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From: EcoSnails: Ashley Ortenburg, Alisha Patel, Tianze Hu, Melissa Peters
Project Title: Mollusca Inspired Microplastic Removal Robot
Sponsor: Maha Haji, Assistant Professor, University of Michigan Department of Mechanical Engineering
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Subject: Executive Summary

PROJECT DEFINITION AND BACKGROUND

Microplastics are harmful to the environment and humans, but are difficult to collect. Current plastic removal processes focus on collecting larger plastic pollution, while existing microplastic solutions are not sustainable or highly effective. We were tasked with designing and prototyping a sustainably-powered, mollusk-inspired robot that will be able to efficiently draw in and collect microplastics from a lake's surface and is remote-controllable. Additionally, we will simulate how the full-scale robot will operate to optimize its collection and storage mechanisms. Prior work includes a bench-top testing setup that focused on the undulating plate mechanism and a lab-scale prototype that focused on integrating autonomous controls using cameras and sensors.

KEY USER REQUIREMENTS

Category	User Requirements
Self and Sustainably Powered	Generates and stores sufficient power for operation
Collects microplastics	Collects and stores microplastics within 0.1 mm to 5 mm diameter
Floatation	Net buoyancy force is greater than 0 at all times
Stability	Must be stable at maximum pitch and roll angles

SELECTED CONCEPT & FINAL DESIGN

Our final design consisted of propellers for propulsion, pontoon-style floats for flotation, and solar panels for energy generation. Additionally, it also has an undulating plate that will draw microplastics into the microplastic container, which consists of 0.1 mm mesh to trap the microplastics, along with a 5 mm mesh at the front that will allow microplastics to be collected while preventing larger debris from entering the device. The microplastic container also has different components within. It has a gear system to actuate the undulating plate and a one-way gate valve to allow plastics in and keep them in, even when the system is off or the water is flowing in the reverse direction. Finally, it also has a waterproof box for the electronics of the system, including a battery to store energy for times when the solar panels are unable to generate sufficient energy, a Raspberry Pi computer to control the device, and other necessary electronic components.

MANUFACTURING PLAN AND COST

Using the details from our final design, we anticipate the full-scale robot to cost roughly $2,000 to manufacture. It will use sustainable materials that are reliable and safe and will not release microplastics or other harmful toxins to the environment.

ANALYSIS AND TEST RESULTS

From our engineering analysis and simulation work, we found that the proposed design will meet our power, flotation, and stability requirements. Alternatively, from our simulation work and prototype testing, we found that further work must be done to increase our microplastic collection rate.

DESIGN CRITIQUE AND CONCLUSIONS

Overall, this project worked to design a sustainable microplastic collection robot design that integrated stakeholder input, engineering analysis, and ethical and environmental concerns. Due to time constraints, the prototype functionality, empirical testing, and depth of simulations were only partially validated. While this design has a strong potential to work, further testing and optimization are required to fully verify long-term performance and viability.

Mollusca Inspired Microplastic Removal Robot

By:

EcoSnails: Ashley Ortenburg, Melissa Peters, Alisha Patel, Tianze Hu

Section Instructor: Dr. Maha Haji

Sponsor: Maha Haji, Assistant Professor, University of Michigan Department of Mechanical Engineering

University of Michigan - ME 450, Fall 2025

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ABSTRACT

Microplastics are harmful to the environment and humans but are difficult to collect. Current plastic removal processes focus on collecting larger plastic pollution, while existing microplastic solutions are not sustainable or highly effective. We were tasked with designing and prototyping a sustainably-powered, mollusk-inspired robot that will be able to efficiently draw in and collect microplastics from a lake's surface and is remote-controllable. Additionally, we will simulate how the full-scale robot will operate to optimize its collection and storage mechanisms.

TABLE OF CONTENTS

PROJECT DEFINITION AND BACKGROUND 1
KEY USER REQUIREMENTS 1
SELECTED CONCEPT & FINAL DESIGN 1
MANUFACTURING PLAN AND COST 1
ANALYSIS AND TEST RESULTS 1
DESIGN CRITIQUE AND CONCLUSIONS 1
ABSTRACT 2
TABLE OF CONTENTS 3
PROJECT INTRODUCTION, BACKGROUND, & INFORMATION SOURCES 5
DESIGN PROCESS 8
DESIGN CONTEXT 10
Stakeholders 10
Social 13
Intellectual Property 14
Environmental & Ethics 14
Power Dynamics 15
USER REQUIREMENTS & ENGINEERING SPECIFICATIONS 16
CONCEPT GENERATION 19
CONCEPT SELECTION PROCESS 24
SELECTED CONCEPT DESCRIPTION 28
PROBLEM DOMAIN ANALYSIS AND REFLECTION 30
Hydrostatics/Hydrodynamics Analysis and Iteration 30
Drag Force and Propulsive Power 32
Electrical Power Analysis 34
Algae Growth Analysis 36
FINAL DESIGN DESCRIPTION 38
VERIFICATION AND VALIDATION PLANS 41
Verification Plan 41
Prototype 42
Simulation 44
Power Simulation 44
Microplastic Collection and Distance Traveled Simulation 45
Verification Requirements and Specifications 47
Validation Plan 52
PROJECT PLAN 54
Critical Path 57
Anticipated Challenges 58
Domain Analysis 58
DISCUSSION 59
Problem Definition 59

Design Critique 60
Risks 60
REFLECTION 60
Health, Safety, Welfare, and the Global Marketplace 61
Culture, Privilege, Identity, and Style based Team Interactions 61
Inclusion and Equity 62
Ethics 62
RECOMMENDATIONS 63
CONCLUSION 63
Acknowledgements 64
BIOGRAPHIES 65
Alisha Patel 65
Ashley Ortenburg 65
Melissa Peters 66
Tianze Hu 66
APPENDIX 67
A. Rectangular Hull 67
B. Circular Hull 70
C. Pontoon-style 72
D. Keel 73
E. Miscellaneous 77
F. Verification Plan Methods 80
G. Build Design Bill of Materials 87
H. Manufacturing Plan 88
REFERENCES 89

PROJECT INTRODUCTION, BACKGROUND, & INFORMATION SOURCES

The project sponsor, Professor Maha Haji, has tasked our team with designing a sustainably powered, mollusk-inspired robot to collect floating microplastics from the lake surface while remaining remotely controllable and scalable to full-scale operations. This matters because microplastics (<5 mm) are widespread, accumulate in surface water layers, and pose risks to ecosystems and people [1,2]. In the Great Lakes, including Lake Ontario near the Oneida Lake watershed, surface-trawl surveys show microplastic pollution across the entire basin ("basin-wide"), with debris concentrating in convergence zones, defined as regions where currents and wind-driven circulation gather floating material [1]. Toronto-area studies report significant microplastic inputs from stormwater and wastewater to nearshore surface waters [3], and sediments in Toronto Harbour and Humber Bay reveal persistent contamination hotspots [4]. Therefore, we target a lake-surface-focused, low-power, low-bycatch solution with clear, measurable specifications for the project.

Early work by Prof. Sunghwan Jung's group at Cornell University used a thermoplastic polyurethane (TPU) undulating plate system, inspired by the locomotive foot of apple snails, to study how traveling-wave deformations along a flexible plate generate thrust in shallow water (Figure 1) [5]. Their benchtop setup and companion educational robot showed that a simple oscillating plate can create surface-flow convergence suitable for educational microplastics collection (Figure 2), but the fully soft TPU construction and exposed components were not intended for long-term field deployment and raised concerns about material shedding and potential chemical leaching in water[5].

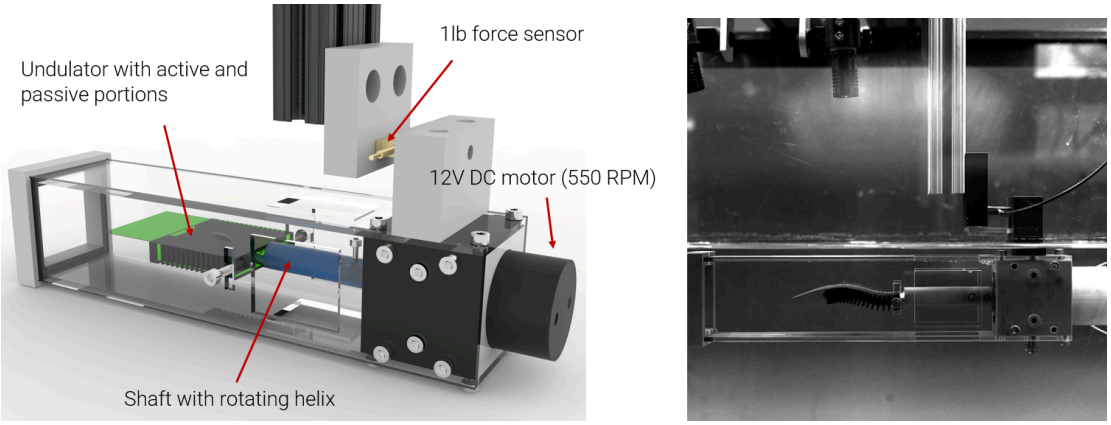


Figure 1. Benchtop testing setup for a TPU undulating plate: (left) annotated CAD showing the undulator with active and passive sections driven by a 12 V, 550 RPM DC motor via a rotating helix and instrumented with a 1 lb inline force sensor; (right) corresponding experimental apparatus in the water tank.

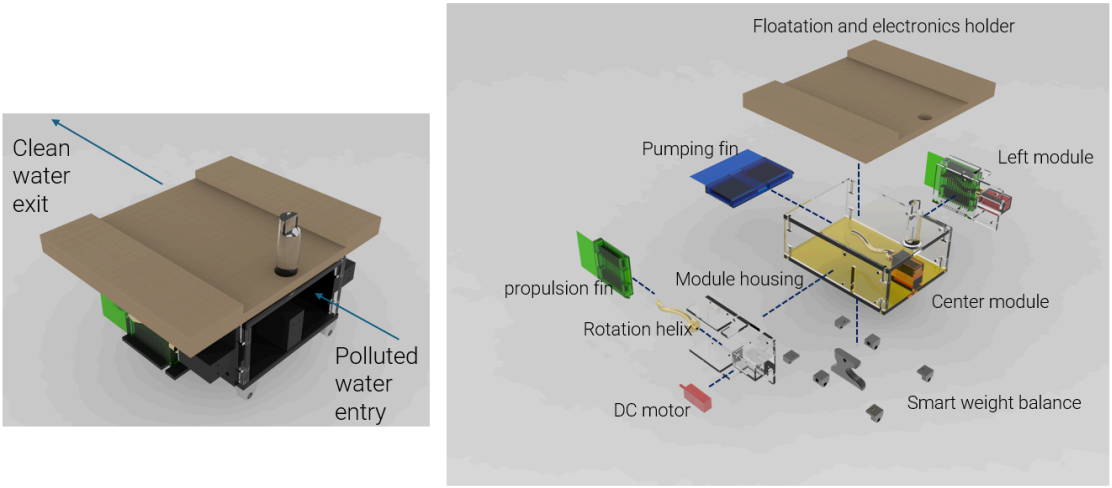


Figure 2. Educational, non-autonomous surface robot from Prof. Jung's group: assembled view with flow path (left) and exploded view of the modular components (right).

Building on that, PhD student Stephan Wagner at Cornell developed a lab-scale autonomous prototype using a Raspberry Pi, cameras, and sensors, and replaced the TPU undulating plate with a solid polylactic acid (PLA) sheet to improve robustness and ease of fabrication (Fig. 3a) [5]. In Prof. Haji's group, two students later designed a segmented **slatted undulating-plate module** (Fig. 3b) [6]. The slats were intended as a modular step toward a future metal plate that could better withstand long-term loading and field conditions. However, this **slatted-plate module** still has integration issues: many fasteners and exposed gears, a top-mounted drive, and side walls that protrude into the intake path, increasing debris-jam risk and blocking flow. For DR3, we instead emphasize non-shedding materials, an enclosed simplified drivetrain, and an unobstructed intake and collector path for the final system, while using 3D-printed parts only where they speed prototyping and fit validation.

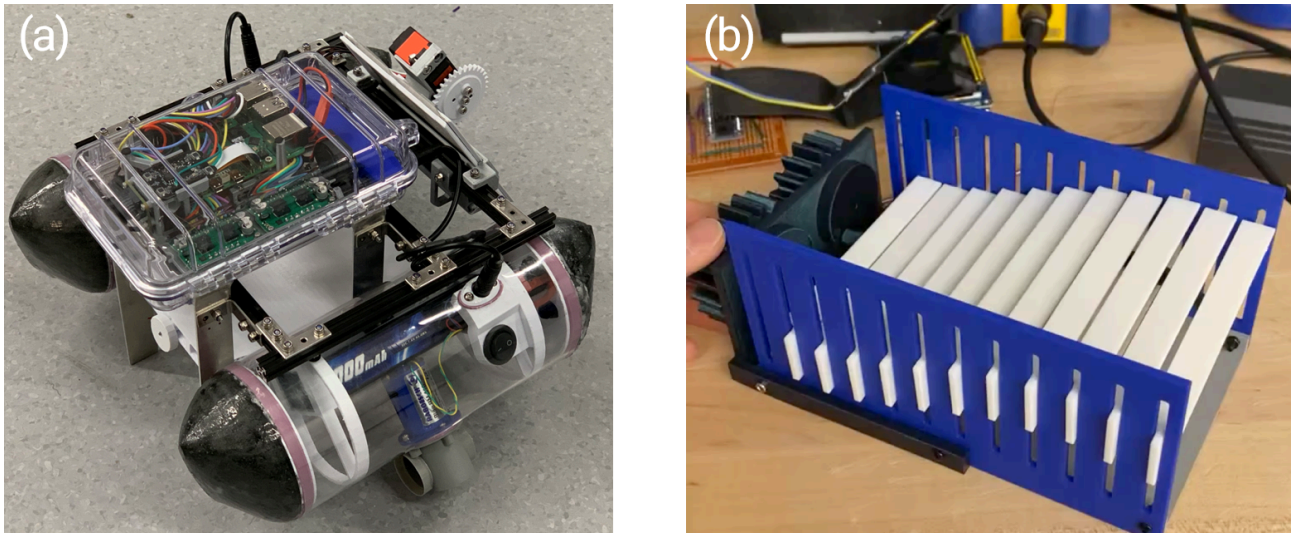


Figure 3. (a) Stephan Wagner's autonomous lab-scale robot with a solid PLA undulating plate. (b) Segmented, slatted, undulating plate module developed later.

Benchmarking against other existing devices reinforces the project's niche. Current similar robots include: skimmer robots (e.g., Beatbot) that rely on impeller-driven suction, are tuned for pool conditions rather than open-water surface layers, and can entrain non-target debris [7], the dock-mounted Seabin, which is fixed to marinas, requires shore power for its pump, and cannot target drifting surface slicks away from docks [8], and "robo-fish" concepts, which are largely lab-scale or educational prototypes with limited throughput and payload, often prop-driven mobility, and no demonstrated renewable power pathway at field scale [9]. Compared to those, our intended system (Mollusca) is differentiated by an explicit surface-layer capture focus, low-bycatch operation, renewable-ready power, low power operation, and simple 1–2-person deployment. These comparisons translate the problem motivation into targetable specifications and early verification tasks. The benchmark categories in Table 1 are intentionally the same as our key requirements so we can directly see where current solutions do or do not meet our goals: effective capture of floating debris smaller than 5 mm, minimal bycatch, low power demand, readiness for renewable-energy integration, and straightforward 1–2-person deployment.

Requirements	 Skimmer Robot	 Seabin	 Robo-Fish	 Mollusca
Floating <5 mm debris capture	✓	✓	✗	✓
Low bycatch intake	✗	✗	–	✓
Low power	✓	✗	✓	✓
Renewable energy powered	–	✗	✗	✓
1-2 person deployable	✓	✗	✓	✓

Table 1. Benchmarking of four surface-collection concepts against key requirements: ✓ meets, ✗ does not meet, – limited or unknown. Devices: Skimmer Robot (Beatbot pool-cleaner robot) [7], Seabin (fixed dock-mounted skimmer) [8], Robo-Fish (biomimetic microplastic-collector prototypes) [9], and Mollusca (this project).

Prior work includes designing two different undulating plates and demonstrating feasibility using simple robots built to test them. Additionally, some initial work has been done on the autonomous system with movement and undulating plates and basic robot design ideas and some of their

problems have been identified, such as drag due to different storage container concepts. Gaps remaining in the work include the design of the microplastic storage container and the hull and overall design of the robot as well as autonomous system design and other sensor requirements. Our designs address the design of the hull and overall robot as well as the microplastic storage container by focusing on these physical aspects and ensuring our ideas work with energy collection and usage, hydrostatics, drag force, and algae growth analysis.

Our objectives are to (1) demonstrate a benchtop, scaled-down robot in a water tank that collects less than 5 mm surface-layer debris using an undulating-plate mechanism and a one-way intake that prevents backflow and reduces bycatch, while verifying buoyancy and stability, and (2) deliver a full-scale design CAD—including intake, pontoons, thrusters, electronics enclosure, and solar-ready power system.

Our information sources combine primary inputs: sponsor and stakeholder interviews with lake managers, previous researchers on this project [6], and secondary materials: peer-reviewed Great Lakes, Lake Ontario, and Toronto Harbor studies, standards and guidance, and technical docs for competitor devices. These sources drive our requirements, specs, and verification plan. Applicable standards will be finalized with the sponsor. Still, our working set includes navigation lights for visibility for small craft under the U.S. Navigation Rules [10], marine electrical and battery safety for small-craft DC systems [11], stability and buoyancy assessment for small boats [12], and radio and remote-control compliance for unlicensed devices [13]. Contacting stakeholders and reading relevant research sources has worked best for our team. We experienced a few challenges when there were knowledge gaps with our contacts and it was somewhat difficult to find information about regulations regarding our potential deployment locations. We determined that based on research of similar locations, though in the final validation step, proper measures must be taken to ensure these regulations are correct for the exact deployment location.

DESIGN PROCESS

This section will detail how our design process model was selected and how it applies to this project. When choosing the best model for this project, we heavily considered which model would yield the best quality product in the shortest time. Additionally, we wanted to ensure that the chosen process included steps for iteration and systems engineering. These were the most crucial factors because the project must be completed prior to the end of 2025 and therefore, the team must be very strategic with how time is spent by minimizing the cost of late design changes.

From these requirements, there were two main models that the team considered using. The first model was the ME 450 model which was shown on the first day of class and it focuses on iteration between stages and continuously gathering information, applying engineering principles, and considering the problem context throughout the design process. The second model was the V-model, and it focuses on creating validation requirements for each step to ensure product quality and catch design errors earlier on [14]. We found that, for our project, it would be most useful to use

a portion of the standard ME 450 design process that includes the problem definition, concept exploration, solution development & verification, and the "ribbon" steps as shown in Figure 4.

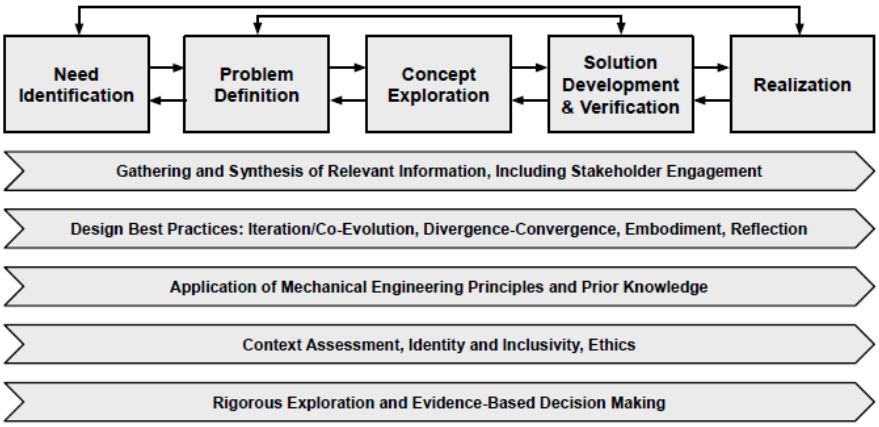


Figure 4. This is an image of the design process model [15] that has been followed so far by Team 2. It is important to note that the need identification and realization steps should be excluded from the team's design process model because this is a semester-long project and the scope of the project was preselected and does not include time for mass producing the product.

This model is a better fit for this design problem because it will allow the team to iterate between each step and would help the team focus on making changes while the design cost is low, whereas, following the V-model would cause us to have a higher design cost when making retroactive changes. The inclusion of the ribbons, specifically, convinced the team to pursue this model because the ribbons would allow the team to constantly apply stakeholder input into the design and interweave the social and environmental contexts into the design process.

Moving forward, the team has completed the problem definition and concept exploration phases and are entering the solution development & verification stage. The stage definitions will help promote the development of a high quality and effective design while ensuring that our team is taking a structured approach during each phase of the design process. The team will continue to use the ribbons to ensure that inclusivity, ethics, and stakeholder expectations are being considered as the design progresses. To achieve this, we plan to set up meetings with a few of our stakeholders to get their opinions on the design direction that was chosen by the team as well as to get advice about how to solve issues that we may run into when pursuing this design.

DESIGN CONTEXT

The design context section explores the broader context of the project, as it influences the design. This includes stakeholders who have their own input, to society, intellectual property, the environment, ethics, and connection between everyone involved.

Stakeholders

Many stakeholders have been identified throughout this project. There are many who work directly on various parts of the project, some who fund us, and others who will be impacted more by the solution but may not be intertwined in the project. Figure 5 shows the level of interest compared to power and influence of each stakeholder. This helps determine who to keep closer and work more directly with, and who needs to be in mind, but may not need direct input on the project. Figure 6 displays the connection to the problem for each stakeholder. Primary stakeholders are directly affected by the problem and solution, secondary stakeholders are indirectly affected, and tertiary stakeholders can affect the solution's success, but are not affected by either the problem or solution.

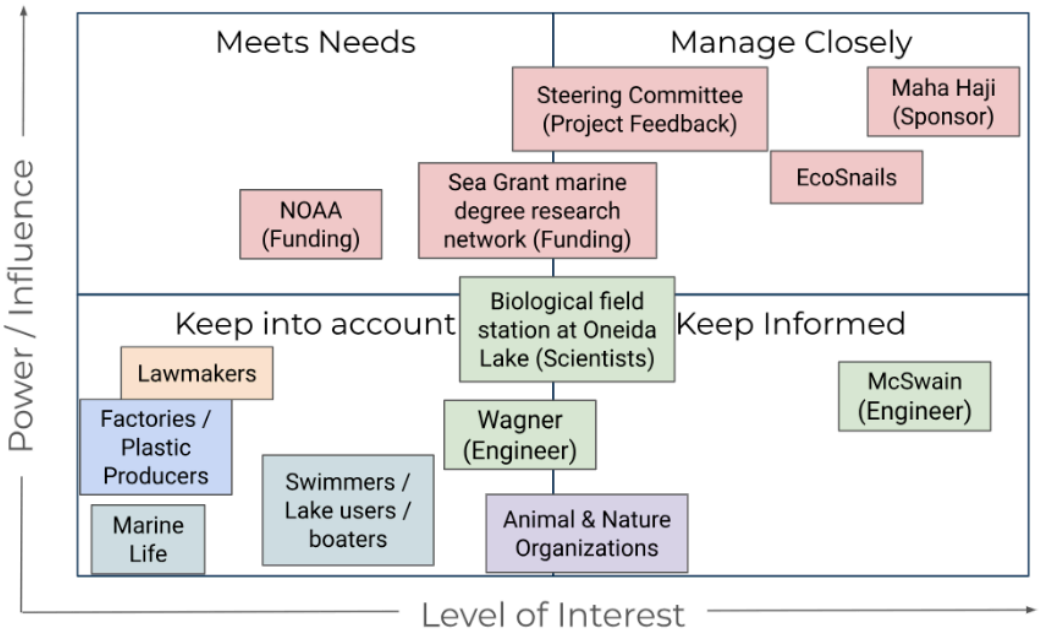


Figure 5. Stakeholder map based on level of interest compared with level of power and/or influence of each individual or group. These get separated into four boxes: "manage closely" for high interest and high power, "meets needs" for low interest and high power, "keep informed" for high interest and low power, and "keep into account" for low interest and low power.

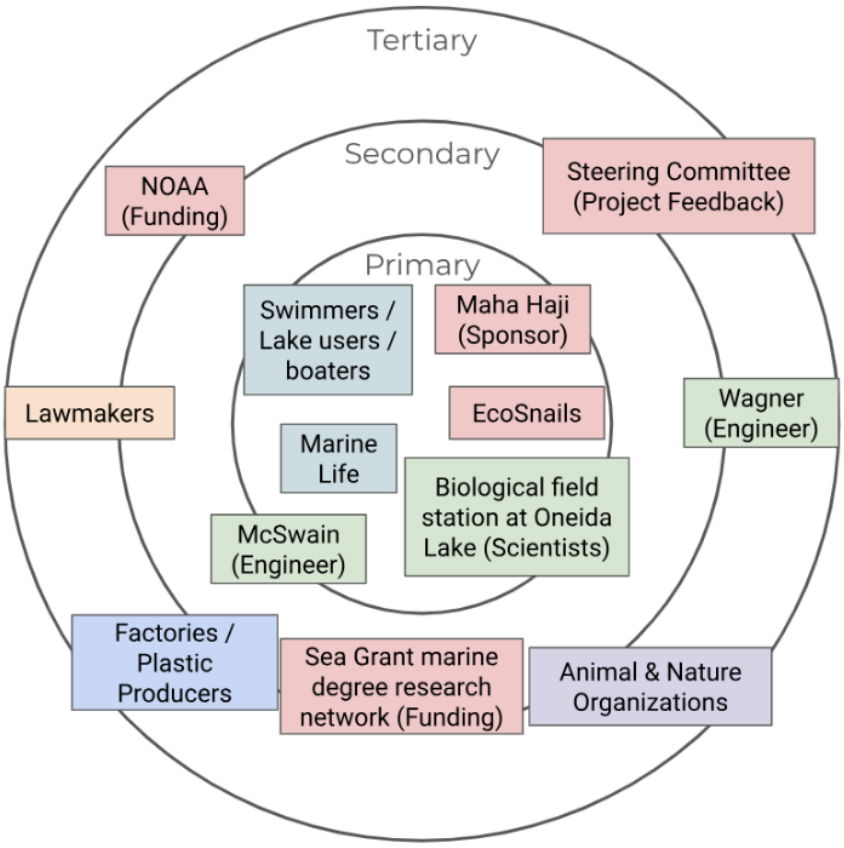


Figure 6. Stakeholder map based on directness to the problem of each individual or group. Primary stakeholders are directly impacted by the problem and solution, secondary stakeholders are indirectly affected, and tertiary stakeholders are outside the immediate problem context but may influence the solution's success.

Dr. Maha Haji is our most interested stakeholder and has the most power and influence; we stay in close contact with her as she helps us connect with others in the project and is impacted in all ways by managing and organizing multiple parts of the project. She is a primary stakeholder as she is directly affected by the problem through her work. We continue to communicate with her multiple times a week.

The project steering committee is a tertiary stakeholder who provides feedback throughout. They feel positive about the project as they are giving advice on it and want to improve the plastic in our waters. We review their meeting materials to ensure we are on the right track and communicate through Haji to keep them informed.

