Floating-Point II 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 7th 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, modular hardware software design, robust and reliable buoy navigation, a robust composite hull, and an expandable sensor suite.

Introduction

The Robotics Association at Embry-Riddle Aeronautical University presents the Floating-Point Autonomous Surface Vehicle (ASV) system as a competitive solution to the 2014 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, hydrophones and scanning laser rangefinder.

Hull Design

The Floating-Point II ASV (Figure 1) system is designed to improve upon previous platforms in both stability and overall performance. 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 relative to the water for hydrodynamics and optimal sensing.

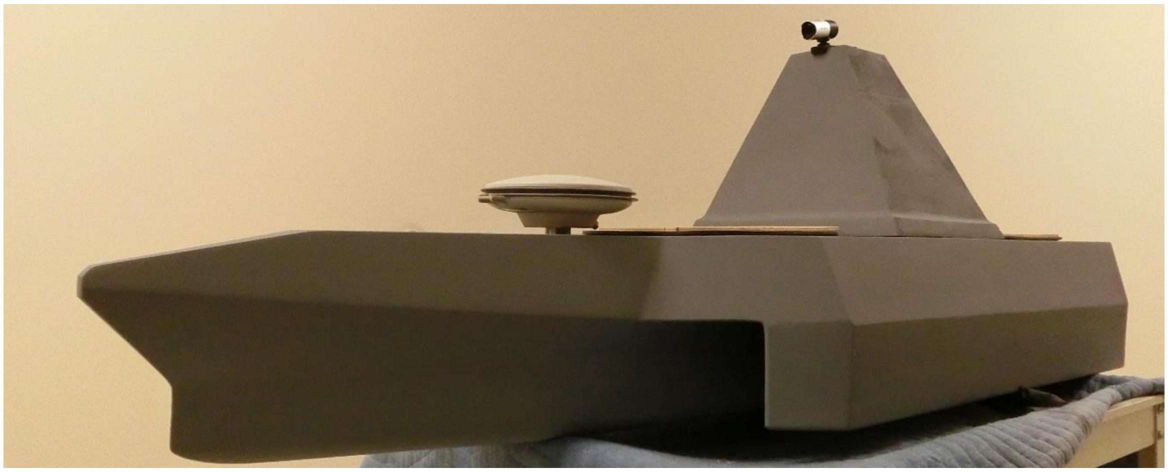

Figure 1. ERAU FLoating-Point ASV

Propulsion is provided by a pair of Graupner impellors. The water jets are located in a separate water tight compartment at the aft end of the platform allowing for easy installation and maintenance, all while isolating the motors from the rest of the onboard electronics. These thrusters are gimbaled allowing for the redirecting of thrust 10 degrees off of the platforms centerline. In addition to the lateral gimbaling the thrusters also have a thrust reversing system. When these two systems are used together they afford the Floating-Point II ASV a high degree of speed and maneuverability. The Floating-Point II ASV can outperform the Embry-Riddle vehicle entered into the competition last year. The new vehicle weighs only 42 lbs, making it easy to transport.

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 successfully complete the navigation challenge, 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.

Sensors on the left hand side of the figure send data to the onboard ODroid XU 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 and the gimbal and thrust reverser controls. The system also contains a Wi-Fi data link used for testing and debugging in addition to data transmission.

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 safely located at the rear of the platform.

The sensor suite used on the Floating-Point II system encompasses multiple sensor modalities, including LIDAR measurement, cameras and hydrophones. Localization will be provided using a NovaTel Propak to combine high precision Inertial Measurement Unit (IMU) and GPS data.

External sensing and perception of obstacles is achieved using an array of sensors that view the world in multiple spectra. Due to the low reflectivity of water in the IR range a Velodyne HDL-32E LIDAR was chosen as a primary sensing modality (Figure 2). The LIDAR also allows for accurate determination of range for docking and trajectory planning, this is further enhanced by placing the sensor above the platform in such a way that its field-of-view is maximized.

