The Phoenix by UM::Autonomy
RoboBoat 2023: Technical Design Report

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1. Abstract

To compete in the 2023 RoboBoat competition, The UM::Autonomy team created *The Phoenix*, an improvement of the Sea Serpent from the previous year. This year, the team focused on reliability and maintainability during design for all subteams. In order to complete the Navigation, Docking, and Projectile tasks, the team improved development methods to decouple development between software and hardware. A pipelined approach for autonomous navigation makes development more agile and reliable. A trimaran design is used for the hull in favor of stability and larger deck space, and more capable thrusters were used for greater control. The electrical box was overhauled to implement greater safety features in modularized, simple components. Separating testing methods ensures that software and hardware teams can work in parallel, while weekend in-water testing puts the entire system in the competition environment.

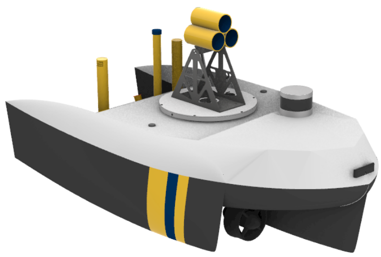

Figure 1. *The Phoenix* Render

2. Technical Content

The team's approach for RoboBoat 2023 was to divide up the tasks that the team would attempt into three majors groups being Navigation (tasks 1, 2, 4, and 8), Docking (task 3), and Projectile (tasks 6 and 7). To achieve this the team designed an autonomous trimaran automated with sensing inputs from camera, LiDAR, GPS, and IMU. This year the team decided not to attempt the ocean cleanup task and to focus on achieving the other tasks to high accuracy to maximize points.

The team prioritized reliability and maintainability during the design phase. In particular, the team's primary objectives for hardware designs were safety, stability, maintainability, and transportability. Through a combination of simulator, in water, and bench testing, the team was able to comprehensively validate the team's designs.

2.1 Competition Strategy

2.1.1 Navigation Tasks

For the autonomous navigation necessary for the Panama Canal, Manatees & Jellyfish, Northern Passage, and Coral Reef challenges, the team chose the systems logic in figure 2.

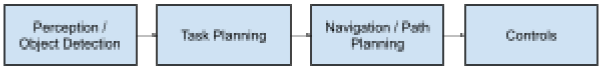

Figure 2. AI Team Systems Architecture

This modular approach allows for parallel development while abstracting away parts of the challenges that don't apply to the whole AI pipeline. This provides added redundancy for changes in competition challenges, and lets the team test each system individually as a module, which increases overall reliability.

When approaching a given navigation challenge, the Perception team identifies objects using a camera and a computer vision (CV) deep learning model that identifies buoy shape and color. This detection method was chosen due to its high accuracy, and ability to be trained on new objects, allowing it to be maintained for future years. To detect object distances the team chose to use a Velodyne LiDAR which has an accuracy of around 2 cm for accurate mapping.

After receiving information on buoy type and location from Perception, Task Planning determines where the vessel should move by sending a waypoint to the Navigation team. Waypoints are generated in the middle of the two closest red and green buoys. The team decided to organize sets of two buoys into gates to generalize to all navigation tasks, since each task only differs in the formation of gates.

The decision making algorithm that Task Planning uses varies depending on the current task in order to reduce complexity. Separating the decision making algorithms allowed for team members to decouple problems from one another and parallelize development, which increased overall productivity.

For the Panama canal task, the vessel has to move through two gates that were formed by cylinder buoys. In this task, Task Planning sends a waypoint to tell the vessel to move until the Perception team detects an object, at which point the waypoint is set in between the gate. Once it goes through the first gate, the process is repeated for the second.

For the Northern Passage task, Task Planning first uses a method similar to the one used in the Panama Canal task to set a waypoint between the green and blue buoys. The algorithm then sends the vessel forward until it detects the blue buoyant and then moves around it. The vessel is then sent back to the entrance of the competition.

For the Magellan's Route task, Task Planning identifies which buoys are obstacles and which ones form a gate. After the first red and green buoys are found, Task Planning creates a waypoint 40 meters ahead of the current position. Once a buoy is detected, a new waypoint near the detected object is sent. Once the vessel has reached the waypoint, Task Planning checks the number of detected buoys ahead and their distance from the vessel. If there are 2 buoys that are equidistant from the vessel, then the buoys are classified as a gate and the team sends a waypoint to pass through it. Otherwise, the buoy is classified as an obstacle so the vessel goes around it and checks if it is yellow or black. This process is repeated every time the vessel passes through a gate.

Every waypoint that Task Planning generates is sent to Navigation. Once Navigation receives a new waypoint, it then uses a Hybrid A* algorithm to generate a path between the vessel's current location and the next waypoint. The Hybrid A* algorithm works by creating a smooth path within a 2D space based on vessel actions such as acceleration. This year, the team has chosen this Hybrid A* approach to more reliably compute a path that takes the vessel's dynamics into account.

The vessel then follows the path generated by Navigation, using the PID control algorithm. Controls uses the VectorNav VN-300 sensor to calculate the precise pose of the vessel. When turning the vessel, the difference in the present heading and the target path is used as the error, and the control algorithm provides thruster commands. Then, the provided path is used to determine the velocity and acceleration needed to maintain the path. Overall, this corrects the vessel and compensates for wind and waves during movement, maintaining the desired position, velocity, and acceleration along the provided path. The team chose to use PID due to its simplicity and thus maintainability, compared to a previous LQR algorithm which had a steeper learning curve. Furthermore, the code is updated to stop moving in the absence of commands for safety.

As the vessel moves, the Perception team continually detects objects. Task Planning creates and reevaluates previous waypoints as new objects are detected, and Navigation and Controls are run against every new waypoint.
This allows us to make development more efficient, and achieve autonomous navigation with high accuracy and reliability.