Next, the scientists at the Biological Field Station at Oneida Lake, including James Watkins, work with us to help build our understanding of the environment and regulations of the planned lake deployment site. They are a primary stakeholder as they work directly with the lake; they are interested in seeing what is eventually designed, as well as controlling the lake regarding laws and safety through the design, use, and disposal processes. Communication with Watkins occurs primarily through email as questions arise, though this is approximately monthly. Additionally, we

are looking at other deployment regions and are completing our own research of those areas, so his information is valued strongly for Oneida lake and weakly used for extrapolation with other sites.

Our team, the EcoSnails, is another primary stakeholder, as the one responsible for completing the project and finding the solution for the optimized hull design. We are positive about it because we are working hard on it and want it to be the best possible solution. We ensure the complete process is better for the environment than the requirements to build it.

Additionally, two other engineers and stakeholders, Georgia McSwain and Stephan Wagner, are working on optimizing different components of the final robot. We communicate with them occasionally to understand the various parts and the best methods for the design. McSwain's part is much more closely integrated with our work, as she works on modelling the full-scale undulating plate design that must fit within the hull. Stephan works on autonomous testing with a small lab-scale robot, so the physical-side is less important to him. Therefore McSwain is much more interested, and informs us of any new observations, as a primary stakeholder. Wagner explains his work to give more background, but is a tertiary stakeholder, as his project is more distant from our work. They will both use our hull discoveries in updated prototypes of robots, whether it be lab-scale or full-scale. McSwain attends and gives feedback on our design review presentations, staying well connected with us and we continue to connect mostly through email, though meetings may occur if found needed. Wagner has more distant work, so we communicate less with him.

The Sea Grant Marine Degree Research Network is a part of the National Oceanic and Atmospheric Administration (NOAA), and they provide funding for the project as tertiary stakeholders. As we are a small part of the project, we do not currently contact them directly, rather our strong communication with Haji allows us to find others in the group who can inform us directly about any concerns that arise.

Another group of tertiary stakeholders are lawmakers in the area. The lawmakers control the regulations regarding the environment and other factors. As we do not have a decided on deployment location, the exact groups have not been identified, though we expect there to be local, state or province, and federal lawmakers. They can change and make laws that affect our deployment requirements. They may feel either positively or negatively impacted by the project, depending on their views, though cleaner waters ultimately help everyone. We keep in contact with Watkins for any updates and information on Oneida lake, but as deployment approaches, we will ensure proper communication is made to follow all rules and regulations while staying in good graces.

Next, we have factories and plastic producers. They may not notice any direct effect on them and feel neutral, as tertiary stakeholders, as we are working on the other side of their plastic waste disposal. Though the cleaner waters may cause changes to their allowances and methods of disposal. Our manufacturing will include minimal parts from the plastic producers, though other manufacturers will receive business for the prototyping and ultimate building of the robots.

Lastly, swimmers, boaters, and other lake users, including marine life, have an interest in the project as they appreciate cleaner, safer waters, and are directly impacted by the project—or primary stakeholders. They do not hold much power, however, though with them in mind, we ensure the robots are safe to be around and improve the environment they are within. They feel positive about the removal of microplastics, but may find the addition of the non-natural robots intrusive into their spaces. They will be contacted as deployment approaches, but limited contact will be made before.

Overall, Haji has connected us with many different stakeholders and sources of information, and she continues to be the most influential person we communicate with on the project. All those who actively work on the project feel positive about it. We will continue to connect with stakeholders as we have more questions.

Social

Beyond the interest of the sponsor, society as a whole wants to keep the Earth's water clean. This allows for better and safer swimming for humans and animals, cleaner drinking water, and more beautiful nature. With these improvements, people and animals should become less sick due to microplastics and their effects on the body. It will also create a less waste-filled environment with better-looking beaches and waterways. Figure 7 displays microplastics from the Great Lakes which hurt marine life, humans, and everyone around.



Figure 7. Microplastics found on a Great Lakes beach. [16]

Based on prior interviews with the sponsor, they value the social and human aspect of the project below the environmental impact, but above education, and finally profit. The main priority has always been cleaning the water and maintaining the environment to ensure better all-around quality for usage for all. This includes humans, marine life, and all industrial usage. The robots are deployed in lakes where the water flows out to the ocean to attempt to collect it before it gets diluted and becomes more difficult to collect. It has always been based on cleaning the environment, but the reasons for the need for a clean environment are based on society and water needs. Education is prioritized third, as it will help future projects help the environment and work

on similar issues. Previously, some people have worked on strictly educational models to determine optimal designs and teach others the impacts and possibilities of the mechanisms. Lastly, the profit has been the lowest priority, as although there is a cost limit, this was based on limited funds, rather than increasing profit. The importance of this project lies in the environmental improvements and the health of the world around us.

The order of these impacts our design as we are more focused on efficiency and the environmental costs of the hull and power requirements to move. This overrides the effect on people around. Given that we achieve the requirements to be safe, we will focus less on the aesthetics humans will see while using the lake, and more on the functionality. This may feel like a negative impact on humans, but with the plastic removal, society will overall be affected positively.

Intellectual Property

Intellectual property (IP) has not played a significant role in the project so far. This is a more research-based project and less secrets within the process. Applicable IP protections could include patents and copyrights which could be applied to different components of the robot, or the robot itself. The intellectual property created through the project is owned by the individuals who create it, as defined by the University of Michigan policy [17].

Environmental & Ethics

There are many requirements from the environmental side. Most importantly, the robots must help the environment more than they cause damage. This makes more requirements on sustainable material sourcing, energy production and usage, and specific material choices to eventually build with.

The materials chosen will be based on two things—they are sustainably sourced and whether they will hold up in the lake environment during use. For sustainable sourcing, determiners will include the costs to the environment of the parts becoming waste if not used in the robot initially or if it is recyclable after use on the robot. Additionally, the materials must hold up in a lake environment—any material will go through testing to determine waste created from deterioration, whether corrosion, fatigue, or overload, within a lake environment, and how much harm that creates to the area around. Using this information, it will be determined whether the material is worth using for the improvement it adds or makes up any possible improvement in pollution it releases itself. Sustainability will also be weighed during the manufacturing process, as well as understanding scrap waste production and disposal processes of that as well as energy requirements for production.

Less sustainable aspects of the design can be made more sustainable by choosing better materials, sourcing those materials and the production, and determining energy sources used in the pipeline for manufacturing. Through ensuring materials and production are sustainable for life in the water and the possibility of parts lost in the water, the disposal processes are also strongly linked sustainability. We will ensure the robot can be recycled or will cause more benefit than harm by collecting more microplastics than releasing pollutants. Some of these changes may cost more as

they can be more expensive materials or processes to ensure cleanliness. Additionally, some of the components may be less efficient in actual use, but this will again be based on weighing the benefits and drawbacks of each idea and what effects they cause.

There should be limited ethical dilemmas regarding this project. We will have to ensure all decisions are made to improve the environment most, rather than what may be easiest. This can create more work but will ultimately improve the design and overall project. As our main goal is cleaning the environment, ensuring the harm production causes to the environment stays minimal, through waste and carbon neutrality are important values. When decisions are made, we will ensure we are working towards the best possible response, rather than what may seem easier, and ensure ethics are kept in mind.

The local community lake users, including boaters, swimmers, and marine life, may not like the look of the robots, but similar to the prisoners' dilemma, the not-as-great look with the robot will lead to better outcomes than without it and better lake viewing. Oneida lake is currently used primarily for recreation, but has a research station where different designs, like remotely operated buoys for environmental data collection, are implemented, so this robot would not be out of the ordinary if placed within the current research area. The community appreciates the work the Biological Field Station completes, so staying with them and Cornell will keep community approval. Overall, the ethics are good for the deployment as there will not be too much affect to the lake and community.

Our personal and professional ethics expected to uphold by the university and future employers are built up through this project, as we focus on environmental improvements and building those possibilities. There are limited factors that could create unethical decisions within this project.

Power Dynamics

There are many different power dynamics throughout the project with all the stakeholders. First, our project sponsor is the same as our instructor and mentor. This creates an interesting dynamic as there is more information based on our closeness to those leading the project but also teaching the class and informing our decisions. This can cause less creativity in the design process as they may imagine previous prototypes when recommending various solutions or directions to go in. Additionally, other stakeholders who work on the project have been completing various, distinct parts for some time now and as newcomers, we have an interesting experience learning from everyone and what they have already learned.

This disconnect stemming from not creating enough space for various stakeholders’ ideas and questions, including those directly involved when it is deployed, may cause a disconnect between what we create and what they wish to see and interact with. Additionally, as our sponsor will not be a primary end user, we may unintentionally misinterpret or overlook requirements, though through extensive communication with multiple stakeholders, we attempt to decrease any possible divide.

USER REQUIREMENTS & ENGINEERING SPECIFICATIONS

This user requirements (UR) and engineering specifications (ES) section will delve into what our project's requirements are and how we translated these requirements into engineering targets. This also includes how we determined the project requirements and engineering targets, along with their relative importance.

To determine the requirements for our project, we interviewed several of our stakeholders, including our project sponsor, engineers who are currently involved in the project, and scientists at the Biological Field Station at Oneida Lake, to get a deeper understanding of what is needed and wanted for this project. After conducting these interviews, we also performed further research into the requirements from major regulatory agencies that the robot would be required to operate under, such as Coast Guard regulations and local regulations in potential deployment areas. Through this work, we have been able to translate all these requirements into quantifiable and verifiable engineering targets.

The requirements for our project can be sorted into four main categories: safety, performance, maintenance, and deployment requirements. From our interviews with various stakeholders and research, we have determined that, generally, requirements under safety and performance are the most important requirements (UR 1-4) and are the highest priority to be completed for the project to be successful. Safety and performance requirements are the highest priority for our project because they include most of the regulatory requirements and standards that, if not successfully achieved, would likely result in the device not being deployable, rendering any other achieved engineering specifications useless. While the maintenance and deployment requirements are less of a priority for the project because the device would be able to be used on the water without being fully successful in those specifications, the requirements are still important to the long-term success of the project. For example, a maintenance requirement not being met will not stop the device from being permitted to enter the water, but it will make the device less efficient and require more resources than desired. In Table 2, all of the user requirements and engineering specifications are ranked by priority and their importance to the overall project.

User Requirement	Engineering Specification	Source
1. Safe	1.1. Have a white all-round light visible from at least 3.2 km in all weather conditions 1.2. Propulsion system shuts off when an object larger than 25 cm in any direction is within 1 meter of the robot	1.1. US Coast Guard Standards [10] 1.2. Stakeholders (lake users)
2. Self- and sustainably-powered	2.1. The design needs to produce enough power to sustain its energy needs 2.2. The design must be able to store 67 Wh of surplus energy	2.1. Project Sponsor (Prof. Haji) 2.2. Developed based on electrical power needs of system

User Requirement	Engineering Specification	Source
3. Collect microplastics	3.1. Collects plastics with 0.1 mm to 5 mm diameter 3.2. Does not collect objects > 5 mm 3.3. Collects at least 3.75 kg (75% of 5 kg max) of microplastics over 30, 8-hour missions (microplastic concentration of $5x10^8$ p/km^3)	3.1. Project Sponsor (Professor Haji) 3.2. Stakeholder (McSwain) 3.3. Stakeholder (McSwain)
4. Minimize negative environmental impacts	4.1. 90% of materials used in the design are sustainably sourced and/or recyclable/compostable at end of life 4.2. Does not negatively affect marine life, swimmers, boaters, etc. by adhering to noise and heat requirements in deployment areas 4.2.1. Noise specifications: in any state of performance, ambient noise must remain less than 85 dB when measured 15 m from robot 4.2.2. Heat specifications: in any state of performance, robot must not raise the temperature of water by more than 2°C within 1 m of the robot 4.3. Less than 10% of collected material is marine life and other non-microplastic debris	4.1. Developed based on overarching goal for sustainability 4.2.1. Toronto Harbour Regulations [18][19] 4.2.2. Toronto Harbour Regulations [18][19] 4.3. Developed based on overarching goal for sustainability
5. Reliability	5.1. The design must run properly (all systems operational/functional) 75% of the time	5.1. Developed based on overarching goal for efficiency and effectiveness
6. Durable	6.1. Can complete missions for 4 weeks with at least one 8 hour mission per day	6.1. Stakeholder (McSwain)
7. Low cost	7.1. <$10,000 per robot	7.1. Stakeholder (McSwain)
8. Floats	8.1. Net buoyancy force greater than or equal to 0 N	8.1. Project Sponsor (Professor Haji)
9. Stable	9.1. Metacentric height of greater than 0 m, even when filled with 5 kg of microplastics and at maximum pitch and roll angle 9.2 Maximum pitch and roll angle of 20°	9.1. Project Sponsor (Professor Haji) 9.2. Stakeholder (McSwain)
10. Viable under operating conditions	10.1. Remains functional under maximum wind speed of 13 m/s for 30 seconds 10.2. Minimum operating water temperature of 0°C 10.3. Maximum operating water temperature of 45°C	10.1. Developed based on maximum wind speed experienced across all potential deployment locations 10.2. Project Sponsor (Professor Haji) 10.3. Developed based on component specifications
11. Easy to deploy for 1-2 people	11.1. Must be at most 45 kg 11.2. Needs to be deployable without specialized equipment 11.3. Less than 30 minutes to deploy once on site	11.1. OSHA Standard [20] 11.2. Project Sponsor (Professor Haji) 11.3. Project Sponsor (Professor Haji)

User Requirement	Engineering Specification	Source
12. Easy to maintain	12.1. Less than 60 minutes to remove any debris on external and internal surfaces 12.2. Needs to be cleaned at most once a month 12.2.1. Cleaning is required when 25% of the surface of the intake area is blocked by debris	12.1. Project Sponsor (Professor Haji) 12.2. Project Sponsor (Professor Haji)
13. Remote controlled	13.1. Robot should be continuously and consistently controllable (propeller and undulating plate) up to 300 m from operator	13.1. Stakeholder (McSwain)
14. Within size constraint	14.1. Approximately 0.5 m long x 0.4 m wide x 0.2 m deep 14.2. Holds 5 kg microplastics	14.1. Project Sponsor (Professor Haji) 14.2. Project Sponsor (Professor Haji)

Table 2. Table of User Requirements and Engineering Specifications, listed in order of priority and importance. Also included in the table is the source of the requirement, whether that be a stakeholder, a regulatory authority, etc.

As previously mentioned, within these requirements and specifications, there are several codes, laws, and standards that must be followed or met. At greater length, the safety specification includes the US Coast Guard standards for lights on water vessels from sunset to sunrise [10]. Additionally, under the requirement to minimize environmental effects, the noise and heat specifications are taken from local laws from Toronto Port Authority, which regulates the noise [18] and thermal output [19] for Toronto Harbor, which is a potential deployment location with stricter deployment regulations than our other potential deployment site, Oneida Lake. Finally, under the requirement for the device to be easy to deploy for 1-2 people, the weight specification is based on the OSHA standard for lifting limits [20].

CONCEPT GENERATION

During this phase, many concept generation and development methods were used to ensure that a wide variety of ideas within the solution space were created. We ideated in different locations, mindsets, and time constraints to ensure diverse concepts were created, as seen in the Appendix where ideas were grouped by hull design, including rectangular, circular, pontoon-style, keel, and miscellaneous body

Individual Concept Exploration

In the beginning, we each explored different methods, including SCAMPER, brainstorming, and design heuristics, to complete the individual ME 450 concept generation learning block activity and examples of the generated designs can be seen below. These methods helped us get in the mindset of creating solutions for our problem statement while also promoting creativity. Our individual concept generation activities resulted in the creation of 80 ideas. Three of the most notable ideas that came from this method are shown in Figure 8, 9, and 10. These ideas were particularly interesting because they tried to leverage different energy generation methods.

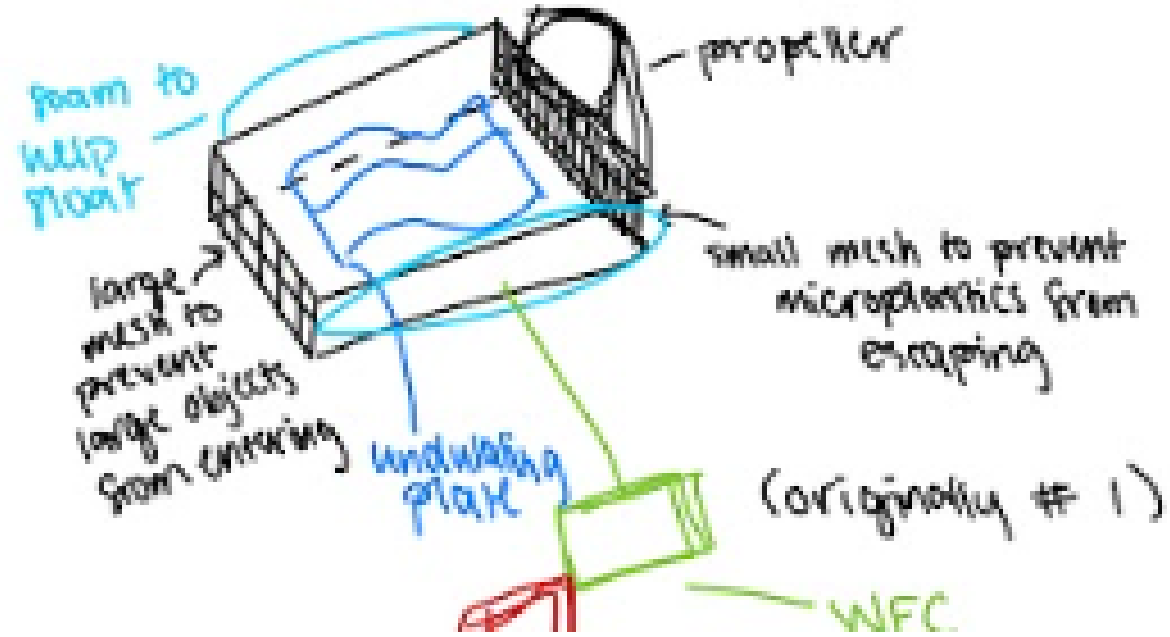


Figure 8. This design includes foam along the sides of the robot to help it float and uses a coarse mesh at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of.

As seen in Figure 8, this design is wave-powered and collects its energy using a wave energy converter that is housed behind the undulating plate on the water's surface. This design was interesting because it tried to leverage the waves that the undulating plate would create to power itself.

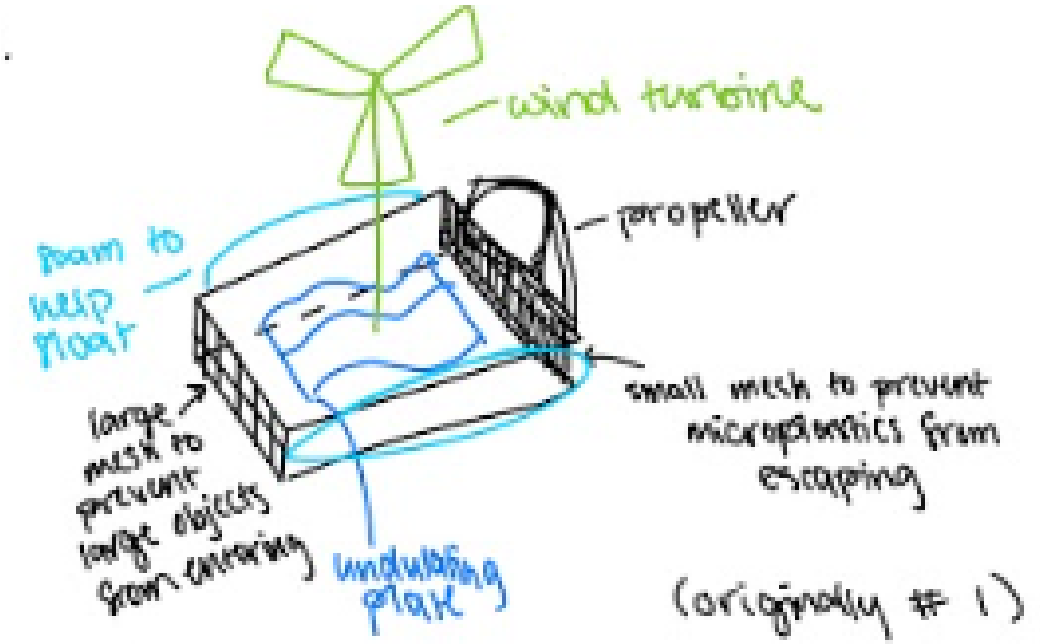


Figure 9. This design is wind-powered by a wind turbine; this design uses foam along the sides of the robot to help it float and uses a coarser mesh at the entrance and a finer mesh at the exit to ensure that microplastics do not escape from the storage area.

The design in Figure 9 uses a wind turbine that is mounted on the top face of the robot to generate energy to power the propeller and other electrical systems. This design stood out because it was one of the first designs to consider using wind energy to generate power.

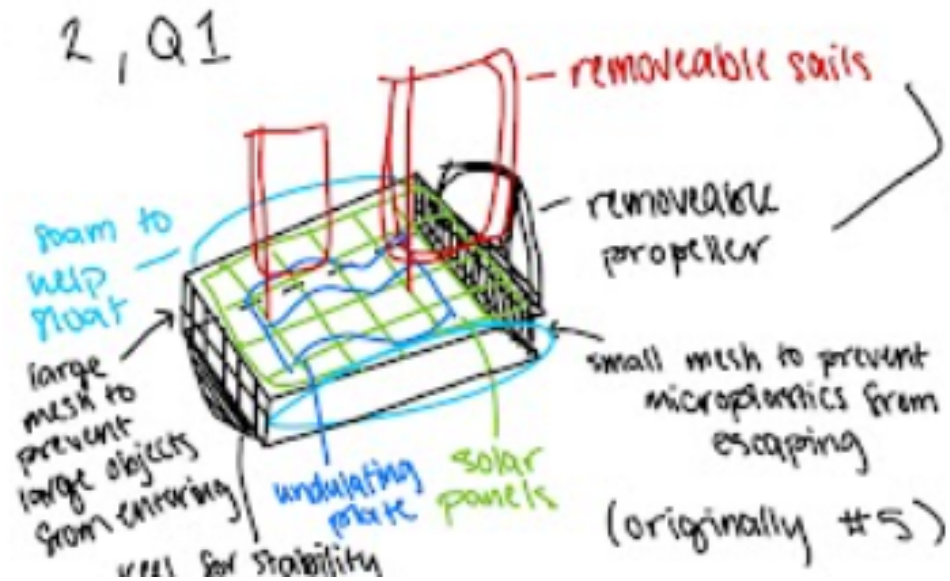


Figure 10. This design includes foam along the sides of the robot to help it float and uses a coarse mesh at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of. It is wind and solar-powered, has a keel at the base for stability, a removable sails for days that have low wind conditions, and a removable propeller for high wind speed days.

The design in Figure 10 combines solar and wind-power generation methods by using removable sails and a removable propeller design to account for changes between day to day conditions during its month-long mission. This design also promotes easy maintenance and faster repairs of the robot if one of the sails or propeller blades is damaged during its mission.

All three designs illustrate various ways we can use renewable energy to power the robot and represent the diverse thinking approach we all took when conducting our individual concept exploration. Before moving into teamwide concept exploration, all of the individual designs were compared and designs that were overly similar were discarded. The designs were deemed to be overly similar if they had the same hull profile, propulsion system, energy generation method, and filter design. After this process, we were left with about 65 designs.

Team Concept Exploration

After forming a few ideas individually, we had a brainwriting session as a group and continued generating ideas with an adjusted 4-3-5 method, from the original 6-3-5 method, as we only have four members. This method uses a cyclic method where four members write three ideas in five minute rounds, while passing the concepts around to expand upon each other's ideas. We chose this method because it emphasized equal participation from all team members and we thought that iterating off of existing ideas would help more unique ideas come to light. Our brainwriting session yielded 48 concepts and we found that the ideas shown in Figure 11 and Figure 12 stood out because of their unique hull designs.

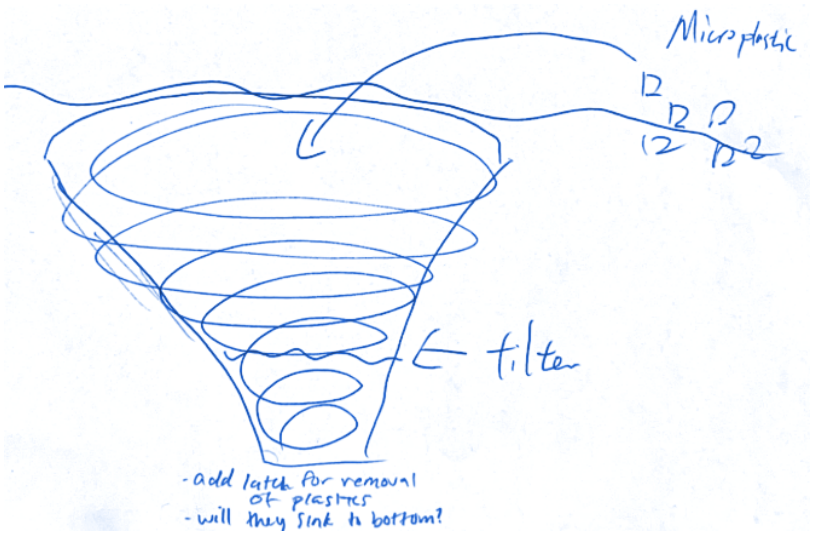


Figure 11. This design employs a vortex influenced design that has a circular shape that microplastics can enter through the top from. It has a latched receptacle that holds the collected microplastics for easy removal.

The design in Figure 11 was particularly interesting because it had a circular design and relied on most of the robot being underwater which had not been considered before. The design would create

a vortex that would pull the microplastics down to the storage area and allow water to escape from the bottom of the hull.

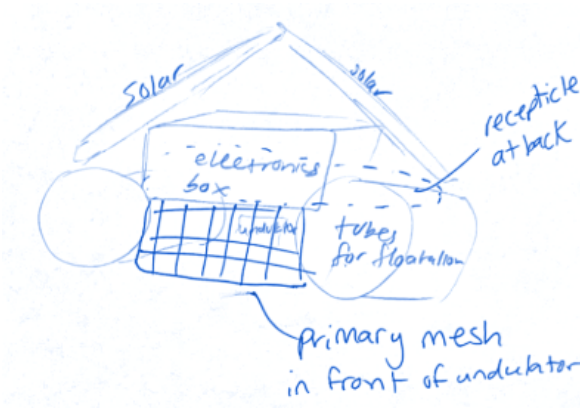


Figure 12. This drawing includes a pontoon-style hull that has angled solar panels to increase the amount of solar power that can be collected throughout the day. It also includes a larger mesh at the front of the robot so that microplastics can freely flow in and then become trapped in the storage mesh near the back of the robot.

Additionally, Figure 12 was interesting because its hull design included angled solar panels and a pontoon-style water interface. This design stood out because it made us consider if angling the solar panels would increase the number of solar collection hours within the day as it might be able to collect power when the sun is not directly overhead.

From completing our brainwriting session, we discussed how there were three main subfunctions that were present in all designs. Those three functions were the ability to move through the water, power itself, and float. We noticed that if any design failed any one of those subfunctions, the design would not be able to achieve the main goals of the project. This influenced us to pursue the morphological chart method because it requires the problem solution to be broken into subfunctions to promote connecting ideas that would otherwise be overlooked. Using these subfunctions, we created a morphological chart to help generate 10 ideas that would focus on fulfilling each subfunctions individually. Figure 13 shows an image of the morphological chart that was created by our team and includes the solutions that were generated for each subfunction.

