EMBRY- RIDDLE AERONAUTICAL UNIVERSITY

Floating-Point ASV System

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This journal paper describes design and functionality of the Autonomous Surface Vehicle designed and built by Embry-Riddle Aeronautical University for their entry into the 6th International RoboBoat Competition hosted by AUVSI and ONR. The Embry-Riddle team has developed new and innovative design features in order to complete the challenges in the competition. These features include an improved hull, flexible motor mounts, robust and reliable buoy navigation, a turret-mounted Nerf gun, and a Linux-based aerial quad-rotor sub-vehicle.

Introduction

The Robotics Association at Embry-Riddle Aeronautical University presents the Floating-Point Autonomous Surface Vehicle (ASV) system as a competitive solution to the 2013 RoboBoat Competition challenge. Goals of the Floating-Point team are fulfillment of all mandatory tasks (thrust and speed), navigation of the optional buoy channel, and completion of all additional tasks posed by the challenge stations. The Floating-Point ASV system was developed with innovative solutions for meeting these goals. The final design of the system includes a stable yet maneuverable tri-hull boat platform, safe, reliable power and propulsion systems, a powerful on-board processor, and array of mission critical sensors. In order to complete tasks at the challenge stations, these sensors include a camera, infrared thermal sensor, button bumper, robotic claw, and a turret mounted Nerf gun.

Hull Design

The Floating-Point ASV system is designed to improve upon previous platforms in both stability and turning speed. It features a tri-hull configuration with the center hull bearing most of the load and the two exterior hulls providing stability. The two outside hulls draft one inch less water than the center hull to lessen drag yet provide counter forces that resist pitch and roll. The leading edge of the center hull is angled thirty degrees relative to the water for hydrodynamics and for docking against the ramp as specified in the Catch the Ball challenge station.

Propulsion is provided by a pair of Seabotix thrusters. The thruster mountings are designed to be attached to the outside hulls and to be adjustable along their length. Adjusting thruster location along the length allows precise control over the center of thrust for optimum performance as subsystems are developed and modified. This year, the thrusters are mounted two inches higher than last year to avoid lake debris being entangled in the motors. The wide separation of the thrusters improves turning rate, increasing maneuverability of the vessel in tight quarters. The Floating-Point ASV can outperform the 3rd place vehicle Embry-Riddle entered in the competition last year. The new vehicle weighs only 35 lbs, a ten percent decrease compared to the previous year's vehicle.

System Integration

The Floating-Point system is comprised of commercial off the shelf (COTS) parts integrated together using a custom control sensor board. A collection of sensors is used to navigate the buoy channel, locate challenge stations, and complete the various challenge tasks. These sensors were selected to maintain the adaptability and simplicity of the system while achieving the required perception. Figure 1: Systems Integration Diagram illustrates the sensor suite and flow of data through the system.

