United States Naval Academy 2011 Autonomous Surface Vessel

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***Abstract*—In this paper, the design of the U.S. Naval Academy's 2011 entry to the Association for Autonomous Unmanned Vehicle Systems International (AUVSI) is presented. We will specifically cover the vehicle's mechanical/electrical construction, and our approach for solving the buoy chain navigation challenge problem.**

I. INTRODUCTION

The United States Naval Academy has designed and constructed an autonomous unmanned surface vessel (ASV) for entry into the 4^{th} annual Autonomous Unmanned Vehicle Systems International (AUVSI) competition held in Virginia Beach, VA in June 2011. Specifically, the specification set forth in [1] specify that the delivered vehicle exhibit the following hard requirements:

- Must possess autonomous and remote operation.
- Must exhibit remote/local safety disconnect of power.
- Must occupy a volume less than 6ft. (length) x 3 ft. (width) x 3 ft. (height).
- Must weigh less than 140 lbs.

The above list will serve has our primary design specifications. The remainder of the paper presents our 2011 vehicle as designed according to the above objectives.. In Section II, the vehicle's mechanical/electrical design is presented. In Section III, we discuss our proposed approach to autonomous navigation of a buoy channel.

II. THE VEHICLE

Motivated by the design specifications and largely by our previously constructed vessel (see Figure 1), our challenge this year was to reproduce the functionality of the 2010 vessel in a smaller and lighter form.

Figure 1: USNA 2010 ASV Vessel

ENS Jon Weissberg (a member of the 2010 team) took this assignment on upon returning from the 2010 competition (while all design alteration were fresh). Over the summer of 2010, Jon constructed mechanically and electrically the 2011 vessel of Figure 2 (note: this figure does not include the added camera on the bow).

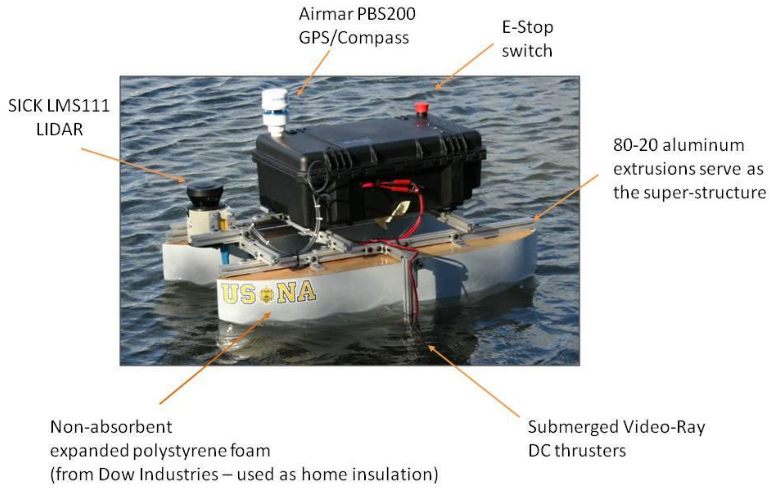


Figure 2: 2011 USNA ASV

A summary of the vehicle mechanical parameters are provided in the following table.

Length	Beam	Height	Draft	Weight
3.5 ft. (42 in)	2.6 ft. (31 in)	2.2 ft. (26 in)	0.8 ft. (9.5 in)	58 lbs.

Table 1: Summary of ASV mechanical characteristics

The vehicle pontoons were constructed from a non-absorbent polystyrene foam (from Dow Industries) which is utilized for home insulation. The foam was covered with a thin fiber glass mesh and painted with a thin wood decking for mounting purposes. The superstructure that joins the two pontoons and serves as the skeleton backbone for mounting is 80-20 aluminum extrusion. A pelican case houses the all the required electronics. The magnetic heading and global position of the ASV is measured with the Airmar PB200 weather station. An initial experiment was performed with the Airmar GPS sensor to determine its precision. The sensor was held at a constant location and approximately 1600 data points were acquired as shown in Figure 3.