	Able to move through water	Able to float	Able to power itself
1	Propellers	Pontoon-style	Solar
2	Sails	Keel	Wind
3	Undulating Plates	Inflatable Float	Wave Generation
4	Rudders	V-style	
5	Separate Robot Pushing	Drone Thrusters	
6	Drone Thrusters		

Figure 13. This morphological chart includes the three main subfunctions from our problem. Each subfunction column was filled in with potential solution methods for solely that subfunction.

Using the morphological chart shown in Figure 13, we were able to connect a random box from each column and combine them to create a new idea. This allowed us to create a particularly unique design, shown in Figure 14, that includes a drone that is able to move through the water by hovering above the surface as it collects microplastics with a suction system.



Figure 14. This drawing includes a drone that hovers over the surface of the water and sucks the microplastics upwards from the surface of the water.

The design in Figure 14 stood out because it stretched the bounds of what it meant for the solution to move through the water. All in all, individual and team concept exploration helped our team fully explore the solution space and produce almost 140 solutions to this design problem.

CONCEPT SELECTION PROCESS

To consolidate all of our 138 generated ideas, we used many techniques to determine the best design for our project. Starting with determining the similarities and differences between the designs by function, including using our morphological chart, seen in Figure 13, once again in a non-traditional way, we realized many parallels between the designs. Using these parallels, we were able to eliminate common concepts as described earlier in the Concept Exploration section and this brought our remaining number of concepts down to about 100. We then designed a concept map to fit the designs into four categories for the overall shape and flotation method, displayed in Figure 15. This helped us understand the basics of each design to filter and connect them to their most comparable ones, creating a more manageable set of about 40 ideas. These were grouped into pontoon, keelboat, round, and miscellaneous with about 10 designs in each section.

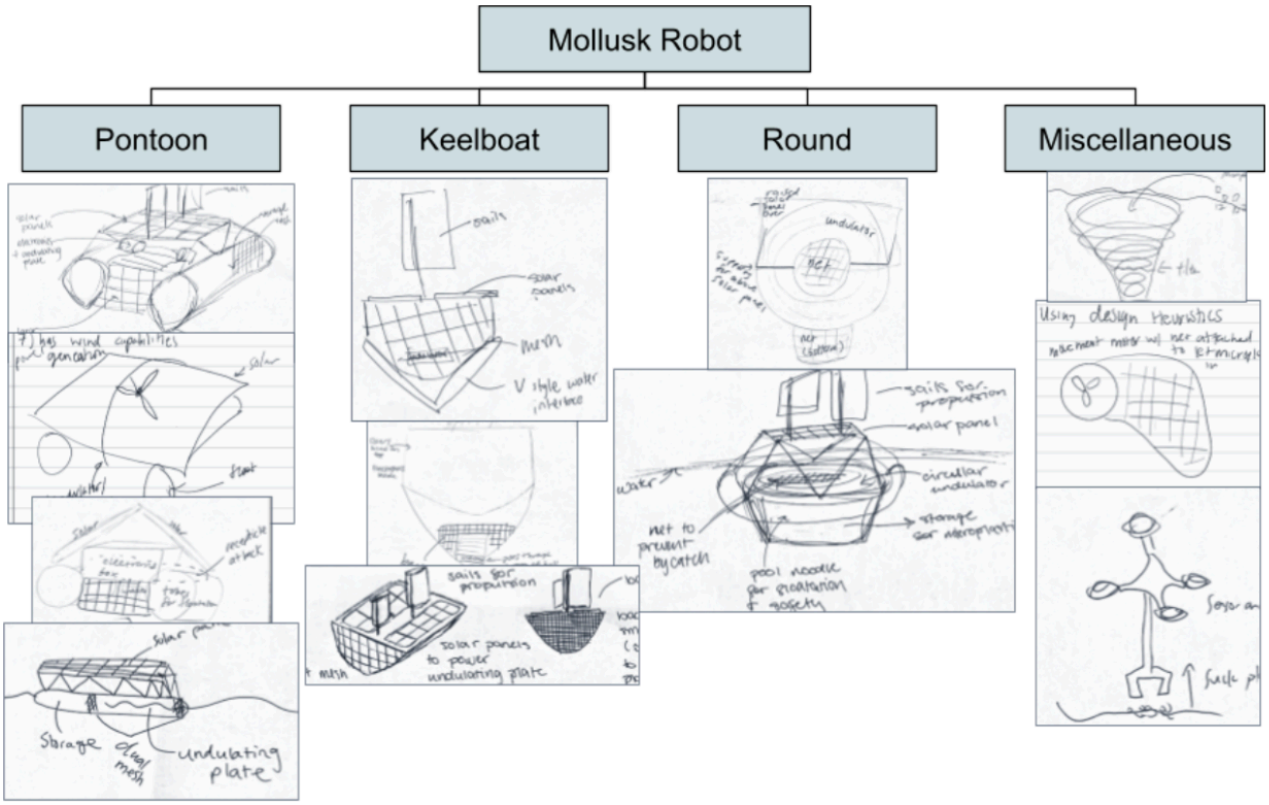


Figure 15. Concept map with many designs to help categorize them by similarities into manageable sets. Here it places the designs into one of four categories based on floatation device and basic shape: pontoon, keelboat, round, and miscellaneous.

Next, a gut check was performed with basic calculations. Calculations for the solar panel are explained in Equation 1, given the performance ratio (ɣ), panel rating (R_{panel}), peak sun hours *(PSH)*, and comparing that to the needs of the components that will probably be on the robot. Ensuring the panels collect enough energy to power the active electronics and add to its storage battery for future use. The selected panels are from Open Waters Solar, and take in 220 W per square meter with the performance ratio already included [21]. Our robot will have approximately 0.2 square meters of

panel on top; using a conservative average peak sun hours at Oneida lake of 4 hours, we calculate an average power collection of 176 Wh per day. Using this allowed us to determine if using solar panels to gather solar energy is the best choice as it is simple yet efficient in collecting renewable power. Other methods, such as wave generation and wind power, require more components and are heavier, and therefore require more energy to use and may create more instability. Small wind turbines collect energy best when the wind is over 9 mph [22]; Oneida lake and other similar lakes average around that speed, but the wind can be unpredictable [23], which is not preferable when relying on it to power the whole robot. Additionally, this size turbine is more often used on sailboats and RVs [24], so they are larger, heavier, and will risk the stability of the robot. Wave energy generation techniques are another option, though as we are deploying in smaller lakes, there are minimal waves, and therefore minimal energy to collect through those means. Through these advantages and disadvantages, we determined solar was the most efficient and best way to meet all of the requirements. This process went from three to one option for energy collection, resulting in our team having 20 remaining design concepts.

$$P = \gamma \times R_{Panel} \times PSH \quad (1)[25]$$

Next, when screening the concepts, we discarded the vortex design shown in Figure 11 and drone design shown in Figure 14 as they did not fit our requirements of floating and easy to maintain, respectively. Additionally, we discarded 15 other ideas because they had a storage design that would be very prone to clogging and causing flow collapse during operation, which is one of most critical anticipated challenges. As our designs commonly overlapped with different aspects, each design that didn't work, resulted in multiple getting removed from contention. After this screening step, our team had a total of 3 remaining concepts. These were definitely interesting ideas and may have inspired other concepts, though do not directly work with our set of requirements and specifications.

Next, a Pugh chart was formed to evaluate the top 3 remaining concepts, as seen in Table 3, to determine the best option out of the three remaining design sets. The requirements were given weights to account for different levels of importance. Each design was rated on each of the requirements from -2 to +2, with +2 being the best score possible where the design would work best for the design, and -2 being the worst, though still meeting the requirement. These weights were multiplied by the solution's score to find the final score. The keelboat design was taken to be the baseline and received all 0s. The keelboat was chosen to be the baseline, as we assumed it would be neutral at stability, deployment and collecting plastics, an overall middle of the road design compared to other potential designs.

Each requirement is rated according to their importance. This is similar to the priority rankings in the requirements above. Safety and environmental impacts are the most important as this cannot run without being safe and there is no point if it is going to release more pollutants than it collects. Reliability and durability are less important in our design as we cannot test them properly, though we try to pick components that are strong and will last. Most requirements have a weight of 4 as they are more important and are what we focus on mostly in the design. The last two requirements have lower weights as they are less involved and important in our decisions. The remote controlled

requirement is focused on a design that will not be the final design in the overall project and the size constraint is based on ease of deployment, so the size itself is less important.

Table 3: Decision Matrix with design sets scored by importance of the requirements, by corresponding weights, and ability for that design to complete it. The baseline (keelboat) design received all zeroes to be neutral. The pontoon-style boat showed to be the best design with the highest final score.

Requirement	Weight	Keelboat (Baseline)	Pontoon	Round
1. Safe	5	0	0	0
2. Self- and sustainably-powered	5	0	0	0
3. Collect microplastics	5	0	+1	-1
4. Minimize negative environmental impacts	5	0	0	0
5. Reliability	3	0	0	0
6. Durable	3	0	0	0
7. Low cost	4	0	0	0
8. Floats	4	0	+1	+1
9. Stable	4	0	+2	+2
10. Viable under operating conditions	4	0	0	0
11. Easy to deploy for 1-2 people	4	0	0	-1
12. Easy to maintain	4	0	+2	-1
13. Remote controlled	2	0	0	0
14. Within size constraint	1	0	0	0
Total		0	**25**	-1

The round design, shown in Figure 15 as the first concept in the round category, is less effective as it may collect non-microplastics, and there is not an effective way to prevent the non-microplastic particles, including animals, from getting caught in the collection bin while keeping the microplastics inside as they will continue to float. It would also be more difficult to deploy with the collection bin underneath. The keelboat design, shown in Figure 15 as the first concept in the keel category, has a lower safety factor on floatation and is less stable in the calm waters we will deploy in, while being difficult to remove the plastics once inside. With these differing factors, the pontoon-style design, shown in Figure 15 as the first concept in the pontoon category, would work best, with a score of twenty-five, over the other keelboat and round design which received 0 and -1

respectively. Once this was completed, we were not concerned with slight differences because the pontoon style design was so far ahead of the other designs.

We checked for gaps and biases throughout this process within our designs through asking other groups to see if they had any other ideas, following with displaying our ideas. We added any ideas they had and took notes of points they made to ensure we found the best solution without missing chunks of information.

Lastly, we removed the sails from our design as it was brought to our attention that they may block the sunlight from hitting the solar panels and deny power to the robot. These sails were meant for easier movement, but with the potential of blocking solar rays to the panels and raising the center of gravity point, they created more opportunity for problems with both power generation and stability.

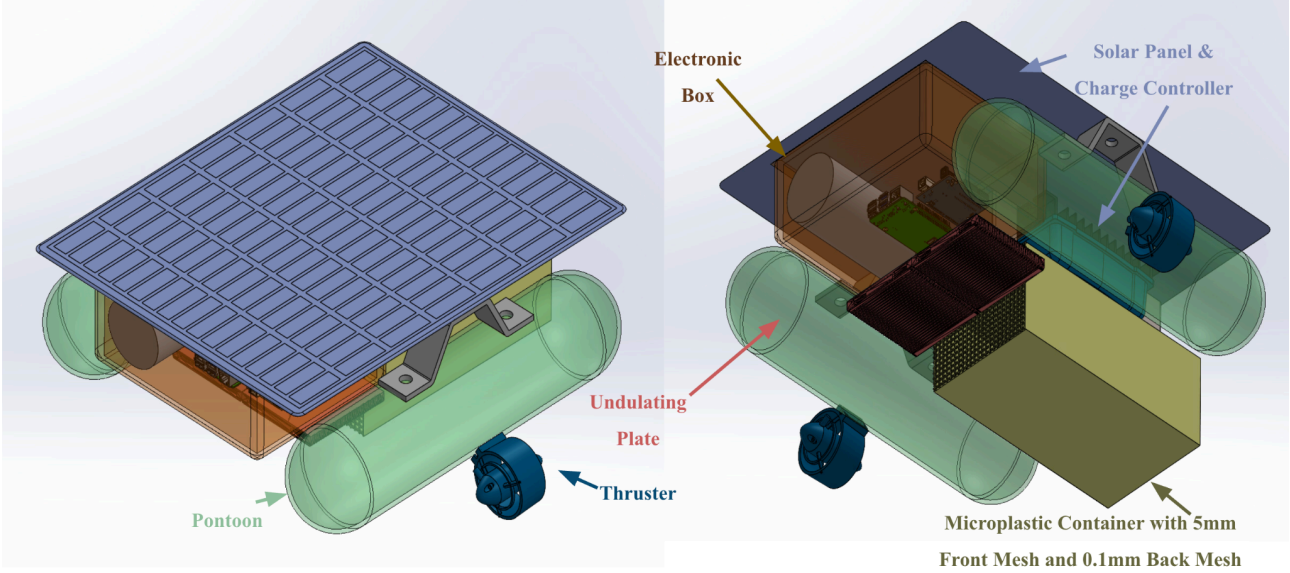
Although we did not choose our alternative designs, we learned more through them as they made us see other options and understand the requirements and improve our chosen design based on those options. It is strongly recommended that many designs are explored for learning about and clarifying the requirements and specifications and being able to pull smaller design elements from them for improvements of your chosen design.

When we were initially tasked with this project, a pontoon-style hull was proposed, though we were encouraged to explore other configurations and pathways. This initial design used solar panels atop to collect energy, with two toons, the pontoon floatation tubes, underneath. This had the undulating plate between the toons with an unknown collection device and way to hold the electronics within.

Our selected concept is very similar as it is again a pontoon-style with two toons, the undulating plate between, and solar panels on top. We adjusted the collection method with two mesh plates and a waterproof box to connect electronics sitting above the water's surface under the solar panel. This concept is justified through initial analysis with theoretical tests and the decision matrix. The pontoon-style is much more stable and modular than the other designs, helping maintenance and functionality. We see some fixation of the early idea as there has been prior research work for the project with testing using a similar design, though we did ensure this works well. The design may benefit from further concept development, but that would require a full overhaul of the project and change the prior work on the project as it may use other methods to collect microplastics.

SELECTED CONCEPT DESCRIPTION

After following the concept generation and selection process described above, along with initial engineering analysis to understand the feasibility of our top designs, we settled on the following full-scale concept, or "Alpha Design", seen in Figure 16.

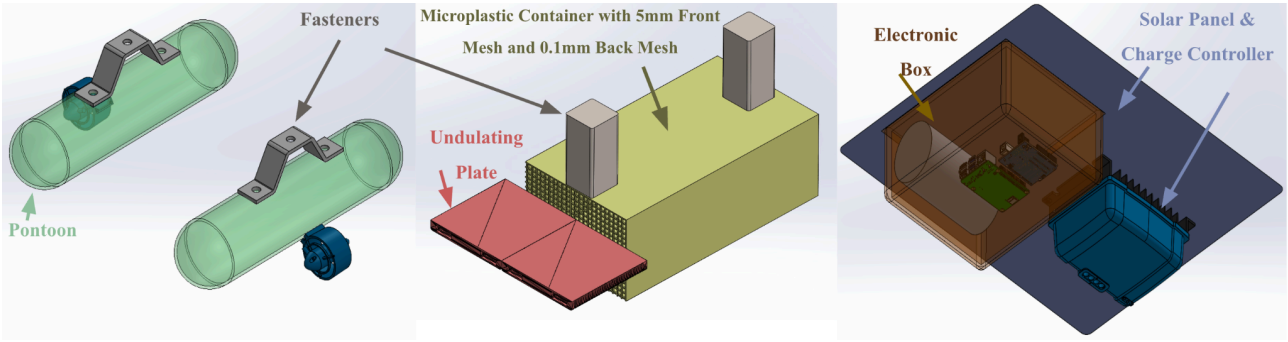


(a) (b)

Figure 16. Color Coded Isometric view of Alpha Design, (a) Bottom isometric view, (b) Topisometric view

The "Alpha Design" consists of propellers for propulsion, pontoon-style floats for flotation, and solar panels for energy generation. Additionally, it also has an undulating plate that will draw microplastics into the microplastic container, which consists of 0.1 mm mesh to trap the microplastics, along with a 5 mm mesh in the front that will allow microplastics to be collected while preventing larger debris from entering the device. Finally, it also has a waterproof box for the electronics of the system, including a battery to store energy for times when the solar panels are unable to generate sufficient energy, a Raspberry Pi computer to control the device, and other necessary electronic components.

The "Alpha Design" can be broken down into the following subsystems: propulsion and flotation, microplastic collection and storage, and electronics, as shown in Figure 17.



(a) (b) (c)

Figure 17. Subsystem Layout. (a) Propulsion and Floatation subsystem, consisting of pontoon floats, thrusters, and fixtures. (b) Microplastic collection and Storage subsystem, consisting of the undulating plate mechanism, intake mesh, and storage mesh. (c) Electronics subsystem, consisting of the waterproof box for electronics and the solar panel.

Our concept is modeled after the pontoon-style design from our concept generation and selection process with modifications to reduce the complexity with improving efficiency of the design. One modification is that the "Alpha Design", unlike the pontoon-style design, does not have sails. This change was made due to concerns that the sails would block the sunlight from reaching the solar panels, which are the main energy generation method of the device. With our detailed CAD design, which includes approximate weights and centers of gravity, along with accurate sizing, we will be able to rigorously analyze the design using the engineering concepts detailed later in the Problem Domain Analysis and Reflection section.

While the selected concept overall was not chosen due to heavy sponsor influence, some components of the concept were influenced by the sponsor. Specifically, the undulating plate mechanism was included because our sponsor had previously worked with the mechanism and found it to be successful. Additionally, the idea for the pontoon-style floats was one of the ideas that our sponsor had been considering. A more objective, and less sponsor influenced, selection process would potentially have a different microplastic collection method, but would likely have remained the same. Additionally, due to the minimal sponsor influence on the design, none of the calculations were artificially adjusted to satisfy the sponsor. This project is not truly difficult, in the sense that we are capable of understanding and completing the necessary engineering analysis along with future work in simulation and prototyping. This project is difficult, however, given the one semester constraint of ME450.

PROBLEM DOMAIN ANALYSIS AND REFLECTION

This problem domain analysis and reflection section will explore our project's engineering specifications and discuss the engineering fundamentals that will need to be understood to assess our design in relation to the specifications. Additionally, this section will also delve into the challenges that we may face when assessing whether our design meets our engineering specifications. The main fundamental engineering topics that will be critical for our project are the durability and life cycle analysis, hydrostatics and hydrodynamics analysis, the drag force and propulsive power analysis, the electrical power analysis, and algae growth analysis.

Durability and Life Cycle Analysis

As for durability and life cycle analysis, we will need to ensure that the device will be able to achieve the desired lifetime. When performing this analysis, we will need to consider corrosion from chemicals in the environment, in addition to fatigue and overload due to repetitive and excessive stress, due to waves. When looking into corrosion, our current potential deployment locations are all freshwater lakes rather than bodies of saltwater, so we will not need to safeguard against salt corrosion, but we will need to take into account other contaminants in the water. When performing this analysis, we will check the material specifications of chosen components to ensure that they are able to withstand corrosion, fatigue, and/or overload that the design may encounter. Understanding the durability and life cycle of the design will be important when assessing the requirement of the device's durability (UR5), specifically with regard to engineering specification 5.1, for which we need to assess if the design will be able to complete daily eight hour missions for four weeks. This specification may be particularly difficult to assess given that we may be able to find information on the durability of individual components, but it will likely be challenging to interpret what the durability of the entire system would be, especially when adding in custom manufactured components that will be less likely to have accurate durability information. To ensure that our design meets the durability requirements, we will carefully consider the durability rating on the components that are purchased in addition to the materials that will be used in the full-scale model.

Hydrostatics/Hydrodynamics Analysis and Iteration

Finally, through our hydrostatics and hydrodynamics analysis, we will need to ensure that the device remains buoyant and stable, despite changes in weight and center of gravity due to collected microplastics. We will need to calculate the forces involved in the system to ensure that the device remains positively buoyant, even with varying amounts of microplastics. To do this we would ensure that the weight of the water displaced by the device is greater than the weight of the device. Additionally, we will need to calculate the metacentric heights of the device, especially when the weight changes, along with the pitch and roll angles. In Figure 18, there are both stable and unstable systems which display how the restoring or overturning moments act. If the center of gravity is above the center of buoyancy, the system is unstable and vice-versa, it is stable if the center of

gravity is below the center of buoyancy. Additionally, if the metacenter is above the center of gravity, it is stable for that direction.

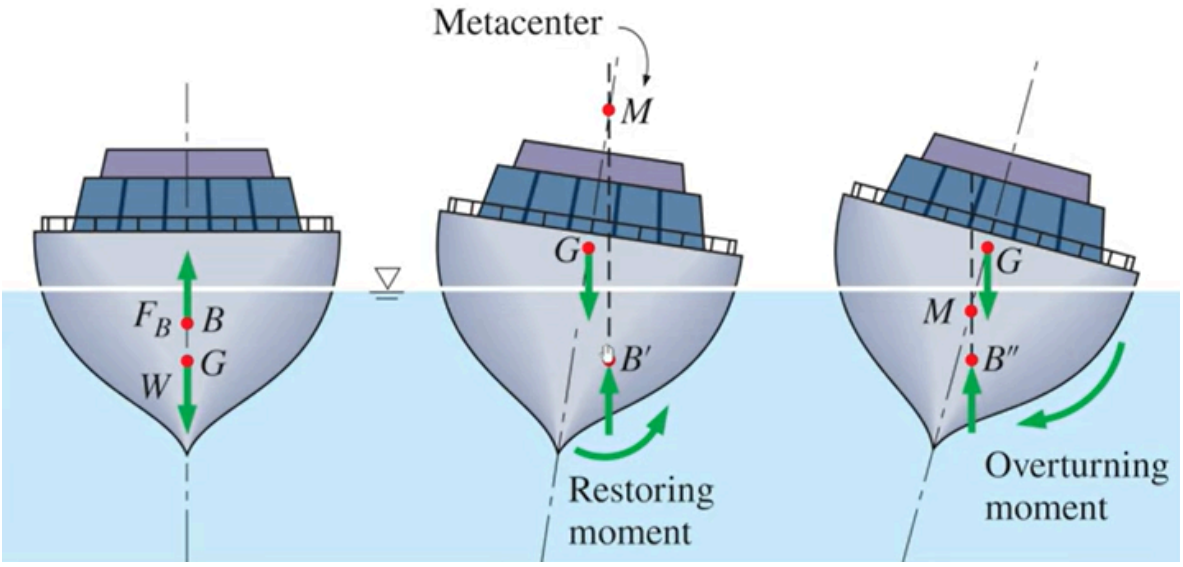


Figure 18 [27]. Displays stable (left and center) and unstable (right) conditions for a vessel. If the center of gravity is above the center of buoyancy, the system is unstable, and vice-versa, it is stable if the center of gravity is below the center of buoyancy. Additionally, if the metacenter is above the center of gravity, it is stable for that direction.

To calculate the metacentric height, we will need to first determine the center of buoyancy, *B*, by finding the geometric center of the displaced volume of water, and the center of gravity, *G*, using computer-aided design tools, of the device when the pitch and roll angles are zero. Then, we need to calculate the center of buoyancy when the pitch and roll angles are maximized, *B'*. The metacenter, *M*, is then defined as the point where the vertical line through *B* and *G* intersects the line connecting G to *B'*. Once we know the locations of these points, the metacentric height can be calculated using Equation 2, where *GM* is the distance between points *G* and *M*, *BM* is the distance between points *B* and *M*, and *BG* is the distance between points *B* and *G*. For both centers of buoyancy, *GM* needs to be greater than zero for the device to be stable due to a correcting moment. The metacentric height must be calculated for each direction: pitch and roll. They must both be positive to ensure stability.

$$GM = BM - BG \tag{2}$$

The metacentric height of the device may be difficult to calculate because the device will be a complex shape and calculating the center of gravity and centers of buoyancy will be more difficult than for a simple shape. We may be able to use computer-aided design tools to overcome these complexities.

The CAD designs were created with similar materials and weights to the proposed alpha design. Using these in SolidWorks software, we determined the center of gravity, center of buoyancy, and metacentric height which determined the stability of the robot. The center of gravity is 0.110 meters

up from the bottom of the robot, and although the center of buoyancy was below that, the metacenter was higher than the center of gravity in all directions. The center of buoyancy in the pitch direction is 0.086 m above the bottom of the robot, and the metacentric height in that direction is 154 meters up. In the roll direction, the center of buoyancy is at 0.133 m, which is above the center of gravity, so the metacenter is not needed, but was calculated at 77.5 m. Since the metacenter is above the center of gravity, also defined as a positive metacentric height, in all directions: flat, pitch, and roll, it is stable in any direction with a tilt. This helped determine the pontoon was very stable and our best hull design option. Figure 19 displays the water level when the robot is flat, and at pitch and roll angles of 20 degrees, as well as the center of gravity.

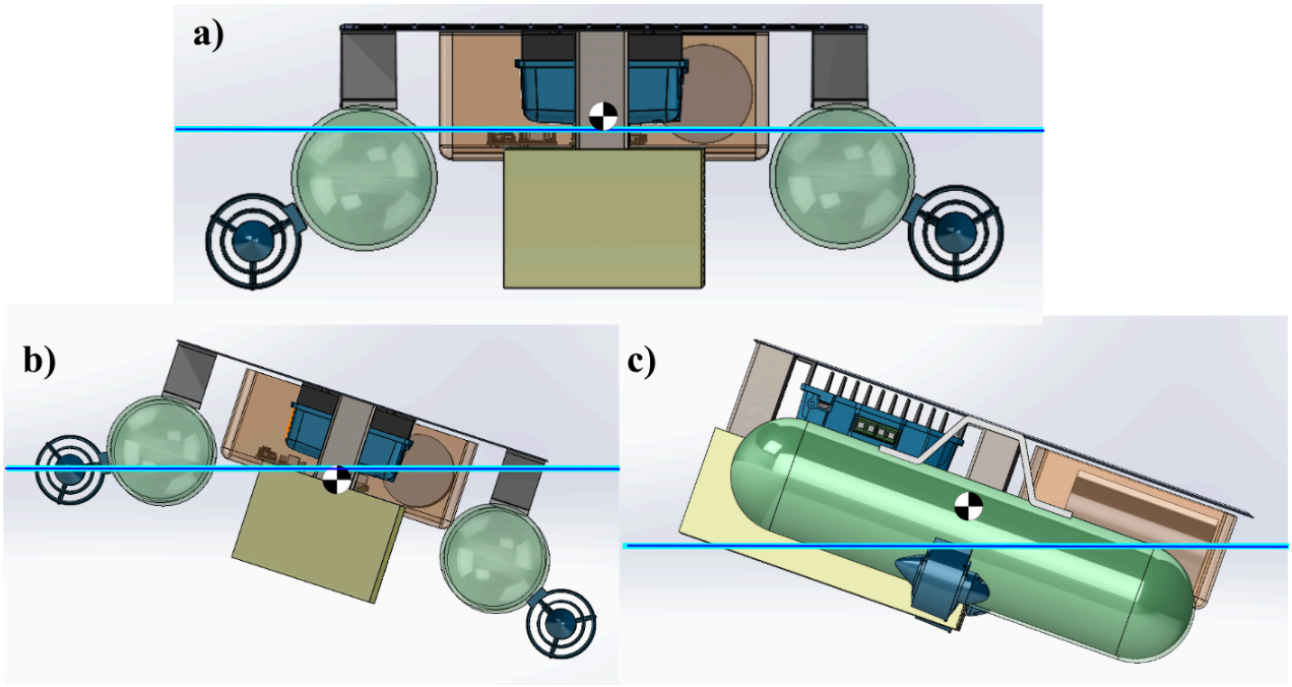


Figure 19. Water level and center of gravity on the CAD at different angles: (a) flat, (b) 20 degree roll, and (c) 20 degree pitch

Using this method, we are very confident that the design will be buoyant and stable and be accurate to the real design. Our confidence level is high, though seeing what exact types of waves occur throughout the lake could be helpful in determining whether the max pitch and roll angles should be increased or decreased. The limitations in this method include ensuring the exact electronics and their exact locations are in the CAD properly, as it may change it slightly, and it should be recalculated with those values, though we are confident that it will still pass the requirements of buoyancy and stability.