2.1.2 Docking Task

For Beaching & Inspecting Turtle Nests, the team is required to identify the color and number of dots on each dock. This was done by applying color filters for each of the possible dot colors, and using blob detection to bound each of the colored dots. The positions of the individual dots are aggregated to show the center of each nest, and from this the team is able to determine the relative position of the three docking locations. Combined with the distance from the LiDAR, Task Planning sets a waypoint at the correct dock. The Navigation and Controls systems then operate to move the vessel to the desired location.

2.1.3 Projectile Tasks

The Feed the Fish and the Fountain of Youth challenges follow the steps of detection, trajectory calculation, and actuation. For the Feed the Fish challenge, the purple hoop is detected using a color filter for the purple color calibrated for multiple lighting conditions and ranges, and then bound to give the position and size of the target. For the Fountain of Youth challenge, a series of grayscale templates are applied to the image, and the best fitting template is used to determine where the target is inside the camera frame (Figure 3).

Figure 3. Fountain of Youth CV Detection

In both cases, the desired trajectory of the projectile (skeeball or water jet) is calculated using a known initial velocity, and the poses of the vessel and target. Then, calculated headings and attitudes are used to actuate the aiming platform, and projectiles are fired. This simplistic approach makes sure parts of the system can be tested separately to ensure reliability.

To ensure station-keeping of the vessel when launching projectiles, the estimated force is used to actuate the thrusters. Surge forces are directly negated, while an angled launch causes torque, requiring driving thrusters in opposite directions to control yaw. Sway forces cannot be directly counteracted with the configuration, so they are compensated for by the projectile's aiming.

2.1.4 Ocean Cleanup Task

This year the team chose not to attempt the Ocean Cleanup Challenge and to focus on achieving the other tasks to high accuracy.

2.2. Design Strategy

2.2.1 Mechanical Strategy

The vessel was designed to have many improvements from the Sea Serpent hull the team used last year. The primary design priorities for the hullform were to optimize stability, thrust to weight ratio, accessibility, and transportability.

2.2.1.1 Vessel Arrangements

A trimaran hullform was chosen to provide a large deck area for accessibility while providing great stability in trim and heel, as seen in Figure 4. *The Phoenix* has a length of 56”, a beam of 30”, and has an overall height of 26”.

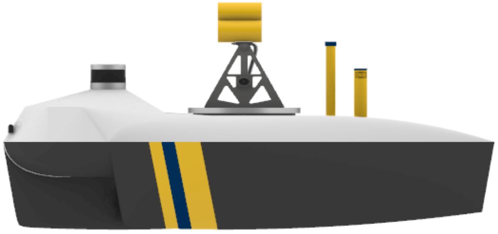

Figure 4. The Phoenix's Hull and Superstructure

The lowered monohull sub shell was designed to rest above the waterline and provide an extra counter moment to resist trim and heel. The subshell was sized proportional to the modular electrical box with considerations of accessibility and handling. The subshell is capped by the superstructure which holds sensors and seals the hull cavity. The sensors are mounted to allow for unobstructed forward vision for the LiDAR and camera. The sensor layout can be seen in Figure 5.

A detailed spreadsheet of the vessel's weights and centers can be found in Appendix C.1.

Figure 5. Sensor Layout

2.2.1.2 Propulsion

This year the team chose to use two Blue Robotics T500 thrusters - as opposed to the Sea Serpent's four T200 thrusters - to allow for greater responsiveness and efficiency (Appendix E). These thrusters were placed between the hulls (Figure 6) as opposed to below the hulls to allow for increased transportability, but it is at the cost of losing clean water flow at the inlets. Additionally, with an increased thrust to weight ratio, flipping the vessel became a concern. To avoid this, the thrusters were placed near the bow. This means the thrusters will breach the water surface and lose thrust far before flipping the vessel. The team's path planning algorithm does not consider reverse movement, so flipping with the aft leading was not considered. This self leveling system adds redundancy for the event of malfunction.

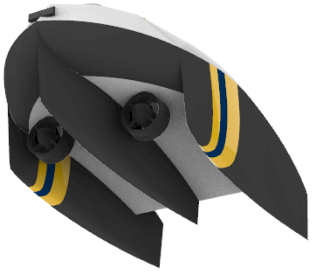

Figure 6. Thruster Location

2.2.1.3 Material Choice

The vessel's hull and superstructure were fabricated out of carbon fiber as opposed to fiberglass from last year. This allowed for hull weight reduction which has the benefits of an increased thrust to weight ratio, and ease of transportability.

2.2.1.4 Projectiles Hardware

The vessel’s skeeball launcher and water cannon were designed with the priorities of reliability, simplicity, and accuracy with the constraints of deck area and aiming compatibility with one another.

The team considered many options such as a compressed air cannon as well as AC or DC water pumps, and ultimately selected a spring-based system for the skeeball launcher and a DC water pump for the water cannon due to their reliability compared to safety and reliability concerns for the cannon. Both were mounted on a common aiming assembly to reduce complexity and meet the team’s design goals.

Maintaining a consistent and predictable water stream requires laminar flow. To achieve this a 3D printed nozzle with an internal honeycomb pattern was used. The team chose to draw in filtered lake water from a split intake which adds redundancy in the case of a filter clogging.

The solution for launching the skeeball is a spring-loaded launching mechanism, with three barrels that are preloaded on land, seen in Figure 7. The team chose this solution as opposed to alternatives such as compressed air or a robotic arm as this best met the team’s goals of simplicity and reliability.

Both systems are mounted on a common turntable with planetary gears, to control yaw aiming. Pitch control is achieved through an axle that rotates along the horizontal axis.

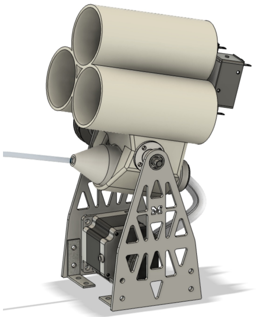

Figure 7. Skeeball launcher and Water Cannon

2.2.2 Electrical Strategy

Last year’s competition provided the team with insight about which systems proved successful and which required modification. This year the team redesigned the electrical box, prioritizing reliability, safety and maintainability. As such, the team’s priorities were to create a robust design that incorporates failsafes, improves maintainability by using easily available components, and increases modularity.

