Double Precision Autonomous Surface Vessel

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***Abstract* - Embry-Riddle Aeronautical University (ERAU) is entering the Double Precision Autonomous Surface Vessel (ASV) into the 2018 AUVSI Foundation Roboboat Competition. Due to a lack of available personnel in the months leading up to competition, the team is comprised of members of both the Robotics Association at Embry-Riddle (RAER), and the Daytona Beach Homeschoolers (DBH), leveraging the strengths and capabilities of both groups. The competition strategy discussed within this paper informed the design process of the vehicle in a significant way, imposing several specific requirements on the vehicle design and construction. This includes the presence of various sensors, and planning far in advance where their mounting locations will be. The resulting vessel represents a year of hardware design and construction by RAER, and is running software developed and implemented by DBH. Combining these two teams results in a strongly bonded group that intends to leverage its experience and home-field advantage to stand out among the competition.**

Figure 1: The Double Precision ASV during a test in the ERAU Henderson Welcome Center pond.

I. COMPETITION STRATEGY

Experience with previous years' Roboboat competitions has influenced the team's chosen competition strategy greatly, as has the merging of our teams. Robust software, paired with advanced sensing and processing, and the ability to successfully and reliably complete certain tasks, tends to lead to success in competition. This informed the design and strategy for the team going forward.

The competition is heavily reliant on autonomous navigation. Therefore, the priority for development of an autonomous vehicle is to ensure that the vessel can travel to a predetermined position reliably. It was determined that the easiest implementation of this would be to use a simple waypoint following behavior as provided in the Pixhawk autopilot that is being used for our control interface. The Pixhawk could then be fed commands via a serial interface to the onboard sensor processing computer. Results of implementation of this waypoint following behaviour will be discussed in Section IV, Experimental Results.

Once the ability to autonomously navigate in open water was determined to be sufficiently reliable, efforts were made to implement obstacle avoidance behavior. This relies on the various sensors described in Section III, Design Creativity, and detailed in Appendix A. The sensors are processed using an onboard computer running LabVIEW modules in a Windows 7 environment, creating a virtual representation of the real world that other software modules can respond and react to.

Historically, interoperability challenges have been worth high point values in the competition. Because of this, the team has made a concerted effort towards developing the components required for completion of the Automated Docking Task. Focusing on this task has informed not only the physical architecture of the system, but the network and electronics architecture as well.

II. Design Creativity

During the Fall and Spring semesters, the ERAU Roboboat team fell under new leadership, which was anxious to develop an entirely new watercraft for the first time since 2014. This approach had been floated at least twice since 2015, but it was implemented this year in order to keep enthusiasm high among some of the hardware-oriented team members.

The team approached the design process with several lessons learned from 2017 in mind. Keeping the vehicle sitting level in the water was challenging, and required ballast adjustments due to added components moving the center of gravity slowly upward each year. Additionally, while the vessel had sufficient thrust to complete the course with time to spare for the possibility of repeating a run, there was a distinct lack of control authority for turning. This made the tasks that required tight maneuvering, such as the Find the Path task, difficult. These two problems had wildly different solutions, but were both designed around to ensure ERAU could remain competitive in the upcoming competition.

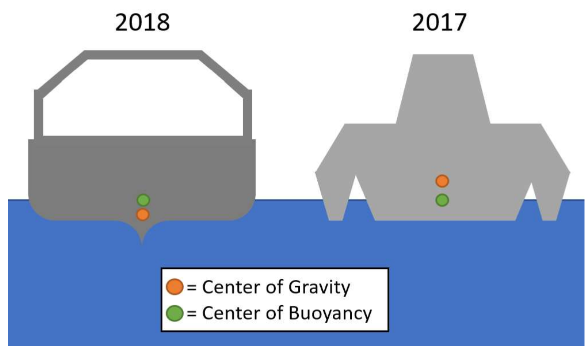

Figure 2: Depiction comparing center of gravity and center of buoyancy between previous and current vessel designs.

The balance of the vessel was addressed by designing a hull with a wide base, which allowed the vessel to reject roll disturbances. Preventing the vessel from rolling also prevents the the center of buoyancy from moving, which is also important for stability if it could be coupled with a low center of gravity. Extra ballast sitting below the waterline was used to keep the center of gravity low, even when a superstructure was attached to allow for elevated positions for GPS and LiDAR sensors. The hull design was developed further by keeping more lessons from the previous vessel in mind. Examples of this include ensuring easy access to the equipment bays inside the hull, temperature regulation within the equipment bays, and electrical interference with the GPS antenna from proximity to the rest of the equipment.

Figure 3: The two radiators that transfer internal heat to the water below the vessel, and the steel rods used as ballast in the bottom of the hull.