Drag Force and Propulsive Power

This subsection estimates the hydrodynamic drag across the expected operating speeds and converts that drag to propulsion power and daily energy to check feasibility against the available solar and battery supply. The analysis assumes freshwater with density $\varrho = 1000$ kg/m^3, representative of

small-lake operation. A typical pool-cleaning robot speed band of v = 0.05 – 0.20 m/s is adopted as a conservative operating range based on comparable autonomous cleaning and survey robots [29]. The pontoon frontal reference area is A = 0.063 m², with effective projected areas of 0.314 m², and 0.015 m² for the pontoon side and front plates, respectively. Drag coefficients are taken as C_D = 0.4, 1.2, and 1.3 for the pontoon front, side, and flat plate configurations, respectively—values typical of submerged blunt bodies and small-diameter cylinders at low Reynolds numbers [30]. A lumped propulsive efficiency η = 0.5 is used to include drivetrain and motor losses.

Drag is modeled with the standard quadratic relation,

$$F_D = \frac{1}{2}\rho v^2 C_D A \quad (3)[30]$$

Propulsive power is the drag multiplied by speed divided by the overall efficiency,

$$P = \frac{F_D v}{\eta} \quad (4)$$

Evaluating these expressions at three representative speeds gives concrete checkpoints. At v = 0.05 m/s, the forward drag is approximately F_D = 0.0485 N and the corresponding propulsion power is $P \approx 0.00485$ W. Over an eight-hour operating period, this totals about 0.0388 Wh. At v = 0.20 m/s, the maximum-speed case gives F_D = 0.776 N and P = 0.31 W, consuming roughly 2.48 Wh over the same duration. For turning maneuvers, evaluated at the lowest speed v = 0.05 m/s with the pontoon side exposed, the drag increases to F_{turn} = 0.47 N, giving P turn = 0.047 W. These results are summarized in Table 4 below.

Table 4. Summary of Drag Analysis

Situation	Velocity (m/s)	Drag Force (N)	Power (W)	Energy for 8 hours (Wh)
Low-Speed Forward Movement	0.0500	0.0485	0.00485	0.0388
High-Speed Forward Movement	0.200	0.776	0.310	2.480
Low-Speed Turn	0.0500	0.470	0.0470	0.376

This demonstrates that even during turning, when both hulls experience higher side resistance, the propulsion demand remains well below the continuous supply capability.

For context, the daily solar energy input from the panel array is approximately 201 Wh/day under peak-sun conditions. Even at maximum speed, the eight-hour propulsion requirement (≈ 2.48 Wh) occupies only ~1.2% of this budget, leaving greater than 198 Wh for control, sensing, and navigation electronics.

Because drag scales directly with both the frontal area and the drag coefficient, streamlining hull and appendage geometry (e.g., tapering pontoons, minimizing exposed mesh) can reduce required propulsion power nearly in proportion. Similarly, improving overall drivetrain efficiency proportionally lowers electrical demand. These relationships provide clear design levers to balance endurance, maneuverability, and solar energy constraints. We are confident that the propulsive power will overcome the drag force without using too much of the energy and it will work together.

Electrical Power Analysis

Within the topic of the electrical power needs of a system, we will need to calculate the power needs of the device with all components, which will include motors, various sensors, IMU, and more. We will have to understand the various requirements of each component, for example, voltage, current, and power requirements to successfully combine these components into an energy efficient system. Additionally, since we may use solar panels as our main power source, we will need to select the appropriate solar panels along with batteries to store excess power for later use.

Understanding the electrical power needs of a system is vital for being able to assess the requirement of the device being self- and sustainably-powered (UR2), specifically with regard to engineering specifications 2.1 and 2.2, for which we need to assess if the design is producing enough power to sustain its energy needs and if the design can store 67 Wh of surplus energy.

The quickest and easiest path to understand the power production of the solar panel is to do analysis using data from a potential solar panel supplier. To compute the available daily power, we made a few key assumptions. First, the maximum solar panel surface area we can use for this application is approximately 0.2 m^2 because this is the maximum surface area possible according to ES 14.1. Secondly, we are interested in a solar panel made by OpenWatersSolar that when taking into account the performance ratio has a panel rating per area of about 220 W per square meter [21]. Finally, near Oneida Lake in New York, there are about 4.57 peak sun hours per day in the summer [26]. Using equation 1, we were able to calculate the power produced by the solar panel in Wh, where P is power produced, ɣ is the performance ratio, R_{panel} is the panel rating, and PSH is the number of peak sun hours.

$$P = \gamma \times R_{Panel} \times PSH \quad (1)[25]$$

Using equation 1, we found that this panel would produce about 201 Wh per day. To meet engineering specification 2.2, we need to source a battery that has a 67 Wh capacity and has a high charge/discharge efficiency when transferring power in and out of the battery. We chose a 67 Wh minimum capacity because we wanted the robot to be able to operate an entire day if there was insufficient solar energy available, with a 25% buffer to prolong the lifetime of the battery. We want the battery to have a high charge/dischary efficiency, also known as a low conversion loss efficiency, because our only power source are the solar panels, so it is crucial that we minimize the loss of unused power in the system. From our analysis, we plan on using a Blue Robotics Lithium-ion Battery [28] because of its comparatively low weight, strong performance characteristics, and a maximum capacity of 266.4 Wh. This battery would meet our power storage

requirement while being a low-weight and low-cost solution. Additionally, we sourced a Blue Marine solar charge controller [31] to ensure that the battery would not be over-charged or deep-discharged from the energy collected by the solar panel. This component will help preserve the lifetime of the battery and ensure that the robot is using its battery in a safe manner and maximizes power storage.

After sourcing a battery and solar charge controller, we moved forward with selecting other electrical components of the system, such as undulating plate motors, thrusters, and other sensors, that cumulatively use less power than the system produces to meet engineering specification 2.1. and are low-cost solutions. For sourcing the undulating plate motor, Figure 20 was used to verify how much power our chosen motor would draw.

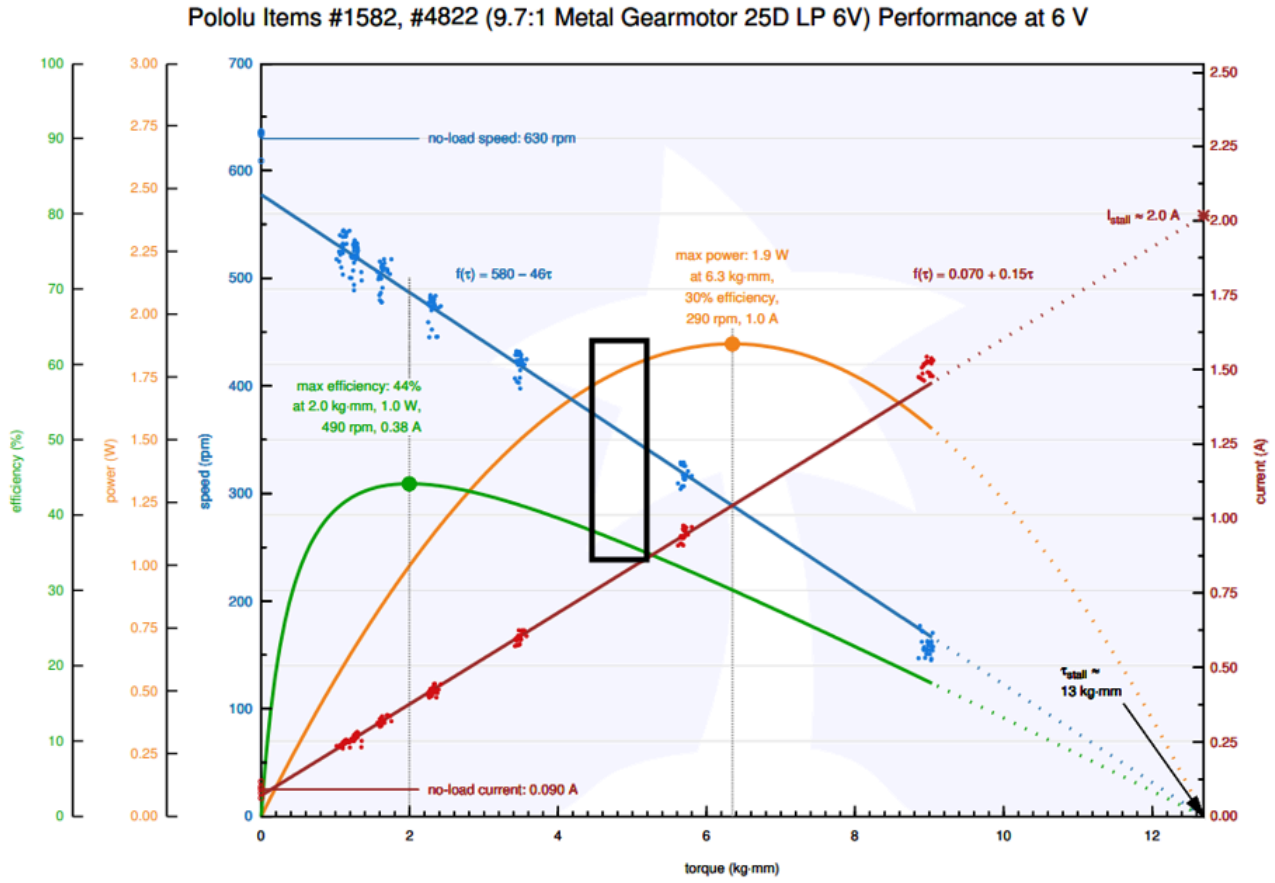


Figure 20. This performance curve shows the experimental efficiency (green line) and power consumption (orange line) of the chosen motor at our ideal operating range (area within black box).

From our electrical analysis, we were able to find a Pololu motor [32] that would employ a 9.7 to 1 gear ratio to help the motor efficiently drive the undulating plate helixes. Using the performance curve of this motor model as shown in Figure 20, we were able to identify that when run at 360 RPM, two motors would consume about 27 Wh per day of operation. This information drove our decision to use these motors for powering the undulating mechanism because it is relatively

low-cost and would safely drive the undulating plate helices within our target range of 120 to 360 RPM.

Next, we wanted to find a thruster that could provide enough thrust to allow the robot to complete a full day's mission with ease. Our main requirement was that the thrusters must provide enough force to compensate for the maximum drag experienced by the robot during forward, reverse, and turning operations at maximum speed. To mitigate future maneuverability issues, we added a safety factor of two to the maximum drag estimate to ensure that the robot would have the capability to continue its mission in spite of unexpected conditions such as high wind or wave speeds. Our next step was to research thruster capabilities and find its estimated power consumption. Using the interactive Thrust-Power curve provided on the Blue Robotics website, we found that it would use 16 Wh per day in the worst case scenario that requires 1.55 kgf of thrust, which occurs when the robot is moving forwards and uses the safety factor of two. From researching with these requirements in mind, we found that using a Blue Robotics T200 Thruster [33] would be the best option because of its comparatively low-cost and low power consumption.

Finally, we sourced a Raspberry Pi Zero to serve as the microprocessor and an Arduino GIGA R1 to serve as the microcomputer. In addition, we sourced an Arduino GIGA R1 compatible camera to allow for flow visualization of water exiting from the back filter as a countermeasure for potential microplastic clogging during operation. We also sourced an Inertial Sense IMU to help measure the motion and orientation of the robot and a FlySky remote-control system that is GPS enabled and has a greater than 300 meter connection range. We chose this combination of sensors because of their low price and low power consumption, and we are confident that they will work though additional testing is recommended to see actual usage and abilities when they are all connected together.

Algae Growth Analysis

To understand the cleaning requirements of the system, we need to understand when the propulsion system's speed to power ratio will decrease as described by ES 12.2.1. To ensure that we are able to meet this specification, we need to understand the growth rate of algae on the intake and storage mesh of the device because the algae growth on the mesh will block water from flowing through the system which will increase the drag on the device and reduce the speed to power ratio of the propulsion system. Thus, this analysis will require knowledge in the hydrodynamics field to quantify the relationship between the area of the mesh that is covered by algae and the drag force of the mesh on the device, which would be related to the power required by the propulsion system to operate at certain speed.

In using algae growth rate to understand the cleaning requirements of our system, we make the key assumption that the mesh being covered by algae is the deciding factor for whether the device needs to be cleaned. We are also assuming that the mesh being blocked is what would have the most impact on the propulsion system's speed to power ratio. The quickest and easiest method is to empirically test this by placing small squares of the intake and storage meshes in pond water samples.

The variables of this test are: the mesh density (0.1 mm and 5 mm) and the lighting conditions (full sunlight, partial sunlight, and no sunlight). The test plan is as follows: cut 0.1 mm and 5 mm mesh into twelve 50 x 50 mm samples for each mesh density (24 samples total). Then, place one sample of each mesh density into separate containers (6 containers total, with 4 samples per container, with two samples of 0.1 mm density, and the others of 5 mm density). Fill three of the containers with pond water and three with tap water (to act as the control) and then place one of each container into the designated location so one pond water and one tap water container receives full sunlight (in front of a south-facing window), one pond water and one tap water container receives partial sunlight (in front of a north-facing window), and the last pond water and tap water container receive no sunlight (wrapped in an opaque towel). All containers will be kept indoors to ensure consistent temperatures. For 2 weeks, record daily measurements of the area of each mesh sample that is covered by algae. The testing matrix is summarized in Table 5 below.

Table 5. Test Matrix for Algae Growth Analysis

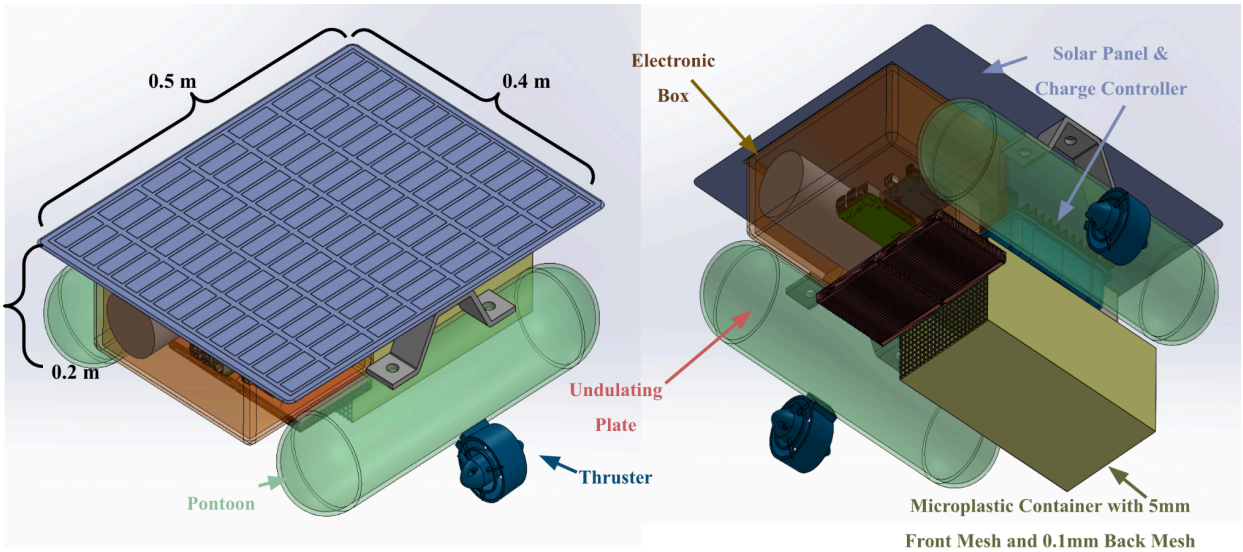
Variables			
Mesh Density	0.1 mm (12 samples)	5 mm (12 samples)	
Lighting Conditions	Full Sunlight (four 0.1-mm samples, four 5-mm samples)	Partial Sunlight (four 0.1-mm samples, four 5-mm samples)	No Sunlight (four 0.1-mm samples, four 5-mm samples)
Water Type	Pond Water (six 0.1-mm samples, six 5-mm samples)	Tap Water/Control (six 0.1-mm samples, six 5-mm samples)	

After the data is collected, we can use these results to plot a time vs. algae area covered curve, for each sunlight condition and mesh density (6 curves total). We can then analyze these curves to understand the overall trends of algae growth on the different meshes and for different lighting conditions, which will allow us to estimate the growth rate of algae on the meshes of the device in the summer time and determine if we are able to meet the cleaning requirements. This is because we would know how many days it takes for algae to cover a certain area, so we can calculate the number of days it would take to cover 25% of the intake mesh. Thus, we would be able to verify that we will be able to meet engineering specifications 12.2 and 12.2.1. We are less confident in this test and it is further out of scope of our project as it gets more into the material selection. We strongly recommend empirical testing of the materials chosen in the right environment, using the actual deployment location’s conditions, to ensure they do not harm the environment and too much biofouling does not build up quickly.

FINAL DESIGN DESCRIPTION

The final design retains the overall architecture of the Alpha Design, incorporating targeted modifications informed directly by the hydrostatics, drag, power, and algae analyses. It integrates these conclusions into a compact 0.50 m × 0.40 m × 0.20 m platform that satisfies the exact size requirement from our Requirements and Specifications and holds 5 kg of microplastics, as tested in SolidWorks, thereby transforming the selected concept into a manufacturable system. The robot is organized into three primary subsystems: (1) propulsion and flotation, (2) microplastic collection and storage, and (3) electronics and power—coupled through a simple structural frame. Each subsystem geometry and placement is determined from analysis to ensure positive net buoyancy, static stability, sufficient power margin, and effective collection of 0.1–5 mm surface-layer debris with low bycatch.

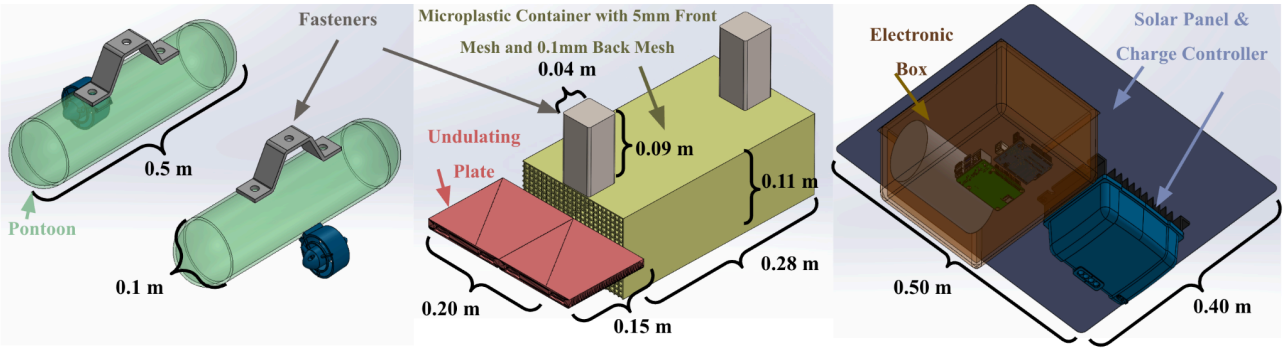
Figure 21 presents color-coded isometric views of the final design, highlighting how these subsystems integrate within the 0.50 m × 0.40 m × 0.20 m footprint. The top view shows the thin OpenWater solar panel spanning the deck and anchored to the waterproof electronics box [21], which houses the BlueRobotics battery [28], Raspberry Pi, and other sensors or electronics, with the solar charge controller [31] mounted behind the enclosure. The bottom view reveals the bio-inspired slatted undulating plate and front 5 mm mesh mounted ahead of the removable collection cartridge, the twin pontoons sized for positive buoyancy and roll stability, and the low-profile thrusters rigidly fixed to the pontoon brackets for differential steering. Together, these views demonstrate a manufacturable embodiment that packages propulsion, intake, and electronics while preserving a low center of gravity and unobstructed solar exposure, consistent with conclusions from the buoyancy, stability, and power analyses.



(a) (b)

Figure 21. Color Coded Isometric view of Final Design, (a) Top isometric view, (b) Bottom isometric view.

While Figure 21 shows the entire assembly, Figure 22 decomposes the system into dimensioned subsystems/components that provide a manufacturing framework for a full-scale system.



(a) (b) (c)

Figure 22. Subsystem Layout. (a) Propulsion and Floatation subsystem, consisting of pontoon floats and thrusters). (b) Microplastic collection and Storage subsystem, consisting of the undulating plate mechanism, intake mesh, storage mesh, and two fastener pillars. (c) Electronics subsystem, consisting of the waterproof box for battery, electronics, the solar panel, and the charge controller.

Propulsion and flotation are provided by two 0.50 m long, 0.10 m diameter pontoons mounted in parallel and rigidly connected to the solar panel deck with two struct channel stands (Fig. 22a). These dimensions are selected from hydrostatics calculations that confirm net positive buoyancy at maximum payload with the waterline sufficiently below the deck, and from stability analysis showing a positive metacentric height and maximum pitch and roll within the 20° limit when the storage bin is full, thereby satisfying ES 8.1, 9.1, 9.2, and 14.2. Low-profile thrusters are mounted near the aft of each pontoon such that thrust lines are close to the hydrodynamic center of drag, below the center of gravity, and easy to deploy because they lie flat on the ground (UR 11), reducing pitch and roll disturbances. Their operating range is selected using the drag force and propulsive power analysis to keep cruise speeds in the same order as benchmark pool-cleaner robots while remaining well within the daily power budget, justifying differential-thrust steering feasibility for both prototype testing and future lake deployment.

The microplastic collection and storage subsystem (Fig. 22b) refines earlier concepts into a meshed, surface-layer intake that directly addresses trapping issues. Two undulating plates span between the pontoons and are guided by structural pillars that maintain alignment and prevent interference with the cartridge. Both our full-scale design and our prototype uses a one-piece 3D-printed PLA plate based on prior undulating-plate designs [5,6] to validate kinematics and flow integration. A 5 mm mesh at the cartridge inlet and a finer internal liner retain target 0.1–5 mm particles and allow water to exit. This staged-mesh, guided-plate configuration eliminates earlier inconsistent mesh layouts that risked trapping plastics within the plate region or allowing reverse flow, and it is explicitly sized to support ES 3.1–3.3 and 4.3 by promoting selective capture, low bycatch, and easy removal of accumulated debris. Additionally, a one-way valve, inspired by venous flap valves in blood vessels, will be integrated at the microplastic bin outlet to prevent backflow and retain collected

debris, as they can work with no energy and therefore need no power. The flow of the water due to the robot itself's movement or the running of the undulating plate will open and close the valve based on needs and keep the plastics in. Different options for a gate were looked into, but using a gut check we determined we wanted to keep it least complex with the automatic actuation already built in.

The electronics and power subsystem (Fig. 22c) is centered on a sealed deck-mounted waterproof box that houses the BlueRobotics battery [28], Raspberry Pi, motor controllers, and solar charge controller [31]. The thin solar panel [21] is mounted flush across the top of the frame, reducing mass above the waterline and aiding compliance with stability and deployment requirements (UR 2, 8, 9, 11). Component positions are chosen to cluster mass near the geometric center, maintain a low center of gravity, leave the undulating intake and cartridge unobstructed, and provide straightforward wiring paths to the thrusters and future sensors. The electrical power analysis demonstrates that the chosen panel and battery configuration generate more energy per day than the estimated consumption and stores sufficient surplus, satisfying ES 2.1 and 2.2 and showing a realistic path to self- and sustainably powered operation.

The following is an assembly plan with a bill of materials detailed in Table 6. The frame and deck are supported on two McMaster-Carr strut-channel standoffs used as compact stands to elevate and anchor the solar panel and electronics enclosure relative to the pontoons [32]. The solar generation is represented by a thin OpenWater-style or equivalent 50 W flexible marine solar panel matched to the 0.50 m × 0.40 m footprint [21]. The flotation is provided by a pair of small metal or modular plastic pontoon floats of approximately 0.10 m diameter and 0.50 m length sourced from vendors offering customizable small pontoon logs, demonstrating that our buoyancy geometry can be realized with off-the-shelf or lightly customized marine hardware [35]. Control and propulsion hardware include a Raspberry Pi 4 Model B, two BlueRobotics T200 thrusters for differential steering, one BlueRobotics 4S 18 Ah battery to meet the energy storage requirement [28][33], and two Pololu 1582 to drive the undulating plate helices. Solar charging is handled by the Victron BlueSolar MPPT 75/10, 75/15, 100/15, or 100/20 controller family [31], which is appropriately sized for the selected panel and battery combination. The intake module is captured as a "Microplastic Intake & Storage Assembly" consisting of the undulating plate (3D-printed for the prototype or manufactured from metal slats in future iterations), front and rear mesh panels (two 5 mm front meshes and one finer rear mesh around 0.1 mm), and a removable storage cartridge, all dimensioned in CAD to slide in and out for cleaning. Finally, the design assumes a set of stainless steel M4–M6 bolts, nyloc nuts, washers, waterproof connectors, and miscellaneous mounting hardware to assemble the pontoons, stands, frame, thrusters, panel, controller, and intake module into a single rigid unit. This explicit mapping from CAD geometry to commercially available components and simple custom parts shows that every major element is either commercial off-the-shelf or directly fabricable with ME450 resources, reinforcing the feasibility of the final design.

Table 6. Full Scale Bill of Materials

Subsystem Component	Qty	Total Cost ($)	Example Product
Flotation	2	360 est.	Small sealed aluminum or HDPE pontoons [35]
Propulsion	2	460	BlueRobotics T200 Thruster [28]
Power Storage	1	425	BlueRobotics Li-ion Battery (14.8 V, 18 Ah) [33]
Undulating Plate Motor	2	67.90	Pololu 9.7:1 Metal Gearmotor [32]
Solar Generation	1	400 est.	OpenWater Flexible Marine Panel [21]
Charge Controller	1	73.10	Victron BlueSolar MPPT 75/10–100/20 [31]
Control Unit	1	49.50	Raspberry Pi 4 Model B
Structural Stands	2	36.28	McMaster-Carr Strut-Channel Standoffs [32]
Microplastic Intake & Storage & Pillar Assembly	1 set	20 est.	3D-printed slatted undulating plate, two 5 mm front meshes, one 1 mm rear mesh, removable cartridge
Electronics Enclosure	1	100 est.	Waterproof polycarbonate box
Fasteners & Misc. Hardware	As req'd	10 est.	Stainless M4–M6 bolts, nyloc nuts, washers, connectors

Finally, we acknowledge that this final design is a robust baseline rather than an end state. Future iterations should refine mesh size and undulation parameters for different debris fields and bycatch constraints; transition from 3D-printed intake components to durable metal or composite slats and standardized gear-motor modules; integrate navigation lighting and obstacle-detection shutoff to address safety requirements not yet implemented; and incorporate autonomous navigation and sensing on top of the validated hull and intake architecture. Stating these limitations and next steps clarifies our engineering judgment: through DR3, the pontoon-style concept has been transformed into a coherent, verifiable system with defined subsystems, manufacturable geometry, and an explicit validation path tied back to the original requirements and prior work [5–9].

