Villanova University

ASV Journal Paper

Villanova University Autonomous Surface Vehicle Team
Philadelphia, Pennsylvania
http://www.students.villanova.edu/ASV

Abstract

The Villanova University ASV team has designed and built a fully autonomous surface vehicle in preparation for AUVSI and ONR's 2nd International Autonomous Surface Vehicle Competition. With a culmination of the knowledge and experience of past and present team members, the unmanned surface vehicle has the ability to complete a set of core tasks essential for this competition. The ASV is able to navigate an intricate course consisting of buoys, identify and neutralize hostile targets, dock with a sinking vessel, rescue stranded survivors and finally return to base. Fully assembled, the ASV weighs just over 100 pounds and is approximately 55 inches long by 25 inches wide by 20 inches tall. This ASV represents the collaborative efforts of the Villanova University Team to create the most effective vehicle possible given the extremely limited amount of time allotted for development.

Introduction

Our team consists of a group of undergraduate and graduate students from Villanova University. Team leader is Jevon Avis, a PhD research assistant. The team includes undergraduates in mechanical engineering John McCloskey, Peter So, Ralph Sullivan and electrical engineer Seth Goodman. Team mentors include John Metzer of the NAVSEA facility in Philadelphia and Dr. C. Nataraj, Chairman of Mechanical Engineering Department at Villanova

Mission

The 2009 ASV Competition is located at the Founder's Inn and Spa and held from June 18th through the 21st. Each team must enter a fully autonomous surface vehicle that has a total of thirty minutes to complete several tasks autonomously. Prior to the run, each vehicle must try to generate its maximum amount of thrust in 10 seconds. The first task once the run begins is to pass through two gates, marked by black piping with reflective yellow tape, as quickly as possible. Next, the boat has to navigate its way through a set of buoys, consisting of green markers on the left and red on the right, while also avoiding flotsams marked by yellow buoys. After having navigated through the "reef", the ASV must locate and dock with the sinking transport ship designated by two flashing amber lights and a large "X." After touching the "X" marked on the wrecked ship for 5 seconds, the next task is to find and pick up the stranded lifeboat, which will be a standard life buoy. Next, an on-board weapons system must hit two pirate ships, which consist of floating circular targets, with a water gun and finally finish by going back to the original dock. Additionally, the ASV must meet a number of required constraints including size, weight, max speed, power supply, and safety features.

MECHANICAL SYSTEMS

Hull and Frame

The hull of the ASV was designed to be lightweight and buoyant under considerable loads. It also needed to be of a reasonable size and capable of efficient hydrodynamic movement. After several design considerations the Thule 682 Sidekick, a lightweight, car mounted cargo unit was chosen as the hull. In order to ensure a waterproof interior, a fiberglass cover was fabricated which is tightly secured to the internal frame.

The frame was designed to support the thin hull as well as to serve as a mounting surface for the components of the ASV. Hollow, one inch by one inch aluminum tubing with a $1/20^{th}$" thickness was welded together to form a structure which could stabilize the load of the ASV. Aluminum was selected for the frame over other possible materials for its combination of its lightweight and resistance to corrosion. The hull is attached to the frame with rivnuts along the frames perimeter. All systems of the ASV were mounted on the hull within the frame as efficiently as possible

Figure 1: Frame

Propulsion

Forward and reverse motion of the ASV is provided by the propulsion system, designed to make real time adjustments to the speed and direction of the propeller and motor. Power allocation, as well as the weight and size of the boat were taken into consideration when developing the propulsion system. Based on these factors a Minn Kota 40 pound thrust trolling motor was selected for the ASV, which proved capable of meeting all of our requirements.

A propeller shroud was also added from last year's design to address a recently levied requirement intended to ensure that the propeller could not accidentally injure staff or team members in the area of the active vehicle. The shroud was custom-fabricated out of steel and has a two-inch clearance in front of and behind the propeller

A tacho-generator is used to control the speed of the propeller. It attaches directly to the motor shaft internal to the motor housing. A DC voltage directly proportion to the rotation speed of the motor is outputted into the AMC motor driver. The motor driver also receives a reference voltage signal from the system's control box to attain the desired speed The difference between these two voltages creates a minimized feedback error resulting in a closed control loop.

