The Phoenix Returns by UM::Autonomy
RoboBoat 2024: Technical Design Report

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1. Abstract

At the 2024 RoboBoat Competition, *The Phoenix* sets sail once more — emerging stronger from the trials and tribulations of its past, UM::Autonomy's 2024 vessel focuses on simplicity in design and workflow in order to further ensure a reliable, maintainable, and modular system, the details of which are documented in this paper. This year, the team prioritized maximizing performance on the tasks involving autonomous navigation and docking, rather than the newer advanced capabilities tasks. Understanding the tighter time constraints of this season, this meant greater emphasis was placed on design validation and in-water testing, which was facilitated by maintaining an operable vessel and reducing design complexity from last year. This design strategy was complemented with a testing strategy that relocated the team permanently into its testing environment, made testing a weekly process from the start of the season, and allowed for multiple modes of testing to guarantee success.

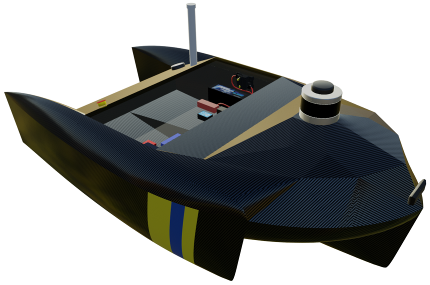

Figure 1. "The Phoenix" Render

2. Technical Content

2.1 Competition Strategy

Under the shortened competition season this year, the team's strategic vision for RoboBoat 2024 was to primarily focus on Navigation (Tasks 1, 2, 5, and 8) and Docking (Task 3). Duck Wash (Task 4) would be a secondary priority, and the Delivery Octagon (Task 7) tertiary, with the team choosing to omit attempting the Collection Octagon (Task 6). The latter three tasks, needing further development and therefore adding system complexity, were deprioritized, and development was made modular and independent of the vessel. This would ultimately serve to maximize available testing time with an operable vessel.

The team's guiding design strategy was the reliability and maintainability of the vessel through simplicity in the system and in the team's workflow. This meant reducing system and workflow complexity in favor of a straightforward approach, and emphasizing design validation through testing. The rushed development timeline from last season made it clear that in a season that was even shorter, it was infeasible to build a new boat, and rather that time should be spent on software improvements.

As a result, the team chose to improve UM::Autonomy's 2023 vessel, The Phoenix, while maintaining operability for testing throughout the season.

2.1.1 Task-by-Task Strategic Breakdown

For the autonomous navigation necessary for the Navigation Channel, Follow the Path, Speed Challenge, and Return to Home 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.

Previously, this system architecture separated Navigation and Controls into the domain of two different subteams - however, the 2023 season showed that these two were far too interconnected to be split apart.

When approaching a given navigation challenge, the Perception team identifies objects using a camera and a computer vision (CV) deep learning model, YOLOv8, 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. Objects discovered on the water are remembered ("mapped") to allow navigation around buoys that are not currently visible to the camera.

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.

2.1.1.1 Navigation Channel

For the Navigation Channel task, Task Planning instructs the vessel to move continuously through the first pair of buoys. Once Perception algorithms detect the second pair of buoys, the continuous movement is preempted and the vessel is commanded to go within the gates.

2.1.1.2 Follow the Path

To complete the Follow the Path task, Task Planning identifies the furthest red and green buoys that form a gate and creates a waypoint between them. This is repeated until no more buoys are seen, marking the end of the task.

Every waypoint that Task Planning generates is sent to Navigation. Once Navigation receives a new waypoint, it uses an A* algorithm to generate a path between the vessel's current location and the waypoint. The A* algorithm works by creating an optimal path with modifications to account for the vessel's dynamics. This approach allows for reliable paths that the vessel can accurately follow.

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.

2.1.1.3 Speed Challenge

For the Speed Challenge task, Task Planning first sets a waypoint between the green and blue buoys. The algorithm then sends the vessel forward until it detects the blue buoy and then circles it. The vessel is then sent back to the entrance of the challenge.

2.1.1.4 Docking

For Docking, the team is required to identify the color—or shape in the case of the duck—on each dock. Once the banner is identified and located using computer vision, a plane is fitted using LiDAR data to determine its normal vector. Task Planning then lines up the boat along this vector. The Navigation and Controls systems then operate to move the vessel to the desired location, reversing the vessel into the corresponding dock.

2.1.1.4 Duck Wash & Delivery Octagon

In completing the Advanced Capabilities challenges, the team took the simplest design approach. For duck wash, the vessel enters and hits the dock to reach optimal distance from the banner. The vessel then shoots water at the banner from the bow, while running the thrusters at low power as a means of stationkeeping, while also correcting for heading.

In the Octagon challenges, our focus this year is exclusively on the Delivery Octagon using preloaded racquetballs. This part of the challenge requires the precise deployment of rubber ducks and balls into designated sections of an octagon structure. Our strategy for the Delivery Octagon involves detecting vision targets located at the center of the octagons, using a similar plane-fitting algorithm to docking to determine orientation. These targets will guide the boat to align accurately with the specific drop zones for the ducks and balls.

2.2. Design Strategy

2.2.1 Mechanical Design Strategy

After a delayed fabrication timeline for the vessel hindered testing time last season, the Mechanical subteam prioritized maintaining an operable vessel for in-water software testing at all times. The team additionally sought to improve the efficiency and maintainability of the vessel based on lessons learned at the 2023 RoboBoat

Competition. Meanwhile, all advanced capabilities development was done in parallel and tested independently.