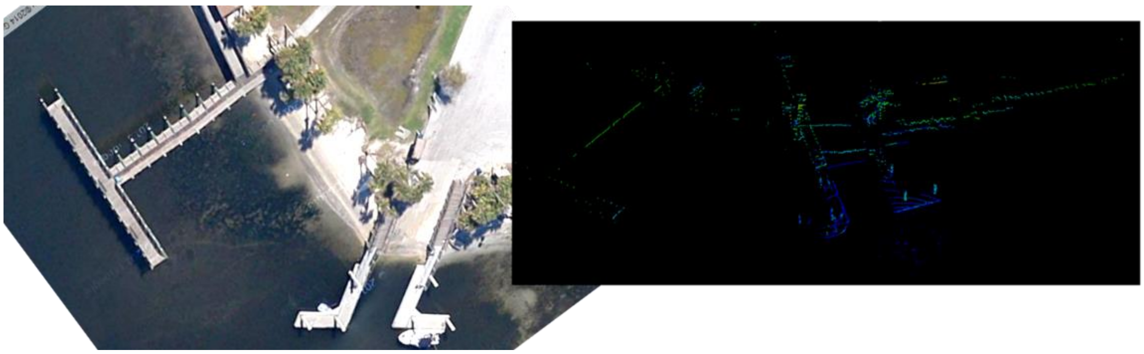

Figure 2. Velodyne Data Showing Low IR Reflectivity from Water Areas.

A set of cameras are used to identify objects by size, shape, type, and color. The camera and LIDAR data are then segmented into discrete objects whose positions will be tracked and updated in the global coordinate frame using Bayesian particle filters. For detection and ranging of submerged sonar pings, an array of four Sparton NavEx hydrophones will be placed below the vessel. Ranging to the underwater source will be achieved using a combination of time-of-flight calculations and beam forming.

On-board systems integration, control, and health monitoring are implemented using an Ethernet-based communication backbone. A Ubiquiti Rocket multi-antenna radio with diversity is integrated into the Ethernet backbone to bridge external communications. This system has gone through frequent testing by the ERAU team, transmitting high bandwidth data from over a mile away and in radio frequency hostile environments. Although not useable for direct control by the team in competition, this data link will enable the team to perform real-time diagnostics and monitoring while testing from either a chase boat or a nearby shore location, and provide the RoboBoat judges with full access and control to the platform.

An independent direct command and control link is also maintained with the vehicle at all times using a frequency hopping, spread spectrum, commercially available RC system. This system has the ability to implement emergency stop functionality as well as switch from manual control, to either a paused state or autonomous control. Functionality has been tested at ranges up to 0.5 miles, which is well in excess of those posed by the RoboBoat venue. In the event of loss of RC signal, hardware circuits will disable power to the motors and stop the vehicle.

Energy storage is provided by four Lithium Polymer batteries, providing 20 Amp hours. Onboard power systems make regulated 24V, 12V and 5V power sources available. The platform also has the ability to utilize 24V nominal power, allowing for a high and medium thrust configuration depending on the operating environment. Added robustness and safety have been instilled in the platform with a comprehensive safety system including fusing of all electrical lines and reverse polarity protection.

Software Architecture

The software architecture uses an event driven, self-monitoring, cross-platform structure designed to allow for implementation of features that include multi-sensor state estimation, variable autonomy modes, external sensor incorporation, intelligent trajectory planning, reconfigurable control algorithms, external communication, and hardware redundancy overrides (Figure 3). Once these modules have passed a base level of performance they are integrated into the main platform and field tested. The onboard computing solution for the Floating-Point II ASV is an off the shelf Dell Laptop and an ODroid XU. To further enhance reliability all software onboard Floating-Point II is compiled as an executable and run on the Windows and Linux cores. This allows for the restart of individual modules or entire nodes of software while without impacting the performance of separate standalone modules.