Steering

The steering system is responsible for maneuvering the vehicle. It is able to obtain and maintain a steady course in a desired direction. A 210-series 12V 88in-lb RH gear motor-shaft window motor provides the actuation for the system. It was chosen because of its compact design and high torque capability. A 15 tooth, quarter-inch pitch sprocket, a 150-tooth gear, and an optical incremental encoder attach to the window motor's custom-made shaft. The 150-tooth gear is in mesh with a 25-tooth gear which is connected to a potentiometer. The potentiometer works in a closed-loop and provides us with accurate feedback to maintain shaft direction. The 15-tooth sprocket controls the direction of the boat's motor using a 90 tooth, quarter-inch pinch sprocket that attaches to propulsion motor. An ANSI 25 chain connects the two gears and creates a drive gear-chain system with a 6:1 ratio. This ratio results in high torque and a low speeds, between 0-30 degrees per second. The encoder serves both as a bearing to the window motor shaft, and a redundant back-up position feedback

The software for the steering assembly communicates with the steering motor controller in order to position the motor at a desired angle specified by the navigation system. The potentiometer will relate the position of the motor to the AMC controller to close the steering algorithm loop. This loop follows a Proportional Integral Derivative (PID) control scheme to control the offset from a set point from a pre-established zero position. To help minimize error, the PID was finely tuned. To do this SimuLink was used an the final parameters for the proportional, integral, and derivative term are 200, 0.2, and 50 respectively. Below is the block diagram for the boats closed loop steering controller. The transfer function was based on the equations of motion of the motor.

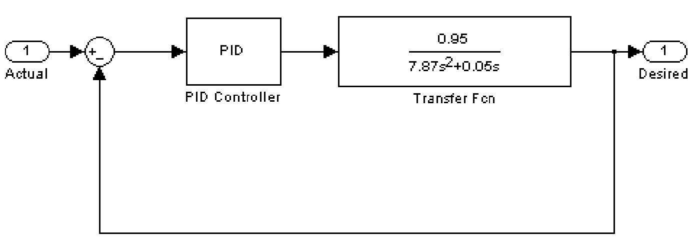

Figure 2: Motor mount and steering system

Weapon System

The ASV must be equipped with a weapons system capable of locating multiple target, or pirate ships, and being able to neutralize those targets with accurate shots. When designing the weapons system several factors were taken into account. First, because of the need to attack multiple targets, an ideal system would be able to fire multiple times without the need for a conventional reloading procedure. Next, the targets must be fired upon in a timely manner due to the constant shifting of the boat in relation to the targets. Being able to fire accurately means firing before the ASV's position changes drastically. To ease the burden on the system of responding nearly instantaneously it should have the ability to move within two degrees of freedom. The first should allow for movement horizontally to adjust for slight changes in the position of the boat. The second will take into consideration the varying distance from the target, and allows the gun to move vertically. Finally, a key factor in the system is the ability to recognize the targets using a vision system which would be incorporated into the design.

After considering the factors needed for the system it was decided that a standard wash-down pump would serve as the main component. An intake hose supplies water to the gun system at a rate of 5 gallons per minute, which is then focused into a precise jet by a small nozzle at the end of the system. The gun is directed by two servo motors, controlled by a pulse width, allowing for vertical and horizontal movement simultaneously. This pan-tilt system that controls the direction of fire also supports the camera for the video feed for the weapon system (Figure 3).

Figure 3: pan-tilt camera/weapons system

Recovery

The idea for the recovery system was to keep it as simple as possible. Rescuing the survivor a drift (life buoy) was simplified into two basic components. The first step was recognizing the life buoy using the same vision system, which was used for obstacle navigation and general tasks performed by the ASV (aside from the weapons system). The second step was to deploy the recovery system. The actual recovery system was planned to consist of a net which deployed off the bow of the ASV, a motor to lower the net into the water and the motion controller and potentiometer to ensure accuracy and control. At the time this paper was written, the actual recovery system had not been finalized.