VERIFICATION AND VALIDATION PLANS

Through verification and validation of the design we will determine the feasibility of this solution with regards to the requirements and specifications through both simulations, a physical scaled prototype, and later, the final design will be validated by those who will actually use the actual final product.

Verification Plan

The verification of the design will be based on our requirements and specifications through both simulations and a physical scaled simple prototype with scaled requirements.

Prototype

A prototype with similar dimensions will be constructed out of less expensive, simpler items. It is designed using standard 50 mm polyvinyl chloride (PVC) tubes for the pontoons, and everything is scaled to that proportion of 1:2. PVC was chosen as they are easy to source and use. A simple plastic bin could have been used as an "electronics box" and would hold any additional weight to be accurate to the scaled down prototype weight of just under 1 kilogram total, equivalent to all of the components—including the electronics and solar panels that are not put on the prototype. After building the prototype, the extra weight of the microplastic storage container compared to the normal one, no additional weight was needed as the prototype weighed 0.96 kilograms, and the prototype floated at the right height for the undulating plate movement, so no proxy electronics box or additional weights were needed. As shown in Figure 23, the prototype storage is built as a three-module assembly: a gear module, a one-way gate module, and a container module. The undulating plate is 3D-printed in PLA and driven by a standard drill through the gear module, which uses bevel gears to redirect the drill input so the internal helix underneath the plate spins in the correct direction even when the drill is held at a different angle. The captured flow then enters the container module, which is scaled to fit the benchtop prototype while still using the same mesh specification as the final design to preserve the intended filtration behavior. Between them, the one-way gate module is integrated inline to block reverse flow and prevent collected microplastics from being pushed back out of the container during motion or transient flow changes. Figure 24 displays a labelled CAD of the smaller prototype. All of the components are held together with glue and tape for the prototype adjustability and inexpensiveness.

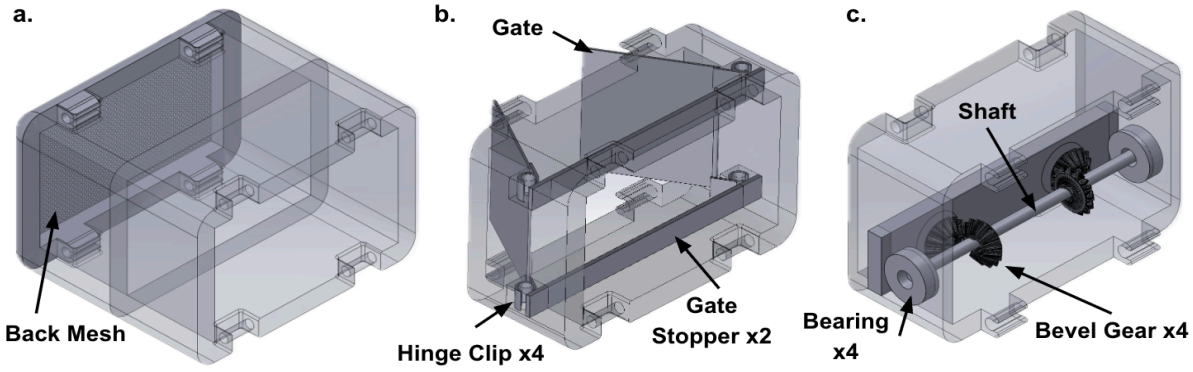


Figure 23. Prototype design: a) container module with back mesh, b) one-way gate/valve module, and c) gear module.

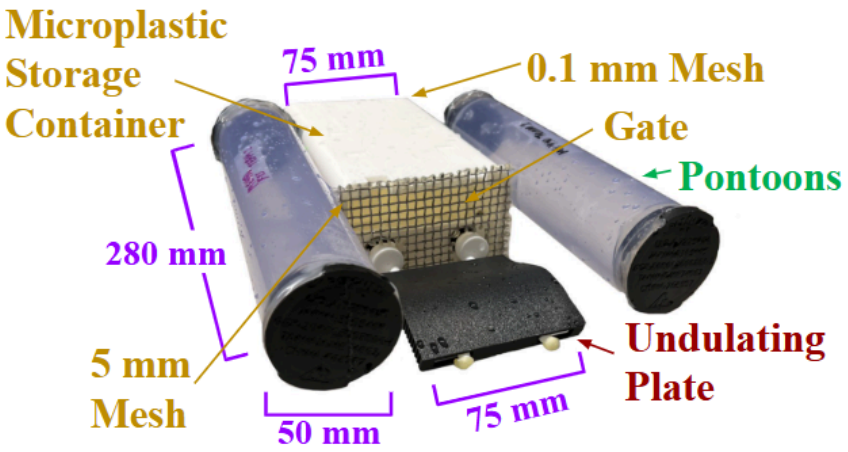


Figure 24. Labelled photo of actual built prototype. The pontoons are 50 mm in diameter and 280 mm long, the undulating plate is 75 mm wide, and the plastic container is 55 x 75 x 0.130 mm with 0.1 mm mesh on the back and 5 mm mesh on the front. This is half the length in each direction or about one-eighth size overall. The one-way gate is inside the microplastic storage container and harder to see.

The prototype is built to ensure two critical requirements are met; First, simple buoyancy and stability tests to ensure the pontoon is a stable vessel with the weights and everything accounted for, and secondly the microplastics flow through and are collected and stored, but larger pieces are rejected. The specifications of buoyancy and stability are with respect to size, so as the prototype is scaled down it should remain consistent with the full-scale requirement, though the calculated full-scale values are the used, and the prototype test is only for ensuring other tests with the prototype are feasible. The first two microplastic specifications are based on size of the microplastics which we will continue to use without scaling as we test the exact meshes that will be on the full-scale robot. The third microplastic specification will be scaled down to collecting 75% of available microplastic particles in 5 minutes to allow for more repeatability and space within the storage compartment. The scaled down requirements and their reasonings are displayed in Table 8.

These tests will be completed in the small tank in the Ford Motor Company Robotics Building on the University of Michigan's North Campus, seen in Figure 25.



Figure 25. Tank in the Ford Motor Company Robotics Building used for testing the prototype. It is 0.67 m by 2.2 m at the surface water level, and we filled it with about 0.5 m deep water for testing.

The tank will be filled with 0.5 m deep water to allow for limited forces from the bottom of the tank when used and a simple test will be conducted where the prototype is placed into the water for 10 minutes and checked that it floats consistently. Then, although Oneida Lake is very flat, to ensure feasibility for different external forces, splashing and waves will be made by hand to mimic the lake environment and test stability. The last stability tests will be performed by rotating the prototype to a pitch of twenty degrees, as stated in our requirement ensuring it rotates back to the upright position. This will be repeated in the other direction with twenty degrees of roll performed to ensure it is stable in both directions. Each of these tests will be completed three times for reliability and reducing random errors.

The next test regarding microplastic collection involves 200 grams of mini fuse beads, similar to mini Perler™ beads, which will float on the surface for us to collect as microplastics. We will also include other larger beads and various larger, other-material pieces to ensure they are rejected and do not clog the robot's undulating plate or meshes. Two tests will be performed with these conditions.

First an unpowered test is executed by placing twenty grams of microplastics in the storage container and the design is simply pushed forward, back, and turned for two minutes to check the PLA one-way valve functions correctly by keeping the microplastics in the container, while holding out any larger pieces. This will be repeated five times.

Next the drill will be connected through the gears to the undulating plate helix to rotate it and test the plate for functionality within the whole pontoon-style design. Based on McSwain's research the optimal speed of the undulator is 360 RPM. Our drill has limitations, moving consistently at a slower speed, so we will use the drill at 150 RPM for five minutes, and the prototype should collect plastics. The weight of the plastic, before and after the test will be found, as well as a simple check for larger unapproved items within the storage container. This test will be repeated three times.

Simulation

Two main simulations were conducted to model the behavior of the robot during operation using MATLAB Simulink and Simcscape. The first dealt with simulating the power consumption of the robot during a standard 8-hour deployment. The second simulation focused on approximating the amount of microplastics that the robot could realistically collect in its deployment location.

Power Simulation

The main goal of the simulation was to account for unexpected losses and add safety factors to the power consumption of components to ensure that this is a conservative model. We wanted to create a conservative model because we wanted to ensure that the robot would be able to operate successfully even in unideal conditions. This simulation uses all of the electrical components that were sourced in the Electrical Power Analysis section of this report. From using the specifications and characteristics of the chosen electrical components, we were able to successfully model the behavior of the robot on a typical summer day deployment. There were three main areas that we wanted to evaluate: power consumption versus generation, net power in the system, and the state of charge of the battery. All of these three areas give us a clear

understanding of the behavior of the electrical system during a typical day of operation. The results from this simulation are shown in Figure 26.

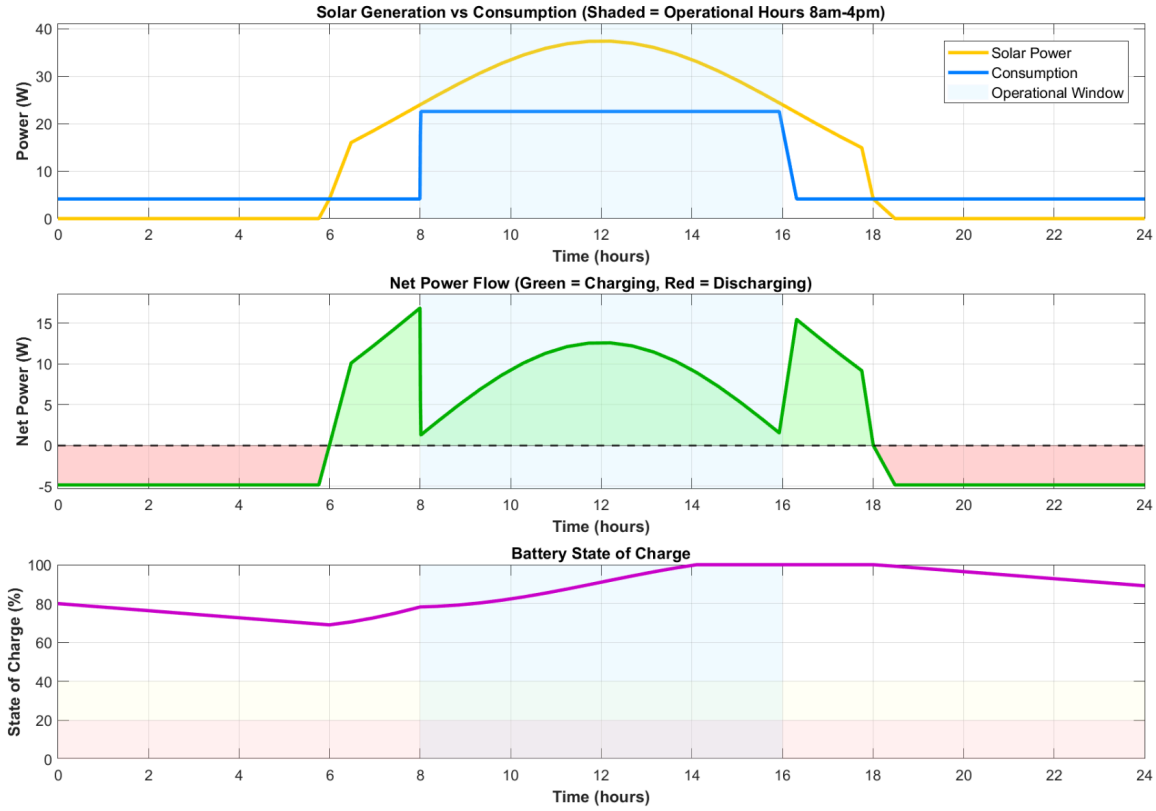


Figure 26. Plots of the data collected from the power simulation. The topmost plot shows the relationship between solar power generation and electrical system consumption. The middle plot shows the net power in the system over the span of a whole day. The bottom most plot shows the state of charge of the battery throughout a day of deployment.

From Figure 26, we can see that throughout the day, the solar panel generates more power than the electrical system consumes. Additionally, we can extrapolate that the battery is being charged for the majority of the 8-hour operation period, but it is battery powered for about the first and last hour of the operation window. Finally, when assuming that the battery starts the day with an 80% charge, it will end the day with about an 89% charge.

Microplastic Collection and Distance Traveled Simulation

The main goal of this simulation was to combine the power dynamics of our design with the microplastic collection and speed dynamics to allow for the determination of optimal design parameters by comparing the results of the simulation for various designs and deployment environments. We wanted to create a model that would be able to quickly and efficiently inform design decisions rather than requiring empirical testing for every possible combination of design parameters, especially for optimization based on microplastic collection results. This simulation models the mass of microplastics collected based on the fluid flow rate over the undulating plate and the concentration of microplastics, using the input parameters in Table 7 below.

Additionally, the distance traveled is calculated using our set input speed of 0.2 m/s along with the design of the rover to determine the power needed by the thrusters to counteract drag force that acts on the rover.

Table 7. Input Parameters for Microplastic Collection Simulation

Input Parameter	Value	Units
Wavelength	0.23	m
RPM	360	RPM
Undulating Plate Amplitude	0.07	m
Undulating Plate Distance from Surface	0.055	m
Undulating Plate Width	0.15	m
Microplastic Concentration	0.5	particles/m^3
Operating Time	240	hrs

Using the parameters in our final design, we found that our final design would collect 6.2 g of microplastics per each 8 hour mission and travel 5733 m, as shown in Figure 27.

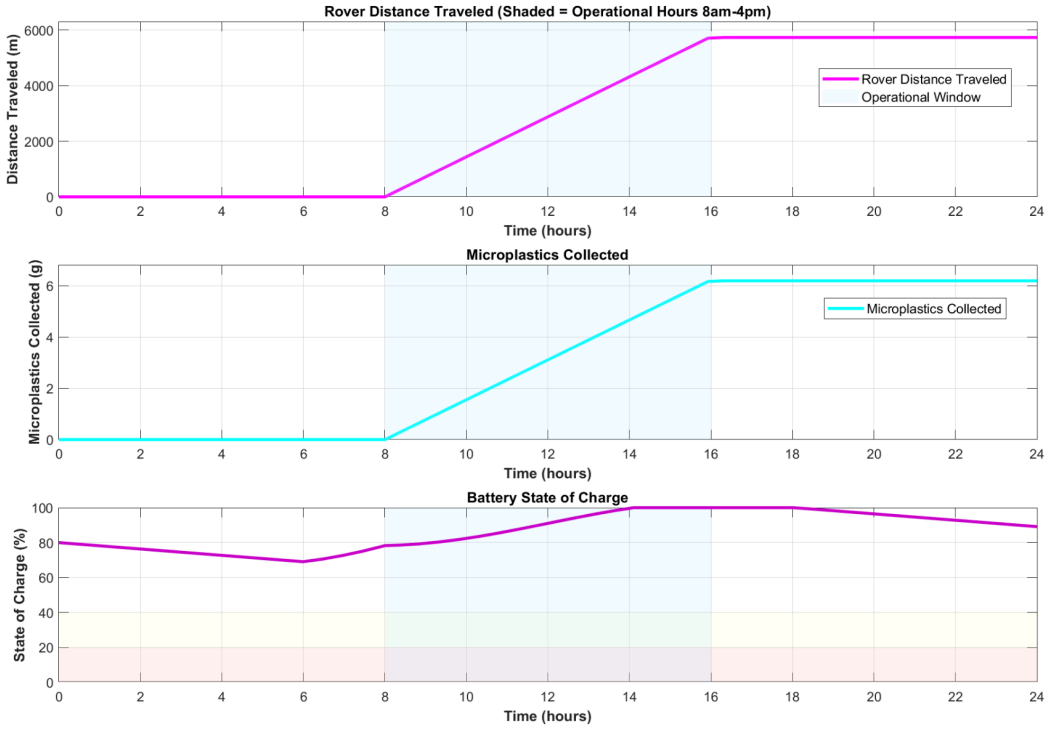


Figure 27. Plots of the data collected from the microplastic collection and distance traveled simulation. The topmost plot shows the distance traveled over the span of a whole day. The middle plot shows the microplastics collected over the span of a whole day. The bottom most plot shows the state of charge of the battery throughout a day of deployment.

This means that over the course of 30 days of 8 hour missions, the design would collect 0.186 kg of microplastics, which is lower than our specification of 3.75 kg. Despite this, the microplastic collection simulation can be used in the future to perform efficient design optimization of the undulating plate mechanism.

Verification Requirements and Specifications

The critical specifications for our project are: 2.1, 2.2, 3.1, 3.2, 3.3, 8.1, 9.1, and 9.2 because these specifications are vital to the success of our project, while the rest of the specifications are more focused on regulatory requirements or specifications that only impact the success of design when the final design is fully finalized and implemented, including but not limited to cost, weight, and size of the design.

Table 8. Verification Matrix of all Specifications (Critical Specifications are highlighted)

Engineering Specification * scaled for prototype	**Verification Method** * scaled for prototype	**Verified with Prototype/ Final Design**	**Status**	**Results**
1.1. Have a white all-round light visible from at least 3.2 km in all weather conditions	Material Selection: Ensure that a white all-round light is selected that meets this Coast Guard specification	Final Design - Bill of Materials	Fail	Current design does not have this light yet
1.2. Propulsion system shuts off when an object larger than 25 cm in any direction is within 1 meter of the robot	Testing: Place various sized objects (which have at least one dimension that is larger than 25 cm) at various distances from the device (including 1 m and closer) to ensure that the device is able to detect these objects and shut off the propulsion system accordingly	Final Design - Manufactured	Out of Scope	N/a
2.1. The design needs to produce enough power to sustain its energy needs	Power Analysis: Calculate power production and usage of all components of the final design analytically	Final Design - Bill of Materials	Pass	Power generated (201 Wh) > consumed (46 Wh) per day
2.2. The design must be able to store at least 67 Wh of surplus energy	Material Selection: Ensure that selected batteries have capacity of at least 67 Wh	Final Design - Bill of Materials	Pass	Selected battery stores 266 Wh
3.1. Collects plastics with 0.1 mm to 5 mm diameter 3.2. Does not collect objects > 5 mm	Material Selection: Ensure front meshes are 5 mm and and the rear mesh is 0.1 mm.	Final Design - Bill of Materials	Pass	Front meshes are 5 mm and rear mesh is 0.1 mm
* 3.3. Collects at least 75% of microplastic particles in 5 minutes (200 g of particles dispersed over an area of 1.2 m^2)	* Testing: For 5 minutes, run the prototype's undulating plate mechanism in a pool/tank of water (surface area of 1.2 m^2) and 200 g of microplastic sized particles. Check the amount collected.	Prototype	Fail	Collected 39% of microplastics
3.3. Collects at least 3.75 kg of microplastics over 30, 8-hour missions (microplastic concentration of $5x10^8$ p/km^3)	Microplastic Collection Simulation: Use simulation to determine the weight of microplastics collected over the span of 30, 8-hour missions.	Final Design - Simulation	Fail	Collected 0.186 kg of microplastics

Engineering Specification * scaled for prototype	**Verification Method** * scaled for prototype	**Verified with Prototype/ Final Design**	**Status**	**Results**
4.1. 90% of materials used in the design are sustainably sourced and/or recyclable/compostable at end of life	Material Selection: Ensure that a sustainably sourced and recycled materials are selected	Final Design - Bill of Materials	Out of Scope	Material selection is still underway
4.2. Does not negatively affect marine life, swimmers, boaters, etc. by adhering to noise and heat requirements in deployment areas 4.2.1. Noise specifications: in any state of performance, ambient noise must remain less than 85 dB when measured 15 m from robot 4.2.2. Heat specifications: in any state of performance, robot must not raise the temperature of water by more than 2°C within 1 m of the robot	Testing: For 8 hours, place the device in the water and run all systems. Monitor the ambient noise from 15 m away from device and monitor the temperature of the water from 1 m away	Final Design - Manufactured	Out of Scope	N/a
4.3. Less than 10% of collected material is marine life and other non-microplastic debris	Testing: After one 8 hour mission, weigh the total amount of material collected and then sort the material by microplastics and non-microplastics. Weigh the amount of non-microplastic material	Final Design - Manufactured	Out of Scope	N/a
5.1. The design must run properly (all systems operational/functional) 75% of the time	Testing: Time how long the device is fully operational over the course of eight 8 hour missions over the course of 8 consecutive days (1 mission/day)	Final Design - Manufactured	Out of Scope	N/a
6.1. Can complete missions for 4 weeks with at least one 8 hour mission per day	Material Selection: Source hull material that will not degrade within 4 weeks of water interaction and source waterproof electronics	Final Design - Bill of Materials	Pass	Components have been successfully sourced
	Testing: Assess device condition after performing eight 8 hour missions over the course of 8 consecutive days (1 mission/day)	Final Design - Manufactured	Out of Scope	N/a

Engineering Specification * scaled for prototype	**Verification Method** * scaled for prototype	**Verified with Prototype/ Final Design**	**Status**	**Results**
7.1. <$10,000 per robot	Material Selection: Ensure that total component costs are under $10,000	Final Design - Bill of Materials	Out of scope	Material selection is still underway
8.1. Net buoyancy force greater than or equal to 0 N	Hydrostatics: Use free-body diagram to evaluate buoyancy of system	Final Design - CAD Model	Pass	Buoyancy force greater than 0 N
9.1. Metacentric height of greater than 0 m, even when filled with 5 kg of microplastics and at maximum pitch and roll angle 9.2 Maximum pitch and roll angle of 20°	Stability Analysis: Use free body diagram to evaluate the metacentric height in cases where center of mass is lower than center of buoyancy	Final Design - CAD Model	Pass	Metacentric height of 154 m at max pitch angle and 77 m at max roll angle
10.1. Remains functional under maximum wind speed of 13 m/s for 30 seconds	Hydrostatics: Use free body diagram with applied wind drag of 13 m/s to ensure that the device is still stable and can float. Calculate with added wave forces.	Final Design - CAD Model	Out of scope	N/a
10.2. Minimum operating water temperature of 0°C 10.3. Maximum operating water temperature of 45°C	Material Selection: Ensure that all (both purchased and manufactured) components used in the device are able to withstand temperatures of 0-45°C	Final Design - Bill of Materials	Out of scope	Material selection is still underway
11.1. Must be at most 45 kg	Material Selection: Ensure that the weight of all (both purchased and manufactured) components used in the device totals to less than 45 kg	Final Design - Bill of Materials	Out of scope	Material selection is still underway, though current design at 9 kg, so expect will pass
11.2. Needs to be deployable without specialized equipment 11.3. Less than 30 minutes to deploy once on site	Testing: Have 5 groups of 2 people attempt to deploy the device into the selected deployment location (Toronto Harbor or Oneida Lake) within 30 minutes	Final Design - Manufactured	Out of Scope	N/a

Engineering Specification * scaled for prototype	**Verification Method** * scaled for prototype	**Verified with Prototype/ Final Design**	**Status**	**Results**
12.1. Less than 60 minutes to remove any debris on external and internal surfaces 12.2. Needs to be cleaned at most once a month 12.2.1. Cleaning is required when 25% of the surface of the intake area is blocked by debris	Testing: Deploy system for one month and use camera to monitor intake area. Have 5 groups of 2 people attempt to clean external and internal surfaces within 60 minutes after this 1 month deployment	Final Design - Manufactured	Out of Scope	N/a
13.1. Robot should be continuously and consistently controllable (propulsion system and undulating plate) up to 300 m from operator	Material Selection: Source components that support a greater than 300 meter distance range Testing: Place the robot 300 meters away from the operator and verify that the robot maintains connection with the remote controller. Repeat 5 times	Final Design - Bill of Materials Final Design - Manufactured	Pass Out of Scope	Components have been successfully sourced N/a
14.1. Approximately 0.5 m long x 0.4 m wide x 0.2 m deep 14.2. Holds 5 kg microplastics	Material Selection: Verify that final design is within these constraints	Final Design - CAD Model	Pass	Final design made with these dimensions

From the verification test plans that we have completed, we found that our design will be successful in achieving all of most goals pending final design testing except our safety lighting requirement. We plan to remedy this by implementing exterior lighting into the CAD design and power consumption estimation prior to its full-scale implementation. We have about 80% confidence in our results and this number will be further increased after full-scale testing occurs on the manufactured design.

In the cases of our flotation and stability specifications (8.1, 9.1, 9.2), we have opted to verify them with both the final design and the prototype to ensure that these capabilities are met by this design. We will verify that the final design meets the flotation and stability specifications via hydrostatic analysis using the CAD to ensure that these specifications are met for the entire design. Similarly, we will also verify this for the prototype as well because the flotation and stability requirements are critical to the overall function of the prototype and we need to ensure that we will be able to use the prototype to verify other specifications, though this is only a basic test and should not be used for real needs. Alternatively, we decided against verifying our power consumption specification with the prototype due to cost constraints and lead time associated with obtaining our sourced electrical components. We believe that our engineering analysis sufficiently indicates that our self and

sustainably-powered specifications (2.1, 2.2) will be met because when sourcing components, we estimated the worst case power consumption of each component and took into account efficiency losses to account for unexpected losses during operation. Conversely, we have chosen to verify our microplastic collection specifications (3.1, 3.2, 3.3) solely using our prototype. We decided that this would be the quickest and easiest path to evaluate this specification because running a simulation or performing analysis on this specification would be very time-consuming and complex. The difficulty in creating an accurate and useful simulation for this specification arises from the complex flow pattern that occurs from the interactions between waves from the robot's motion and the waves created by the undulating plate. Building the physical prototype makes it easier to control these interactions because waves can be generated by simply pushing the prototype through the water and rotating the gears attached to the undulating plate. Thus, we chose to validate the collection of the undulating plate mechanism using the prototype to ensure that when scaled up for the full-scale implementation, it will still have a sufficient collection rate.

Through our prototype testing, to estimate if the plastics will flow out at any time, we found minimal losses due to the one way gate that was implemented. The losses also were also found to sit over the undulating plate, and the moment the system is turned back on or moved forwards, the plastics will be recollected. This assures us that the system works well, though adding a spring or mechanism to ensure the gate is normally closed may help and can be implemented in future designs.

Within our second test, we found that at 150 RPM of the undulating plate over 5 minutes, we collected 39% of the available 200 g of microplastics. This does not meet our requirement of 75%, but this does not take into account the differing time available or the drill speed change. Using the previous research on speed to collection rate, the speed at which the undulating plate collects is dependent on input speed [36], meaning increasing the speed will increase our collection rate. Additionally, because our final design is also not meeting this specification, based on the microplastic collection simulation, we will need to further optimize the undulating plate design using our microplastic collection simulation in order to achieve this specification. However, with these modifications, we are confident the robot will be able to pass our microplastic collection rate specifications.

Our stakeholders should believe that our design will work because of our thorough engineering analysis, planned verification testing, and iterative design process. These components have helped us ensure that all of the user requirements and engineering specifications will be met by our design choices and that there is a clear plan for proving that the manufactured final design will work as intended.

Validation Plan

To assess if our chosen design meets the goals of our original problem statement, we have created three full-scale validation plans to cover all aspects of the design. These three validation plans, as

seen in Table 9, focus on characteristics that will impact the customer and will all be tested using the full-scale manufactured design.