However, the primary benefit of the adopted software architecture is that it will allow incremental increases in system complexity without major revisions of the software, "complexity through iteration." Thus, the team can start testing with available hardware (as demonstrated where preliminary propulsion and localization systems) before integrating the competition grade hardware allowing the ERAU team to remain test-ready throughout the project life cycle; even as hardware is upgraded or new sensors integrated.

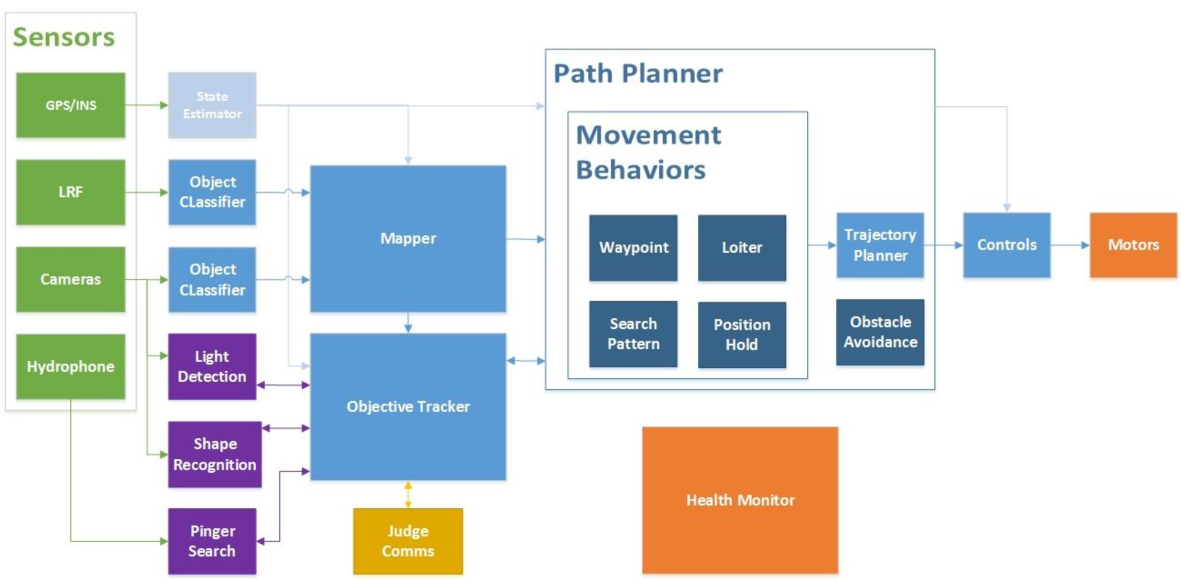

Figure 3. ERAU WAM-V Software Architecture

The software platform executes actions in parallel and asynchronously. Sensors asynchronously feed a group of object classification blocks. These blocks use various discrimination and classification methods to identify objects and give the range and bearing of each classified obstacle to the Mapper Block along with their confidence in both identification and location. The

State Estimator feeds localization and environmental data into the Objective Tracker, Mapper, and Path Planning blocks. The Objective Tracker feeds high level objectives into the Path Planner. Taking the high level objective, as well as obstacle information from the Mapper, the Path Planner designs a trajectory for the vehicle to follow. Finally this trajectory is fed into the Controls Block which ensures the trajectory is followed.

The Onboard Health Monitoring System (OHMS) incorporates multiple lessons learned from previous AUVSI competitions to track the operating state of onboard components and increase the reliability of the autonomous system. Current and voltage sensors track the operational state of the hardware while the software platform provides for heartbeat detection, state tracking, and restart of the software modules.

Guidance, Navigation and Control

Embry-Riddle's approach to autonomy for the Floating-Point II ASV is based on a set of motion behaviors. These motion behaviors are located inside of the Path Planner block as seen in Figure 3. The overall concept offers a high degree of robustness and repeatability in a marine environment. Each sensor processes its data and sends it to the Mapper and Objective Tracker. The Path Planner receives objectives from the Objective Tracker and a list of known obstacles from the Mapper. This data is used to select which of the four motion behaviors (waypoint navigation, loiter, search pattern or position hold) are most appropriate for the situation, these behaviors in turn are subsumed by one another, and the resultant emergent behavior allows Floating-Point to avoid obstacles and perform the various tasks required.