ELECTRICAL SYSTEMS

Electrical System

The electrical system of the ASV distributes power to all of the systems onboard. To supply sufficient power, two 12 volt Odyssey batteries were chosen. These waterproof batteries were ideal for the needs of the ASV, namely the 24 volts required by the propulsion motor. By wiring the two 12 volt batteries in series we could obtain the necessary 24 volts. Additional systems throughout the vehicle were powered by two DC to DC converters; one to supply 5 volts, the other 12. The GPS, INS, encoder, compass and video card run off of the 5 volt supply while the control box and cameras required 12 volts.

E-Stop

To ensure the safety of AUVSI staff and team members an emergency stop system, or E-Stop, was configured which would disable all potentially hazardous elements of the ASV. The main component of the ASV taken into consideration is the propeller. Although a shroud is present around the propeller, extra precautions are always taken to ensure the safety of all. The E-Stop can be engaged one of two ways, either via a wireless signal from a remote controller or by a large red button atop the ASV's frame. Should either be activated the power to the motor is shut down by means of the inhibit feature of the motion controllers. Power to the motor will remain off until a reset button is pressed.

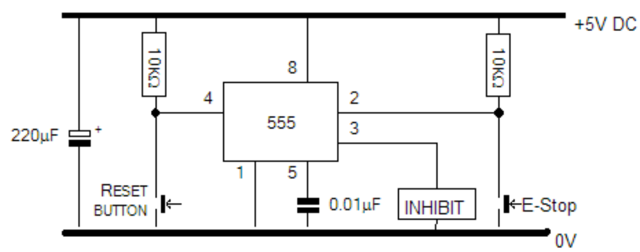

Figure 4: E-stop Circuit

Control System

The control system is responsible for overall control of the mission and mission planning. It will be comprised of two things, the main hardware of the control box and its associated software. The control box itself is a custom made *Pelican 104* made by *Pathway Technologies Inc.* The *Pelican 104* is a small industrial PC based on the PC/104 specification that runs *xPC Target 3.3 as* an operating system. Inside the control box, five PC/104 cards interface internally with the main PC/104 control bus and externally by a 50 pin D-Sub connection. There are two Diamond Systems Diamond MM-16-

AT analog input output cards. Also from Diamond Systems, an Emerald EMM-XT card has four RS-232 ports. RTD Embedded Technologies, Inc. made the last two cards. They are the RTD DM6804 and the RTD DM6814.

The control box interfaces with number of components and sensors including five *Advanced Motion Control* motor controllers, an encoder, four potentiometers, a TI C6000 video processing card, a GPS, an INS, and a compass. The five AMC motor controllers, the encoder, and the four potentiometers interface with our Diamond MM-16-AT cards. An analog voltage output is sent to the motor controllers that then turn the desired motor. The potentiometers are used on all the motors except the propulsion motor. For the former, the voltage outputs are sent back into the control box to be processed. In this way, how far the motor shaft turns can be determined. For the propulsion motor, its output is monitored through a tachometer inside the motor housing and the output is sent into its corresponding motor controller. This keeps the motor turning at a constant RPM. On the steering shaft, a potentiometer and an encoder are used. The potentiometer is used in order to position the boat's motor at an absolute zero to make sure the USV drives straight. After this is accomplished, the encoder takes over due to its higher level of accuracy (up to a tenth of a degree). The output of the encoder feeds into a control loop that uses a proportional integral derivative controller to obtain this high level of accuracy. The video card connects to the *Pelican 104* simply with a cross over cable. It sends UDP packets that are obtained by the software and processed. The three sensors, GPS, INS, and compass, connect to the Emerald MM-XT card via a custom made 50 pin D-Sub connection. There outputs are fed into our navigation algorithm and give us the ability to control the USC's motion and positioning in the water.

In any project like this, the software is a key component. All of the software is written in Matlab and Simulink. The entire program is embedded onto the boat so it will start when the boat is turned on. One main control loop controls the entirety of the mission. Each objective is placed into a smaller triggered subsystem. This allows the software to make sure it completes the first objective before it attempts to accomplish the second objective. As stated previously, all of the sensory data from the external instruments and cameras feed into these subsystems and provide appropriate data that allows the USV to know where it is at any moment in time. All of this data is logged and extracted after the fact so that during the run the data can be viewed and analyzed so that it can troubleshoot any problems it may encounter.