2.2.2.1 Revamped Motor Control System

Last year, the Sea Serpent used a Lynxmotion SSC-32U USB Servo Controller to translate the commands sent by the central computer into PWM signals that the thrusters could use. This hardware is now controlled by the Arduino, combined with the stack light display. This improves the safety of the system by showing the status of the overall system at all times.

2.2.2.2 Physical Emergency Stop

Last year’s emergency stop system used a microcontroller to stop the thrusters. While simplistic, this did not account for different failure modes - an unresponsive Arduino would make it impossible to stop. This year, the E-stop and the remote E-stop are input to the relay’s coil through a circuit that electronically disconnects the power when E-stopped. The output is also monitored by the Arduino, which notifies the computer accordingly. Overall, reliability was added at the cost of complexity.

2.2.2.3 Increased Modularity

Being able to resolve hardware issues quickly is critical. This year, the team reduced the amount of permanent connections and solder joints in favor of removable connections, and used standardized connectors to make replacements simpler. This helps towards the team’s goal of increased modularity. An example of this is the new power supply system, which consists of components connected to each other via standard EC5 connectors rather than being soldered like previous years. The team expanded this approach to other parts of the electrical system such as the thrusters and ESCs, which now use standard MR60 and XT90 connections.

2.3 Testing Strategy

The implementation of rigorous, multifaceted testing was one of the team's main priorities following the 2022 RoboBoat Competition, where the most crucial failures originated from a lack of experience testing the system as a whole, and a lack of routine handling procedure.

As a result, the Systems Engineering position was expanded into its own small subteam, and its scope expanded to include facilitating dry, in-water, and simulator testing throughout the season in cooperation with the other sub teams. Reliable testing times and locations for in-water testing were secured, while scheduling dry testing for each subteam with testing rigs. Lastly, in order to optimize in-water testing time, Systems Engineering worked with Task Planning to facilitate a fully-working simulator model in ROS Gazebo, so that individual AI subteams could roughly test their code before any dry or wet testing was conducted. This was imperative in saving time spent troubleshooting while in the testing environment.

2.3.2 In-Water Testing

The team approached in-water testing with heavy focus on a reliable, consistent testing facility outfitted with competition equipment. To facilitate this, the team approached the Marine Hydrodynamics Laboratory Tow Tank Basin.

Figure 8A. CV Object Detection

The team used the tank during both days during the weekends, and brought in the buoys and challenge rigs needed to simulate the competition environment.

The control system was validated in the water by subjecting the vessel to various external forces and testing its ability to correct its motion.

Figure 8B. CV Object Detection

The procedure and testing guideline used in testing in the MHL is described in detail in Appendix B.

2.3.1 Simulator Testing

To ensure proper testing of AI systems before putting the vessel in the water, the team conducted extensive simulator testing within Gazebo. The team was able to simulate the vessel's movement and test different challenges, such as Magellan's route, for all modules of the code. The simulator is essential for subteams to consistently test progress without needing to wait for in-water testing. Because of the team's agile methodology, the simulator is extremely beneficial for verifying that the decision making algorithms work as intended and are complete. Pictured below is an example of how the team uses the simulator, running Navigation and Controls code to simulate the vessel moving through buoys.

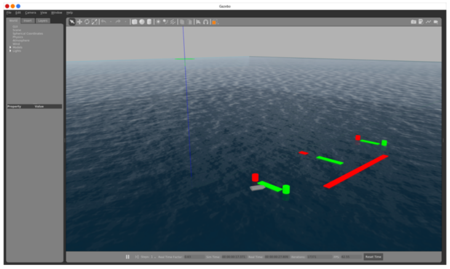

Figure 9. Testing Task Planning, Path Planning and Controls algorithm to successfully travel between buoys

The simulator also helps decouple processes, as AI subteams can test independently. Though the simulator is an idealized environment and thus lacks the randomness of in-water testing, it allows us to validate logic quickly and remotely.

2.3.1.1 Simulator Physics Data

The physical parameters of the vessel in surge and sway were calculated using the website tool *Prelimina.com* and equations F.2, both of which can be found in Appendix F. These degrees of freedom were deemed to be the most important for the motion of the vessel in the simulator.

Prelimina was used to find the resistance force from the water in surge, and takes input of the hull CAD model, speed, and draft. The software outputs approximations for the resistance at intervals of speed, and a line of best fit is used to plot this as a function, as seen in Appendix F, Figure A7.

Hand calculations were used to find the resistance in sway as a function of velocity squared, as seen in Appendix F.2. A coefficient of drag was approximated to be .9 due to the rectangular shape of the hulls in sway, and a prismatic coefficient of .1429 was found using the CAD software Rhino.

2.3.3 CV and LiDAR Deep Learning

When training a deep learning model, the lack of transparency into the model means the team needs to understand what the model is actually learning. The team prevented having the model overfitting on specific examples by using different shades, poses, and ranges for the training data. This ensures that the model learns to identify shape and design and not other environmental factors.

2.3.4 Dry Testing

Dry testing was used not only in conjunction with in-water testing, but also in lieu of it, especially during the weekdays when testing in-water wasn't an option. Systems Engineering worked with the various subteams to determine dry testing needs and fill them accordingly with test rigs and setups, and ensured that smaller features could still be tested without the need for in-water deployment.

The team was able to dry test the CV and Deep Learning algorithms by mounting the camera on the vessel and placing objects in front of the camera in the workspace. Another example was testing code for the Controls team, where the vessel is rotated on land and the correction response of the thrusters is tested.

2.3.5 GPS and IMU Testing

Because vessels can move around and drift in water freely, the vessel must rely on GPS receivers to determine location, combined with an Inertial Measurement Unit for heading. However, testing indoors hinders the GPS signal. Instead, Marvelmind indoor positioning units are used, which is accurate down to 10cm. Relying on magnetometer and gyroscope fusion provides about 5° of heading accuracy. While this is very good compared to satellite-based GPS, this method is less reliable compared to multiple outdoor GPS antennas.