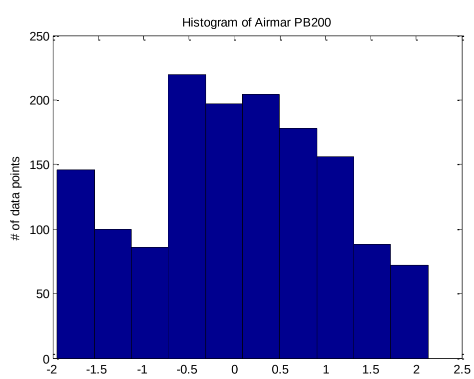
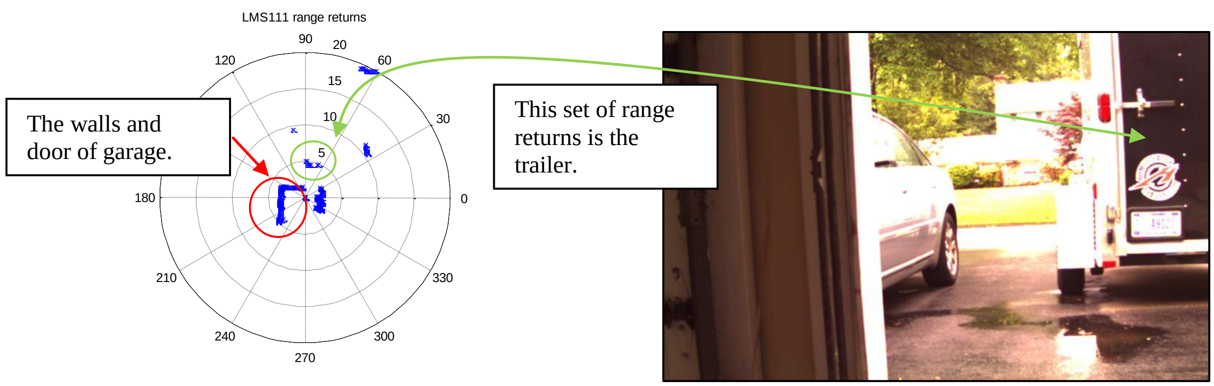


Figure 3: Histogram of GPS sensor

From the above experiment, the standard deviation of the Airmar receiver was calculated to be approximately $\sigma = 1.04\,(\mathrm{m})$ or 3.0 (ft.). The SICK LMS111 laser range sensor was utilized to detect obstacle within a 270 (deg) field of view ($\pm 135\,(\text{deg})$ on either side of the bow) out to a range of 16 (m). A uEye USB camera (shown in Figure 4) was mounted in-line with the LMS111 to provide visual feedback information (note: the uEye camera was not mounted on the vehicle at time the image was taken in Figure 2).

Figure 4: uEye USB camera

During each control cycle, the GPS, compass, and LIDAR and camera are polled for range measurements/images respectively. In Figure 5, a sample acquisition process of the LIDAR and camera is observed. In this scenario, the vehicle is located within a garage facing outward toward a parking area. If we were interested in determining the color of the trailer and we knew something of our environment, then we can narrow down the image search space (that is, we do not have to identify the location of the trailer as the LIDAR has performed this task).



(a) (b)

Figure 5: (a) Sample laser return and (b) the corresponding acquired image

Our intent is to utilize the LMS111 to determine to global position of the buoys (or obstacles). We then utilize the image acquired from the camera and the position of the objects from the LIDAR to search a smaller image space to determine the probability that the identified object is either red or green (so that we can determine the direction of the channel).

Two DC thrusters from VideoRay served as actuators for the vessel. Each thruster produces approximately 10 (lbf) at 24 (V). An alternative, more powerful BLDC thruster set from VideoRay were considered and acquired, but were not incorporated on the 2011 ASV due to the readily available dual channel, DC power amplifiers by RoboteQ. These power amplifiers have proven reliable in numerous projects and have an established interface.