2.2.1.1 Waterproofing

In-water time at the 2023 RoboBoat Competition revealed microscopic leaks along the vessel hulls' seams. This was a result of a rushed development cycle, as well as the carbon-fiber resin wet-layup cure being insufficient. This was fixed with multiple more wet layups with a resin better fit for in-water applications.

2.2.1.2 Propulsion

This year, the team continues to use the two Blue Robotics T500 thrusters that allow for greater responsiveness and efficiency (Appendix E). In-water performance at the 2023 RoboBoat Competition showed, however, that these thrusters were being underutilized due to improper mounting that led to propeller ventilation. Thruster mounting didn't match the vessel's waterline, leading to air intake that resulted in efficiency loss, especially when hit with waves or when colliding with the boat's own wake while turning.

This was accounted for by printing better mounts that lowered the thrusters 4.2" further into the water. In addition, the thrusters were back-mounted in order to take advantage of cleaner inlet flow near the back, rather than towards the front where it is dirtier. While this loses the advantage of self-leveling when applying excessive thrust, it proves to be a better solution for a reliable turning and forward propulsion.

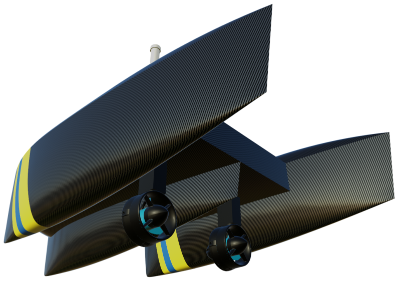

Figure 3. Thruster Location

2.2.1.3 Duck Wash

For the Duck Wash challenge, we have integrated a trio of mini 12V 5W pumps, each with a capacity of 280L/H, wired in series. These pumps, chosen for their ease of integration and modularity, draw filtered lake water through a single intake located under the bow into the hull. The water is expelled through a custom-designed 3D printed nozzle positioned beneath the Velodyne sensor. This nozzle features an internal honeycomb pattern, ensuring a consistent and non-turbulent flow. The team then incorporated adjustable pins for fine-tuning the height of the water stream, adding precision to the setup. This low-power DC pump system offers the advantage of easy maintenance, allowing for quick replacement of individual pumps if necessary.

2.2.1.4 Delivery Octagon

For the Delivery Task, we've developed an innovative arm system using stripped carbon fiber fishing rods and molded flexible racks. This design was inspired by the concept of a linear slide system but adapted to address concerns about corrosion and weight. The toothed racks, driven by motors, enable rapid extension and retraction of the fishing rods, facilitating quick deployment of the ducks and balls. The system's primary components, including motors and spools, are mounted on the hull, minimizing impact on the boat's balance and center of buoyancy. The arm system, entirely 3D printed, features two parallel rods with individual spools and motors, ensuring lateral stability and strength. At the ends of these rods, a container with electromagnetically controlled trap doors houses two separate sections for ducks and balls, allowing for precise and timely release of each.

Our approach this year marks a departure from traditional methods such as compressed air cannons or robotic arms. By leveraging 3D printing technology and innovative materials like carbon fiber, we've developed a hardware system that not only meets but surpasses our design goals of simplicity, reliability, and efficiency, while also accommodating the unique demands of the Duck Wash and Octagon Delivery tasks.

Figure 4. Dual Fishing Rod Delivery CAD model

2.2.1.5 Vessel Arrangements

Vessel weight reduction through a simpler system slightly changed vessel dynamics, although the trimaran hull form provided accessibility and stability in trim and heel. *The Phoenix* has a length of 56", a beam of 30", and has an overall height of 26".

The Duck Wash was incorporated into the system at the bow, with the tube for the water intake being routed through the port side of the upper subshell. This would isolate leaks fairly well, while also being far from the waterline to cause any leaks in the first place.

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

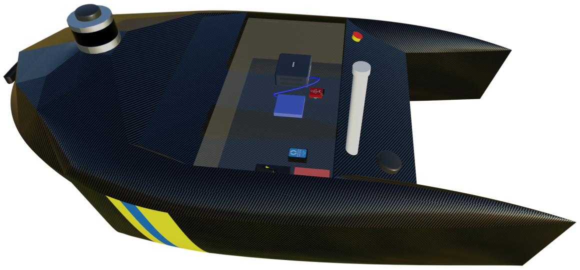

Figure 5. Sensor Layout

2.2.2 Electrical Design Strategy

Last year's competition provided the team with insight into the effectiveness of the electrical system under environmental conditions. While the system proved capable, it lacked resiliency, as the jostling of the harsh wind and water would cause frequent disconnections. This was mainly as a result of lots of fragile connections and unnecessary system complexity.

As a result, this year's electrical strategy was focused on simplifying the electrical system, and improving safety and reliability while maintaining modularity for advanced capabilities.

2.2.2.1 PCB & Small-Form-Factor Computer

We realized that a lot of our parts can be replaced or combined, resulting in a more compact system with less wiring. This can enable us to easily spot and fix errors during competition trials. We replaced our big bulky computer with a lighter small-form-factor computer that is better tailored to the team's needs. In addition, the team designed a Printed Circuit Board (PCB) to combine many of our components that control thrusters, reducing the number of individual components. A custom binary API was created to interface between the computer and the USB-connected microcontroller on the PCB.

2.2.2.2 Safety & Reliability

Safety was a priority in our design. This year, the team continued to significantly reduce the amount of permanent connections by opting for removable connections. We improved on our standardized connector system by switching from EC5 connectors to more reliable XT90 connectors. We further enhanced our power board by introducing a PCB to transition from unreliable screw terminals to soldered connections. Further, more information is sent directly to the operator this year, including internal temperature, humidity, and battery voltage. to better monitor the vessel's health.