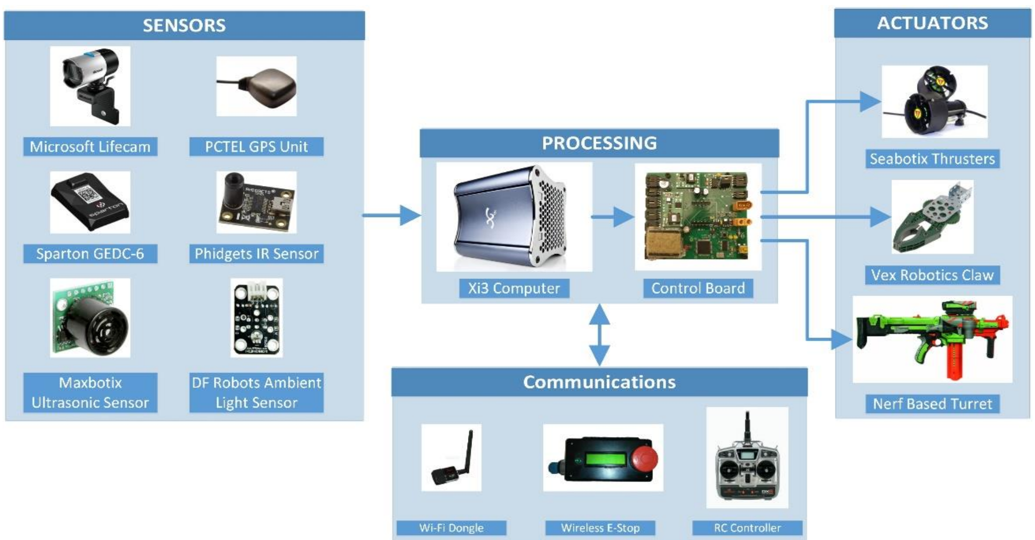

Figure 1: Systems Integration Diagram

Sensors on the left hand side of the figure send data to the onboard Xi3 computer running Ubuntu Linux and the Robot Operating System (ROS). After processing all of the necessary data for the current task, messages are sent to the custom control board which processes the output. Control signals are then sent to the required actuators that include thrusters for movement, a robotic claw for the Capture-The-Flag station, and a Nerf gun mounted turret. The system also contains a Wi-Fi data link used for testing and debugging in addition to transmitting data for the Rock, Paper, Scissors, Lizard, Spock station.

To ensure safety, all manual control signals are sent to the control board directly, bypassing the computer. A wireless emergency stop solution was developed to allow remote deactivation by the safety crew. Upon pressing the button, power provided to the motors is terminated. A 2.4 GHz

Spektrum controller, used for manually controlling the vehicle in water, sends commands directly to the control board's microprocessor. The vehicle also includes the required on-board emergency stop button for redundancy.

Buoy Identification and Navigation

Buoy Detection

The primary difficulty associated with navigating the buoy channel course is unambiguous identification of the buoys using computer vision and image processing. The system must work reliably regardless of lighting conditions, specular reflections from the water, or background noise. To help deal with changing lighting conditions, the Floating-Point ASV system incorporates a DFRobot ambient light sensor, which adjusts brightness of the image before processing.

To find buoys, images are processed using the hue-saturation-luminance (HSL) color model. Instead of extracting an entire color plane before additional processing, a range of HSL values is used to help separate the buoys from the image through the use of a threshold. Each color buoy will have a narrowly-defined set of HSL values that vary slightly depending on the lighting conditions. By comparing images of the same buoy under different lighting, a range of HSL values is constructed for each of the five potential buoy colors (red, green, yellow, blue and submerged white).

Vision Algorithm

Vision processing is performed using the C++ programing language and the Open Source Computer Vision (OpenCV) library. OpenCV provides a full set of filters and image analysis tools, simplifying development of the vision software.

The vision algorithm begins by applying a color threshold. This threshold only allows pixels that fit within the empirically determined range for each buoy color to pass the filter. Using this threshold produces a binary gray scale image. Pixels that do not fit within the HSL range are set to 255 (black), and pixels that match the filter are set to 0 (white). When a buoy of the target color is found in the image, there will be a high concentration of white pixels in its location. HSL ranges used in the thresholding are shown in Table 1.

Table 1: Buoy HSL Ranges

	Red	Green	Blue	Yellow
Hue	1	50	100	25
	8	80	115	40
Saturation	110	50	125	160
	255	255	255	255
Luminance	0	0	0	160
	255	255	255	255

Typically, an image with a buoy will have large "blobs" that have passed through the filter alongside positive particles that passed the threshold but are not buoys. To remove these false positives, a small particle filter is applied. This step successfully leaves only the buoy of interest in the binary image. The third and final step of this algorithm is a circular contour analysis, which determines the size and center of the buoy based on position of all pixels that have passed through the filter. After performing this algorithm for each buoy color, the center point of each buoy is then placed in the vehicle's frame of reference. Averaging red and green buoy locations generates a vector pointing towards the center of the buoy pair. This center oriented vector can now be used by the navigation and control algorithms as a drive point. If only one buoy, either green or red, is found, then the boat will produce a vector pointing towards the direction of the missing buoy, e.g. right of the red buoy if the green buoy is not found. An example of these steps is shown in Figure 2. An image with both a red and a green buoy is analyzed with the binary output of each step shown.