Navigation System

The navigation system combines a GPS, digital compass, and INS in order to determine the position of the ASV. The GPS will determine the ASV's initial position, as well as the ASV's new position. Because the GPS is not accurate enough to be used alone, it is combined with an INS to obtain the best possible results. The INS consists of three orthogonally oriented accelerometers and gyroscopes, which measure the ASV's acceleration and rotation rate along each axis. The acceleration was integrated twice to obtain the position, using an initial velocity of zero and an initial position determined by the GPS. The INS is very accurate for short term measurements, but increases in error over time. Therefore, the INS data was sent through a kalman filter, which minimizes error by taking into account current and previous measurements, as well as noise. The GPS also has inaccuracies in determining the exact position, but these errors don't change over time, making it fairly accurate over long term measurements. Combining the two will result in very accurate data points for both short and long-term measurements.

The orientation of the ASV is important in determining which direction it is traveling as well as cancelling out the effects of gravity. The GPS outputs a latitude and longitude coordinate. Those coordinates were then converted into an absolute reference frame, were the initial position is defined as (0,0), and the new position is measured relative to this defined origin. The INS will have a similar output format, were the acceleration will be measured and the position will be determined relative to the origin, except instead of having a fixed x and y axis, as used with the GPS, the axes will rotate as the boat rotates. Therefore a global transformation matrix is setup using the direction obtained by the compass. In order to cancel out the affects of gravity it is necessary to measure the pitch and roll angles, in addition to the heading angle. Once the INS accelerations are in a global reference system the affects of gravity can be removed and a kalman filter was used to combine the GPS and INS values and obtain the most accurate coordinates of the ASV.

The navigation system is useful in locating the sinking vessel and life ring, so the ASV does not have to rely purely on vision, but will have a good estimate of the location beforehand. Once all tasks have been completed, the ASV can navigate back to the dock by finding the shortest between its current position and starting position.

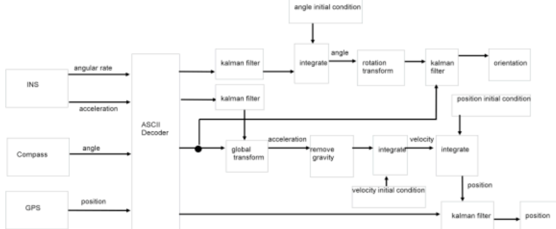

Figure 5: Navigation System Algorithm

Video

The vision system is responsible for recognizing the dynamic and real-time video data that is pertinent to the system's primary tasks. The video processing was realized through a Texas Instrument DSP processor platform, shown below, using the MATLAB and Simulink programming environment.

The information contained in the UDP packets was kept relatively simple in order to keep the packets small and to keep processing to a minimum on the control box. However, the actual video processing is relatively complex. Originally, in order to decrease problems resulting from reflections on the water, the bottom half of the image is disregarded. However, with the addition of the GPS and a more reliable color processing code, a virtual map of the course is created and then processed using the YCrCb color space. Each pixel within this color space is made up of three values from the three matrices that make it up; one from Y, one from Cr, one from Cb. Since a specific color will have a distinct color combination within these three matrices, three separate processes are used to find where these values exist in a given matrix and these results are logically combined together. This successfully extracts the desired color from the given image. From this output, one can compute the distance and angles to each of the desired buoys. With this the control box will continue updating its virtual map with changing distances and angles as the boat travels through the obstacle course. Ultimately, the output from the video card should be the angles and distance to each buoy that it sees within the image as a vector.