2.2.3 Software Design Strategy

This year, the Artificial Intelligence team focused on quick iterations. By reducing compile times and improving simulations, new strategies could be tested rapidly by team members. Unnecessary layers of abstraction were removed to reduce cognitive load and improve traceability of data flow while still keeping subteams' work independent.

2.2.3.1 Navigation & Controls

The Navigation & Controls subteam spent this past year striving towards reliability. On the Navigation side, we aimed to optimize our path generation by reweighing the costmap to ensure the buoy followed the best path (Figure 6). For Controls, we have made modifications to our thruster inputs so the vessel follows the path we generate more accurately. Although these changes added complexity to our system, they resulted in more reliable paths that our vessel can more precisely navigate. Through rigorous testing in our simulated Gazebo environment, we have validated that these optimizations increase the reliability of our system.

2.2.3.2 Task Planning Shift to Python

The greatest shift this year was the decision to rewrite our codebase into Python. Previously, the team used in C++ because of its speed and usage at the University. However, unless members were familiar with locking needed for multithreading to perform multiple tasks at once, the boat would stall in between every step as it scanned for more buoys or potential gates. Moving to Python removes these requirements.

Using Python's async/await support, we are able to simplify a common pattern: keep the boat moving continuously while simultaneously executing the search and planning algorithms. This also allowed a significant reduction in complexity by sending more data to relevant subteams. Specifically, in the Follow the Path challenge, the navigation team is informed of gate locations so the boat can avoid going outside of the allowed area, seen in the map in Figure 6.

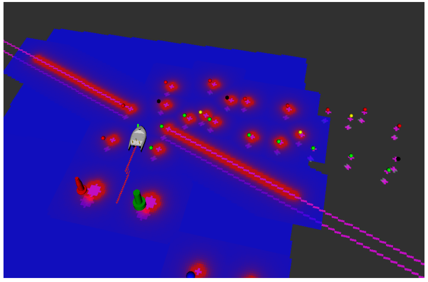

Figure 6. Costmap including illegal zone outside gates

2.3 Testing Strategy

Design validation through rigorous, multifaceted testing was instrumental in the team's success in the 2023 RoboBoat Competition - with over 100 hours recorded for in-water testing time, it guided UM::Autonomy's success in software development and fine-tuning. However, there was still much room for improvement in the way that the team facilitated this testing.

This year, the team focused on centering the team's workflow around design validation through various testing modes. Firstly, this was done by relocating the team permanently into our in-water testing location, the Marine Hydrodynamics Laboratory, and having testing slots reserved as early as the first week of September. In addition, weekly in-water testing became an integral part of team meetings, and a means of monitoring iterative development. Where in-water testing was infeasible, simulation testing in Gazebo was used so that individual AI subteams could refine their code before any bench or in-water testing.

2.3.2 In-Water Testing

The extended support of the staff at the Marine Hydrodynamics Laboratory this year made it possible for the team to access their indoor tow tank for in-water testing more regularly.

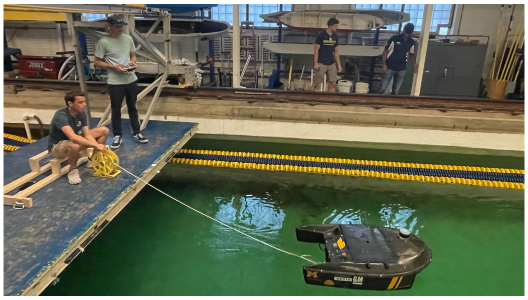

Figure 7. In-Water Testing at the MHL Tow Tank

In previous years, the biggest hindrance to testing capability proved to be moving team equipment and vessels back and forth from our workspace in the Wilson Center 2 miles away. To combat this, the team resolved to relocate weekly team meetings into the MHL, and center the workflow around iterative development that results in meeting in-water sprint goals biweekly. Additionally, thanks to the MHL staff, our vessel and equipment found a new home in the MHL itself, further allowing us to make testing a core part of our team and our routine.

In-water testing was used to validate changes in code for all three AI subteams. For Perception, in-water testing helped validate the effectiveness of the code against realistic lighting and environmental conditions. For Navigation and Controls, it served to corroborate the effectiveness of the costmap and the generated path with realistic vessel dynamics. For Task Planning, it will be most helpful in carrying out testing for complete multi-task functionality.

Figure 7.1. 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 Follow the Path, for all modules of the code. Even challenges like Duck Wash could be simulated by simulating a water stream. 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.

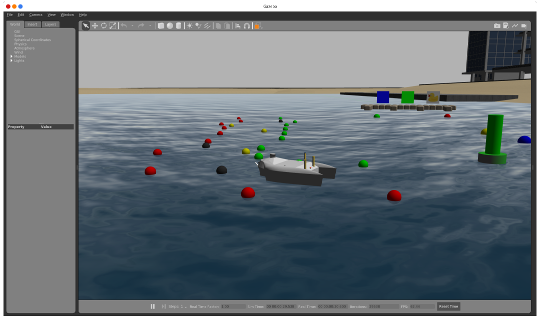

Figure 8. Testing Task Planning, Path Planning and Controls algorithm to complete "Follow the Path"

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. 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 or in-water while connected to the base station 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 obstructs the GPS signal. Instead, Marvelmind indoor positioning units are used, which is accurate to around 10cm. Relying on magnetometer and gyroscope fusion provides about 5° of heading accuracy. While this is very good compared to typical GPS receivers, this method is less reliable compared to the multiple GPS antennas supported by our unit.

