Design, Development, and Testing of an Unmanned Surface Vessel (USV) for Oyster Aquaculture

by

Annemarie Dapoz

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ABSTRACT

To sustainably feed the growing worldwide population, development of aquaculture technology is necessary. However, it heavily lags behind that for terrestrial agriculture. The Oystermaran team at MIT Sea Grant is working on developing a vehicle to address a section of this need. Close quarters flip-bag oyster farming, common in Massachusetts, is a physically demanding job which is done entirely manually as there is no existing technology to fit into the crowded oyster field. The team developed the Oystermaran - an unmanned surface vessel designed specifically maneuver through the crowded farm and flip the baskets. This thesis covers the complete mechanical design, development, and initial testing of the 2nd Oystermaran vehicle. Built as a flexible design to allow adaptations and tuning on-site, the Oystermaran V2 featured interchangeable bows, adjustable frame and mechanism dimensions, and worked to add mechanisms and capabilities that aquafarmers requested. Multiple rounds of testing and adjustments were conducted and the Oystermaran V2 proved to be a complete platform the team can continue to test and develop to eventually make a fully autonomous vehicle.

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Chapter 1

Introduction

There is a strong need for technological development in aquaculture to sustainably and ethically feed the planet's growing population. However, aquaculture significantly lags behind terrestrial agriculture in creating and adopting new farming technology.[1] A key area for development here in New England is in oyster farming as all work is currently done manually. There is no avaliable technology to aid oyster farmers without heavily sacrificing their yield. To develop a solution to this problem, this project creates the Oystermaran, an Unmanned Surface Vessel (USV) designed to reduce the required manual labor and at least partially automate the process of labor intensive process of flip-bag oyster farming (Figure 1.1).