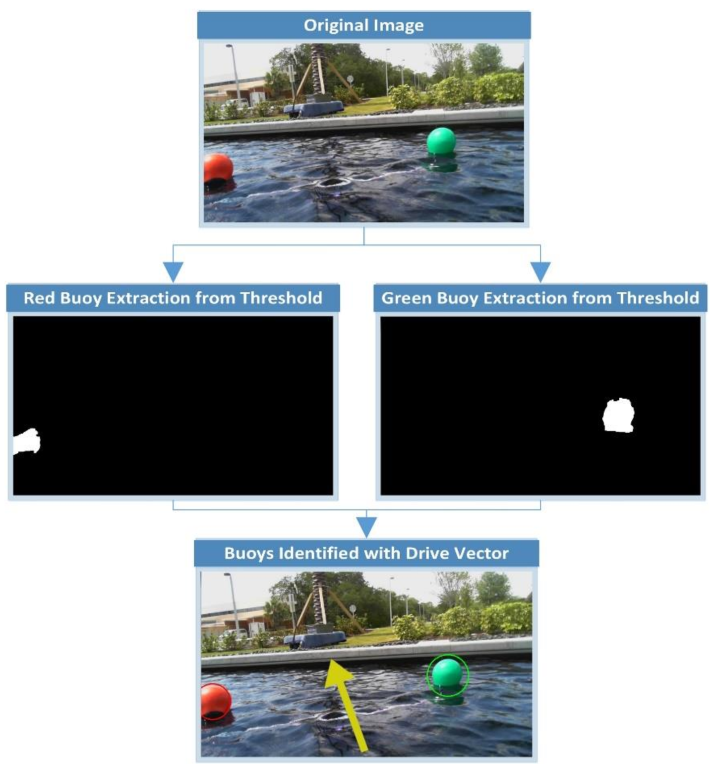

Figure 2: Buoy Identification Flow

Navigation

To navigate through a buoy gate, the vehicle attempts to align the center horizontal pixel of the image with the center horizontal coordinate generated by the vision algorithm. When a yellow obstacle buoy is present and between the red and green buoys, a new drive vector is determined by choosing a midpoint within the largest gap in the channel: either between the green buoy and yellow buoy or between the red buoy and yellow buoy. This new drive point is then used to navigate. In either situation, the algorithms are performed for each frame received from the camera. This means that the vehicle is always reacting to its new position and the position of the buoys. The competition course does not contain any hard turns or trap situations in the channel, so the vehicle can navigate purely reactively. This makes the navigation simple, streamlining the process and saving computing power for other competition tasks.

Challenge Stations

To navigate from the end of the buoy channel to the challenge stations, the Floating-Point ASV system uses a combination of GPS waypoints and compass headings starting at the blue buoy marking the end of the channel. Upon reaching a minimum distance of 2 meters, the vessel will begin to attempt the respective challenge station.

Rock, Paper, Scissors, Lizard, Spock

Completing the Rock, Paper, Scissors, Lizard, Spock station begins with the Floating-Point system detecting the signs and driving towards them. Upon arriving at the GPS waypoint for the station, a Hough Circles algorithm is applied to create an image mask for circle surrounding the hand symbol. Each hand symbol has an HSL range which represents the color surrounding it. Next, a HSL histogram is used to produce a score of how likely an observed sign's color in the image matches one of the hand symbols. Once a hand symbol is identified, an onboard Phidgets infrared temperature sensor records temperature of the symbol. This process is then repeated sequentially for each of the remaining three hand symbols and the hottest hand symbol is determined. Upon identifying the hottest symbol, the distance from the sign to the boat is approximated using the size of the hand symbol in the image and the on-board ultrasonic sensor. The GPS coordinates of the sign are calculated using the estimated distance and the boat's current position and compass heading. The hand symbol that beats the symbol on the hottest sign and its GPS location are then reported back to the server using Transmission Control Protocol (TCP).

Shoot Through the Hoops

Completing the Shoot Through the Hoops station is based on the operation of the custom turret system, as shown in Figure 3. The team's solution for launching a projectile through the hoop was to purchase and modify a COTS fully automatic Nerf Vortex Nitron gun, which fires small round disks. Movement of the turret is controlled through the use of two waterproof Hitec servos for pan and tilt. The hoop identification algorithm begins with the Floating-Point system searching for circles using the same method as the Rock, Paper, Scissors, Lizard, Spock station. After finding at least one circle the boat will reposition until all three hoops are in view. The turret mounted camera is then rotated such that the circle on the far left side is positioned in the center of the image. Once aligned, the turret-mounted Nerf gun will fire its first shot. After running the image processing algorithm again to realign the hoop, the second shot is fired within a second of the first shot. The process is then repeated for the other two hoops.