The electrical layout for the vehicle is shown in Figure 6.

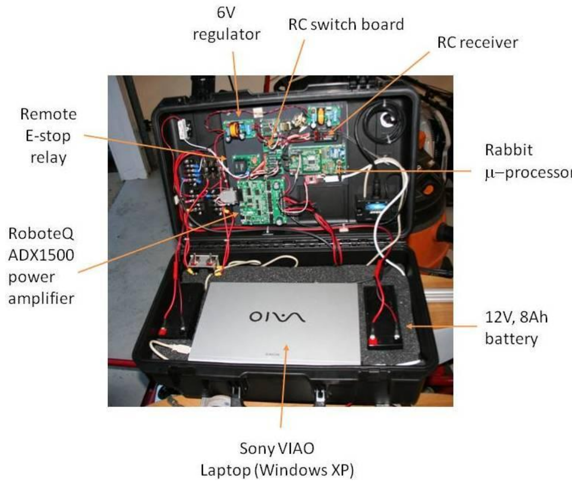


Figure 6: The electrical layout

Two 12 (V), 8 (Ah) batteries provide a 12 and 24 (V) bus for the electronics (a small 6 V regulator is utilized for lower voltage electronics). The ability to switch between autonomous and remote controlled operation is achieved through a custom designed printed circuit board (denoted as RC switch board in Figure 6). This board receives an RC signal via the Futaba receiver that disconnects primary power to the RoboteQ power amplifier (in addition the local E-stop button on the top of the pelican case). The low-level heading control is implemented on below custom navigation board (see Figure 7).

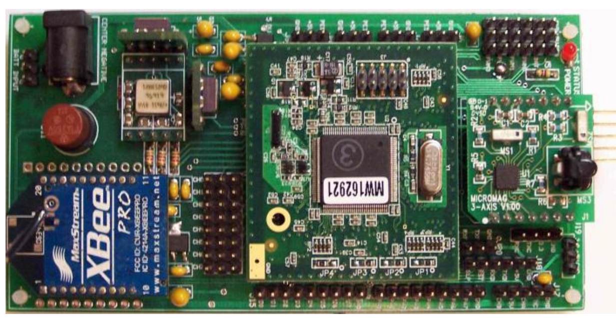


Figure 7: WSE navigation board

The above board was designed, developed, and constructed by the Technical Support Division of the Systems Engineering Department specifically for use in mobile vehicle applications (including ground, aerial, and underwater vehicles). The board is centered around the Rabbit 3000 microprocessor and is equipped with a Micromag magnetic compass, three axis rate gyros and accelerometers, a Trimble global position system, and a MaxStream wireless serial modem. The Rabbit 3000 is programmed in Dynamic C to receive desired heading commands from the high-level navigation software (implemented in MATLAB on the Sony laptop) and then implement a low-level PD heading controller at a frequency of 35 Hz which generates the commanded thrust. The thrust command is sent serially to an SV203 board that then generates the corresponding RC pulse train to be received by the RoboteQ power amplifier.

The high level motion planning (such as the buoy channel navigation algorithm of Section III) is implemented (at an approximate frequency of 0.5 Hz) within the MATLAB software environment running on the Sony Viao laptop under the Windows XP operating system. The high-level software accepts the following feedback measurements: 1) global *(x,y)* vessel location from the Airmar GPS, 2) the ASV magnetic heading from the Airmar sensor suite, 3) range to obstacles or buoys from the SICK LMS111 LIDAR, and 4) a forward looking image from the uEye camera. Given these four feedback quantities, the output of the high-level navigation functions which are to be sent to the low-level navigation board are: 1) a desired heading and 2) a desired forward/reverse thrust bias. The high-level buoy channel navigation algorithm is presented in the subsequent section.