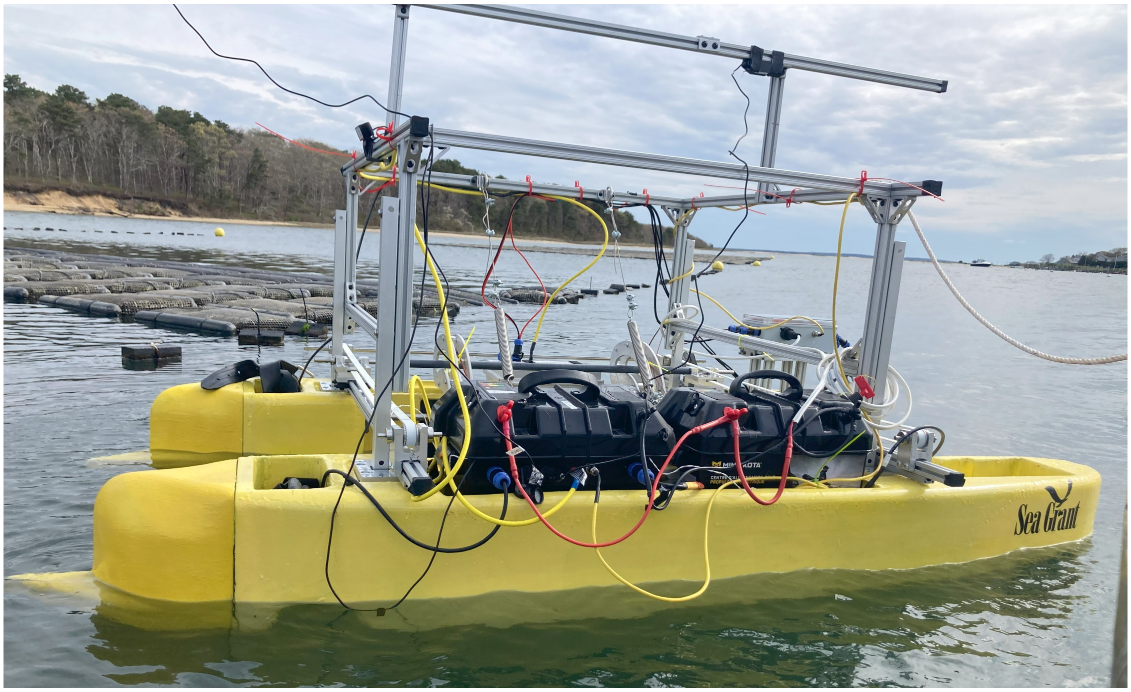

Figure 1.1: The Oystermaran in front of Ward Aquafarms on Cape Cod, MA

1.1 Motivation

One of the main goals of MIT Sea Grant is to develop technology which is beneficial to the community and the environment but not often addressed by companies due to the work requiring significant research and development. The Oystermaran (named as a portmanteau of "Oyster Catamaran") is one such technology. The goal of the project is to develop a fully functional prototype of an unmanned oyster farming vehicle for close quarters flip-bag farming. Once a solution is determined, validated, and therefore de-risked, a company or co-op could take the prototype and create a vessel farmers can use in their operations.

When MIT Sea Grant first approached aquafarmers about the best place to add new devices into their work, they quickly pinpointed oyster farming. According to the farmers, demand is high for New England oysters as cold water oysters are less susceptible to pathogens than those from warm waters. Oysters are frequently farmed in Massachusetts and sent all over North America. However, the process of growing oysters is literally back-breaking work as farmhands lean out of the sides of kayaks to flip baskets of oysters which can reach almost 30kg (60lb). It's a physically demanding, time intensive, and repetitive job which farmworkers don't want to do - but the perfect scenario to implement a robot.

In addition, oyster farming in particular has the benefit of being known to clean the surrounding water. As filter-feeders, oysters live on particles in the water and water quality improves around oyster farms (more detail in section 2.1.1). Oyster farming is a sustainable way to grow more seafood, so by making oyster farming less labor intensive and beginning to automate the process, the Oystermaran project has potential to benefit farmers, consumers, and the environment.

1.2 Project Overview

The Oystermaran has three main systems: mechanical, electrical, and autonomy. This thesis covers the complete mechanical design of the current Oystermaran, comprising of the custom hulls and bag handling mechanism. The electrical system powers the vehicle and controls the vehicle's components, while the autonomy system will detect and align on the baskets then run the flipping process. The current autonomy program is working on identifying and tracking the baskets, more detail can be found in the thesis "Aquaculture Basket Detection and Tracking for Autonomous Surface Vehicles" by Fiona Gillespie [2].

1.3 Thesis Outline

This thesis begins with a background of aquaculture technology, especially as it relates to shellfish farming and New England specifically. Then, an overview of the system is presented. The design of the vehicle components and their testing and iterations are shown and discussed, as well as the results of field testing. The thesis concludes with a summary of the successes and shortcomings of the vehicle and proposed solutions for continuing the prototype's development.

Chapter 2

Background

Historically, both fishing and aquafarms have been detrimental to the environment and the development of sustainable fisheries, including aquaculture technology, is necessary for feeding the population while maintaining the health of the ocean [3]. However, despite aquaculture technology being shown to increase productivity and reduce risk for aquafarms, development of the technology has been slow [1].

2.1 Brief Review of Relevant Aquaculture Knowledge

The growth and development of aquaculture is necessary for food and environmental sustainability. As the global demand for food grows higher and the amount of wild-caught seafood stagnates (and should go down to to prevent overfishing), more sustainable aquaculture technology is needed [4].