3. Conclusion

The UM::Autonomy team created *The Phoenix* for this year's competition. The main goals of the team were reliability and maintainability during design for all subteams. The team had decided to focus on the Navigation, Docking, and Projectile tasks. The new structure for development this year focused on decoupling efforts between software and hardware. The hull is a trimaran due to the added benefits of stability and larger deck space, and more capable thrusters were used for greater control. The electrical box was remade completely in order to improve safety features and use simple components in replaceable modules. In the future, the team will further increase reliability and maintainability, focus on testing existing prototypes earlier during development, and build upon this year's experience to improve the vessel.

4. Acknowledgments

UMAutonomy would first like to thank corporate sponsors for their assistance with design and funding. Special thanks to Ford Motor Company, Boeing, APTIV, Northrop Grumman, Raytheon, and Siemens for their support. The team would especially like to thank Raytheon for dedicating time for multiple design reviews this season.
In addition, UMAutonomy would like to thank university sponsors for their assistance. With the constraint of not being able to test outside in the Michigan winters, the team would like to thank the MHL staff for generously allowing us to test the vessel there.

Furthermore, the subteam leads are grateful to Dr. Singer for the considerable leadership guidance and advising he has given the team. The AI subteams are also grateful to post-doc Junwoo Jang for helping to overcome a multitude of software issues. Mariah Fiumara and Katelyn Killewald have also greatly helped the team through challenges of student organization management. Their guidance and support have been instrumental in the project.

The existence and success of our team depends on the incredible support of the University of Michigan, our advisor, our committed alumni, and our industry sponsors. Special thanks to Professor Maani Ghaffari Jadidi, and Professor Kevin Maki for being the team's advisors, and the Wilson Center staff and teams for training our members on how to safely and effectively use equipment and machinery.

5. References

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Appendix A: Components List

Component	**Vendor**	**Model/Type**	**Specs**	**Custom/Purchased**	**Cost**	**Year of Purchase**
ASV Hull Form/Platform	Custom	Trimaran	Carbon Fiber	Custom	417	2023
Waterproof Connectors	Multiple	Deutsch DT Series Connectors	N/A	Purchased	47	2023
Propulsion	Blue Robotics	T500	43.5A max at 24V	Purchased	690	2023
Power System	Multiple	LiPo battery, ATX Power Splitter and Adapter	20Ah at 26V max	Custom	400	2023
Motor Controls	BlueRobotics	Basic ESC 500	50A rating	Purchased	95	2023
CPU	Amazon	AMD Ryzen 5600X	12 thread processor	Purchased	194	2023
Teleoperation	Amazon	X8R Receiver	8 Channels	Purchased	36	2019
Inertial Measurement Unit (IMU)	VectorNav	VectorNav	VN-300	Purchased	5000	2019
Doppler Velocity Logger (DVL)	N/A	N/A	N/A	--	--	--
Camera(s)	Amazon	Logitech C920 Webcam	1080p	Purchased	70	2023
Hydrophones	N/A	N/A	N/A	--	--	--
Algorithms	N/A	PID Control loop	N/A	Custom	--	--
Vision	N/A	OpenCV, Yolov4 deep learning model	N/A	Custom	--	--
Localization and Mapping	N/A	Custom sensor fusion algorithm	N/A	Custom	--	--
Autonomy	N/A	Hybrid A* algorithm	N/A	Custom	--	--
Open-Source Software	N/A	ROS, OpenCV, Ubuntu, YOLOv4	N/A	Custom	--	--

Figure A1. Components List

Appendix B: Testing Plan

I. Scope

The team created testing goals based on different components. The team tested the electrical systems on the old vessel individually, and then moved on to testing each individual AI subteam. The team tested CV and LIDAR intermittently while testing other subsystems of the vessel.

II. Schedule

The team's testing schedule is seen below. The team scheduled each during the week prior - for the MHL, the trained members signed the required papers during Wednesday or Thursday of that week, while for Dexter Community Pools, the team corresponded with Dexter Schools to get the required lifeguard certified members and a staff member present at the location during testing.

In addition, included is the testing breakdown plan that the Systems Engineering subteam developed to determine the prioritization and order of testing in-water. It is important to note that the gantt chart shows not the start and end dates of the testing work for each subteam, but rather emphasizes when each sub team's testing would be the focus of the in-water time.

Date	Timeslot	Location	Trained Members Required	Testing Priority	Testing Accomplished
Jan. 15	12-4PM	MHL	**PR:** Saheth **SO:** Asheya **DC:** Georgia **DR:** Amirali	Systems Check, Basic Logistics	Basic Logistics
Jan. 22	12-4PM	MHL	**PR:** Saheth **SO:** Axel **DC:** Asheya **DR:** Anthony	Electrical	Electrical, Systems Checks
Jan. 28 & 29	12-5PM	MHL	**PR:** Saheth **SO:** Asheya **DC:** Ben S. **DR:** Zain	Controls	Basic Controls Input, TeleOp Control, Indoor GPS Setup
Feb. 4 & 5	12-5PM	MHL	**PR:** Saheth **SO:** Asheya **DC:** Ben S. **DR:** Zain	Controls	Reaching Set Waypoint
Feb. 11 & 12	11-7PM	MHL	**PR:** Saheth **SO:** Asheya **DC:** Ben S. **DR:** Georgia	Nav, Task Planning	
Feb. 18 & 19	11-7PM	MHL	Needed: PR, SO, DC, DR	CV, Task Planning	
Feb. 25		Dexter Community Pools	Needed: lifeguard certification	Entire AI Pipeline	
Feb. 26	11-7PM	MHL	Needed: PR, SO, DC, DR	Individual Challenge Runs	
Mar. 4		Dexter Community Pools	Needed: lifeguard certification	Individual Challenge Runs	
Mar. 5	11-7PM	MHL	Needed: PR, SO, DC, DR	Individual Challenge Runs	
Mar. 11		Dexter Community Pools	Needed: lifeguard certification	Full Course Run	
Mar. 12	11-7PM	Dexter Community Pools	Needed: PR, SO, DC, DR	Full Course Run	
Competition!					