The issue of control authority was solved with a more technical answer than that of the hull design. The ERAU Roboboat team took a lesson from the advanced control systems on other skid-steered aquatic vessels. In particular, it was noted that they often featured azimuth controls for their thrusters, providing more maneuverability and allowing tighter turns. This, combined with the ability to vary thrust forward and back on either side of the vessel, allows for extreme maneuverability that the ERAU Roboboat team has not been able to experience with previous vessel designs.

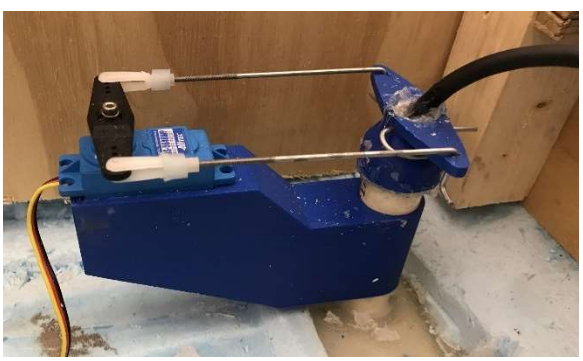

Figure 4: The azimuth assembly, which protrudes through the bottom of the hull to the Blue Robotics T200 thrusters.

The team has included in the vehicle design an arched superstructure that raises some of the platform to improve their functionality. Examples of how an elevated location benefits Double Precision includes isolating a GPS antenna from the electromagnetic interference (EMI) generated by our radio antennae and computer and electronic systems, and raising the camera and LiDAR to provide a better field-of-view (FOV).

The above-surface sensors are complemented by a set of hydrophones below water, which are used to detect and triangulate the acoustic pinger present in the Automated Docking task.

The rear of the vessel is a large, flat platform that provides a wide-open area for an unmanned aerial vehicle to be launched and recovered from. This will increase the likelihood of a successful launch and recovery, which will improve the chances of the team to perform well during the competition.

III. Experimental Results

Testing an autonomous vehicle in any domain, aquatic or otherwise, requires a sequence of separate tests leading up to autonomy. This slow lead-up to autonomous operation is used in order to ensure safe operation once full autonomy has been achieved.

The first test of the Double Precision vessel was a float testing of the hull, which was utilized for the purpose of proving seaworthiness, including factors such as displacement, the sealing of any item protruding through hull, and general stability of the watercraft. This float test is performed prior to any electronics being installed into the vessel, to ensure that the components are not being risked in the process. This initial test took place early in the Spring 2018 semester, after the vessel had completed early fabrication. Iterative changes were made to the platform throughout its testing cycle, including installation of bearings for the azimuth assembly and heatsinks to keep air temperatures inside the equipment bays low. Following each of these modifications, a new in-water test with all electronics removed from the vessel was performed. If the sealing or adhesion of a component was found to be lacking, it was repaired and the test repeated until the vessel was fully seaworthy.

Following the series of seaworthiness tests, the portion of the electronics package required for RC capability was installed in order to test certain aspects of the vessel including its control authority and safety systems. The vessel performed admirably in all portions of this test, as the Double Precision ASV made extensive use of the previous years' experience in creating robust electrical and safety subsystems. Under remote control, the vehicle maneuvered as expected, with superior control authority when utilizing the azimuth control on the thrusters.

Figure 5: The Double Precision ASV being lowered into the water for a test of remote control operation.

The next step in ensuring that Embry-Riddle would be fielding a competitive autonomous vessel was determining how it performed in an autonomous control mode. The first and most simple aspect of this was maneuvering to waypoints. Utilizing the Pixhawk autopilot and its included antenna installed in the vessel, the team was able to navigate to GPS waypoints within two meters. This ensured the vehicle would be minimally competitive, and enabled the software development team to focus their efforts on achieving higher levels of autonomy, which would serve to make the team more competitive. The somewhat high error for a vehicle this scale would end up being corrected with the use of a more powerful GPS antenna.

Due to certain delays in manufacturing, it proved impossible to test higher levels of autonomy in a water environment before completion of this report. However, this loss of testing was mitigated utilizing the growing experience with vehicle simulation that exists within the Robotics Association at Embry-Riddle. The team was able to create a simulated environment in which a virtual boat maneuvered, allowing the full software stack to be implemented, including a mission tracker, path planner, and obstacle avoidance algorithms. At the time of submission, this software stack is being ported from simulation to the vessel's autonomy computer. Preliminary results point to the simulation being a sufficiently accurate analog for the physical vessel, resulting in ample development time for the software stack.