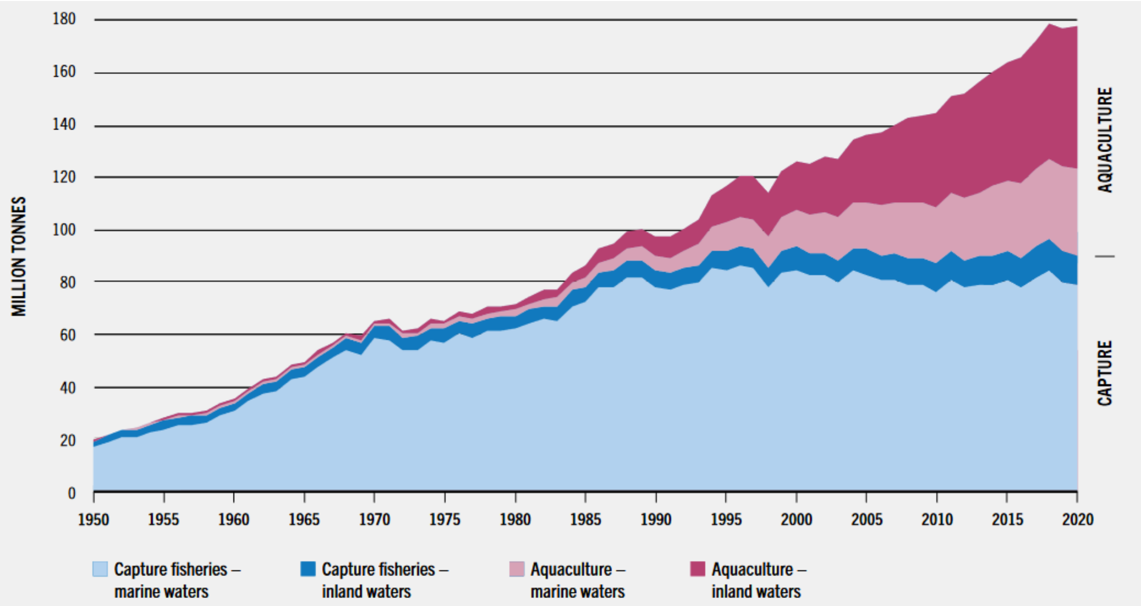

Figure 2.1: Worldwide seafood production, figure 1 in [4]

Aquaculture technology is beneficial for farms's efficiency and is being developed to aid in water quality detection, feed waste reduction, gear inspection, and more [5]. But despite the growing use of marine technology, these solutions tend to focus on vision and sensor based systems and aquafarms continue to rely heavily on manual labor [6].

2.1.1 Ecological Benefits of Oyster Farming

Sustainability and health of the local ecosystem is a major concern for aquaculture development. Farming animals which improve or at least do not adversely affect the surrounding environment is essential for sustainable aquaculture. Oysters meet this criteria, and greater marine biodiversity can often be found alongside bagged oyster aquaculture [7]. Native species in danger of loosing habitat, such as eelgrass, are often found near oyster farms (and farms for other filter feeders) as they improve water quality by removing particulates, especially nitrogen, from the water[8]. Oyster farm gear has not been found to impede the surrounding environment and species, including critical species such as horseshoe crabs, making it an ecologically friendly form of aquaculture [9].

2.1.2 Methods of Oyster Farming

In order to farm oysters, there are multiple available methods. As indicated in Figure 2.2, the in-water methods can be categorized as intertital, subtital, floating, suspended, or on-bottom.