Figure A2. Testing Timeline

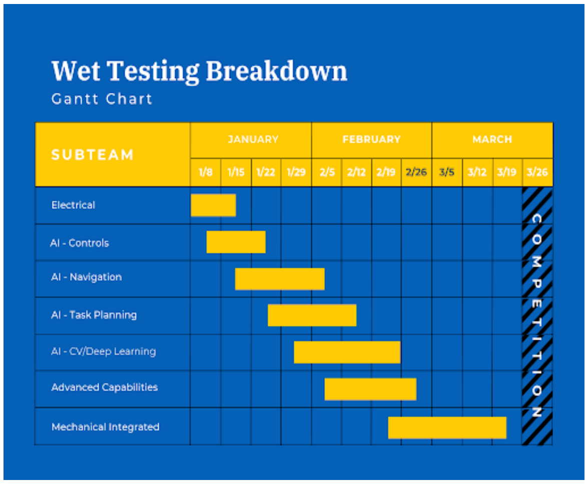
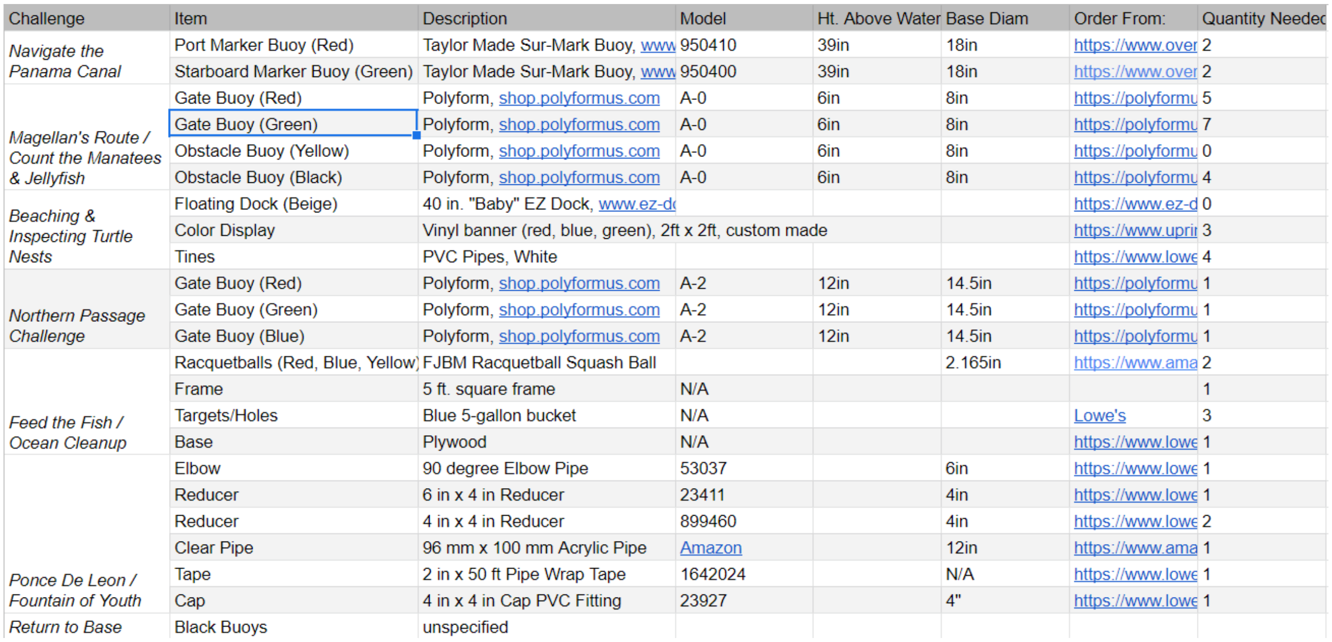


Figure A3. Testing Prioritization

III. Resource & Tools

Included below are the testing hardware the team employed in recreating the test environment. All of the buoys and docks shown below were anchored and placed in the tow tanks for CV and task planning testing.



Challenge	Item	Description	Model	Ht. Above Water	Base Diam	Order From:	Quantity Needec
Navigate the Panama Canal	Port Marker Buoy (Red)	Taylor Made Sur-Mark Buoy, www	950410	39in	18in	https://www.over	2
	Starboard Marker Buoy (Green)	Taylor Made Sur-Mark Buoy, www	950400	39in	18in	https://www.over	2
Magellan's Route / Count the Manatees & Jellyfish	Gate Buoy (Red)	Polyform, shop.polyformus.com	A-0	6in	8in	https://polyformu	5
	Gate Buoy (Green)	Polyform, shop.polyformus.com	A-0	6in	8in	https://polyformu	7
	Obstacle Buoy (Yellow)	Polyform, shop.polyformus.com	A-0	6in	8in	https://polyformu	0
	Obstacle Buoy (Black)	Polyform, shop.polyformus.com	A-0	6in	8in	https://polyformu	4
Beaching & Inspecting Turtle Nests	Floating Dock (Beige)	40 in. "Baby" EZ Dock, www.ez-d				https://www.ez-d	0
	Color Display	Vinyl banner (red, blue, green), 2ft x 2ft, custom made				https://www.upri	3
	Tines	PVC Pipes, White				https://www.lowe	4
Northern Passage Challenge	Gate Buoy (Red)	Polyform, shop.polyformus.com	A-2	12in	14.5in	https://polyformu	1
	Gate Buoy (Green)	Polyform, shop.polyformus.com	A-2	12in	14.5in	https://polyformu	1
	Gate Buoy (Blue)	Polyform, shop.polyformus.com	A-2	12in	14.5in	https://polyformu	1
Feed the Fish / Ocean Cleanup	Racquetballs (Red, Blue, Yellow)	FJBM Racquetball Squash Ball			2.165in	https://www.ama	2
	Frame	5 ft. square frame	N/A				1
	Targets/Holes	Blue 5-gallon bucket	N/A			Lowe's	3
	Base	Plywood	N/A			https://www.lowe	1
Ponce De Leon / Fountain of Youth	Elbow	90 degree Elbow Pipe	53037		6in	https://www.lowe	1
	Reducer	6 in x 4 in Reducer	23411		4in	https://www.lowe	1
	Reducer	4 in x 4 in Reducer	899460		4in	https://www.lowe	2
	Clear Pipe	96 mm x 100 mm Acrylic Pipe	Amazon		12in	https://www.ama	1
	Tape	2 in x 50 ft Pipe Wrap Tape	1642024		N/A	https://www.lowe	1
	Cap	4 in x 4 in Cap PVC Fitting	23927		4"	https://www.lowe	1
Return to Base	Black Buoys	unspecified					