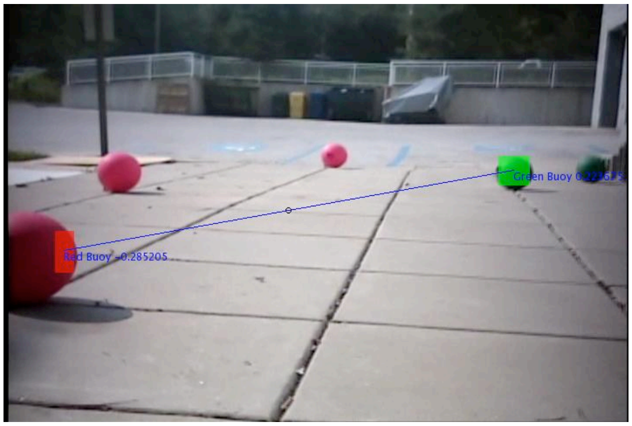

Figure 6: Video Output

After this initial video processing, additional logic and computation takes place. The logic that executes depends on what objective is being sought after. For example if we are attempting to navigate the buoys, all the buoys are recognized through the buoy algorithm and the distance and angles to each buoy as well as their midpoints are calculated. The control box will ultimately allow the boat to travel successfully through the obstacle course.

With respect to its primary tasks, this system is capable of recognizing channel buoys and any number of targets, in real-time, and outputting the necessary vital information to the control box that interprets this information.

Other important aspects of the video system are to recognize the speed gates, locate the strobe lights in order to dock, locate the life ring buoy, as well as locating the round target in order to aim and take a shot. The speed gate has a yellow and black pattern on it so the video system has been set up to locate that specific pattern as well as the color pattern that goes along with it. The control box will ultimately provide the final information so that it can steer through the gates. The strobe lights are orange and flash in a certain pattern. Just like the speed gate detection, the video system will locate the strobe lights using the color and flashing pattern.

The life ring buoy and locating the target are done similarly to the speed gates and the strobe lights. The video system will look for the certain color pattern as well as the shape and size of the item that it is looking for. Once that has been achieved, the control box will then take over and finish that portion of the course before it goes on to the next part.

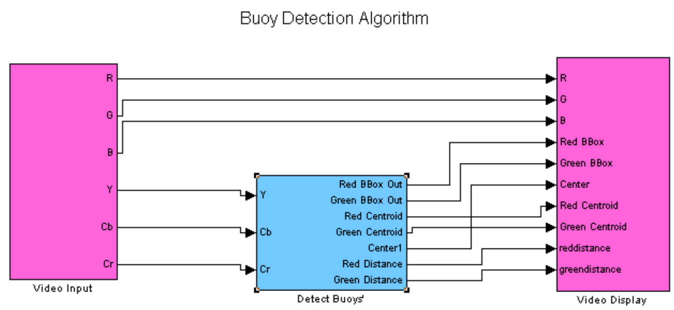

Figure 7: Buoy Detection Algorithm

CONCLUSION

This year's ASV is the accumulation of our team's experience and knowledge. Due to the extensive changes in the competition and our designs, the team was left reorganizing and redesigning many aspects of the ASV under extreme time constraints. This resulted in having less time to perform tests. Despite this, the team managed to manufacture and program a respectable ASV capable of performing the tasks in a timely manner.

ACKNOWLEDGEMENTS

We would like to thank all of our advisors and sponsors for their help; we would not have been able to accomplish our goals without them. Major contributors were the US Navy and Villanova University's Mechanical Engineering Department. *Advanced Motion Control* kindly provided us with four free and one discounted motor controller. *Pathway Technologies* provided us with software. *RTD Embedded*

Technologies, Inc assisted in getting all of our supplies in a timely fashion, while *Vision Technologies, Inc*. provided cameras to us. Our team would also like to thank the Bucks County Park Department for allowing us to use their lake for testing. We would also like to thank former team member, Nicholas Melgar, for his invaluable knowledge of last year's design as well as for his wisdom and charisma.

Much appreciation also goes to Zack Nowosad and Chris Townend for manufacturing custom made parts in Villanova's machine shop. We would also like to thank Lana Vernati who assisted with ordering parts and organizing the trip. Finally, we would like to express gratitude to John Metzer of the NAVSEA/Cardrock Naval facility in Philadelphia and the Mechanical Engineering Chairman Dr. C. Nataraj for advising us throughout the project.