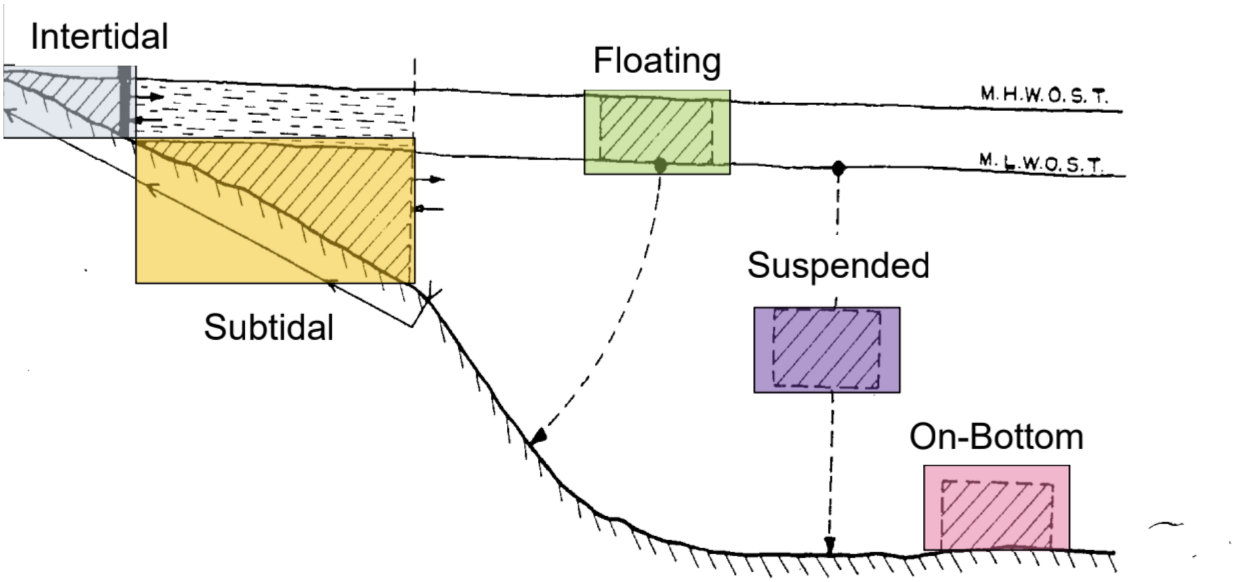

Figure 2.2: Common categories of in-water oyster farming. [10] The Oystermaran targets floating aquaculture.

In each of these methods, the oysters are grown in large porous containers so the shellfish can filter-feed from the surrounding water. However, over time the containers become covered in biofouling, restricting water flow to the oysters and causing a smaller yield. This is a problem for all submerged methods and some farmers accept this trade-off while others either place their bags in the intertidal zone or floating on the surface. Floating bags are very common, but they must be flipped over every 1-2 weeks for the biofouling to flake off in the sun. This method is known as flip-bag oyster farming and is what the Oystermaran is being developed for. Flip-bag farming is popular as it aids in oyster growth and shell development as the process removes biofouling and the motion causes the oysters to grow in a shape more desirable for market [11].

There are other groups also developing methods of automating flip-bag farming. One example is FlipFarm from Blenheim, New Zealand [12]. FlipFarm uses a helix mounted to the side of a work boat to quickly and efficiently flip baskets, as seen in Figure 2.3. The baskets are connected in long chains and as they are passed through the helix their one-sided floats cause the baskets to swing around and flip orientation.

Figure 2.3: **Left:** FlipFarm. Note the wide spacing between the rows of baskets. [12]
Right: The FlipFarm HeliCat, a boat mounted helix for oyster bag flipping. [13]

However, this method requires a significant amount of space - something not possible everywhere. To force baskets through the helix, a minimum 1kW (1.5hp) motor is required, restricting the Heli-cat to farms which can fit a workboat between each row [14].

2.2 New England Shellfish Aquaculture

Here in the Northeastern United States, setting up fields with enough space for a boat to pass through each row is often infeasible without heavily sacrificing farm yield. For Massachusetts, where MIT is located, government permits dictated a limited amount of space to be used for aquaculture [15]. Despite this limited space, Massachusetts produces a tremendous amount of shellfish, with the industry valued at over $28 million USD by Woods Hole Sea Grant [16]. For farmers here, in order to have a substantial harvest with this smaller area they must densely pack their fields with baskets. The Oystermaran team worked closely with Ward Aquafarms, a farm which uses flip-bag method of oyster farming in a tightly packed space. This is very common in New England, and while driving out to the farm the team saw multiple farms with similar setups to Ward Aquafarms where vehicle tests were conducted.

Flip-bag oyster farming commonly consists of thousands of baskets set into a large array. The baskets are flipped every one to two weeks to dry off the biofouling and shake the oysters.

There is currently no technology which can fit into the arrays of oyster baskets and all work is done manually by a worker in a kayak, as displayed in Fig. 2.4.