Figure A4. Testing Hardware

In addition, measurement equipment, such as a tension gauge, were used to get physical metrics from the system, such as for thrust-weight calculations. Besides this, the indoor GPS equipment, as described in the GPS and IMU testing strategy section, were used to simulate running outdoors.

IV. Environment

The vessel mounted on its stand was used as the dry testing environment with a significant amount of empty space in front of the camera for the vessel.

The in-water testing environment that was used was the University of Michigan's Marine Hydrodynamics Laboratory Towing Tank Basin. The tow tank is a long hallway with water in the middle area with a beach area for team members to get the vessel into the water. Buoys of varying sizes can be added into the tank.
Marvel Mind Indoor GPS was mounted in the environment to provide position information.

V. Risk Management

While the MHL is an incredibly important resource for testing, it can also be incredibly dangerous - the facility is over 100 years old, and it is essential that the team understands the risks involved in using the lab and what safety protocol must be followed. The tank is 10-15 feet deep, consists of exposed electrical channels, and has a lot of moving parts, such as a subcarriage that travels the length of the tow tank and is unlocked and moved by foot.

In order to mitigate these risks, the team worked with the MHL to coordinate a training session in the fall with all of its members. This included being debriefed on the safety protocol in the lab, what precautions must be taken, and what to do when something goes wrong. At the end of the session, members were provided with card access into the tank area, which was instrumental in allowing the team to test in-water frequently.

Before each session, the team sought MHL approval, and provided four trained members' names as those that would oversee the safety of the team. Each of these members had a role and a responsibility to the team to employ and assist everyone in employing safe practices, while also being ready to act in the event of an emergency. These four roles and their detailed descriptions are given below.

Person Responsible: Usually the president of the team, the person responsible is the contact point between the MHL and the team. They are responsible for ensuring all relevant paperwork has been completed, submitted, and accepted. The PR is also responsible for providing the necessary safety personnel and equipment for safe operation within the MHL. The PR is the liable party for any incidents during the group's visit to the MHL as well.

Safety Officer: This person is responsible for ensuring all relevant safety equipment and practices are present, properly utilized and being followed at all times. The SO is also responsible for briefing all of the group's personnel on relevant safety procedures before the visit. The SO also makes sure that the personnel are stationed in a manner that allows for expedient action in case of emergency.

Designated Caller: Responsible for maintaining a means of contacting outside emergency personnel during the group's entire time at the MHL. They are responsible for knowing the emergency contact numbers, such as UM DPSS, in case of emergency. The DC also coordinates with the Designated Runner on where to meet outside emergency personnel.

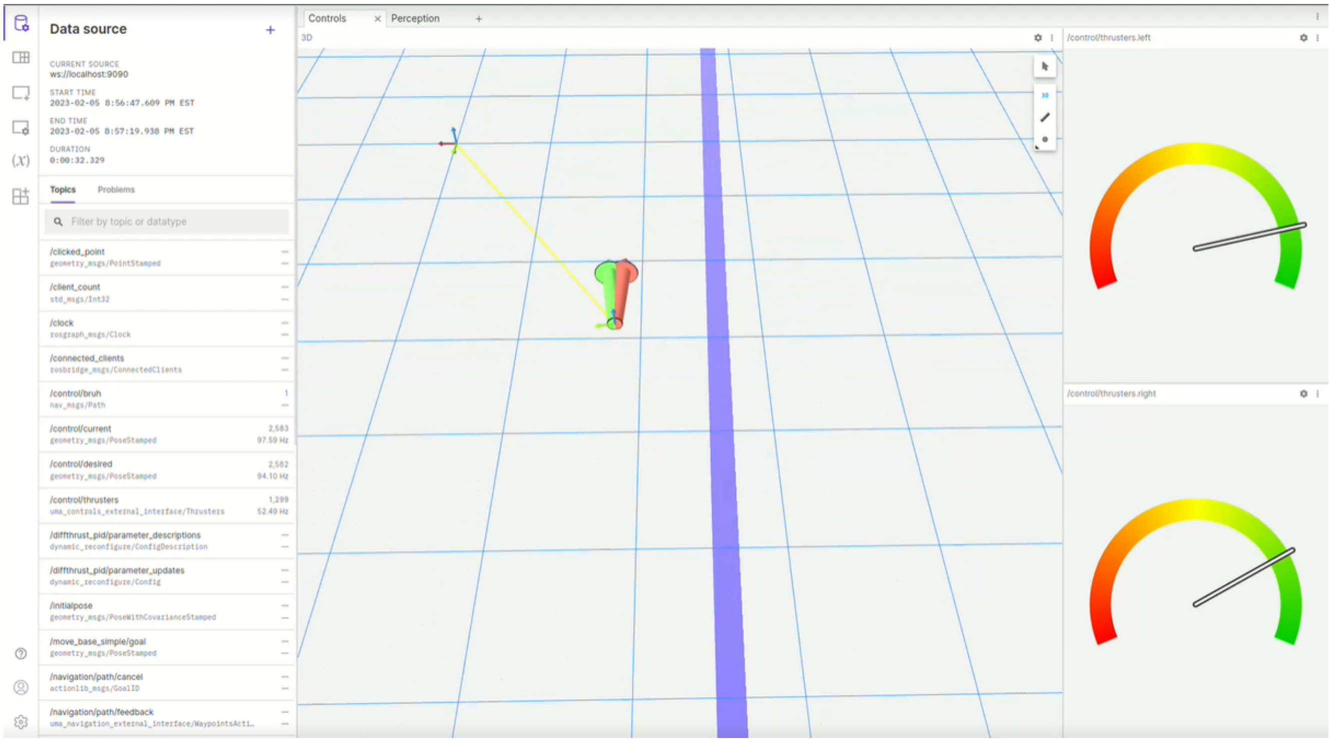
Designated Runner: The DR is responsible for knowing all of the relevant entrances/exits to all spaces during the group's visit to the MHL. They are responsible for knowing where best to meet emergency personnel and how to direct them to the MHL.