Table 9. Validation Trace Matrix for main 3 tests that will be conducted on the final manufactured design

Question	Relevant Requirements	Validation Method	Test Plan Summary	Testing Metric
Successful operation in normal conditions	2, 3, 5, 6, 8, 9, & 10	Usability Testing on Manufactured Final Design	Test at 1.85 m/s wind speed and at 19℃ in deployment location for an hour. Repeat 5 times. Observe impact on intake efficiency	Percentage of particles collected with 2 kg of particles dispersed over a square meter per hour
Regulatory compliance	1 & 4	Usability Testing on Manufactured Final Design	Test for required visibility, safety, noise, and heat regulations	Number of regulations met
User Interface	11, 12, & 14	User Interface Product Trial on Manufactured Final Design	5 groups of 2 engineers go through deployment and cleaning processes	Comfortability rating for deployment/cleaning - ranging from 1 to 5, where 1 is uncomfortable and 5 is comfortable

The first plan consists of conducting usability testing on the final manufactured design under normal operating conditions. Normal conditions were defined as having wind speeds of 1.85 m/s and a temperature of 19℃ because those are the common environmental conditions during the summer in Oneida, NY. The first test will be conducted on Oneida Lake on days that are expected to have normal conditions for the majority of an 8-hour deployment span and will be repeated over 8 days with similar conditions for accuracy. The intake efficiency of the system as a percentage of the particles collected and any visible signs of damage will be recorded at the end of each run. The results of this test will be used to validate if the robot meets our self and sustainably powered (UR 2), microplastic collection (UR 3), reliability (UR 5), durability (UR 6), flotation (UR. 8), stability (UR. 9) specifications. The design will pass this test if it does not require supplemental energy throughout the entire test duration, has a collection percentage greater than or equal to 75%, and has all systems fully operational for 6 out of the 8 test days. Additionally, the design must show no signs of damage, float, and be stable for the entirety of this test.

The second test will be a product trial in which 5 groups of two engineers will be asked to go through the deployment, retrieval, and cleaning processes of the robot. We will then have them fill out a survey where they will indicate their comfort level with conducting these tasks from 1 to 5, where 1 means it was an uncomfortable experience and 5 means that it was comfortable. The results from this survey will be used to determine if this design sufficiently meets our easy to deploy for 1-2 people (UR 11) and easy to maintain (UR 12) specifications if it achieves an average rating of 4 or higher.

Finally, the third test will consist of another usability test where the robot is put in a small tank and is tested to see if it meets the necessary regulatory compliance that it needs for deployment. This

mainly consists of visibility, safety, noise, and heat regulations that will be tested by turning the robot on, measuring if the robot meets all of the respective regulations, and recording the number of regulations met. The number of regulations met must be equal to the total number of regulations tested for this design to meet our safety (UR 1) and minimizing negative environmental impacts (UR 4) specifications.

Overall, our team and project stakeholders get a better understanding of the solution, there is a low possibility that our specifications will change. We do not anticipate that this will happen, but if this were to occur, we would have a meeting with that stakeholder to discuss the motivation for this change and get any advice they have on how we could modify our existing work to comply with the new specification. Additionally, depending on the results from the validation testing plans above, we may repeat the first validation plan for a longer duration if we do not feel like there is sufficient evidence to support that the design will survive a 4 week long deployment. We also may increase the survey sample size to 20 groups of 2 people to improve the accuracy of the rating results and ensure that a wide variety of people's opinions are captured in the survey.

PROJECT PLAN

This section will discuss the plan our team designed to reasonably fulfill the scope of our project within a semester. The project plan was tailored to meet key class-specific and project-specific milestones while setting realistic progress expectations based on the team's manpower, available time, and budget. Additionally, creating a Gantt chart helped us preplan a few safeguards to help reduce the impact of anticipated challenges on the project development. Figure 28 and 29 are images of the semester-long Gantt chart that details the tasks, their owners, and due dates that the team will follow in order to complete the project.

WBS NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
1	**DR1 - Report**		**9/2/25**	**9/30/25**		
1.1	Background Infomation	Tianze	9/4/25	9/12/25	8	100%
1.1.1	Ethical, social and environmental contexts	Melissa / All	9/4/25	9/12/25	8	100%
1.1.2	Research environmental contraints for design	All	9/9/25	9/13/25	4	100%
1.2	User requirements and engineering specifications	Ashley	9/8/25	9/18/25	10	100%
1.2.1	Identify microplastic congregation locations for depth specification	All	9/9/25	9/10/25	1	100%
1.2.2	Research human carrying capacity for specification	Ashley	9/11/25	9/13/25	2	100%
1.2.3	Learn more about existing undulating plate progress	Alisha	9/9/25	9/13/25	4	100%
1.3	Evaluate Project Plan and assess challenges	Tianze	9/9/25	9/30/25	21	100%
1.4	Progress document	All	9/4/25	12/12/25	98	50%
1.5	Presentation	All	9/18/25	9/23/25	5	100%
1.6	Report	All	9/18/25	9/30/25	12	100%
1.7	Peer feedback on other DR1s	All	9/30/25	9/30/25	0	100%
1.8	Upload to canvas - slides pdf, DR1 report, executive summary	Ashley	9/30/25	9/30/25	0	100%
2	**DR2 - Report**		**10/1/25**	**10/21/25**		
2.1	Revise DR1	All	9/23/25	10/1/25	8	100%
2.2	Concept Generation	All	9/25/25	10/6/25	11	100%
2.2.1	Research existing solutions for microplastic removal	Ashley	9/23/25	9/26/25	3	100%
2.2.2	Find places for improvement in existing designs	Tianze	9/25/25	10/3/25	8	100%
2.3	Concept Selection	All	10/1/25	10/6/25	5	90%
2.3.1	Consider design that best suits marine implementation	All	10/1/25	10/6/25	5	100%
2.3.2	Compare existing designs from other groups with researched designs	All	10/1/25	10/6	5	100%
2.4	Initial Engineering Analysis	All	10/1/25	10/6/25	5	100%
2.4.1	Begin robot buoyancy calculations	Tianze	10/1/25	10/6/25	5	100%
2.4.2	Begin metacentric height calculations	Tianze	10/2/25	10/4/25	2	100%
2.4.3	Begin to calculate minimum necessary power budget per mission	All	10/6/25	10/7/25	1	100%
2.5	Presentation	All	10/6/25	10/9/25	3	100%
2.5.1	Peer feedback on other DR2s	All	10/9/25	10/9/25	0	100%
2.5.2	Email PDF of slides to sponsor	Alisha	10/8/25	10/9/25	1	100%
2.5.3	Upload to canvas - slides pdf, DR2 report, executive summary	Alisha	10/8/25	10/9/25	1	100%
2.6	Report	All	10/10/25	10/21/25	11	100%

Figure 28. The Gantt chart outlines all of the necessary tasks required for successfully completing the team's deliverables for DR1 and DR2. Team-specific task numbers were highlighted in pink, class-specific task numbers in blue, and key milestones due dates were labelled within the Gantt chart with a red marker.

WBS NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
3	**DR3 - Report**		**10/22/25**	**11/11/25**		
3.1	Engineering Analysis	All	10/15/25	10/20/25	5	100%
2.4.1	Finalize robot buoyancy calculations	Ashley	10/15/25	10/17/25	2	100%
2.4.2	Finalize metacentric calculations for ensuring robot does not tip over	Tianze	10/15/25	10/17/25	2	100%
2.4.3	Finalize calculations for minimum necessary power budget per mission	Alisha	10/15/25	10/17/25	2	100%
3.2	CAD	Melissa	10/20/25	10/24/25	4	100%
3.2.1	Create CAD of hull	Melissa/Tianze	10/20/25	10/24/25	4	100%
3.2.2	Implement existing CAD into current hull design	Melissa/Tianze	10/21/25	10/23/25	2	100%
3.3	Plan Simulation	All	10/24/25	10/30/25	6	100%
3.4	Initial Verification/Validation	Alisha/Ashley	10/24/25	10/30/25	6	100%
3.5	Plan Prototype	Melissa/Tianze	10/24/25	10/30/25	6	100%
3.5.1	Scale down system for prototyping	Melissa/Tianze	10/24/25	10/26/25	2	100%
3.5.2	Source materials for building prototype	Melissa/Tianze	10/24/25	10/26/25	2	100%
3.6	Implement feedback from previous DR	All	10/21/25	11/4/25	13	100%
3.7.1	Presentation	All	10/30/25	11/4/25	4	100%
3.7.2	Peer feedback on other DR3s	All	11/4/25	11/4/25	0	100%
3.7.3	Email PDF of slides to sponsor	Ashley	11/3/25	11/4/25	1	100%
3.8	Report	All	10/30/25	11/11/25	11	100%
4	**DR4**		**11/12/25**	**12/15/25**		
4.1	Final CAD	Melissa/Tianze	10/18/25	11/15/25	27	100%
4.1.1	Final Prototype CAD	Melissa/Tianze	10/18/25	11/15/25	27	100%
4.2	Final Simulation	All	10/18/25	11/15/25	27	100%
4.3	Manufacture Prototype	Melissa/Tianze	10/31/25	11/15/25	15	100%
4.4	Verification/Validation	Alisha/Ashley	11/16/25	11/19/25	3	100%
4.4.1	Verification/Validation of CAD	Melissa	11/16/25	11/19/25	3	100%
4.4.2	Verification/Validation of Simulation	Alisha/Ashley	11/16/25	11/19/25	3	100%
4.4.3	Verification/Validation of Prototype	Melissa/Tianze	11/16/25	11/19/25	3	100%
4.5	Implement feedback from previous DR	All	11/5/25	11/20/25	15	100%
4.6.1	Presentation	All	11/13/25	11/20/25	7	100%
4.6.2	Peer feedback on other DR4s	All	11/20/25	11/25/25	5	100%
4.7.1	Design Expo Poster	Alisha	11/20/25	12/2/25	12	100%
4.7.2	Design Expo	All	12/4/25	12/4/25	0	100%
4.8	Final Report Handoff	All	12/15/25	12/15/25	0	100%
4.9	Report	All	12/4/25	12/15/25	11	100%

Figure 29. The Gantt chart outlines all of the necessary tasks required for successfully completing the team's deliverables for DR3 and DR4. Team-specific task numbers were highlighted in pink, class-specific task numbers in blue, and key milestones due dates were labelled within the Gantt chart with a red marker. The red line illustrates our current progress within the project schedule.

As shown in Figure 28 and 29, the schedule was built such that each phase flows into the next to promote a structured approach for the team. Many of the initial tasks and milestones are focused on meeting the DR1 and DR2 requirements and that is also true for the rest of the schedule as well.

To meet the DR1 deadline, we focused on clarifying the ethical, social, and environmental contexts surrounding this project as well as researching microplastics and human carrying capacity to establish user requirements and engineering specifications associated with the mollusk-inspired robot.

After completing DR1, our focus shifted towards concept generation, concept selection, and initial engineering analysis. These steps required the team to continue researching existing methods, evaluate concepts for marine applications, and apply mechanical engineering principles directly to the design problem. During the concept selection stage, the project budget was considered to ensure that it will meet the project specifications, including cost constraints. When applying engineering principles to the project scope, the calculations were used to validate design choices and address anticipated power and stability concerns.

After completing the tasks required for Design Review 2, we finalized engineering analysis calculations, created a detailed CAD model of our final design, and started planning out prototype design. At this point, we were able to plan how to effectively scale down the robot for prototyping. Completing these tasks will help our team meet our project-specific milestones pertaining to the CAD model and prototyping development.

After completing DR3, we focused on finalizing the CAD details and adding more details to the power and microplastic collection rate simulations. We were also able to build and test our prototype and use the test results to find areas for further improvements.

To prepare our final deliverables, we verified our design decisions using verification testing and completed our simulations to model the system behavior. Additionally, we completed our validation test planning that will be conducted, in the future, on the full scale design.

Critical Path

In light of completing DR1, we included more internal key milestones for our project, including a CAD, prototype, and final simulation due date. This decision was made because these components were found to dictate our critical path. While completing all tasks is necessary for our success, creating a detailed, realistic CAD model is the highest priority task because it impacts when we can start prototyping and simulating the design. If the team is delayed in creating the CAD model, then the prototype and simulation results will also be delayed, potentially causing our team to not have a completed design in time for the design expo. While those three tasks dictate our critical path, there is still a strong emphasis on meeting design reviews and report deadlines to keep us in line with the course structure. To efficiently progress along this project path and achieve the critical path tasks on time, tasks were divided evenly among the team by considering individual workload and personal

interest. Additionally, we are going to prioritize improving the CAD model as we move forward to ensure that its subsequent tasks stay on schedule.

Anticipated Challenges

We anticipate four linked risk areas highlighted in our executive summary: tight power and cost budgets, intake blockage, stability when the receptacle is full, and environmental interactions. Constraining the design are the needs to run on self-generated power and stay under the target unit cost. Our plan is to tighten the drag/efficiency assumptions with measurements, cap peak operating speeds if needed, and track a live BOM so cost and energy margins stay viable. These risks and constraints frame our early trade studies and will be revisited as we validate thrust–power maps and CAD-based areas.

We also expect intake screens to foul from algae and debris, raising flow resistance and starving the propulsor. To keep maintenance within spec we will run tests across light/temperature to map "percent coverage" to added drag and set cleaning intervals from data. Stability will be safeguarded by keeping collected mass low and centered, partitioning the bin to limit slosh, and checking metacentric height and mass properties across empty–full states in CAD. Finally, safe environmental interaction means proper navigation lighting, shrouded propulsors and intake guards, and verified remote-control range and compliance for public waters. These will be validated before open-water trials.

Domain Analysis

Our project's final deliverable is to produce an accurate simulation of how the design will operate and a scaled-down prototype of the final hull design for the full-scale design. We believe that we will be able to meet these deliverables prior to the end of the semester and have accounted for meeting these goals in the project plan.

To follow our project plan, we must consider the impact that our critical design decisions will impact the schedule. For our project, the main design decisions relate to the hull design and the weight distribution of critical systems (undulating plate, propulsion system, and collection receptacle). This project is difficult because the robot must be stable and float during operation, however, as microplastics are collected, the center of mass may shift, so we must choose a strategic layout of systems to counteract this. Additionally, this project is difficult because the microplastic entrance and filtered water exit are susceptible to being blocked by microplastics, which can cause the system to be unusable. To solve these critical problems, we plan to engage with our stakeholders as well as continue to do research to choose countermeasures or design modifications that will help reduce the impact of these problems. This will allow us to gain knowledge about existing solutions and areas for improvement within those designs.

As the team progresses through the design process, additional steps may be included to account for project definition changes, discovery of new critical information after a design direction is chosen, or anticipated challenges countermeasure changes. If steps need to be added, we will discuss how

this will impact our critical path and how we can counteract any negative impacts on the final deliverables. Then, we will add those tasks into the schedule where we think it fits best for preserving the flow of our project plan.

DISCUSSION

This section will discuss the changes we would make to the existing design if we had more time to create a better problem definition, the strengths and methods to improve the weaknesses of our design, and overview the challenges we met during the design process.

Problem Definition

Overall, we found that our design has several strengths and weaknesses and thus, many areas for improvement and future work. If we had more time to collect data, we would have primarily put more resources towards researching other development locations. To do this, we would have research locations in the U.S. that have the highest number of peak sun hours in the summer and look into research lakes or smaller controlled bodies of water to test in. Since, our biggest concern with our design is regarding the power usage of the system in tandem with sourcing low energy consumption components, it could be helpful to find a location that generally has more peak sun hours during the summer or change the operating conditions of the robot.

In terms of improving our understanding of our design problem, we could have done more research into how we could sustainably manufacture the undulating plate without compromising its functionality. We would have done this by looking into the test results from each of the implementations and compared the motor speed to the collection frequency so that we could determine which implementation would work the best for our self-sustaining requirement.

Additionally, with more time, we would have focused more energy into defining the scope of our simulations. We unintentionally kept delaying work on the model and this negatively impacted us because useful metrics from the simulations could have been used during the design phase to determine the optimal hull design. With more time, we would have started creating and running simulations throughout the design process to help validate our design decisions.

Finally, with more time, we would have conducted more thorough testing on the prototype to better gauge the true behavior of the system. Since we spent a lot of time in the planning phase of this project, we were not able to create a prototype that had all of the same functionality of the full scale design, ultimately leading to our team having a prototype that could not validate many requirements. This could have been improved by conducting a test with a prototype that has real electronics (excluding the solar panel) to test the efficiency of the undulating plate in more realistic conditions. This adjustment would also allow the team to get a better understanding of the impacts of wave dynamics on the system as this interaction is very difficult to simulate.

Design Critique

An area for improvement would be the design of the exterior of the storage container. We went back and forth between having a frame in which each wall would be covered with mesh and having solid walls. Ultimately, we decided that it should not have a large impact on the drag of the robot and that solid walls may be easier to clean. This is definitely a decision that could be revisited in the future if the cleaning advantage is not substantial through the results from conducting the deployment and cleaning survey detailed above.

Another area for improvement is to increase the collection efficiency of the undulating plate. Potential improvements could be increasing the length of the undulating plate, increasing the speed of the undulating plate motor, or performing more verification testing with a prototype that has undulating plate motors that are run consistently at 360 RPM. This specification of 360 RPM was not met during our testing because our test plan included using a drill to power the gear train shaft rather than using a motor to power it. The decision to use a drill to power the system was made due to insufficient time, but is very easy to implement with more time.

A final area for improvement would be to increase the retention of the one way valve that is inside the storage area. Currently, our testing reflected that the existing design does a decent job at ensuring that collected microplastics do not escape into free water, however, our current method could be further improved by adding small springs with relatively low spring constants to help the valve doors close a little faster. The tradeoff for this change is that it would then require more force from the waves to push the doors open.

Risks

During the design process, we faced many challenges that were a result of time constraints and delivery delays. To face the time constraint challenges, we met as a team to discuss how fast we could feasibly complete our critical tasks and how we could pivot to stay on track with our end of semester deadline. If a critical task could not be feasibly completed, we started by asking clarifying questions to our sponsor to ensure that we had a good understanding of the scope of that element. Then, we worked as a team to redistribute tasks within the team to make sure that they were completed on time. We do not anticipate any end-user risks with our final design other than potential comfortability concerns that will be addressed through the comfortability survey detailed above.

REFLECTION

When determining how our design will make the world work better, we have considered the social, environmental, and economic implications. When comparing them to the initial ideas we had in the Design Process section, we found minimal changes. Here we reflect on the overall project and our experiences working with many different people.

Health, Safety, Welfare, and the Global Marketplace

Our project connects to many different factors in the real world. First and foremost, it must be safe to be around humans and marine life as it will be deployed in a lake with public access and marine life. Our work does not focus too much on this as we focused on the general hull design and microplastic container, though we did take into account potential sharp points and ensured they were softened—though either a fillet if possible or added cover material if not, like in the meshes.

Through ensuring our requirement of releasing less microplastics than it collects, we looked to find environmentally friendly materials to work with, these include metals and recycled plastics. The hope is the robot lasts forever, so there is no disposal, but with the initial insight of getting good materials to start, there should be minimal impact after compared to the manufacture. This affects society as there should be less plastics in the environment. Economically, although the initial plan is to only make six robots, the hop in the future is to make more. This will cause more requests for environmentally friendly materials so there will be more focus on them in the economy and in society.

Tools used to determine these impacts include stakeholder maps and life cycle costing of different potential materials, such as plastics and metals and their relationships and reactivity in the environment. Our analysis of stakeholders ensured we take into consideration all of the people affected and see the positives and negatives opinions different stakeholders possess.

We did not focus on whether the design could be of benefit in a global marketplace, as we were focused on a research scope and looking into the early stages of this robot. These in the future could be placed in more places globally, though the marketplace was not considered.

Culture, Privilege, Identity, and Style based Team Interactions

Throughout the project we took different methods to ensure everyone's voices were heard within the group and outside. Understanding how each member worked, we guaranteed each team member's opinions were taken into account. There were times when one person would take the lead on a part of the project without consulting the group, though after, we would talk about it and make sure a good decision was made. There were no obvious cultural, privilege, identity, or stylistic differences that affected our group too much, and we talked through disagreements that occurred as we went along. This minimized potential conflict and connected the group, keeping everyone on the same page.

Limited cultural, privilege, identity, and stylistic similarities with our sponsor were defined, as we all have had diverse life experiences, whether coming from being women in engineering and/or migrating from various locations. The one dynamic we found more prominent was that our sponsor was also our professor for the class which created a power dynamic between design ideas and class grading. She did a good job separating the two roles, though at times there were biases pushing for certain design decisions, often the ones they were looking into already. We worked to ensure these

biases were thoroughly explored and ensured our design was the best possible, regardless of any preconceived notions.

Inclusion and Equity

There are several power dynamics that exist in this project between our team and: our stakeholders and other team members. First, our project sponsor is the same as our instructor and mentor, as discussed previously. Additionally, other stakeholders who work on the project have been completing various, distinct parts for some time now and as newcomers, we have an interesting experience learning from everyone and what they have already learned. Secondly, between team members there were not as many power dynamics because we are all students and thus hold similar amounts of power. Despite this lack of a power imbalance, we did have diverse viewpoints, in addition to our stakeholders' viewpoints, which required us to think critically and objectively assess all ideas when selecting which ideas would inform the project. As a team we ensured that every viewpoint was thoughtfully and diligently considered to ensure that our different cultural backgrounds would serve as a resource to expand our creativity.

Ethics

In the design of our project, we faced several ethical dilemmas, mostly surrounding the lifecycle sustainability of the design. Specifically, in our final design, we worked to source materials that are sustainably produced and will not degrade or release pollutants into the environment when deployed. Because sustainable and durable materials are largely more expensive than less sustainable and durable materials, we had to balance sustainability with low cost and we were able to achieve this by simplifying certain design elements, for example the storage mesh, to be able to reduce overall cost even when using sustainable and durable materials. Additionally, we also have had to compare the environmental benefits and risks with the deployment of this device. Specifically, while this design is able to remove microplastics from the environment, we had to also consider the potential damage that this device could cause to the local environment due to noise, heat, or physical interaction with the environment. We have kept this in mind while developing this design by considering these challenges in our engineering specifications, but we were unable to verify that our project meets these specifications, which needs to be determined before this design can be deployed.

If our design was to enter the marketplace, there would be few ethical dilemmas that would occur given that our design consists of sustainable materials and uses renewable energy sources. The main dilemma that could arise is the disposal of the robots as recycling can often be viewed as an unnecessary cost by consumers, but this could be mitigated by having a buy-back program where consumers could sell back an old robot that we could then ensure is properly recycled.

Our personal and professional ethics expected to uphold by the university and future employers have grown over the course of this project, as we have focused on environmental improvements and building those possibilities.

Overall, we have faced limited ethical dilemmas in the design of our project as it is based in environmentally friendly practices.

RECOMMENDATIONS

Based on our experiences with this project, we recommend implementing several changes. First, for the storage mechanism, we recommend implementing a spring as a part of the one-way gate to ensure that it remains closed when the undulating plate is not on or when the robot is not moving forward. Second, we recommend resizing the undulating plate to increase the flow rate of water across the plate, which will improve the microplastic collection rate. Third, after resizing the undulating plate, we recommend adding the undulating system motors to the scaled prototype to improve the realism of the empirical testing of the microplastic collection rate. In addition to these improvements, we also recommend integrating autonomous controls and implementing a control system for stopping the thrusters if an obstacle is nearby.

CONCLUSION

To improve upon existing microplastic removal solutions, we conducted research to identify key strengths and limitations of existing designs. Additionally, we have followed the ME 450 design process as it will allow us to iterate and adapt to changes throughout the design process. Throughout this project, many stakeholders have been identified to help us define the background and requirements based on the environment, social, ethics, and intellectual property aspects. From stakeholders' interviews and research into relevant regulations and standards, we have determined our project's requirements and translated them into quantifiable engineering targets, which were ranked by importance and priority. Based on these user requirements and specifications, we used many concept generation and development methods to ensure that a wide variety of ideas within the solution space were created. From these initial ideas, we began the concept selection process by using a concept map and a decision matrix to narrow down our ideas to a final "Alpha Design". Using our previously identified engineering fundamentals, we have completed several theoretical analyses and empirical testing to ensure that the "Alpha Design" will meet our user requirements and engineering specifications. This included durability and life cycle analysis, hydrostatics and hydrodynamics analysis, drag force acting on the design, power analysis, and algae growth. Using these results, we modified the "Alpha Design" to account for a different pontoon size to meet our stability requirement and accounted for the weights and positioning of our chosen electrical components to create our final design. Additionally, we created and completed several verification plans to ensure that all of our engineering specifications are achieved by our final design, including simulating the behavior of the robot during operation and prototyping the design to perform empirical tests. We have also developed multiple validation plans to be used in the future to ensure that the final design will solve our original design problem.

Acknowledgements

Special thanks to Maha Haji, Georgia McSwain, and Stephan Wagner for all of their support throughout this project and NOAA for providing grant NA24OARX417C0598-T1-01 to fund the ongoing research for this topic

BIOGRAPHIES

Our team is composed of four engineers, as we work to design a robot to collect microplastics from the water. Each team member has a different background, allowing for various ideologies which build a strong team.

Alisha Patel



Alisha Patel is a senior at the University of Michigan at Ann Arbor, majoring in mechanical engineering and minoring in computer science. She is originally from Memphis, TN and is interested in mechanical engineering because of how its fundamentals can be used for understanding countless, everyday applications. Alisha is looking to work in the automotive industry after graduating and hopes to come back to school for a master's degree after working in industry for a few years. Alisha currently is the Chief Engineer on the UM Human Powered Submarine project team and enjoys teaching new members about engineering fundamentals that apply to the project. Additionally, Alisha is also a part of the UM Society of Women Engineers, where she previously served as the Technical Development Officer.

Ashley Ortenburg



Ashley Ortenburg is a senior majoring in mechanical engineering with a concentration in robotics and a minor in computer science at the University of Michigan - Ann Arbor. She is originally from New Baltimore, MI and became interested in mechanical engineering after watching Iron Man 1 as a child. Since then, she has only become more passionate about the field of mechanical engineering due to its breadth and diverse applications. Ashley is currently working as an Instructional Aide for ME250 and is also a member of the Control and Optimization for Renewables and Energy Efficiency (CORE) lab and is hoping to pursue a PhD in mechanical engineering, specifically in control systems and co-design. After the completion of her PhD, Ashley is hoping to combine her passion for innovation and research with her passion for teaching and work in academia.

Melissa Peters



Melissa Peters is a senior studying mechanical engineering at the University of Michigan - Ann Arbor. She is originally from Northville, MI, and her interests reside in environmental issues and she is looking to work in the sustainability industry or on improving environmental aspects of machinery through efficiency when she graduates. She plans to go back to school for a master's degree after working a few years in industry. Melissa is currently the President of Michigan Robotic Submarine project team and enjoys managing all the processes to build an autonomous submarine, as well as advising the mechanical team specifically on the design and build stages. She is also the Director of Internal Affairs of First Alumni and Mentors Network at Michigan, where she leads the group to host STEM-related events for hundreds of K-12 students and volunteers with FIRST Robotics.