3. Conclusion

UM::Autonomy chose to improve upon their 2023 vessel, *The Phoenix,* with the goal of simplifying the design in order to make it more reliable and maintainable. The team decided to prioritize Navigation and Docking, and attempt the Duck Wash and Delivery Octagon. This would be achieved through a reduction in complexity of the electrical system, modular and independent development of new hardware, greater efficiency in thrust, and an AI pipeline that is simpler and focuses on quick iterations. In the future, as the team shifts to building a new vessel for 2025, the goal will be to similarly maintain this vessel for testing, and incorporate its modularity and reliability into a new design.

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. 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, Jason Bundhoff and Nicole Cheesman, for generously allowing us to test the vessel there, and for allowing us to store our vessel and equipment in the MHL this year.

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-doctoral scholar 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	6S, 20Ah	Custom	400	2023
Motor Controls	BlueRobotics	Basic ESC 500	50A rating	Purchased	95	2023
CPU	Beelink	Intel i5-12450H	12 thread processor	Purchased	300	2023
Teleoperation	FrSky	Taranis X9D+, 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
Algorithms	*N/A*	*PID Control loop*	*N/A*	*Custom*	--	--
Vision	N/A	YOLOv8 via ONNX Runtime + OpenVino	N/A	Custom	--	--
Localization and Mapping	N/A	Custom sensor fusion algorithm	N/A	Custom	--	--
Autonomy	N/A	A* algorithm	N/A	Custom	--	--
Open-Source Software	N/A	ROS, ONNX Runtime, OpenVino, Ubuntu, YOLOv8	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

In early September, the team drafted a timeline for the season's workflow. This timeline was discretized into biweekly segments, where at the end of every two weeks, a measurable sprint goal could be tested either in-water, in-sim, or via bench testing. This timeline is seen in Figure A2.

This season, the team had the fortunate opportunity to have an in-water testing slot reserved for 4 hours every Sunday during the Fall 2023 semester, a period of approximately 16 weeks. This meant that every team meeting would be followed by a testing session, where subteams could use the time to their advantage to gather data. While time for development was also a part of the schedule, this open availability made it possible to facilitate testing frequently.

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.

