the ASV got within 10 meters, the onboard computer would load the next waypoint for the controller to track. One observation from this test was a tendency for the ASV to overshoot its turn to port and the resulting arc to the left of the track line. Early interpretation of these results suggests the error here is caused by not fully calibrating the IMU in combination with our initialization of 000° being slightly off (to the left of 000° T). In future tests, we intend to perform a full calibration of the IMU and use filtering techniques to initialize our IMU to the global reference frame.

VI. CONCLUSION

The Autonomous Surface Vessel project is needed to design, build, and test a vessel that can drive and perform processes on its own without human interaction to compete in RoboNation's RoboBoat competition, which consists of six individual challenges such as mandatory navigation channel, obstacle channel, obstacle field, acoustic docking, object delivery, and the speed gate challenge.

Since its initial beginning at the start of the semester, the project's vessel has undergone a substantial number of modifications and improvements from last year's model. Within this fall semester, the group has designed multiple overlapping solutions, tested available tools in the lab, and replaced certain sensors and software to create a system able to accomplish the tasks. Though there have been a variety of issues that have challenged the group through the semester, the group has learned lessons to avoid any possible issues in the future including always having spare parts or an extra of every tool required for the project to prevent tardiness or failure of project operations.

By accomplishing each challenge set by the RoboBoat competition, thousands of students create incredibly diverse solutions that could assist the maritime community, helping eliminate pitfalls present in human error and reducing the inherent risk to human lives while on the water. Implementing this Autonomous Surface Vessel in the Coast Guard could lead to drastic changes in all 11 missions of the United States Coast Guard, including added opportunities in Search and Rescue operations, Drug and Migrant interdiction, and the reduced risk in many Coast Guard operations. Moreover, it allows for greater risk aversion requiring no crewmembers for unmanned missions in heavy seas or dangerous situations. This increases the Coast Guard's ability to act in all conditions, while also minimizing the potential for any human error or indecision.

Though this project is not one-hundred-percent complete, the group is confident it will have a finished product by the time the team has to depart the Academy. However, there are several mistakes to avoid and opportunities for future capstone groups to be more successful than ours. The group also found that having keen foresight in ordering future parts is essential to the flow of progress with the vessel. It can cause serious and avoidable delays by not ordering or creating two of everything and can hinder our progress. In the future, our group hopes that those who follow can learn from shortcomings and capitalize on advice to further improve the final design.

VII. REFERENCES

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