III. THE BUOY CHANNEL NAVIGATION

To determine the required heading to stay in the buoy channel, the LIDAR initially scans the area in front of the ASV and returns ranges of objects within a 270° field of view with respect to the bow of the ASV out to maximum scanning range of 16 meters of the ASV's current location. The returns from the LIDAR are sent to a clustering algorithm that determines which cluster of returns possibly represent buoy locations (we exclude collections of returns that are obviously too large to represent buoys). The location of these buoys is then sent to the designed buoy chain function that determines the desired heading of the ASV that will enable the vessel to navigate the buoy channel. This function receives the following information: 1) the current position and heading of the ASV, as well as 2) the global frame *(x,y)* coordinates of all detected buoys from LIDAR and cluster detection algorithm.

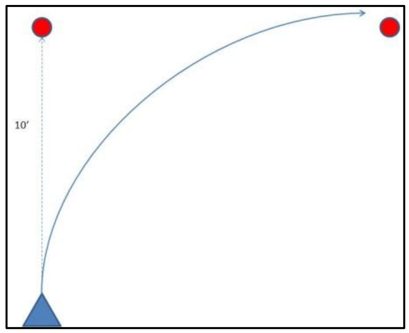


Figure 8: An approach from outside the channel

The channel navigation function first measures and stores the relative angle and distance from the ASV to each of the buoys. By calculating the standard deviation of these angles, the function then decides if the ASV is either inside or outside the buoy channel. If it determines the ASV is outside the buoy channel, it sets the desired heading in the direction of the closest buoy. Once the ASV gets within 10 feet of this buoy, it uses the angles to determine which side, left or right, has the most buoys, and gradually begins turning in the direction of the largest number of buoys so that as it enters the channel (note: if vision is successfully integrated and the color of the buoys are now known, then we will know the direction of the channel), its heading will be nearly parallel to that of the channel, allowing the LIDAR to detect the largest possible amount of buoys. An example of this path is shown in Figure 8. Before it has fully entered the buoy channel, it will detect that it is close enough and transition to a state that navigates within the buoy channel, which will guide the ASV on the appropriate course. In addition, this state will be used to find the entrance to the buoy channel (*i.e.*, locating the direction with largest number of buoys), and therefore the direction the ASV is intended to travel. Furthermore, this approach would also be used if there is a disturbance (such as wind) and the ASV ends up leaving the channel and needs to relocate it, in which case, for simplicity, the default assumption is that the direction with the most buoys is the appropriate one. However, for a scenario in which the general direction of the buoy channel is known, such as in the competition, the overall desired heading from the beginning to the end of the buoy channel (*i.e.*, the general bearing of the channel) will be calculated and made available for comparison to. With the general bearing of the channel known, instead of going in the direction of the most buoys, the ASV will go to whichever direction takes it closer to the overall desired heading, so even if it gets off course temporarily, when it corrects itself it will continue in the right direction instead of going back to the start of the buoy channel (we realize that if the buoy channel makes a "horse-shoe" turn then this approach is not viable).

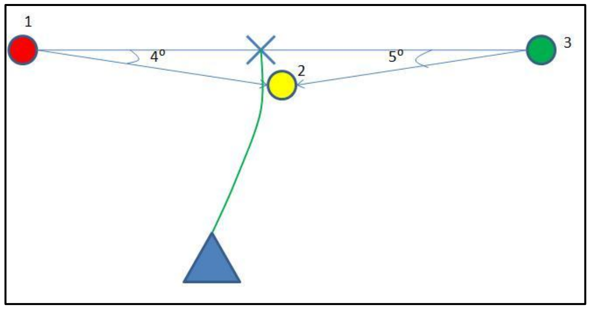


Figure 9: An example scenario within buoy chain navigation

Once the function determines the ASV is in the channel, it uses a different method to determine the desired heading. First, it finds the three closest buoys and compares the angles between them. In the competition, there will be decoy buoys in the middle of the channel that will look exactly like the real buoys to the LIDAR. An example of this situation is shown in Figure 9. If it determines that the middle one is between the other two, within 5 degrees of the line between them, it determines that the middle one is one of the decoy buoys and therefore uses the other two to determine the required heading. In the example in figure 4, for example, the function detects that buoy 2, the yellow one, is between buoys 1 and 3. Because the angle from buoy 1 to buoy 2 is less than 5 degrees off of the line between buoys 1 and 3, it identifies buoy 2 as a decoy. The function would then compute a heading to the point directly between buoys 1 and 3, as shown by the 'x'.