Figure 3: Turret System

Catch the Ball

Completing the Catch the Ball station is accomplished using an innovative onboard aerial quad-rotor sub-vehicle, Exponent, shown in Figure 4. Exponent is a COTS Aerotestra quad rotor frame integrated with sensor and processing suite which includes an ultrasonic sensor, a Logitech webcam, and a quad-core embedded Linux computer. The vehicle is able to autonomously navigate over the dock and search for the ball through the use of the on-board computer and ArduCopter autopilot system. In order to search for the ball and stay within the boundary of the dock, Exponent employs a similar software system to the Floating-Point ASV, running Ubuntu, OpenCV, and ROS. As the Floating-Point ASV

Figure 4: Exponent Sub-Vehicle

reaches the dock, the system sends a start mission message to Exponent, which launches from the top of the deck. When the ball is found, it is retrieved through a Velcro pickup system. Exponent will then return to the boat using GPS navigation and visual identification of the Floating-Point ASV's deck.

Sneaky Sprinkler

Completing the Sneaky Sprinkler station involves similar logic to buoy identification. Images from the webcam feed have a HSL threshold applied for the color red. Next, a Hough Transform is applied to check for two concentric circles. If found, the e-stop button is detected and the original image is run through another threshold operation to find the white color representing the white buoy. Testing at Embry-Riddle has shown that a white buoy submerged six to twelve inches underwater is still visible from the surface. If a white blob is found the boat will slowly drive forward into the button, as shown in Figure 5.

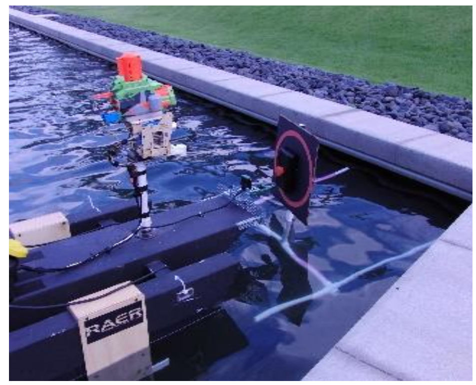

Figure 5: E-Stop Depress

Capture the Flag

Completing the Capture the Flag station begins with the Floating-Point system reaching a distance within 15 ft of the given GPS Waypoint. Similar to the other stations, a HSL filter is applied to the image to track purple and blue blobs, which correlate to the smaller boat. In order to grab the flag, a servo controlled claw, developed using VEX Robotics parts is opened, shown in Figure 6. The Floating-Point system will track the boat and approach it from the back with a speed proportional to its size in the image. When the smaller boat is directly in front of the Floating-Point system at a size that correlates to it being sufficiently close, the claw is closed and the boat moves in reverse to pull the flag off the sub vehicle.

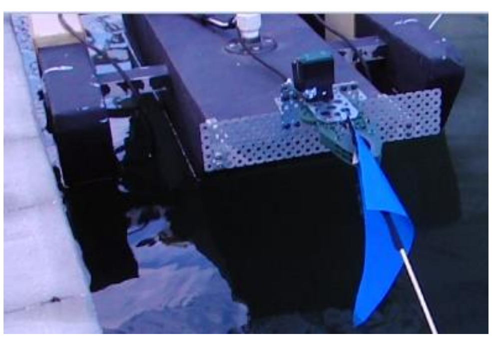

Figure 6: Floating-Point ASV Attempting to Capture Flag

Testing

The algorithms were tested in several stages. Preliminary testing was performed in simulation on the computer, where the filters and other vision processing steps were performed on test images and logged video. The primary method of analysis was examination of the binary image outputs. The filters were adjusted until they produced useful results for all lighting conditions and reasonable distances.