Figure 2.4: A worker at Ward Aquafarms flipping baskets. Note the size of the array (up to 2,800 baskets for this particular farm) as well as the tight spacing and packed conditions

Maintaining the field is an arduous process, both slow to complete and physically challenging as workers must flip the thousands of baskets each reaching up to 27kg (60lbs) at the end of the oysters' growing cycle. The process can disrupt an entire farm as staff are required to aid with flipping and it can be difficult for farms to hire additional workers for the task. To automate farms such as these, a smaller USV solution which can navigate and flip in the crowded array of baskets is required.

2.3 Oystermaran V1

In 2021, a group of students at MIT Sea Grant developed the Oystermaran to begin addressing this problem [17]. Shown in Figure 2.5, the Oystermaran (dubbed "Flippy") is a catamaran-style vessel with a flipping arm which reaches between baskets to flip them, mimicking the motion of a human worker. The original prototype was built then tested at the oyster farm and proved the viability of the Oystermaran concept.

2.3.1 Successes

The V1 Oystermaran was a successful proof of concept and could generally flip lightweight baskets. The vehicle operated by reaching across the baskets, pulling one side out of the air and up towards one hull before pressing the basket against two posts which forced the bottom of the basket out so it would land in the water on its opposing side. It utilized a fairly simple mechanism effectively to prove the Oystermaran could work.

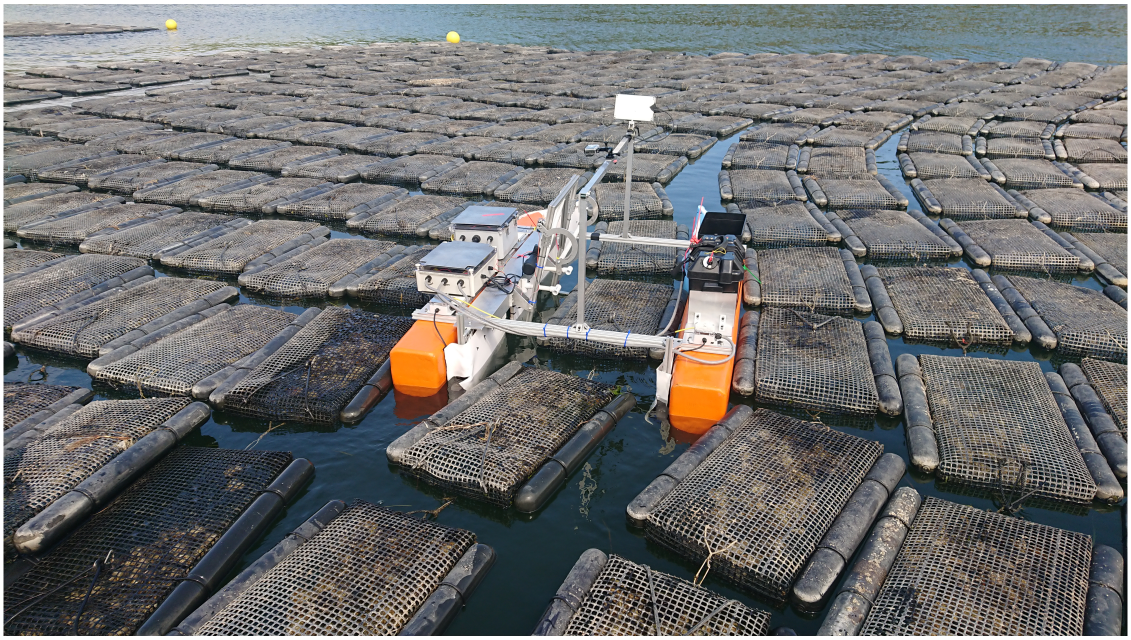

Figure 2.5: The first Oystermaran, shown from the back in the middle of a field.

2.3.2 Shortcomings

However, the original Oystermaran was also slow, frequently got stuck on baskets, had difficulty maneuvering, and could only handle lightweight baskets with young oysters. Baskets would occasionally slide down the way they started rather than flipping, and the team had not learned about basket shaking yet so the vehicle lacked any kind of shaking mechanism. The vehicle experienced major issues with snagging, with baskets getting caught on vehicle elements and the thrusters interfering with the frame which holds the array in place. The hulls, designed for hydrodynamic efficiency, were not maneuverable in the field itself. Its curved bows would slide up on top of the field and essentially beach the Oystermaran on top of the baskets. And as the array shifted with the current, baskets would press in around the Oystermaran and the frictional force would sometimes be too great for the thrusters, trapping the vehicle until a gap opened.