Tianze Hu



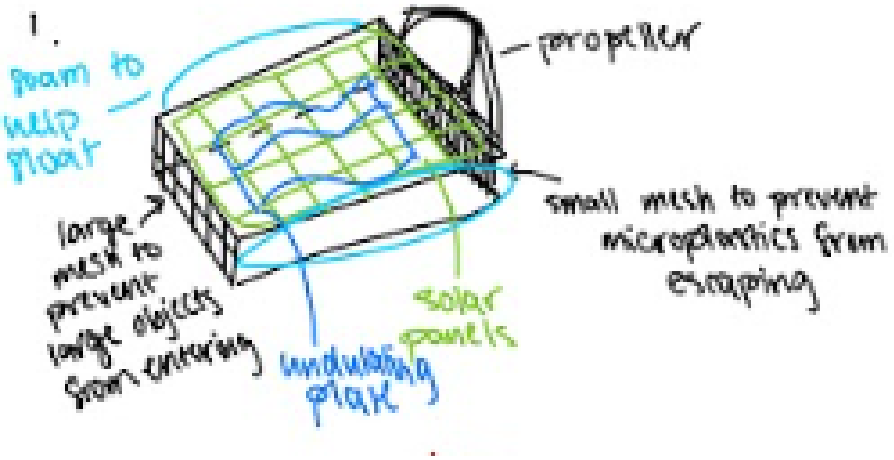
Tianze Hu is a senior in Mechanical Engineering at the University of Michigan–Ann Arbor, concentrating in mechanical intelligence and structural design. He works in the Toyota-sponsored Smart Materials & Structures Design Lab and in a GM-sponsored heat-transfer lab on EV battery safety. Originally from Suzhou, China, he plans to pursue a PhD in soft robotics or mechanical intelligence. In his spare time, he plays electric guitar in a pop band and designs and 3D-prints his own instruments. He is also the founder of the Michigan Chinese Photography Club, which hosts annual exhibitions and competitions.

APPENDIX

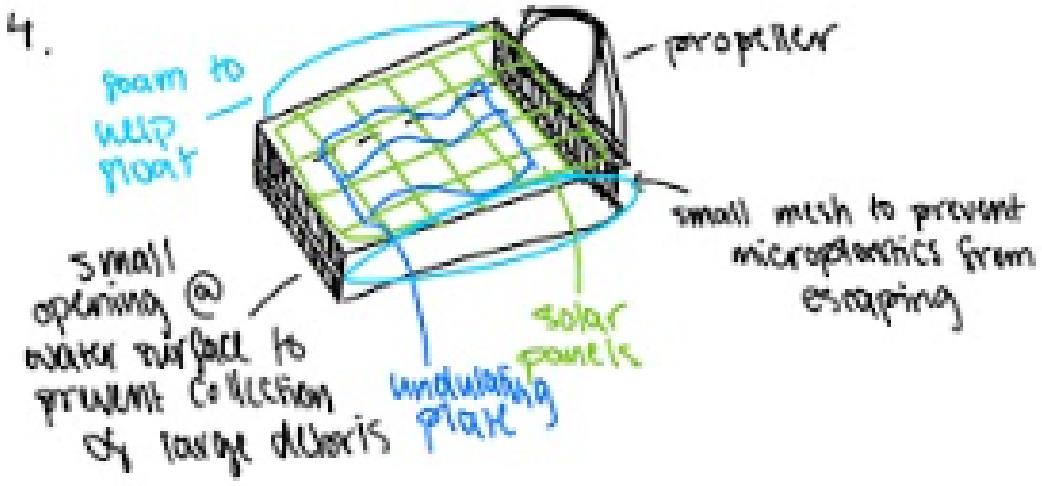
This section includes solution designs and their descriptions that were screened out during the concept exploration and selection processes. Designs were grouped by hull design, including rectangular, circular, pontoon-style, keel, and miscellaneous body types, respectively.

A. Rectangular Hull

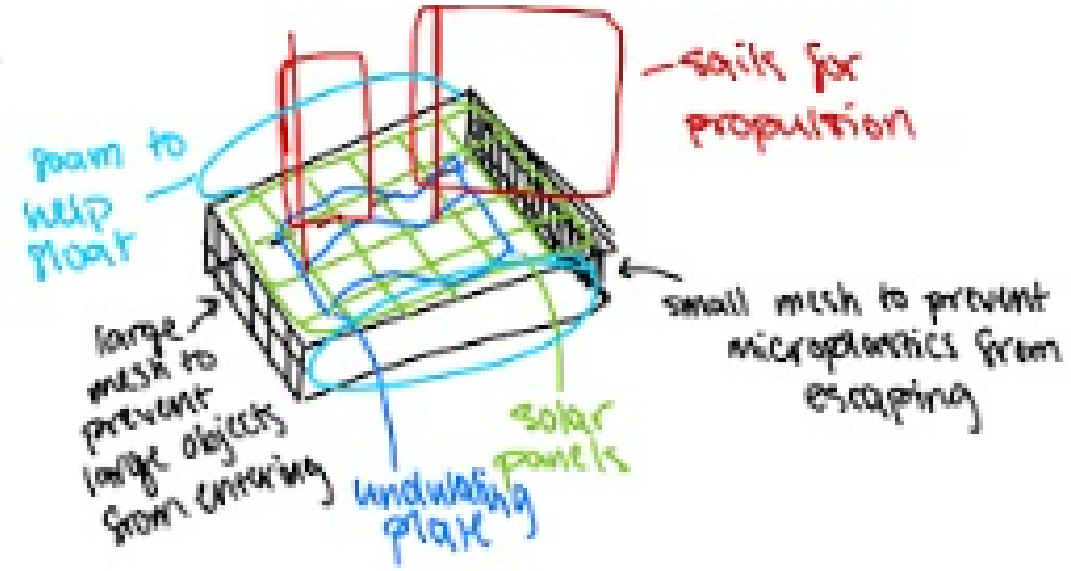
A1. This design includes foam along the sides of the robot to help it float and uses a larger mesh at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of. It is solar-powered and propeller-driven.



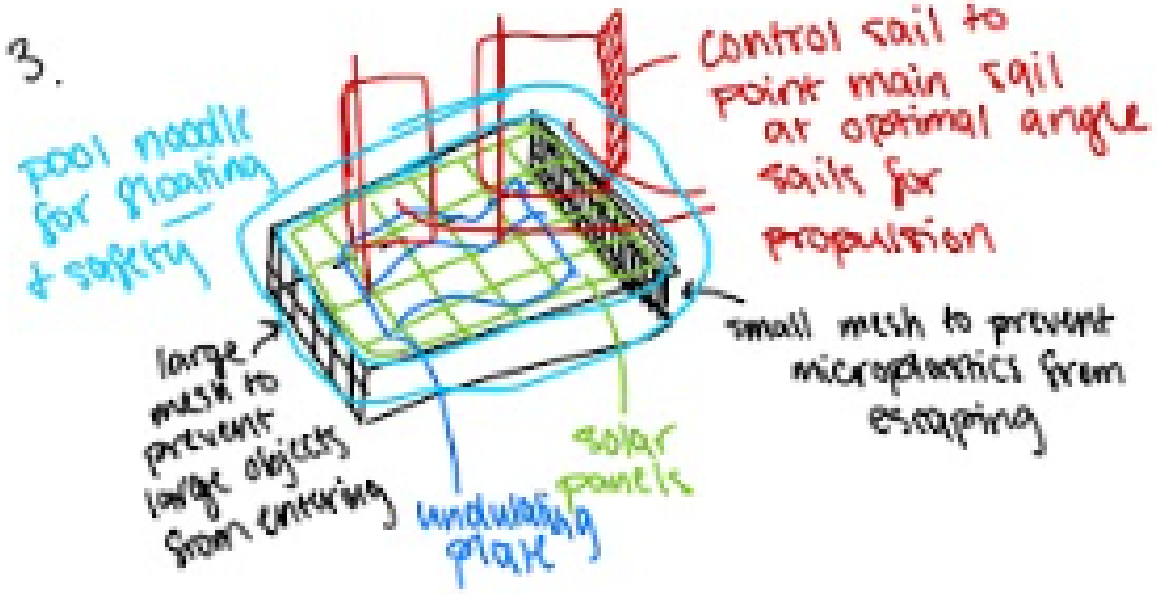
A2. This design includes foam along the sides of the robot to help it float and uses a small gap at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of. It is solar-powered and propeller-driven.



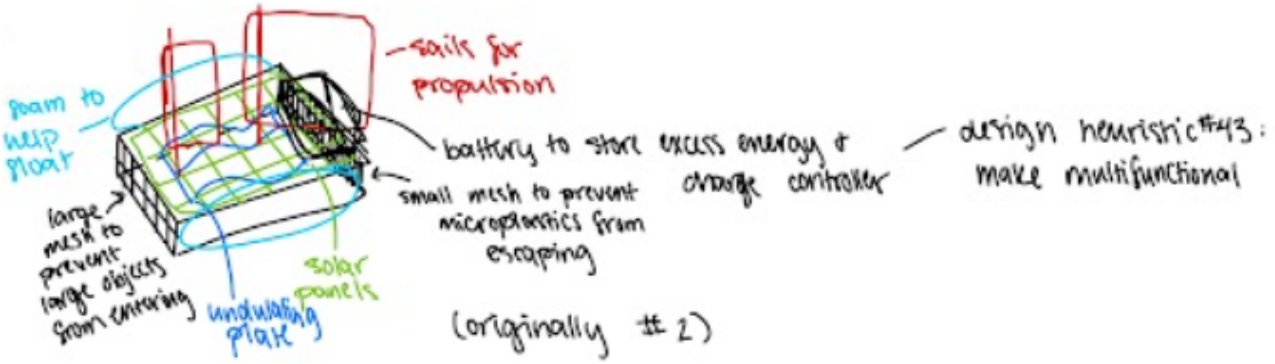
A3. This design includes foam along the sides of the robot to help it float, sails as the propulsor, and uses a coarse mesh at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of. It is wind and solar-powered.



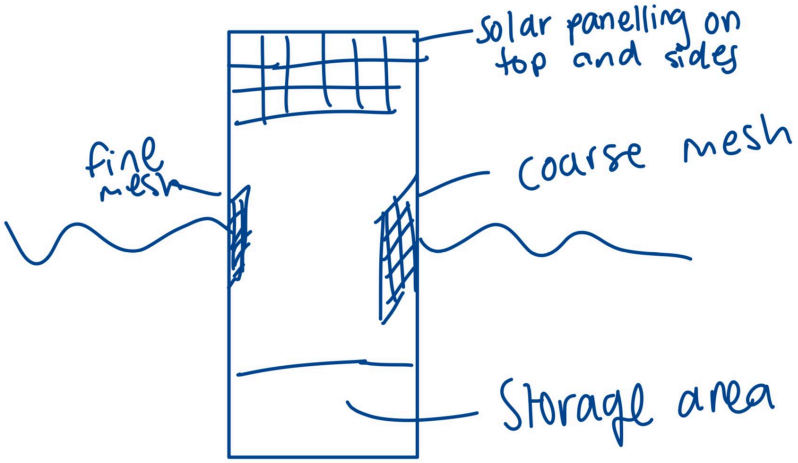
A4. This design includes foam along the sides of the robot to help it float and uses a coarse mesh at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of. This design uses sails as the propulsor and has a control sail design that would be used to point the main sail at the optimal angle. It is wind and solar-powered.



A5. This design includes foam along the sides of the robot to help it float and uses a coarse mesh at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of. This design uses sails as the propulsor and is wind and solar-powered. It also has a battery to store excess energy for instances when an insufficient amount of energy is collected in a day.

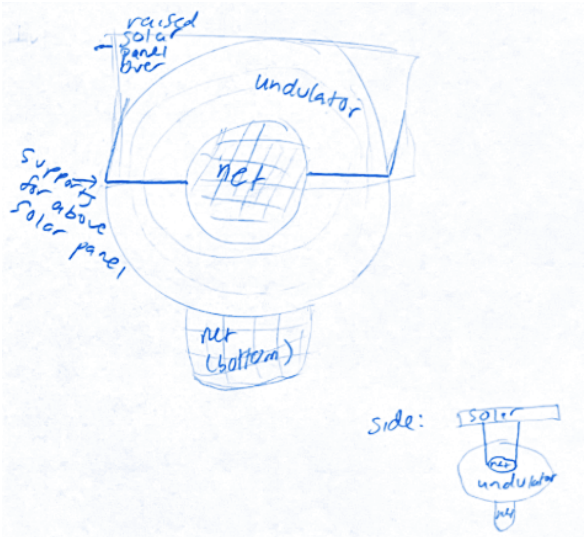


A6. This design has a rectangular body and uses a coarser and finer mesh to trap microplastics at the bottom of the hull while allowing the water to flow out. It is solar-powered and has panelling on the top face and the top portions of all four walls.

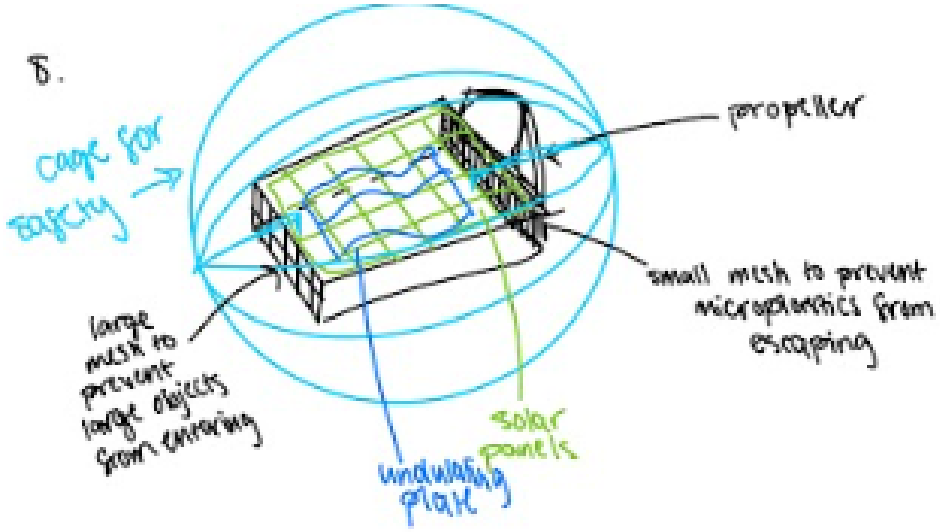


B. Circular Hull

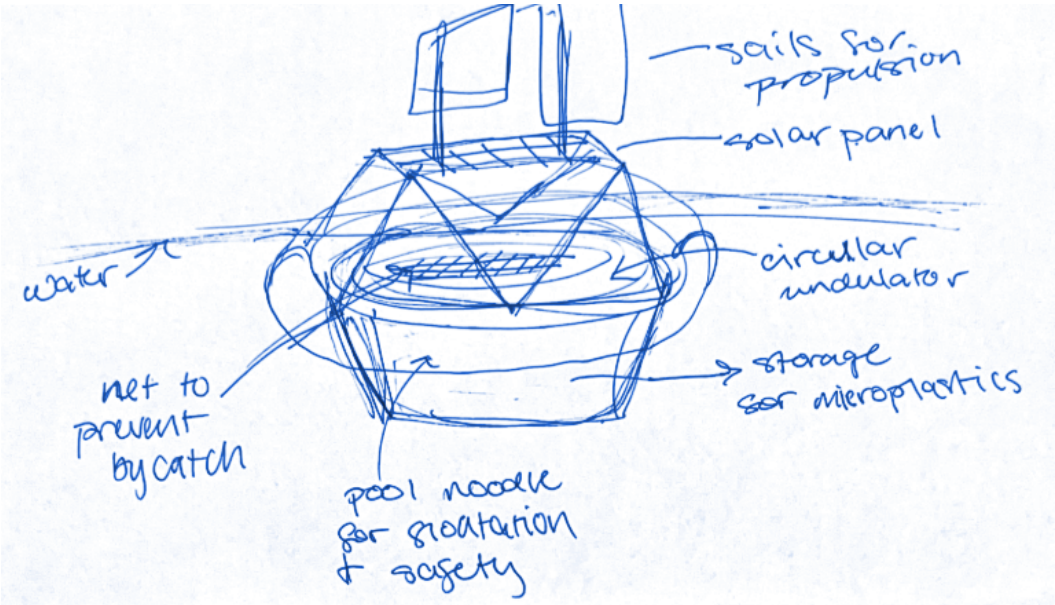
B1. This design employs a circular shape that microplastics can enter through the top from. It has a net at the bottom that stores the microplastics and has raised supports to hold the solar panels about the water surface. This design has multiple undulating plates that all undulate towards the center of the base.



B2. This design employs a circular cage around a rectangular base to protect the robot from environmental obstacles. Microplastics can enter through the larger mesh and the front and water can exit through the finer mesh at the back. This design is solar-powered and propeller-driven and uses an undulating plate.

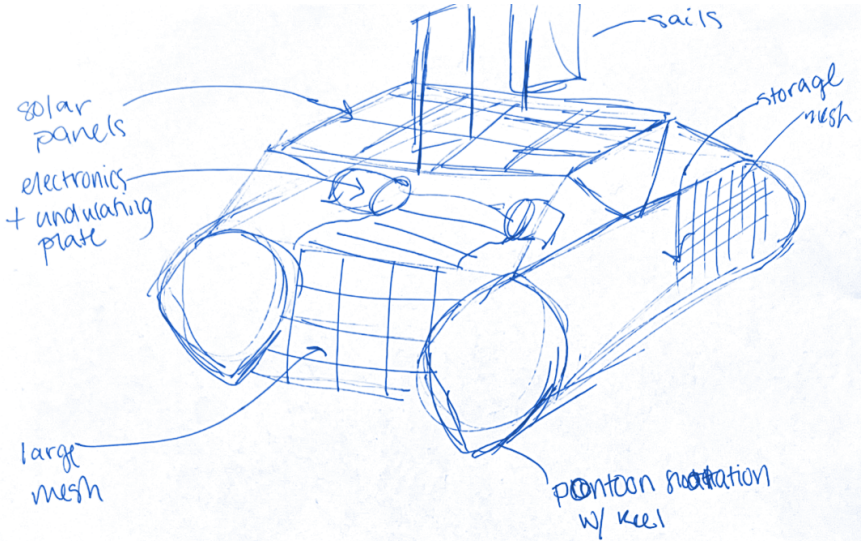


B3. This design employs a circular shape that microplastics can enter through the top from and has a pool noodle wrapped around the exterior to help it float. The opening at the top is protected by a large mesh that will prevent bycatch. It has storage at the bottom for collected microplastics and has solar panels and sails above the water's surface. This design employs multiple undulating plates that all undulate towards the center of the base.

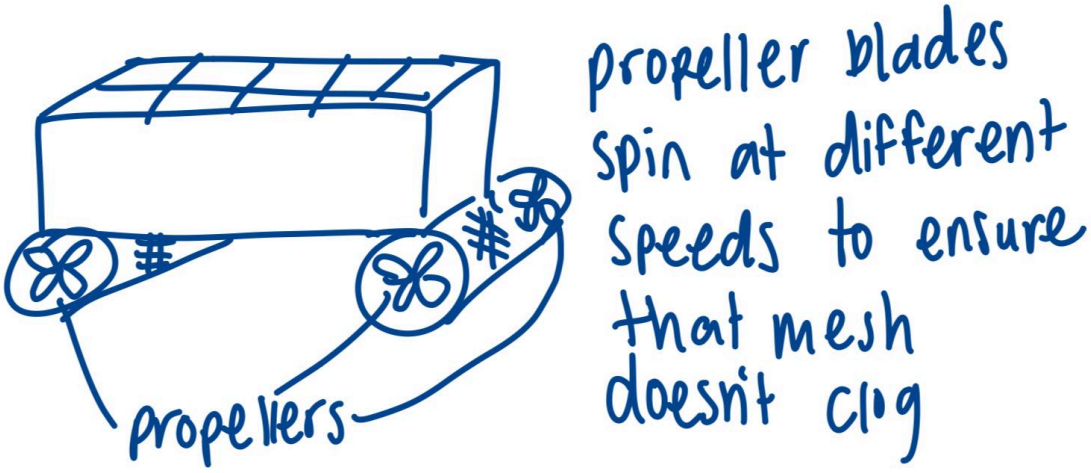


C. Pontoon-style

C1. This design includes a keel shaped pontoon-style hull that employs sails for propulsion. It also includes a larger mesh at the front of the robot so that microplastics can freely flow in and then become trapped in the storage mesh near the back of the robot. This design is wind and solar-powered.

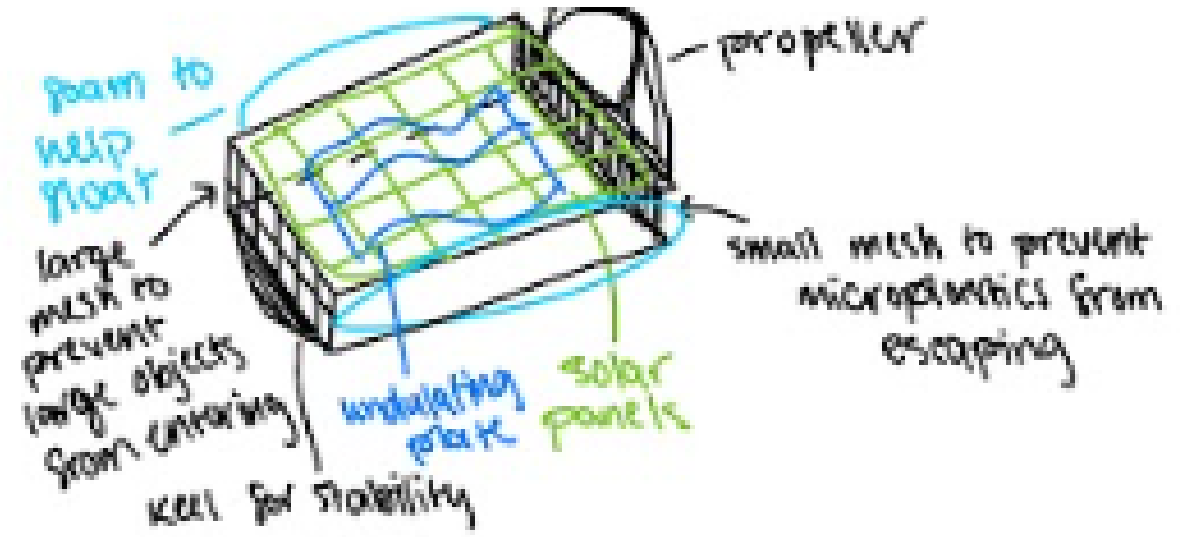


C2. This design has a pontoon-style base that is hollow. The tubes have propellers on each end that rotate at different speeds to reduce clogging of the mesh. It is solar-powered.

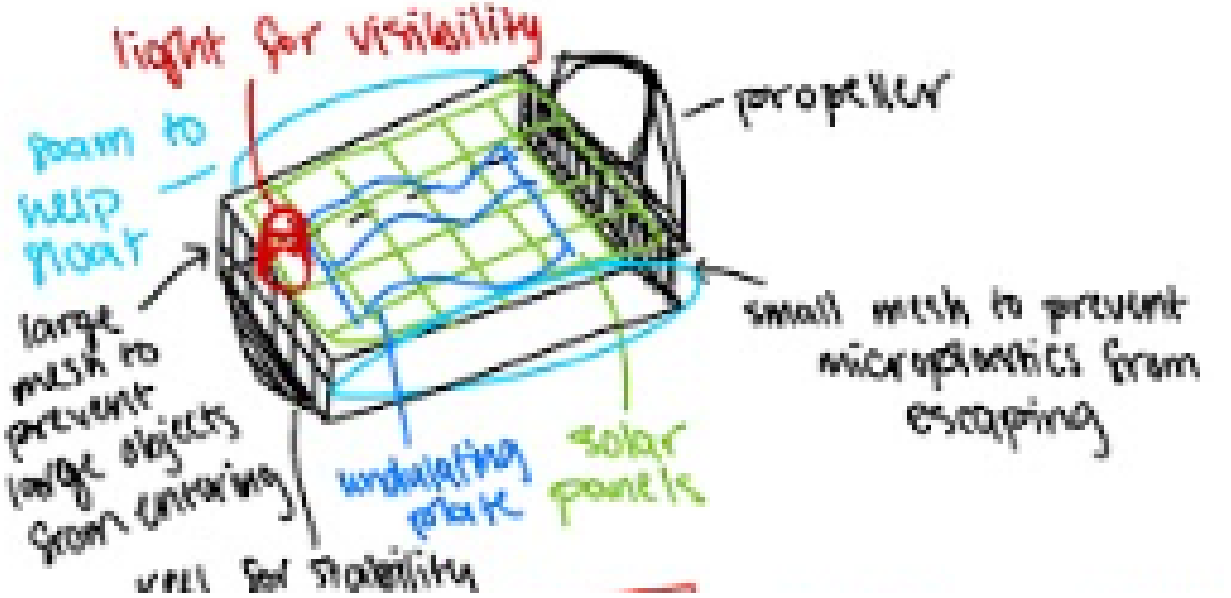


D. Keel

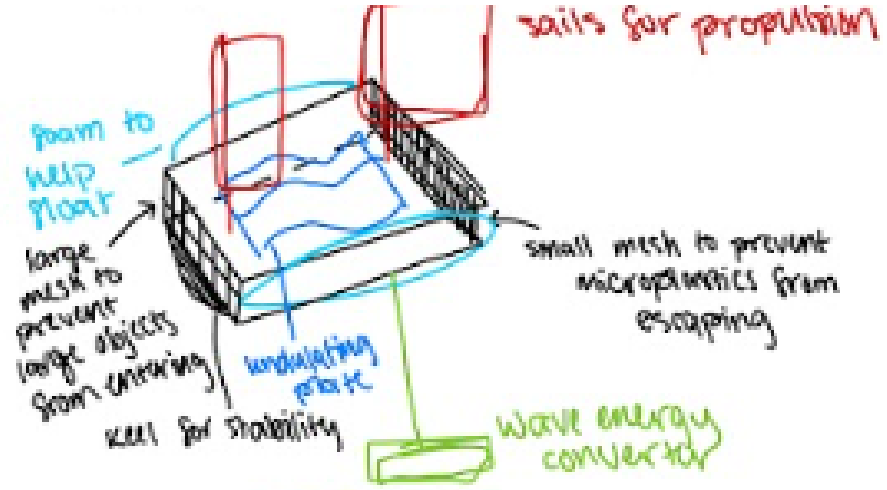
D1. This design includes foam along the sides of the robot to help it float and uses a coarse mesh at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of. It is solar-powered, propeller-driven, and has a keel at the base for stability.



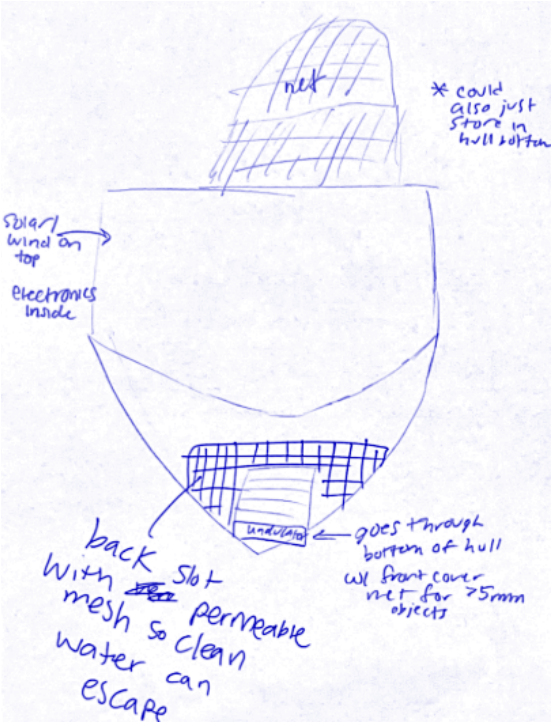
D2. This design includes foam along the sides of the robot to help it float, lights around the perimeter for visibility, and uses a coarse mesh at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of. It is solar-powered, propeller-driven, and has a keel at the base for stability.