If the function determines that the middle buoy is not directly between the other two, the function moves onto the next test. By comparing the distances to each buoy, the function determines which buoy is the outlier, meaning it is either significantly closer to or farther away from the ASV. Since the other two buoys are a similar distance from the ASV, this indicates that they are the corresponding red and green buoys, and therefore the ASV must travel

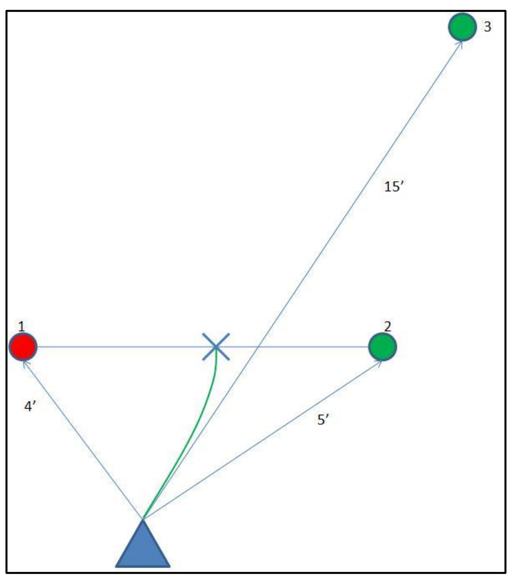


Figure 10: Another buoy channel encounter

directly between them. This aspect of the algorithm is demonstrated in Figure 10. In this example, the distances to buoys 1 and 2 are very similar, only 1 foot difference. However, the distance to buoy 3 is 10 to 11 feet larger, so buoy 3 is identified as the outlier. This indicates that the appropriate course through the channel should be between buoys 1 and 2, and the heading is calculated accordingly.

To approach this point, instead of heading directly at it, the function calculates a heading that will take the ASV towards the point while gradually changing the heading so when it is between the two buoys, the heading of the

ASV is perpendicular to the line between them. This allows the LIDAR to scan the maximum amount of the buoy channel, making the next heading calculation more accurate. The heading that the ASV would follow is shown by the green line in Figure 9 and Figure 10. While this is more complicated than simply following a straight line to the desired point, it has proven to be much more effective at locating the entire buoy channel, which makes the algorithm that much more reliable.

A. Simulation Results

The algorithm was tested using a simulation (which include representative ship dynamics) within MATLAB that sends to the buoy channel navigation function the coordinates of the buoys in a channel. Initially the function had several issues, especially with determining if the ASV was in the channel or not. When there is a bend in the channel, because the ASV is perpendicular to the straight part of the channel before entering the turn, it would see more of one side of the channel than the other. When the standard deviation of the angles to the buoys was computed, it would return a value indicating it was outside the channel, and act accordingly. This resulted in the algorithm plotting a course that would take the ASV outside of the channel. By tuning the value of the standard deviation that indicates if the ASV is in the channel or not, this problem was largely eliminated. Repeated testing showed that the optimal standard deviation was .5 radians, or approximately 29 degrees. If the standard deviation is larger than this, the ASV is outside the channel; otherwise it is in the channel. This improved the accuracy of the algorithm, but it was still not ideal because occasionally even this limit was exceeded and the course calculated assuming the ASV was outside the channel was very different from what it would be if it was in the channel.