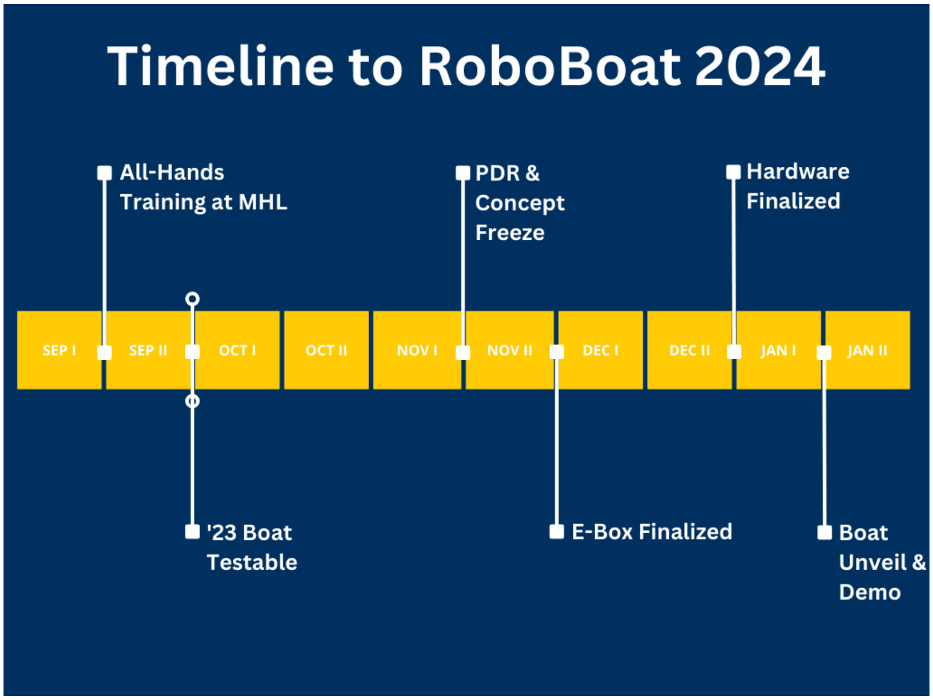


Figure A2. Testing Timeline

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	Unit Price	Total Price
Navigation Channel	Port Marker Buoy (Red)	Taylor Made Sur-Mark Buoy, www	950410	39in	18in	https://www.over	2	$330.00	$660.00
	Starboard Marker Buoy (Green)	Taylor Made Sur-Mark Buoy, www	950400	39in	18in	https://www.over	2	$330.00	$660.00
Follow the Path	Gate Buoy (Red)	Polyform, shop.polyformus.com	A-0	6in	8in	https://polyformu	5	$42.00	$210.00
	Gate Buoy (Green)	Polyform, shop.polyformus.com	A-0	6in	8in	https://polyformu	7	$42.00	$294.00
	Obstacle Buoy (Yellow)	Polyform, shop.polyformus.com	A-0	6in	8in	https://polyformu	0	$42.00	$0.00
	Obstacle Buoy (Black)	Polyform, shop.polyformus.com	A-0	6in	8in	https://polyformu	4	$42.00	$168.00
Docking	Floating Dock (Beige)	40 in. "Baby" EZ Dock, www.ez-d				https://www.ez-d	0	$656.00	$0.00
	Color Display	Vinyl banner (red, blue, green), 2ft x 2ft, custom made				https://www.uprir	3	$12.00	$36.00
	Tines	PVC Pipes, White				https://www.lowe	4	$10.69	$42.76
Speed Challenge	Gate Buoy (Red)	Polyform, shop.polyformus.com	A-2	12in	14.5in	https://polyformu	1	$76.13	$76.13
	Gate Buoy (Green)	Polyform, shop.polyformus.com	A-2	12in	14.5in	https://polyformu	1	$76.13	$76.13
	Gate Buoy (Blue)	Polyform, shop.polyformus.com	A-2	12in	14.5in	https://polyformu	1	$76.13	$76.13
Collection Octagon	Elbow	135 degree Elbow Pipe	53037		6in	https://www.lowe	8	$41.76	$334.08
	Reducer	6 in x 4 in Reducer	23411		4in	https://www.lowe	1	$23.71	$23.71
	Reducer	4 in x 4 in Reducer	899460		4in	https://www.lowe	2	$12.57	$25.14
	Pipe	96 mm x 100 mm Acrylic Pipe	Amazon		12in	https://www.ama	8	$27.50	$220.00
	Tape	2 in x 50 ft Pipe Wrap Tape	1642024		N/A	https://www.lowe	1	$5.50	$5.50
	Cap	4 in x 4 in Cap PVC Fitting	23927		4"	https://www.lowe	1	$16.81	$16.81
Delivery Octagon	Elbow	135 degree Elbow Pipe	53037		6in	https://www.lowe	8	$41.76	$334.08
	Reducer	6 in x 4 in Reducer	23411		4in	https://www.lowe	1	$23.71	$23.71
	Reducer	4 in x 4 in Reducer	899460		4in	https://www.lowe	2	$12.57	$25.14
	Pipe	96 mm x 100 mm Acrylic Pipe	Amazon		12in	https://www.ama	8	$27.50	$220.00
	Tape	2 in x 50 ft Pipe Wrap Tape	1642024		N/A	https://www.lowe	1	$5.50	$5.50
	Cap	4 in x 4 in Cap PVC Fitting	23927		4"	https://www.lowe	1	$16.81	$16.81

Figure A4. Testing Hardware

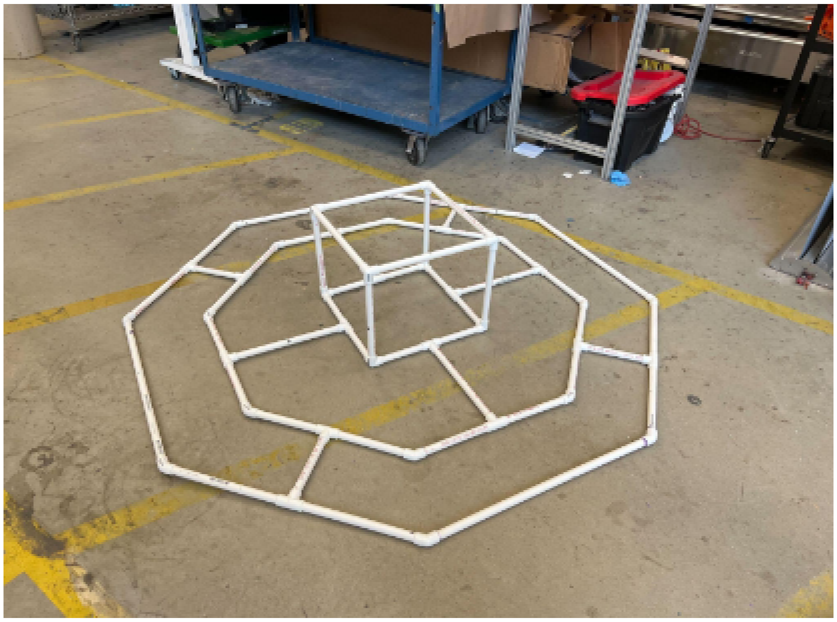


Figure A5. Delivery Test Rig Fully Constructed

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-simulation testing environment was developed by the team's AI lead. Using CAD models of the boat, a physically accurate model ensures that similar behavior is experienced in simulation as on real hardware. A full competition field was also created, using 3D models created both in-house and from others, including the SimLE: SeaSentinel team's published models and the Open Source Robotics Foundation's models of Nathan Benderson Park. This provides context as to exactly how the competition runs—because everything from the sandy beach to buildings to every object the boat interacts with is simulated, members can complete a full competition run from putting the boat in the water to completing every task.

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. The MarvelMind 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.