With these roles, as well as the safety briefing between all attending members, the team is happy to report that there were no injuries in testing whatsoever.

VI. Results

Throughout the two days of testing per week, the team was able to obtain valuable information that was used to continuously update and improve the controls system. Each MHL testing session had a group get specific testing accomplished within that session. They were able to use immediate data to modify and improve in order to achieve the group's goal. The ROS bags of the connected onboard sensors and the data that they published to their respective ROS topics were collected, and could be "replayed" in a sense in order to have data for the other subteams that weren't able to be in the water testing.

Figure A5. CV Output Data from Buoy Recognition



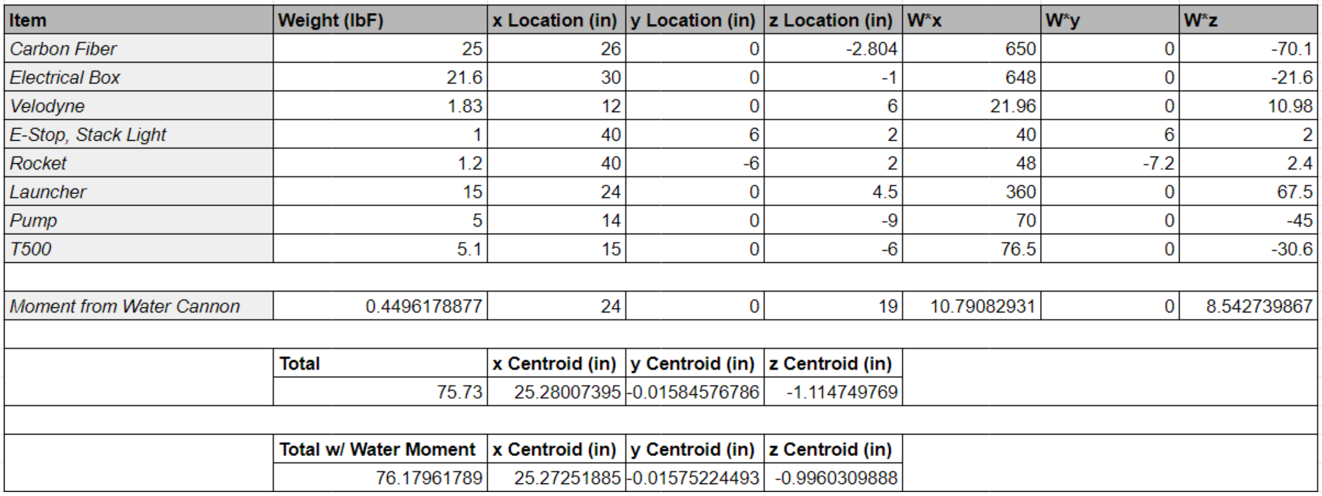
CURRENT SOURCE
ws://localhost:9090
START TIME
2023-02-05 8:56:47.609 PM EST
END TIME
2023-02-05 8:57:19.938 PM EST
DURATION
0:00:32.329

/clicked_point geometry_msgs/PointStamped	—	—
/client_count std_msgs/Int32	—	—
/clock rosgraph_msgs/Clock	—	—
/connected_clients rosbridge_msgs/ConnectedClients	—	—
/control/bruh nav_msgs/Path	1	—
/control/current geometry_msgs/PoseStamped	2,583	97.59 Hz
/control/desired geometry_msgs/PoseStamped	2,582	94.10 Hz
/control/thrusters uma_controls_external_interface/Thrusters	1,299	52.49 Hz
/diffthrust_pid/parameter_descriptions dynamic_reconfigure/ConfigDescription	—	—
/diffthrust_pid/parameter_updates dynamic_reconfigure/Config	—	—
/initialpose geometry_msgs/PoseWithCovarianceStamped	—	—
/move_base_simple/goal geometry_msgs/PoseStamped	—	—
/navigation/path/cancel actionlib_msgs/GoalID	—	—
/navigation/path/feedback uma_navigation_external_interface/WaypointsActi…	—	—

Figure A6. ROS Bag Controls Playback

Appendix C: Hydrostatics

1.0 Weights and Centers of Phoenix



Item	**Weight (lbF)**	**x Location (in)**	**y Location (in)**	**z Location (in)**	**W*x**	**W*y**	**W*z**
Carbon Fiber	25	26	0	-2.804	650	0	-70.1
Electrical Box	21.6	30	0	-1	648	0	-21.6
Velodyne	1.83	12	0	6	21.96	0	10.98
E-Stop, Stack Light	1	40	6	2	40	6	2
Rocket	1.2	40	-6	2	48	-7.2	2.4
Launcher	15	24	0	4.5	360	0	67.5
Pump	5	14	0	-9	70	0	-45
T500	5.1	15	0	-6	76.5	0	-30.6
Moment from Water Cannon	0.4496178877	24	0	19	10.79082931	0	8.542739867
	Total	**x Centroid (in)**	**y Centroid (in)**	**z Centroid (in)**			
	75.73	25.28007395	-0.01584576786	-1.114749769			
	Total w/ Water Moment	**x Centroid (in)**	**y Centroid (in)**	**z Centroid (in)**			
	76.17961789	25.27251885	-0.01575224493	-0.9960309888			