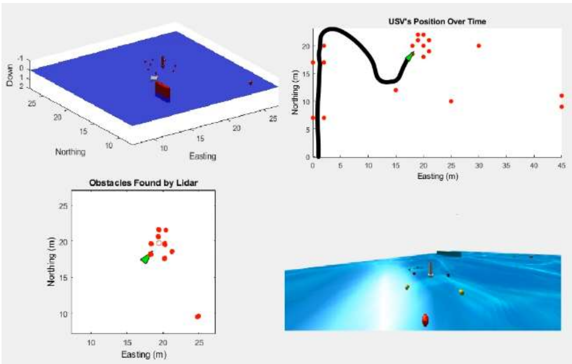

Figure 6: Screenshot of the Roboboat simulation environment.

ACKNOWLEDGEMENTS

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Appendix A: Acoustics Derivations

Hydrophones at 4 locations:

$$h_0 = (0,0,0)$$

$$h_1 = (\alpha, \beta, \gamma)$$

$$h_2 = (\delta, \varepsilon, \zeta)$$

$$h_3 = (\eta, \theta, \iota)$$

Assuming the source is much farther that the hydrophone spacing, the overall distance to the hydrophones from the source at (x,y,z) is:

$$D = \sqrt{x^2 + y^2 + z^2}$$

Looking at the phase difference of arrival, we can compute the distance offset the signal hit the hydrophones 1, 2 and 3 from the reference, 0.

$$\Delta d_1 = \frac{(\Phi_0 - \Phi_1)}{2\pi}\lambda$$

$$\Delta d_2 = \frac{(\Phi_0 - \Phi_2)}{2\pi}\lambda$$

$$\Delta d_3 = \frac{(\Phi_0 - \Phi_3)}{2\pi}\lambda$$

These deltas can also be represented as the difference of the vector from the reference distance D and the actual distance to hydrophones 1, 2 and 3.

$$\Delta d_1 = D - d_1 = \sqrt{x^2 + y^2 + z^2} - \sqrt{(x-\alpha)^2 + (y-\beta)^2 + (z-\gamma)^2}$$

$$\Delta d_2 = D - d_2 = \sqrt{x^2 + y^2 + z^2} - \sqrt{(x-\delta)^2 + (y-\varepsilon)^2 + (z-\zeta)^2}$$

$$\Delta d_3 = D - d_3 = \sqrt{x^2 + y^2 + z^2} - \sqrt{(x-\eta)^2 + (y-\theta)^2 + (z-\iota)^2}$$

Squaring D and d_n:

$$D^2 - {d_1}^2 = x^2 + y^2 + z^2 - (x-\alpha)^2 + (y-\beta)^2 + (z-\gamma)^2$$

$$D^2 - {d_1}^2 = x^2 + y^2 + z^2 - [x^2 - 2x\alpha + \alpha^2 + y^2 - 2y\beta + \beta^2 + z^2 - 2z\gamma + \gamma^2]$$

$$D^2 - {d_1}^2 = 2x\alpha - \alpha^2 + 2y\beta - \beta^2 + 2z\gamma - \gamma^2$$

$$(D - d_1)(D + d_1) = 2x\alpha - \alpha^2 + 2y\beta - \beta^2 + 2z\gamma - \gamma^2$$

$$D - d_1 = \frac{2x\alpha - \alpha^2 + 2y\beta - \beta^2 + 2z\gamma - \gamma^2}{D + d_1}$$

Substituting in $\Delta d_1 = D - d_1$:

$$\Delta d_1 = \frac{2x\alpha - \alpha^2 + 2y\beta - \beta^2 + 2z\gamma - \gamma^2}{D + d_1}$$

Converting the denominator:

$$\Delta d_1 = \frac{2x\alpha - \alpha^2 + 2y\beta - \beta^2 + 2z\gamma - \gamma^2}{2D - \Delta d_1}$$

Rearranging:

$$2D\Delta d_1 - \Delta {d_1}^2 = 2x\alpha - \alpha^2 + 2y\beta - \beta^2 + 2z\gamma - \gamma^2$$

$$2\sqrt{x^2 + y^2 + z^2}\Delta d_1 - \Delta {d_1}^2 = 2x\alpha - \alpha^2 + 2y\beta - \beta^2 + 2z\gamma - \gamma^2$$

$$\alpha^2 + \beta^2 + \gamma^2 - \Delta {d_1}^2 = 2x\alpha + 2y\beta + 2z\gamma - 2\sqrt{x^2 + y^2 + z^2}\Delta d_1$$

Solving for the other two hydrophones:

$$\delta^2 + \varepsilon^2 + \zeta^2 - \Delta {d_2}^2 = 2x\delta + 2y\varepsilon + 2z\,\zeta - 2\sqrt{x^2 + y^2 + z^2}\Delta d_2$$

$$\eta^2 + \theta^2 + \iota^2 - \Delta {d_3}^2 = 2x\eta + 2y\theta + 2z\,\iota - 2\sqrt{x^2 + y^2 + z^2}\Delta d_3$$

At this point, we have 3 equations and 3 unknowns, (x,y,z). A numerical approximation technique can be used to solve for these three.