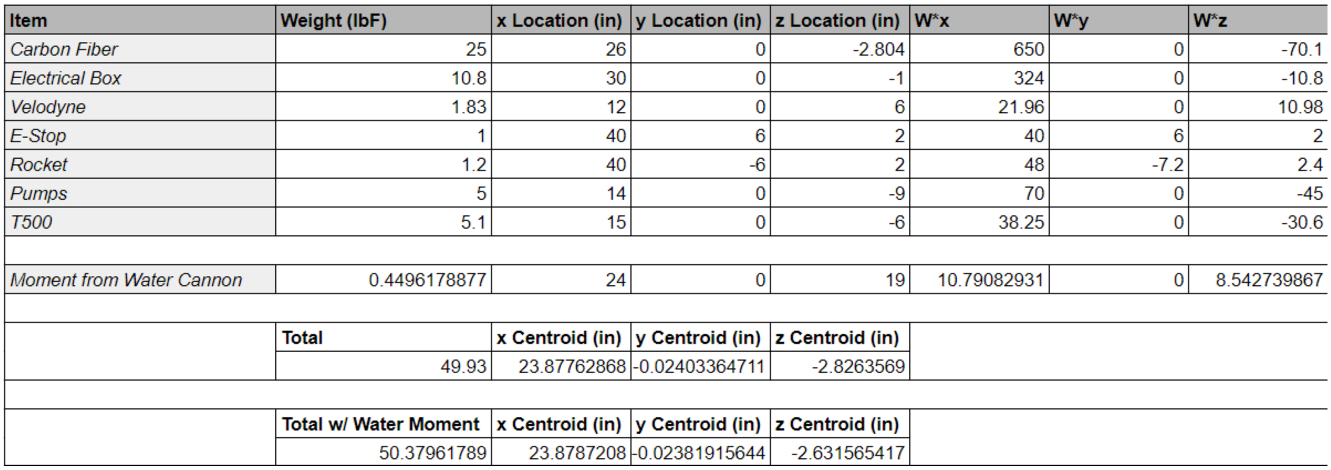
With these roles, as well as the safety briefing between all attending members, the team is happy to report that there were no injuries in testing whatsoever.

VI. Results

Through the weekly testing sessions, the team was able to obtain valuable information that was used to continuously update and software for Nav/Controls and CV primarily. 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.

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	10.8	30	0	-1	324	0	-10.8
Velodyne	1.83	12	0	6	21.96	0	10.98
E-Stop	1	40	6	2	40	6	2
Rocket	1.2	40	-6	2	48	-7.2	2.4
Pumps	5	14	0	-9	70	0	-45
T500	5.1	15	0	-6	38.25	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)**			
	49.93	23.87762868	-0.02403364711	-2.8263569			
	Total w/ Water Moment	**x Centroid (in)**	**y Centroid (in)**	**z Centroid (in)**			
	50.37961789	23.8787208	-0.02381915644	-2.631565417			

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 Variables:

Q_{Pump} = 840 L/H = 0.000233 m^3/s (*volumetric flow rate)*
D_{Nozzle} = 8 mm = 0.008 m
$r_{Nozzle} = D_{Nozzle} /2$ = 0.004 m
$A_{Nozzle} = \pi * (r_{Nozzle})^2 = 5.027 * 10^{-5}$ m
$\varrho_{Water} \approx 1000$ kg/m^3

2.0 Nozzle Output Velocity (v):

$\upsilon_{pump} = \frac{Q_{Pump}}{A_{Nozzle}} = 4.461$ m/s

3.0 Momentum (p):

$p = \rho_{Water} * Q_{Pump} * \upsilon_{pump} = 1.083$ kg*m/s

4.0 Moment (τ):

$\tau = r_{Nozzle} * p = 0.00433$ Nm

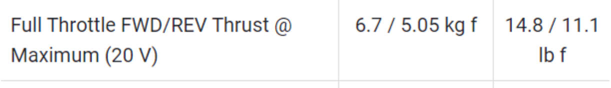
5.0 Force (N):

$F = \rho * Q_{Pump} * \upsilon = 1.039$ N

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

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

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

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

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

Maximum $T_{tot,\,500,\,FWD}$ recorded at 2023 RoboBoat Competition: $24.0\,/\,2 = 12\,lbf\ per\ thruster$

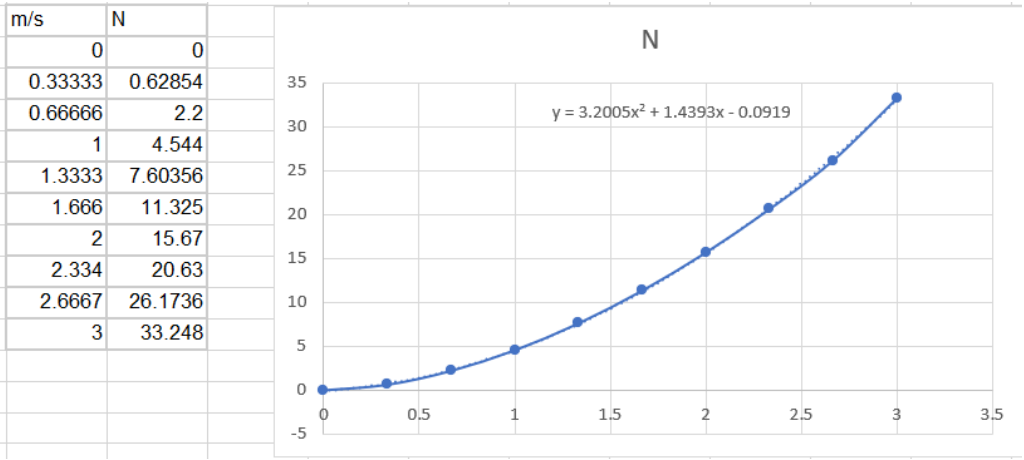
Prop ventilation in 2023 - resulting in 66% loss in thrust

With lowered thrusters, assuming this is improved to being just 16% more efficient