2.0 Trim of Phoenix

Condition	**Sinkage (in)**	**Trim (deg)**	**Heel (deg)**	**Ax (m^2)l;**
Neutral	-7.335	-2.252	0.020	0.00

Appendix D: Water Cannon Trade Study Calculations

1.0 Nozzle Output Velocity:

Q_{Pump} = 5 gal/min (*volumetric flow rate)*
D_{inlet} = 0.8 inches
D_{outlet} = 0.315 inches

$Q_1 = A_1 v_1$
$A_1 v_1 = A_2 v_2$
$Q_1 = A_2 v_2$

$$5\ gal/min\ =\ \pi\left(\frac{0.315\ inches}{2}\right)^2 \bullet v_2$$

v_2 = 6.27 m/s

2.0 Recoil Force:

$$F = v_2 \bullet Q_{pump} = 2N$$

3.0 Moment from Waterblast:

$$M = F \bullet d = 2N \bullet 0.4825m = 0.9652Nm$$

4.0 Trim Caused by Water Blast Moment:

Condition	**Sinkage (in)**	**Trim (deg)**	**Heel (deg)**	**Ax (m^2)**
Water Blast Firing	-7.312	-2.282	0.020	0.00

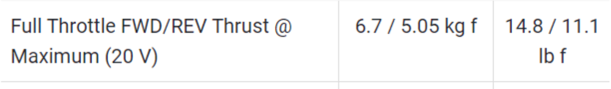
5.0 Pump Weights:

DC Pump Weight: 5.81 lbs
AC Pump Weight: 6.47 lbs

Appendix E: Propulsion Trade Study Calculations

1.0 T200 and T500 Thrust:

T200 @ 20 V



Full Throttle FWD/REV Thrust @ Maximum (20 V)	6.7 / 5.05 kg f	14.8 / 11.1 lb f

T500 @ 24 V

Full Throttle FWD/REV Thrust @ 24 V	16.1 / 10.5 kg f	35.5 / 23.2 lb f

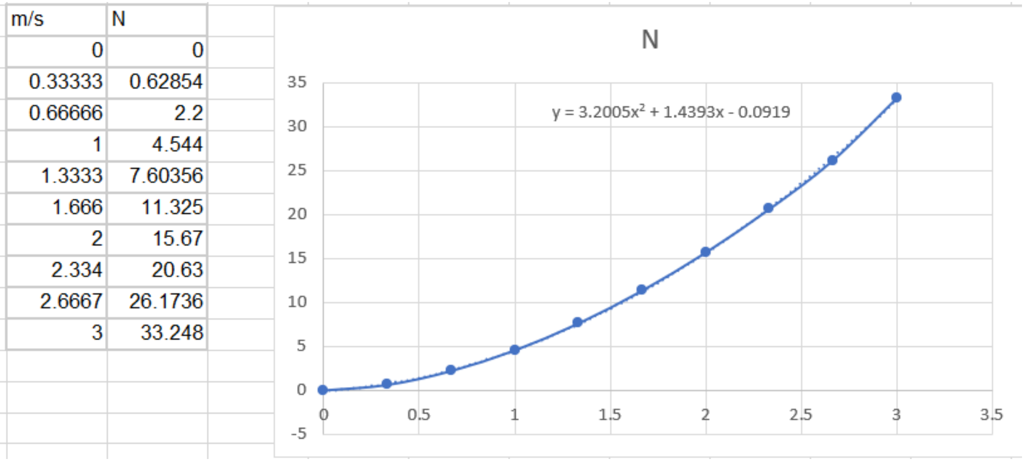
$$T_{tot,\,500,\,FWD} = 35.5 \bullet 2 = 71\ lbf$$

$$T_{tot,\,500,\,REV} = 23.2 \bullet 2 = 46.4\ lbf$$

$$T_{tot,\,200,\,FWD} = 14.8 \bullet 4 = 59.2\ lbf$$

$$T_{tot,\,200,\,FWD} = 11.11 \bullet 4 = 44.44\ lbf$$

Appendix F: Simulator Physical Parameters Calculations



m/s	N
0	0
0.33333	0.62854
0.66666	2.2
1	4.544
1.3333	7.60356
1.666	11.325
2	15.67
2.334	20.63
2.6667	26.1736
3	33.248

Figure A7. Resistance vs. Speed

$F_{surge} = 3.2005v^2 + 1.4393v$ [Ns/m]

Appendix F.2

$F_{sway} = C_D * .5 * \rho_{seawater} * v^2 * (C_{prism})$

$C_{prism} = V_{hull} / (A_{max} * L_{pp}) = .005m^3 / (.03129m^2 * 1.1176m) = .14298$

$C_D \approx .9$

$\rho_{seawater} = 1026\, kg/m^3$

$F_{sway} = .9 * .5 * 1026 * v^2 * .14298 = 66.01v^2$ [Ns/m]

Appendix G: Cost of Carbon Fiber Hull from Component List

Assumptions: Carbon Fiber and Resin are bought in bulk

$$Cost_{CF,total} = Cost_{CF,\,\$/in^2} * (A_{total,,in^2}) + Cost_{Resin}$$

$$Cost_{CF} = .024255\ \$/in^2$$

$$A_{total} = A_{Hull,in^2} + A_{Cowl,in^2} = 6826.78in^2 + 1663.08in^2 = 8489.86in^2$$

$$Cost_{Resin} = 210.99\ \$/1.3gallon\ *\ 1.3\ gallon = \$210.99$$

$$Cost_{CF,total} = \$.024255/in^2\ *\ (8489.86in^2) + \$210.99\ = \$416.92$$