2.3.3 Progression to V2

The eventual goal of the Oystermaran is reliable autonomous flipping. This was not possible with the original vehicle, as the flipping mechanism lacked the full capability users require and the fine manual control needed to overcome the maneuvering issues meant an autonomy program could not be developed. To solve these issues, a second Oystermaran prototype was designed, built, and tested. The Oystermaran V2 targeted these missing components, starting with hulls to allow it to more easily enter the array. The new vehicle would also create a second iteration of the flipping mechanism, adding mechanisms and strengthening the design to allow for handling and shaking of oyster baskets at any point in the growing cycle.

Chapter 3

System Overview

The V2 Oystermaran was designed with testing in mind. Testing of the V1 Oystermaran taught the team that an oyster field is a complicated environment to operate in, and many issues arise during field testing which did not occur in the lab. Therefore, the Oystermaran V2 had to be designed in a way where features could be tuned or switched out if needed.

To accomplish this, a set of hulls with interchangeable noses and an adjustable frame was developed to allow for tuning of major vehicle dimensions during testing. To flip baskets, a new prototype bag handling mechanism which added the new features required to grab, lift, and flip over the oyster baskets was made. The final vehicle design can be seen in Figure 3.1.

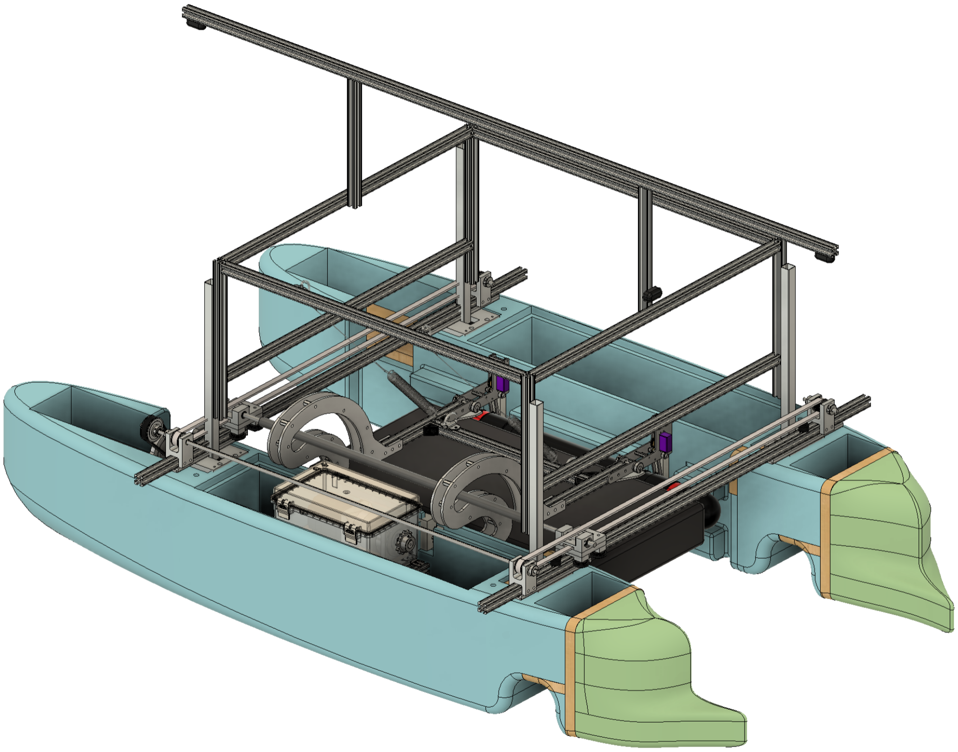

Figure 3.1: CAD of the final V2 Oystermaran

3.1 Requirements

The main requirements of the Oystermaran were to create a vehicle which could fit into the array and maneuver inside of it in order to reliably flip oyster baskets and develop an autonomy program. The critical functional requirements for the vehicle as a whole are shown below in Table 3.1.