APPENDIX B: COMPONENT SPECIFICATIONS

Component	Vendor	Model/Type	Specs	Cost
Propulsion	BlueRobotics	T200 Thruster	7.8 lbf Max forward thrust @ 12V; 6.6 lbf Max reverse thrust @ 12V	$169.00
Power system	Thunder Power	TP4400-3SE55; TP4400-6SE55	TP4400-3SE55: 3S LiPo battery; provides power to the thrusters. 2 Used in parallel to increase runtime. TP4400-6SE55: 6S LiPo battery; provides power to the computer and miscellaneous components on the boat through converters.	TP4400-3SE55: $69.99 TP4400-6SE55: $141.99
CPU	Intel computer; Pixhawk Autopilot	i7-4550U 16GB RAM 256GB SSD Mini-ITX motherboard	Intel computer Quad-core desktop I5 cpu. Micro ATX motherboard with 8 GB RAM. Pixhawk Autopilot On-board IMU, 14 PWM/Servo outputs, UART/I2C/CAN/etc connectivity, on-board computing.	Intel computer: $~800 Pixhawk Autopilot: $249.90
Teleoperation	Fly Sky	FS-T6	6-channel, 2.4GHz	$59.99
LiDAR	Velodyne LiDAR	PUCK VLP-16	3D lidar, 360° horizontal FOV, ±15° vertical FOV, 100m range	$4000.00
Global Positioning System (GPS)	Hemisphere	Vector VS330 GNSS Compass	20Hz update rate, 2cm accuracy maximum, 30cm accuracy typical	N/A
Camera	Microsoft	LifeCam Studio	720p video stream, USB connectivity; encased in a custom enclosure to protect from maritime conditions.	$99.95
Hydrophones	Teledyne Marine	Reson TC 4013 - Hydrophone	4 utilized in an array; Omnidirectional horizontal directivity pattern ±2dB @ 100kHz, 270° vertical directivity pattern ±3dB @ 100kHz, usable range of 1Hz to 170kHz	$1200.00 each
Hydrophone DAQ	National Instruments	NI-9222	4-channel, simultaneous input, 500kS/sec/ch, 16-bit resolution	$1500.00

Aerial Vehicle Platform	DJI	Flamewheel f450	Takeoff weight: 800-1600g Motor Size: 2212 ESC: 15A Battery: 3S LiPo	$240
CPU	Odroid	XU4	2GHz CPU 2GB RAM	$60
Camera	Logitech	C910	1080p Video Recording	$50
Acoustics	N/A	N/A	See Appendix A	N/A
Autonomy	N/A	ROS	ROS used as the framework for the sensor data acquisition and processing. ROS also used for determining GPS waypoints to targets based on	N/A
Team Size			8-10	
Expertise ratio			-Med-high skill level -Primarily upperclassmen or underclassmen with lots of experience -Roughly even split between hardware and software expertise	
Programming Language	N/A		Python, LabVIEW	

APPENDIX C: OUTREACH ACTIVITIES

This year, Team Double Precision, working through RAER, was involved in a number of large scale outreach activities both on and off campus. At Embry-Riddle, the team hosted several outreach events. In the summer of 2017, only a few weeks after the previous RoboBoat competition, ERAU and RAER hosted a robotics summer camp for high school students. Here, 24 students spent a week learning how to build and then program their robots to perform a variety of autonomous tasks ranging from dead reckoning through courses to using computer vision to line follow and acquire specifically colored balls.

At the end of the Fall 2017semester, the team hosted nearly 50 fourth to eighth grade students from Old Kings Elementary School and Milwee Middle School as they learned skills that could be used in their own seaperch platforms. At this event, the students learned about buoyancy and soldering through activities that taught them how to apply these skills.

Another local outreach opportunity that some members of the team took advantage of was mentoring for a local FIRST Robotics Competition (FRC) team, team 2152 SMASH. This team consists of more than 50 students from Spruce Creek High School and University High School. As mentors, the two students were responsible for mentoring the of the mechanical and electrical subsystems. They also taught the students about the engineering and design processes.

The team's outreach efforts also took them out as far as St. Petersburg, FL for one of our largest events of the year. At John Hopkins Middle School, the team ran a two-day long event that the middle school teachers called "STEM Day". During these two days, the team interacted with over 175 sixth and seventh graders as they guided the students through various interactive learning activities such as boat building, resource collection, 3-D printing, and glider building. These activities taught the students valuable lessons in buoyancy, remote operations, additive manufacturing, and aerodynamics.

Through these several varied outreach activities, the team feels that it has meaningfully impacted students of all ages, engaging and encouraging them to participate and pursue education in STEM fields

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