$T_{tot,\,500,\,FWD} = 35.5 \bullet 2 \bullet 0.50 = 35.5\,lbf$

Improves thrust by 11.5 lbf immediately

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

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

Appendix F.2

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

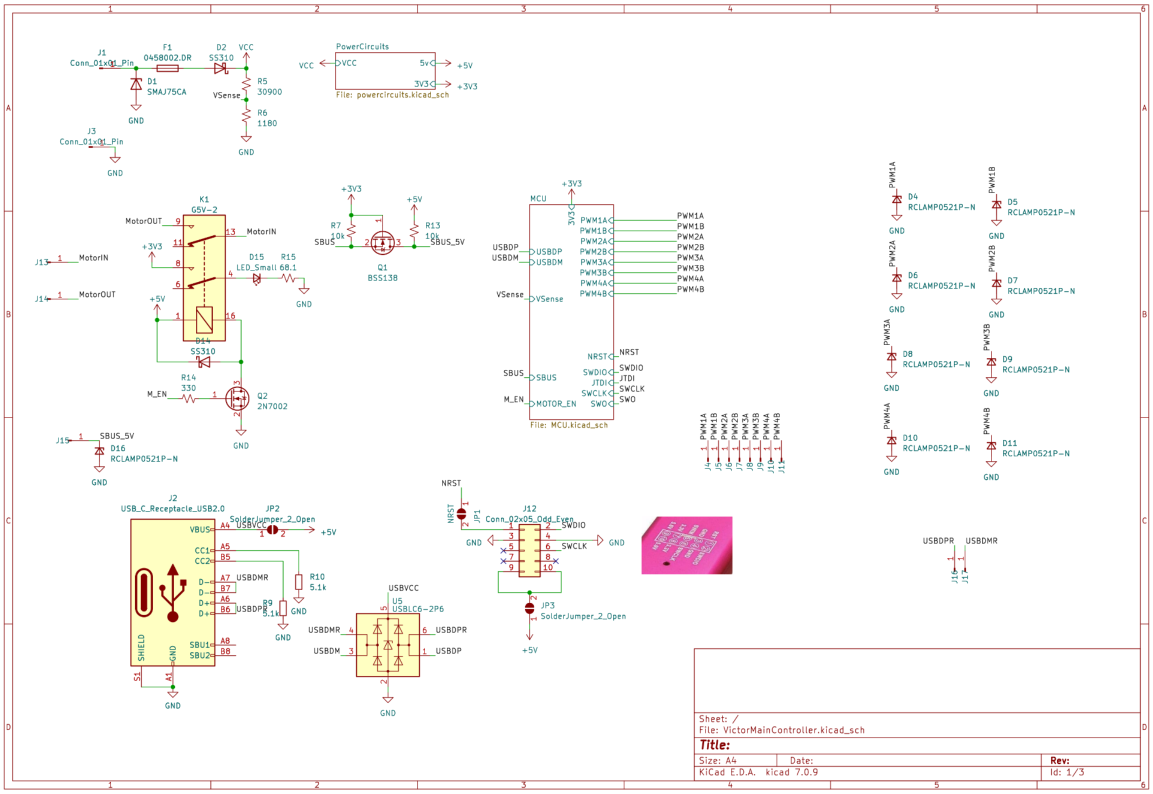
$$C_{prism} = V_{hull} / (A_{max} * L_{pp}) = .005m^3 / (.03129m^2 * 1.1176m) = .14298$$