Trajectory planning is performed using a Dubin's Path algorithm. Dubin's Path assumes a vehicle moving at unit velocity with a fixed minimum turn radius. Using this information as well as a start pose and end pose the algorithm is able to calculate the minimum length path between the two poses. Each behavior modifies the parameters used by the algorithm (minimum radii, starting and end conditions) in order to generate an ideal path that can achieve the "goal". Then this ideal path is modified by the obstacle avoidance algorithm producing a trajectory as close to ideal as possible while avoiding obstacles and returning an achievable path.

Results

Waypoint

Figure 4 shows a path generated at three different operating speeds: 2 m/s (black), 1.5 m/s (red) and 1 m/s (blue), using Floating-Points onboard Dubin's Car algorithm. As the boat slows, it is able to achieve a much tighter turning radius. In the example situation shown, this results in a significantly shorter path at lower operating speeds.

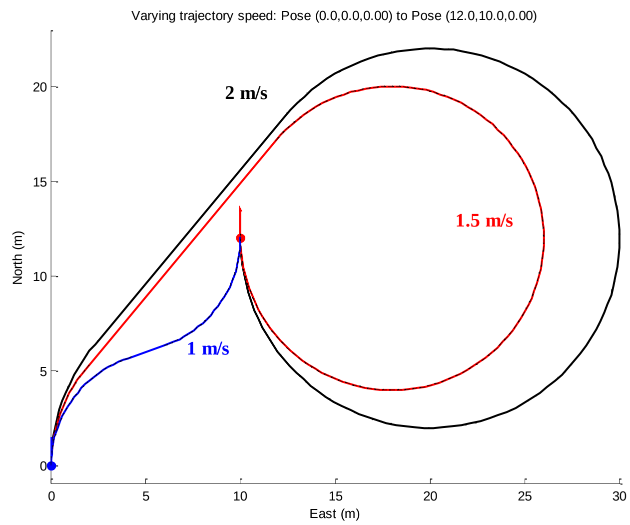

Figure 4. Trajectories at Varying Operating Speeds

The path lengths and travel times for the paths in Figure 4 are given in Table 1.

Table 1. Travel Times at Varying Operating Speeds

Turning radius (m)	Operating speed (m/s)	Path Length (m)	Travel Time (s)
10	2	78.45	39
8	1.5	65.88	44
6	1	16.88	17

As can be seen from Table 1, the method of varying operating speed can produce dramatically different results. In the case of Figure 4 operating at half the speed (1 m/s) resulted in a 53% travel time reduction. Figure 5 shows a path generated using the obstacle avoidance algorithm for a four obstacle case. This figure indicates the algorithm is able to successfully modify the path to avoid the obstacles while maintaining the desired path where it does not intersect obstacles. This approach is not shown to be optimal, but is effective at generating efficient paths in low density obstacle fields while consuming minimal computing resources.

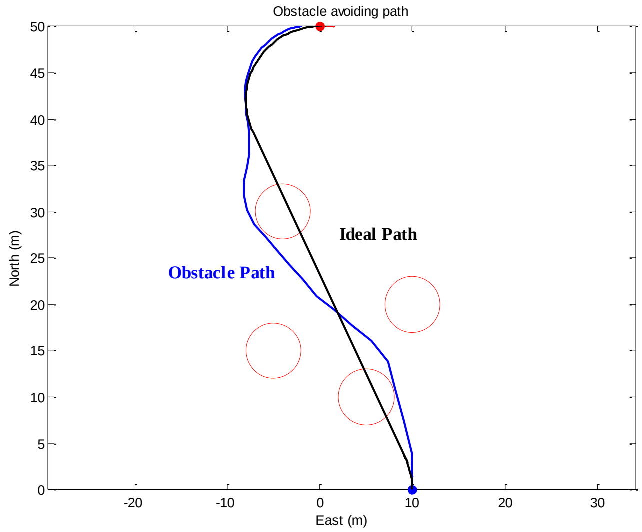

Figure 5. Obstacle Avoidance Path

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.