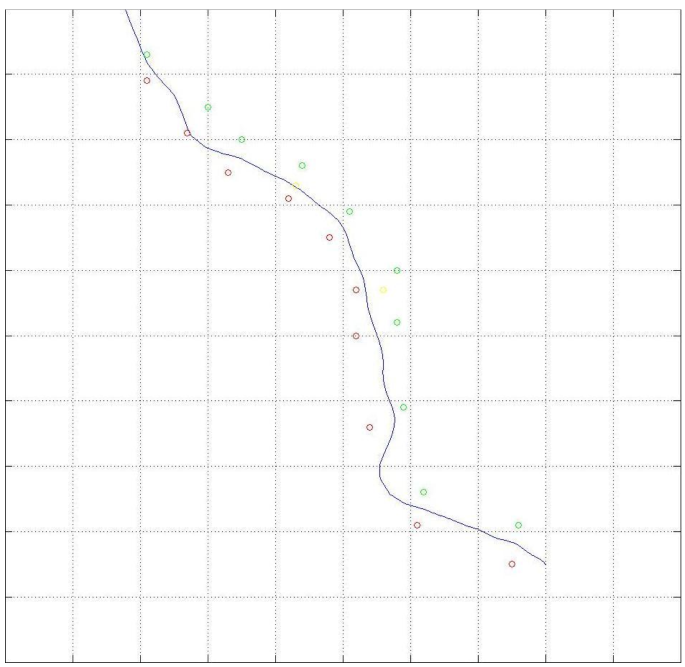


Figure 11: Simulated buoy channel navigation

This problem was solved by increasing the distance from the closest buoy when the ASV begins turning into the channel if it determines it is not in the channel. By increasing this to ten feet as previously described, this caused the ASV to begin turning almost immediately when it was actually in the channel, because the channel is only five to six feet wide. Because it starts turning so soon, the standard deviation would quickly decrease as the ASV turned with the bend in the channel and it could detect more buoys on the opposite side of the channel. At this point, it is not far enough off course to cause it to leave the buoy channel, and it quickly corrects this error and continues on an appropriate course within the buoy channel. These changes also caused the ASV to enter the channel more gradually when coming in from the outside, which increased the accuracy of this aspect of the algorithm as well.

After some adjustments and additions to the algorithm, it was able to accurately return the necessary headings to guide the ASV through the channel. In the same way the function will be implemented with the ASV, the function constantly recalculated the desired heading as the simulation moved the ASV through the channel. The final results of the simulations are shown in Figure 11. This will be tested further on the water over the next month as the ASV program is prepared for the competition in June, and necessary adjustments will be made to the algorithm. The only problem with the algorithm at this point is that it is inconsistent when entering the buoy channel from a position away from the actual beginning of the channel. It will sometimes go through the channel without turning into it, so it simply passes out the far side of the channel. While this is an issue that needs to be addressed in the future, for the competition, we will be starting at the entrance to the channel, and from this starting point the function is very reliable.

CONCLUSION

Over the last year, the 2011 ASV has been placed under numerous field tests and has proven itself reliable with respect to mechanical design and electrical hardware (we have only had to replace one PCB due to inadvertently plugging a USB cable into the SATA port of the laptop). Our primary focus this year has been to successfully navigate the buoy channel autonomously. Midn. Queen spent the entire spring semester developing the previously discussed algorithm for channel navigation and has demonstrated successful attempts under simulation. We fully acknowledge that our single point of failure of our approach lies in the ability of the LIDAR to detect the buoys in the water. The camera system may be employed as a back-up options; however, that approach is riddled with its own challenges. We are currently underway with field trials on the Severn River. We suggest the reader visit our website at: https://sites.google.com/site/usnaasv/home for our most recent updates on our progress.

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REFERENCES

[1] AUVSI competition rules at http://www.auvsifoundation.org/AUVSI/Foundation/Competitions/RoboBoat/Default.aspx, last visited, May 20, 2011.