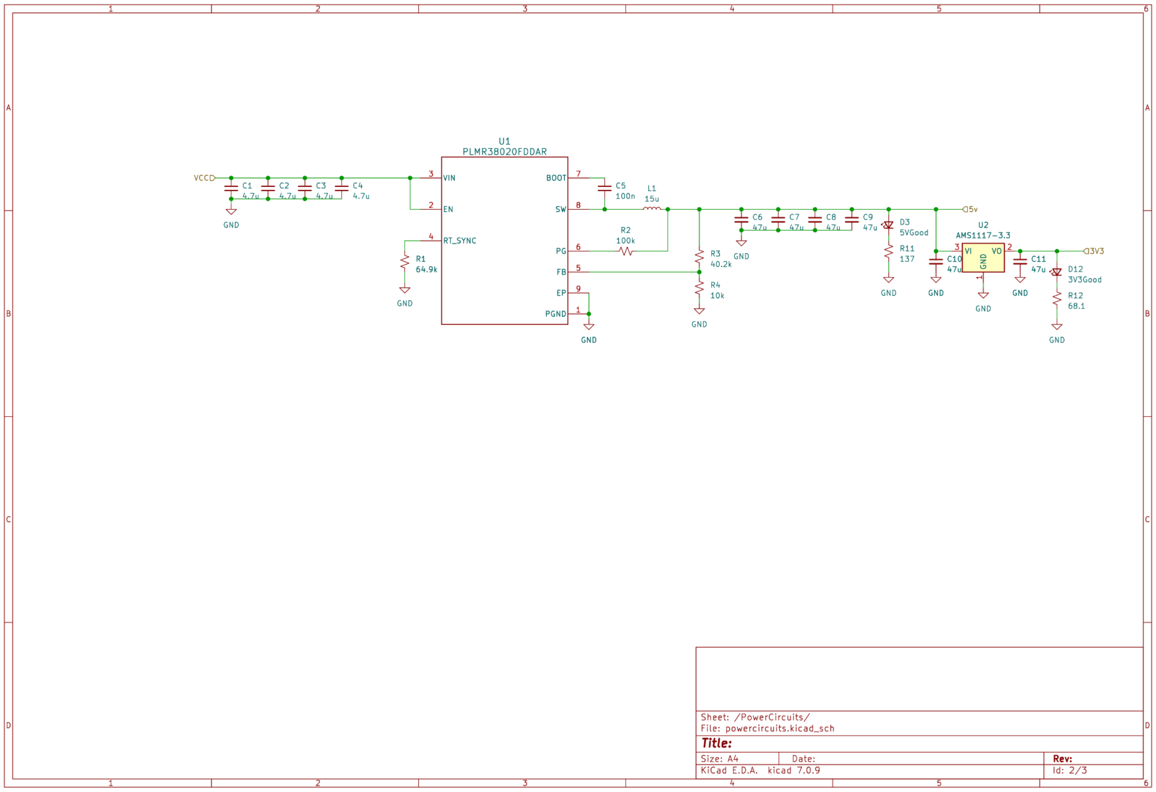
$$C_D \approx .9$$

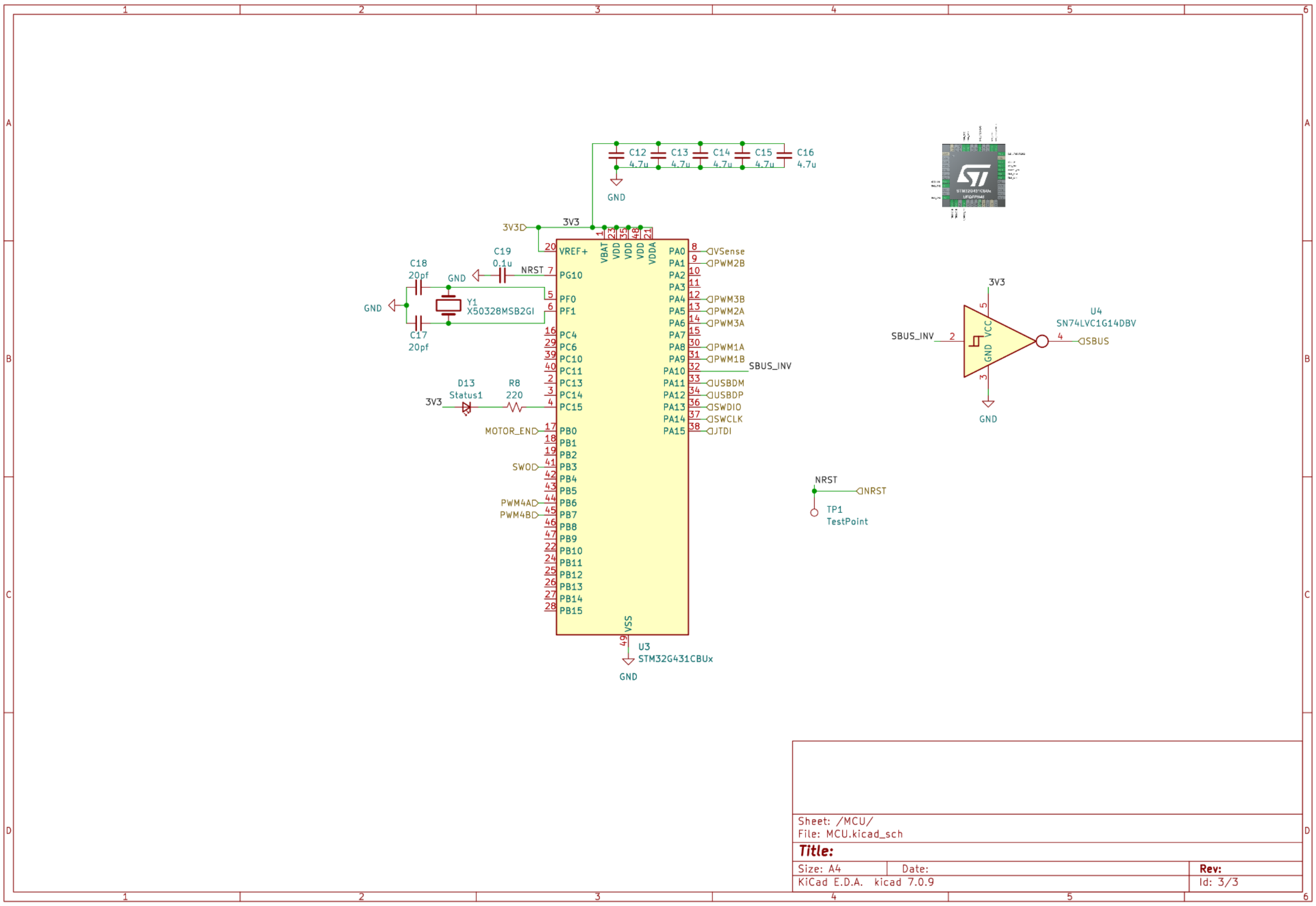
$$\rho_{seawater} = 1026\, kg/m^3$$

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

Appendix G: Electrical Schematics






C12
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C13
4.7u
C14
4.7u
C15
4.7u
C16
4.7u
GND
3V3
3V3
VREF+
VBAT
VDD
VDD
VDD
VDDA
C19
0.1u
NRST
GND
PG10
C18
20pf
GND
Y1
X50328MSB2GI
PF0
PF1
C17
20pf
PC4
PC6
PC10
PC11
PC13
PC14
PC15
D13
Status1
R8
220
3V3
MOTOR_END
PB0
PB1
PB2
SWOD
PB3
PB4
PB5
PWM4AD
PB6
PWM4BD
PB7
PB8
PB9
PB10
PB11
PB12
PB13
PB14
PB15
VSS
U3
STM32G431CBUx
GND
PA0
VSense
PA1
PWM2B
PA2
PA3
PA4
PWM3B
PA5
PWM2A
PA6
PWM3A
PA7
PA8
PWM1A
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PWM1B
PA10
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USBDM
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USBDP
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PA14
SWCLK
PA15
JTDI
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