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.

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 isolates 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.

Obstacle identification is performed individually on a sensor by sensor basis. The onboard HDL32E Velodyne Lidar module detects and classifies objects based on distance, height, number of returns, intensity, and number of rings using multivariate Gaussian distributions and builds a relative confidence using Bayes' theorem. The cameras classify objects based on color, size, and shape. Object classifier nodes feed into a mapping node which uses time of detection and GPS, along with the characteristics determined by the object classifiers to build up object location, type, threat level, and confidence of existence. These objects are then mapped into a global reference frame and tracked over time

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

The RoboBoat competition has been broken into multiple challenges which are designed to increase in complexity and evaluate specific areas of the autonomous platform's capability. These challenges range from channel navigation, to the acquisition and localization of a submerged acoustic beacon, and the interaction of Floating-Point with the challenge judges.

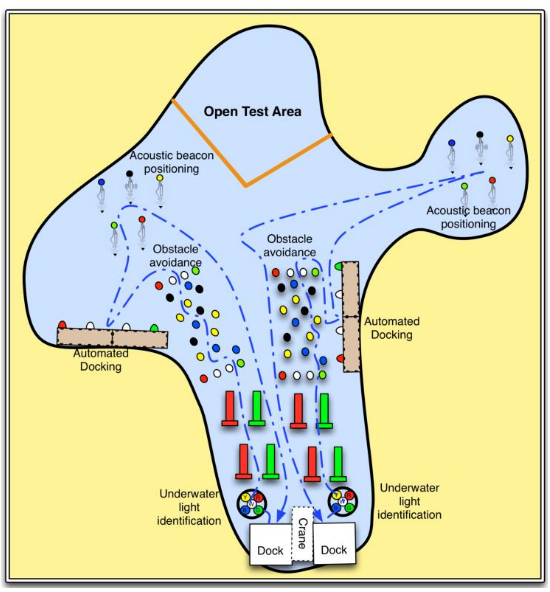

Figure 6. RoboBoat Field General Arrangemet

The first task is to get Floating-Point to navigate autonomously to a pair of buoy ("gates") that are separated by an unknown distance. Then Floating-Point must navigate a linear course between the starting and ending pair of gates. This task requires the team to highlight the degree of navigation, control and repeatability inherent in their platform.

In the underwater search task, the platform must successfully identify and locate a specific underwater device that is emitting an acoustic signal. Once located, the platform must relay the GPS position and depth of the underwater device to competition judges.

The craft docking and target identification task requires the Floating-Point to successfully identify one of three marked docking bays using the provided signage prior to the competition run for that day. Once the docking bay has been located the vessel must maneuver to enter the correct dock, come to a stop, and then leave the dock before moving on to the next task.

In the observation and report task, the platform will conduct observation of an underwater buoy and determine the pattern of colored flashes it is emitting. The platform must then report the sequence of colored flashes before being permitted to move on to the next task.

In the detection and avoidance of obstacles task, Floating-Point must autonomously navigate to the pre-designated entry gate (1, 2, or 3), travel autonomously through a field of floating, stationary obstacle buoys varying in size and color. Completion of this task requires successful traversal of the obstacle field and exit through the designated exit gate (X, Y, or Z) without contacting any of the buoys.

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 using a fusion of cameras and LIDAR data. This algorithm was designed with the goal in mind of being able to run the code in any weather condition without alteration.

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, however the direct measurement from the LIDAR reliably picked up buoys regardless of lighting conditions.

The sensor 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.

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. 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.

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

2014 RoboBoat Competition Final Rules:

http://higherlogicdownload.s3.amazonaws.com/AUVSI/fb9a8da0-2ac8-42d1-a11e-d58c1e158347/UploadedImages/2014%20RoboBoat/RoboBoat_2014_final_rules.pdf

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