Once the filters were proven successful on the test images, they were implemented into a test code that included active motor and servo control. Initially the code was run with no hardware attached. Signals sent to the motor controllers were monitored as logged videos were run. This was done to monitor outputs and observe how the motor commands changed based on the drive point determined through video analysis. Hardware was then hooked up for hardware-in-the-loop testing and the thrusters and turret servos were actuated based off of logged video. Actions were monitored and vehicle reactions were verified. Once this was confirmed, the logged video was switched out for a live feed from the Microsoft webcam in the lab. The vehicle was stationary on a cart, and buoys were held in front of the camera and moved manually to generate responses by the vehicle to "navigate" through them. While one team member moved the buoys, another monitored the LabVIEW based user interface along with the thruster's power and direction to confirm the vehicle was attempting to move in the correct direction. For the challenge stations, mockups were made and also bench tested using live sensor feed.

The final stage of testing was performed in the water. A pond located in front of the newly constructed Embry-Riddle Administration Building was outfitted with a buoy channel. The vehicle was placed on the water and remote controlled in various orientations before being switched into autonomous mode and allowed to navigate the mock channel. The vehicle was monitored visually during the run, and the logs were post-processed to check for performance accuracy. The video logged during the water tests is then run through the test code discussed in the earlier test stages to see the exact values being outputted by the vessel.

Video was logged in the morning, mid-day and early evening as well as several different weather conditions including sun, overcast and rain to provide an extensive catalog with lighting conditions covering all possibilities at competition. This data was used to build HSL filters that detect buoys and challenge stations in all of the conditions without need for adjustment.

Results

One of the main objectives of the project was to create an algorithm that successfully identifies buoys of different colors, determines their location relative to the vehicle, and navigates through a channel of the buoys without missing a single buoy gate. This algorithm was designed with the goal in mind of being able to run the code in any weather condition without alteration

The images show that the algorithm is capable of finding buoys in extremes of both sunny and cloudy weather. Glare during sunnier conditions makes less of the surface of the buoys detectable, but the buoys are still visible at a distance farther than any that will be encountered at competition.

The video logs taken during different weather and lighting conditions were used to determine the success rate of the algorithm. Frames where buoys were visible and within 50 feet (maximum distance in competition) were run through the test algorithm and the binary output was examined. If the channel marker buoys were visible in the binary image and had an assigned pixel coordinate, then the frame was considered a success. If the buoys were not visible in the binary image or if the coordinate location marked an object that was not a buoy, the frame was considered a failure.

The results show that the algorithm detects both buoys 94% of the time when both buoys are present in the image. The algorithm is successful 96% of the time when the buoys are under overcast skies. Detection in sunlight is less successful but still occurs around 90% of the time. Performance during autonomous tests where this data was collected shows that the success rates above are high enough to navigate the successfully navigate the buoy channel. If only one buoy is seen, the boat navigates to either the left or right side of it depending on the color of the buoy and the direction that the boat is travelling.

Another main goal was to complete the challenge stations. As such, similar testing was performed for the identification of objects at the challenge stations. In order to test the Shoot Through the Hoops station feasibility, three Nerf guns, all with electronic propulsion, were tested for accuracy at a target 15 ft away, which is the maximum distance estimated to attempt the station. Guns varied with whether they were fully automatic or semi-automatic type and if they fired darts or disks as projectiles. It was proven the Vortex Nitron, which fired disks semi-automatically, was more accurate than other guns.

Table 2 Nerf Gun Comparison

	Automatic	Projectile	Accuracy at 15 ft
N-Strike Stampede ECS	Fully-Automatic	Darts	65%
N-Strike Elite Stryfe Blaster	Semi-Automatic	Darts	77%
Vortex Nitron	Semi-Automatic	Disks	95%

Conclusion

The Floating-Point ASV System has shown through simulation, lab testing and on-water test runs that it is capable of attempting and successfully completing all of the tasks in this year's RoboBoat competition. In comparison to Embry-Riddle's successful 2012 RoboBoat system, the new Floating-Point ASV System should prove to be more innovative, reliable, and capable than any RoboBoat system developed to date.

References

2013 RoboBoat Competition Final Rules:
https://s3.amazonaws.com/com.felixpageau.roboboat/RoboBoat_2013_final_rules.pdf

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