3.1.1 Key Functional Requirements

Maneuvering	Adjustable spacing between hulls	Frame made of t-slot rail. Maximum frame width of 1.17m (46in)
	Field elements do not snag on vehicle	All mechanism components as well as thrusters inset into the hulls.
	Vehicle can align with basket rows and shake itself free when it become stuck	Lateral thrusters at the bow of the vehicle and forward thrusters in the back
	Fit over field frame into array	Mechanism approaches baskets from top rather than underneath; vehicle sits high in the water
Flipping	Lift oyster baskets with up to a 30kg dry weight and 15kg wet weight	Given a 0.6m lever arm, requires a 180Nm minimum motor. 200Nm motor with spring assists used.
	Baskets are shaken to redistribute oysters	Separate "slider" mechanism which can shake baskets in coordination with the "basket rest" element
	Mechanisms are adjustable to interact properly with each other and the hulls	Areas with critical lengths are also made of t-slot rail

Table 3.1: Critical Functional Requirements

3.1.2 System Constraints

The prototype also had to work around a series of constraints imposed by the environment, user requirements, and lab testing and manufacturing requirements:

- All components able to be manufactured with the available resources at MIT or bought off the shelf
- Vehicle must fit in a standard van or disassemble for transport

- Vehicle must work with existing field. Any changes made to the field for the mechanism to operate must be minimal and only affect parts which require yearly maintenance or replacement
- Prototype is robust enough to be used for multiple years of testing while the electrical systems and autonomy program continue to be developed, including the ability to replace parts

3.2 Summary

The Oystermaran is a prototype vehicle designed to fit into existing space-constrained flip-bag oyster farms. Based on results and testing of a V1 prototype, the mechanical design of a V2 vehicle was developed to build off the first vehicle's successes and address its shortcomings. The final Oystermaran V2 mechanical design meets its criteria by providing a vehicle which adds all known needed mechanisms and capabilities and is adjustable and tuneable for all unknown components so improvements can continue to be made and the vehicle iterated on based on testing results.

Figure 3.2: The Oystermaran V2 in the field with all mechanical systems complete.

Chapter 4

Hull Design

Many of the critical issues regarding V1 of the Oystermaran were connected to the hulls of the vehicle, as discussed in section 2.3. Therefore, V2 required a new design to prevent snagging, remove the chance of accidentally riding on top of the baskets, and aid in guiding baskets around the vehicle. The main goal of the hulls was to create a geometry that could easily maneuver through the basket array, reducing the need for fine manual control to allow for the development of an autonomy program. Much of the information in this chapter and Chapter 5 is drawn from the author's paper "A Prototype USV Designed for Maneuvering in a Crowded Oyster Farm" [18].[1]

Figure 4.1: The hulls of the V1 (left) and V2 (right) Oystermarans. The V1 vehicle has additional guides attached to its bow which allowed it to fit into the field and were added during its testing and redesign process. The bows of V2 were interchangeable, the "combination" nose, the final one developed, is shown.

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4.1 Hull Design Overview

The final vehicle is based around two symmetric catamaran hulls, which allow baskets to slide between them for flipping (Figure 4.2). The hulls were narrowed from V1, making them as thin as possible while still fitting all components. Each hull contains multiple cavities for electronics storage, mechanism mounting, and thruster protection; reducing the number of components extending outside the vehicle which baskets and other field elements could snag on. Four thrusters, two rear facing and two lateral, allow for easy alignment with rows and aid in pushing baskets out of vehicle's way. Finally, interchangeable noses allowed the ideal geometry to be determined via testing.