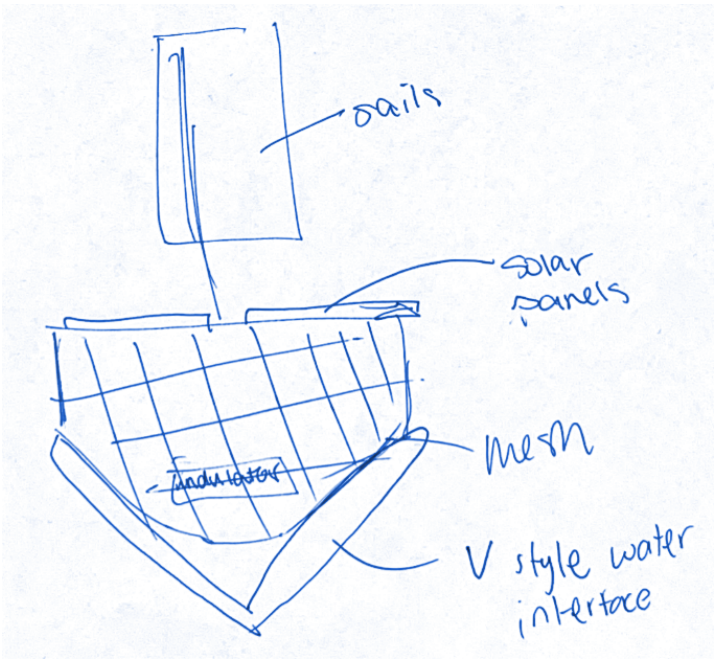
D3. This design includes foam along the sides of the robot to help it float and uses a coarse mesh at the front that microplastics can be drawn in through and a finer mesh at the back for water to flow out of. It is wave and wind-powered via sails on the top face of the robot, has a keel at the base for stability, and a wave energy converter behind the undulating plate.



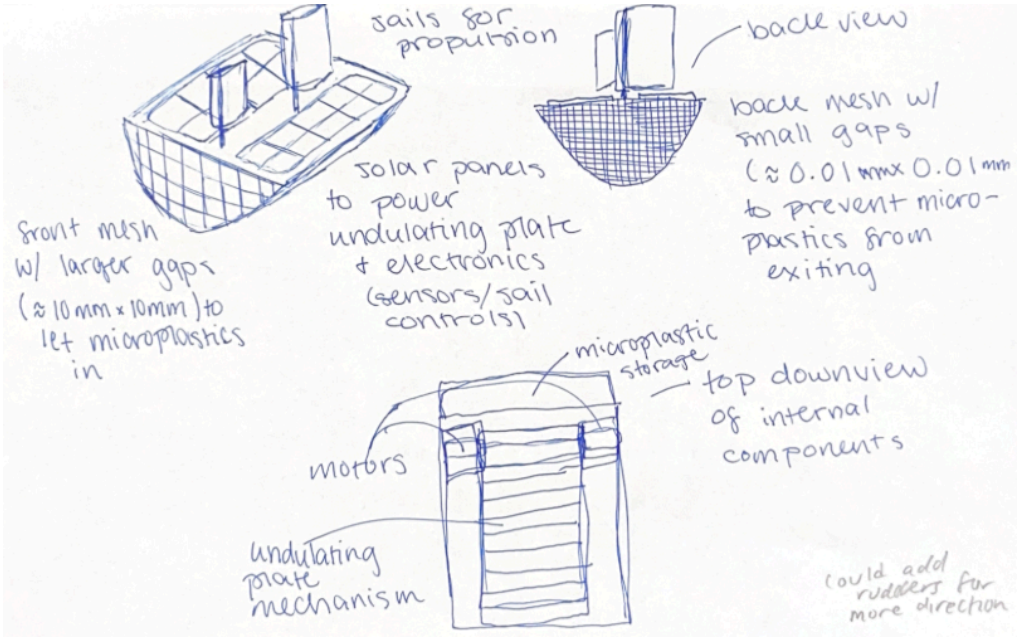
D4. This design includes a coarse mesh at the front that microplastics can be drawn in through and a finer mesh covering a slot for clean water to escape from. It is solar and wind-powered via solar panels on the top face of the robot and has a keel at the base for stability.



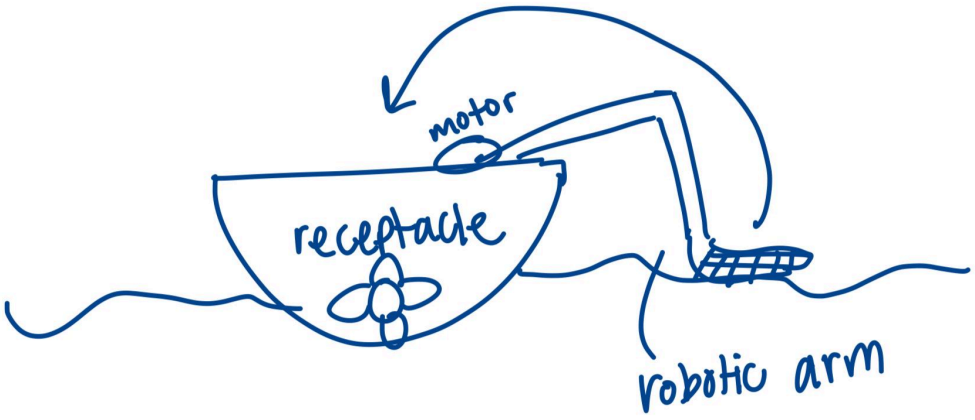
D5. This design includes a coarse mesh at the front that microplastics can be drawn in through and a finer mesh covering at the back face for clean water to escape from. It is solar and wind-powered via solar panels and sails on the top face of the robot and has a v-style keel at the base for stability.



D6. This design includes a coarse mesh at the front that microplastics can be drawn in through and a finer mesh at the back for clean water to escape from. It is solar and wind-powered via solar panels and sails on the top face of the robot and has a keel at the base for stability.

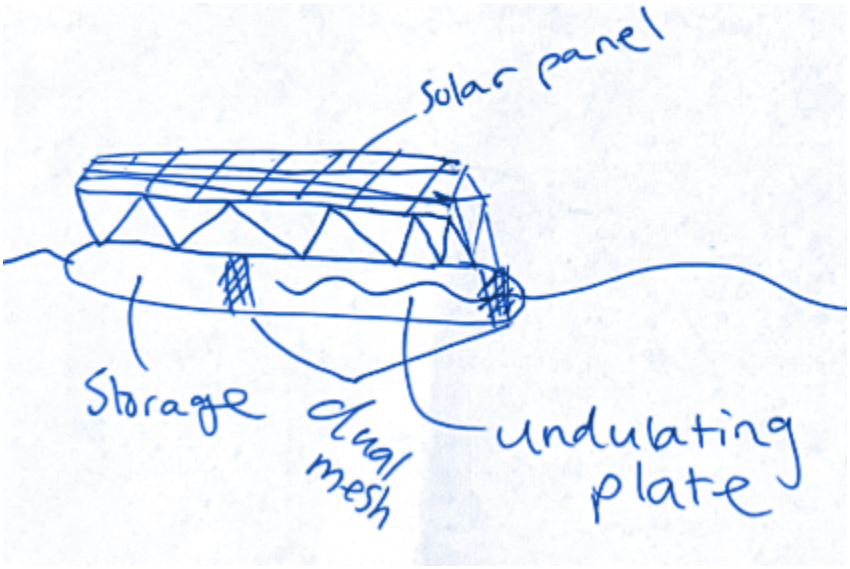


D7. This design has a robotic arm that has a mesh hand that can be moved all around the perimeter of the robot and can be retracted such that the plastics fall in the receptacle in the center of the hull.

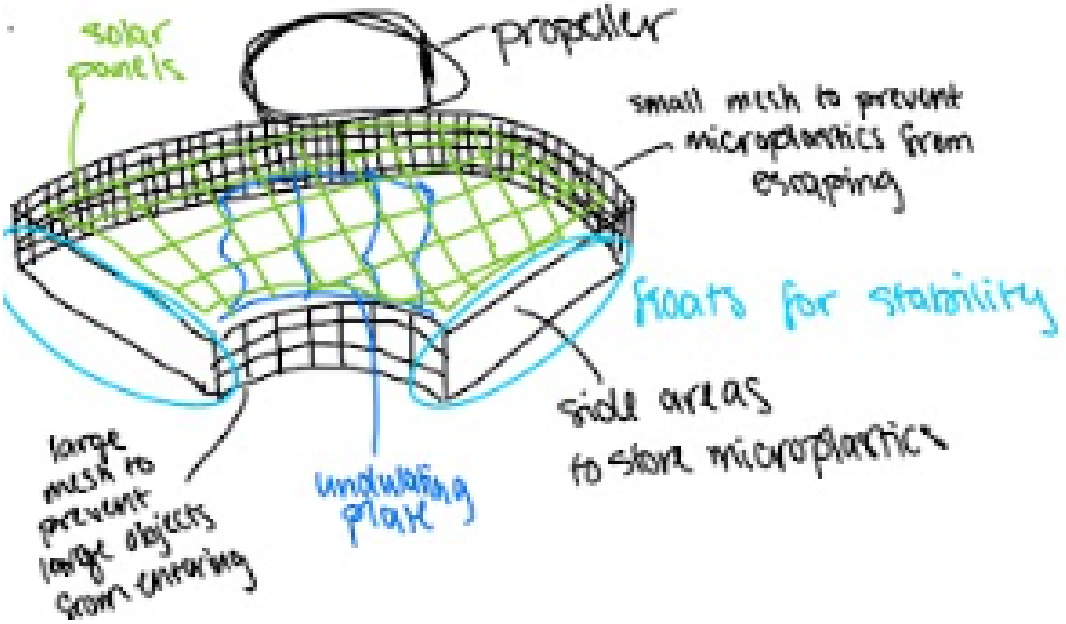


E. Miscellaneous

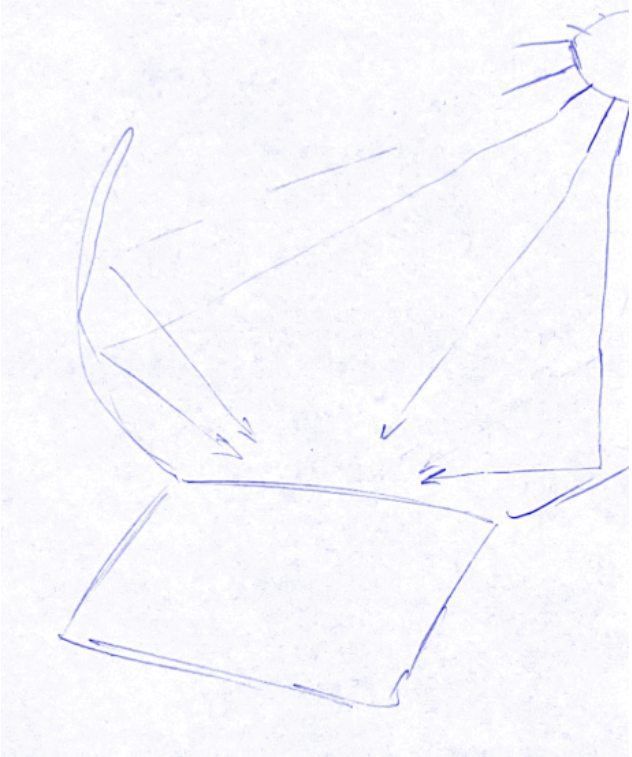
E1. This design has a truss structure along the sides of the robot so that it is less susceptible to tipping over during windy conditions. It has solar panels along the top of the robot and a storage receptacle at the back of the hull. This design has a coarser mesh at the entrance and a finer mesh at the exit to trap water within the storage container while allowing the water to escape.



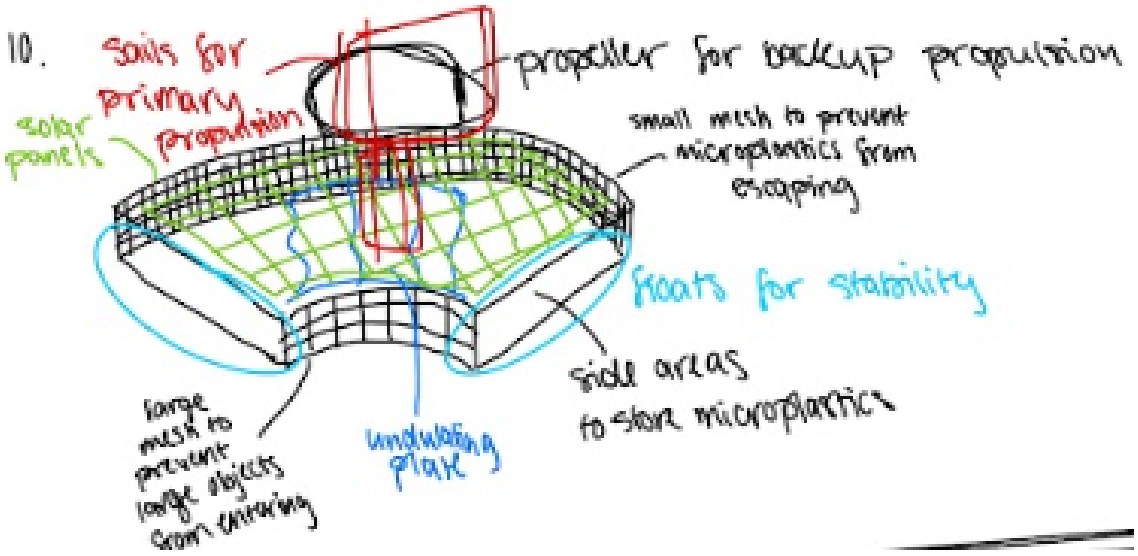
E2. This design has a quarter of a circle hull to allow for a smaller entrance area and a wider exit area to mitigate clogging as it collects microplastics. This design is solar-powered, propellor-driven, and stores microplastics along the walls of the robot.



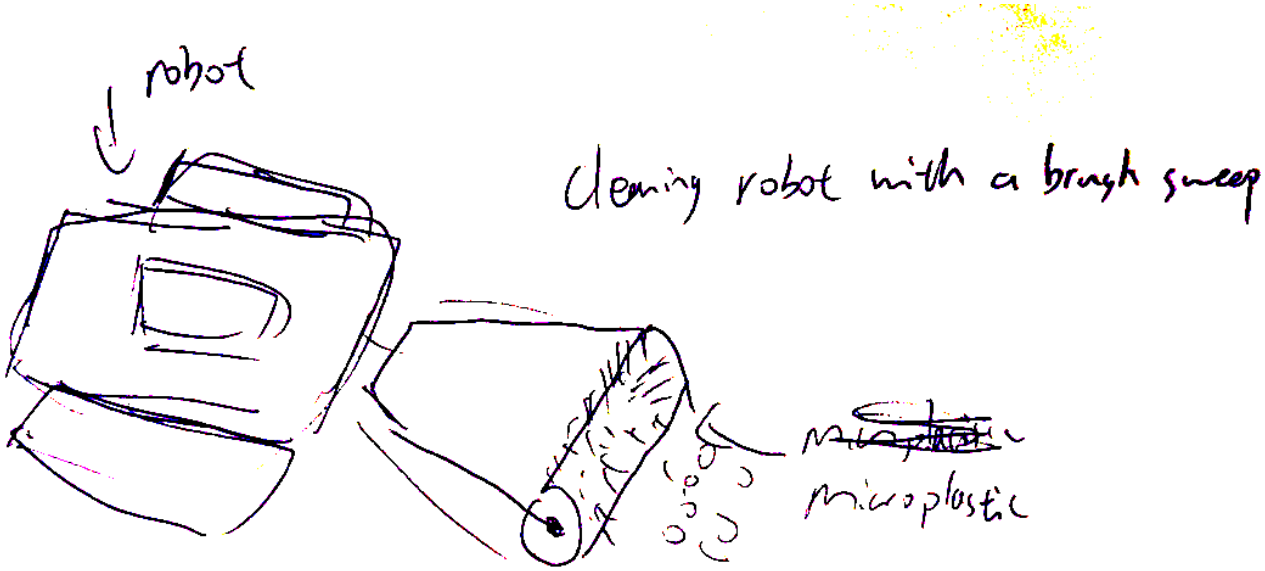
E3. This design shows the use of solar panels that are angled inwards to have a higher concentration of solar power on the solar panels.



E4. This design has a quarter of a circle hull to allow for a smaller entrance area and a wider exit area to mitigate clogging as it collects microplastics. This design is primarily driven using sails and has a backup system of using a propeller. It is solar-powered, and stores microplastics along the walls of the robot.



E5. This design floats along the surface of the water and collects microplastics using a brush that rotates inwards and helps the undulating plate attract microplastics to the storage receptacle within the robot.



F. Verification Plan Methods

F1. Safe

Relevant Specifications:

1.1. Have a white all-round light visible from at least 3.2 km in all weather conditions

1.2. Propulsion system shuts off when an object larger than 25 cm in any direction is within 1 meter of the robot

Verification Plan for Final Manufactured Design:

1.1. - Ensure that a white all-round light is selected that meets this Coast Guard regulation and that the light is added to the design.

1.2. - Place various sized objects, which have at least one dimension that is larger than 25 cm, at various distances from the device (including 1 m and closer) to ensure that the device is able to detect these objects and shut off the propulsion system accordingly.

F2. Self and Sustainably Powered

Relevant Specifications:

2.1. Produces enough renewable power to sustain performance needs

2.2. Stores ≥ 67 Wh

Verification Plan for Final Manufactured Design:

2.1. - Calculate the power production and usage of all components of the final design analytically, as discussed in the Electrical Power Analysis section of the Problem Domain analysis section.

2.2. - Ensure that selected batteries have a capacity of at least 67 Wh.

F3. Collects Microplastics

Relevant Specifications:

3.1. Collects plastics with 0.1 mm to 5 mm diameter

3.2. Does not collect objects > 5 mm

3.3. Prototype Scale: Collects at least 75% of microplastic particles in 5 minutes (200g of particles dispersed over an area of 1.2 m^2)

Necessary Items for Verification:

3.1: N/a

3.2: N/a

3.3 - Prototype Scale Verification:

- Prototype with undulating plate and storage mechanism
- Pool/tank of water with a surface area of 1.2 m^2
- 200 g of plastics that are the same size range (0.1 mm - 0.5 mm diameter) and density (1 g/cm^3)

3.3 - Full Scale Verification: N/a

Verification Plan:

3.1 & 3.2:

Material Selection: Ensure front meshes are 5 mm and and the rear mesh is 0.1 mm.

3.3 - Prototype Scale:

First, disperse 200 g of plastics into a pool or tank. Then, place the prototype with the undulating plate and storage mechanism in the pool or tank with plastics. For 5 minutes, run the prototype. After 5 minutes, turn off the prototype, and remove the collected plastics from the storage mechanism. Let the collected plastics completely dry, and once dry, weigh the collected plastics. Then, compare the weight of the collected plastics to the original 200 g dispersed in the water.

3.3. Full Scale:

Microplastic Collection Simulation: Use simulation to determine the weight of microplastics collected over the span of 30, 8-hour missions

F4. Minimize Negative Environmental Impacts

Relevant Specifications:

Verification Plan for Final Manufactured Design:

Minimize negative environmental impacts. For materials, create a mass-based bill of materials and mark each part as “sustainable/recyclable” with supplier proof; pass if the percentage is ≥90% by mass. For noise, use a handheld sound meter: measure idle/cruise/max at 15 m over water and confirm ≤85 dB(A). For heat, place two waterproof probes at 0.5 m and 1 m downcurrent during max-power operation and verify the water rise stays less than 2 °C. For bycatch, run a standard tank/shore pass, wet-weigh total intake, sieve out greater than 5 mm items, and confirm non-microplastic/marine life is less than 0.5 kg.

F5. Reliability

Relevant Specifications:

5.1. Systems operational/functional 75% of the time

Verification Parameters:

- Batteries will be fully charged prior to Day 1
- Tested over 8 consecutive days during the summer in deployment location
- Put in water at 8:00 a.m. and removed at 4:00 p.m.
- No supplemental power is provided to robot during test

Verification Plan for Final Manufactured Design:

Test full-scale system 8 days in a row and verify that it is fully functional for 6 out of the 8 days

F6. Durable

Relevant Specifications:

6.1. Deployed for 4 weeks with at least one 8 hour mission per day

Verification Parameters:

- Assume that cleaning occurs if necessary

Verification Plan for Final Manufactured Design:

Source hull material that will not degrade within 4 weeks of water interaction and waterproof electronics. Assess robot condition after conducting verification plan for 5.1 and if signs of damage are present, design is not suitable for 4 week deployment.

F7. Low Cost

Relevant Specifications:

7.1. <$10,000 per robot

Verification Plan for Final Manufactured Design:

After components and the materials for manufactured parts have been selected, ensure that the cost of all (both purchased and manufactured) components used in the device totals to less than $10,000.

F8. Floats

Relevant Specifications:

8.1. Net buoyancy force $\geq$ 0 N

Verification Plan for Prototype:

Conduct buoyancy analysis for the robot using realistic weight estimates for sourced components from CAD model. This will be verified by putting the prototype into a tank of water for 5 minutes and observing if the hull takes on water or if it starts to sink.

Verification Plan for Final Manufactured Design:

Deploy the robot into a body of water for 1 hour and observe if it sinks, mitigate any exterior interactions other than waves and wind.

F9. Stable

Relevant Specifications:

9.1. Metacentric height > 0 m, even when filled with 5 kg of microplastics and at maximum pitch and roll angle

9.2 Maximum pitch and roll angle of 20°

Verification Plan for Final Design CAD:

Conduct stability analysis using the center of gravity, center of buoyancy, and the distance between them to ensure that the distribution of mass allows for the robot to right itself if perturbed.

F10. Viable under operating conditions

Relevant Specifications:

10.1. - Remains functional under maximum wind speed of 13 m/s for 30 seconds

10.2. - Minimum operating water temperature of 0°C

10.3. - Maximum operating water temperature of 45°C

Verification Plan for Prototype:

10.1 - Use free body diagram with applied wind drag of 13 m/s to ensure that device is still able to achieve specifications 8.1 and 9.1, flotation and stability.

Verification Plan for Final Manufactured Design:

10.2, 10.3 - Ensure that all (both purchased and manufactured) components used in the device are able to withstand temperatures of 0-45°C

F11. Easy to Deploy for 1-2 People

Relevant Specifications:

11.1. - Must be at most 45 kg

11.2. - Needs to be deployable without specialized equipment

11.3. - Less than 30 minutes to deploy once on site

Verification Plan for Final Design CAD:

11.1 - Ensure that the weight of all (both purchased and manufactured) components used in the device totals to less than 45 kg

Verification Plan for Final Manufactured Design:

11.2/3 - Have 5 groups of 2 people attempt to deploy the device into the selected deployment location (Toronto Harbor or Oneida Lake) within 30 minutes

F12. Easy to maintain

Relevant Specifications:

12.1. Less than 60 minutes to remove any debris on external and internal surfaces

12.2. Needs to be cleaned at most once a month

12.2.1. Cleaning is required when 25% of the surface of the intake area is blocked by debris

Verification Plan for Final Manufactured Design:

12.1 - Have 5 groups of 2 people attempt to clean the device within 60 minutes after the device has experienced 1 month of one 8 hour missions per day

12.2/12.2.1 - Deploy device for 1 month with one hour mission per day and use intake camera to determine when 25% of the surface of the intake area is blocked and whether that is within a month

F13. Remote Controlled

Relevant Specifications:

- 13.1. Remote controllable up to 300 m from operator

Verification Plan for Final Manufactured Design:

Source RC system that is rated to have a 300 m distance capability. Conduct physical tests on land to see if 300 meter range is reliable by moving the transmitter to complete a full circle around the receiver and repeating measurements at 60° angle increments around the center. Repeat 3 times for accuracy

F14. Within Size Constraints

Relevant Specifications:

- 14.1. Approximately 0.5 m long x 0.4 m wide x 0.2 m deep
- 14.2. Holds 5 kg microplastics

Verification Plan for Final Manufactured Design:

Use a tape measure on a flat surface to record the overall length, width, and depth in the operating configuration and accept dimensions if they are within a ±5 % band of ~0.5 m × 0.4 m × 0.2 m. Next, load the bin with 5 kg of wet surrogate particles, operate for a short run, then re-weigh and check for leaks, deformation, or handling issues; pass if it holds ≥5 kg securely. Repeat each 3 times for accuracy

G. Build Design Bill of Materials

The following table includes the components that were used during our process of building the prototype including materials that were readily available in the X50 shop, the workspace for our class. The perler beads and drill attachment can be continuously used for future testing. Additionally, parts of some of the products were not used, such as the meshes and bearings, though can be used in more prototypes and the final design that will be created by those continuing to work on other aspects of this ongoing project.

Item	Quantity	Source	Catalog Number	Piece Price ($)	Contact
5 mm Mesh	1	McMaster-Carr	85385T27	39.25	mcmaster.com
0.1 mm Mesh	1	McMaster-Carr	85385T105	23.54	mcmaster.com
Perler Beads	2	Amazon	B09X325V5C	9.99	amazon.com
Bearings	1	Amazon	B09PKD8QZZ	6.99	amazon.com
3D Print Filament	1	Amazon	B0F83KJ5MM	23.99	amazon.com
Flexible Drill Attachment	1	Amazon	B0DS64FTRC	4.59	amazon.com
⌀ 50 mm Clear Tubes, 280 mm long	2	X50 Shop	N/a	N/a	N/a
⌀ 12 mm Hot Glue Stick	3	X50 Shop	N/a	N/a	N/a
⌀ 50 mm Tube Endcaps	4	X50 Shop	N/a	N/a	N/a

H. Manufacturing Plan

The prototype was built as a modular intake–storage system that could be quickly assembled and reconfigured with standard ME450 tools. All core components—the undulating plate, storage chamber, one-way valve, and gear module—were 3D-printed with integrated snap-fit features so that they locate and lock relative to each other without additional fasteners. After printing, parts were cleaned, checked for fit, and lightly sanded where needed so that the snap joints engage securely but can still be separated for inspection or repair.

Once the internal modules were verified, the flotation and intake elements were attached. Sections of PVC pipe, acting as simple pontoons, were positioned along the sides of the modular assembly and hot glued in place to give the prototype its buoyancy and set the desired draft. The front mesh was similarly hot glued directly to the intake opening on the modular structure so that incoming beads and water are guided over the undulating plate and into the storage chamber while larger debris is screened out. Hot glue was used both as an adhesive and as a quick way to seal small gaps between printed parts, PVC, and mesh.

The gear module houses the main shaft that drives the undulating plate. After the gears and shaft were installed and checked for smooth motion, a handheld drill was coupled to the shaft to provide actuation during testing. The fully assembled unit: PVC pontoons, modular intake–storage–gear structure, front mesh, and drill drive, was then placed in the test tank, and small adjustments to glue joints and snap connections were made until the prototype floated stably and the plate motion and one-way valve behavior matched the intended operation.

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