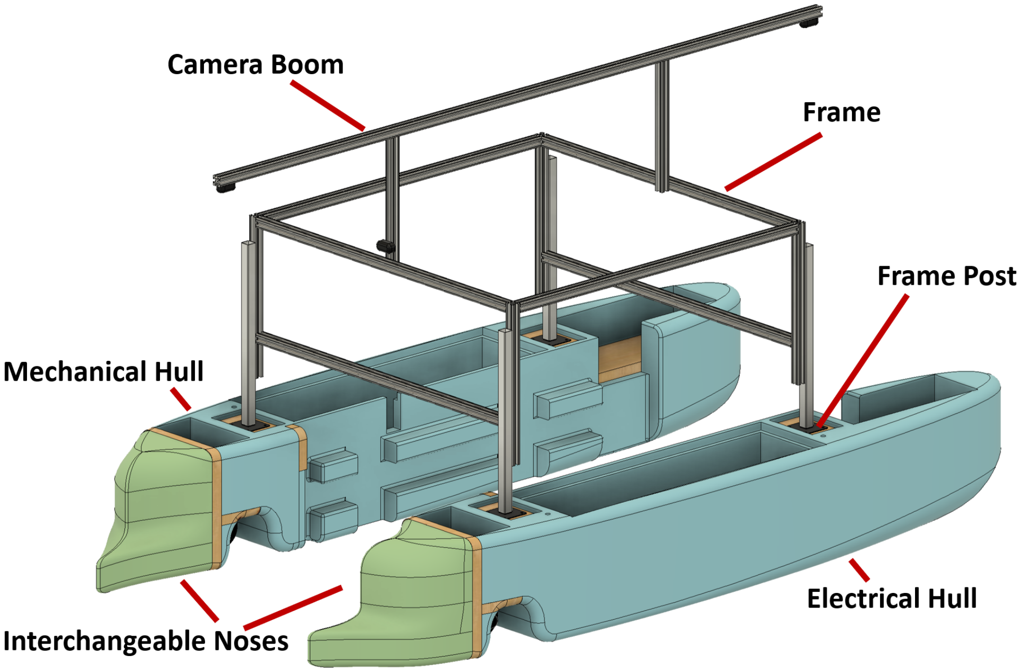


Figure 4.2: The final design, with the final nose shape installed and major components labeled. One hull primarily housed the mechanical subsystems, while the other provided space for the batteries and computers.

4.2 Subsystem Requirements

4.2.1 Key Functional Requirements

The goal of the hulls were to create a lightweight and buoyant vehicle for easy transport which could house all mechanisms and fit into the array without getting caught on field elements. The two hulls are connected by a frame which stretches across the catamaran. A summary of the functional requirements are below:

Category	Functional Requirement	Design Parameters
Hulls	Hulls fit between rows of field	30cm (1ft) max wide hulls, as narrow as possible to fit the battery
	Field elements do not snag on vehicle	Hulls built with cutouts for mechanisms
	Vehicle can easily enter array	Interchangeable noses to test prototype bow shapes; thrusters inset into and protected by the hulls
	Field elements do not snag on vehicle	Hulls built with cutouts for mechanisms
	Electronics mounted inside hulls rather than on top	Electronics cavity sized to fit 2 boxes: a computer and a battery. Additional electronics mounting located in the other hull to be closer to the mechanisms.
	Provide mounting locations to basket handling mechanism and thrusters	Installed marine plywood with tee-nuts underneath fiberglass in certain sections
	Support weight of all mechanisms and components	Minimum 1,000 N buoyancy force estimate
Frame	Easily removable for transport during initial testing	Frame slides onto frame posts and can be installed/removed with only a mallet
	Maximize field of view of cameras	Additional camera boom on top of frame
	Frame and flipping arm do not intersect	Frame is also adjustable vertically (as well as horizontally as discussed in 3.1 to stay out of the way as the flipping arm design changed
	Provides torsional stiffness to keep the hulls in sync	Multiple beams run directly between the two hulls; after dimensions were finalized lower support beams were added

Table 4.1: Hull Functional Requirements

4.2.2 Subsystem Constraints

Constraints on the hulls mainly focused in two areas: what was it possible to build with accessible lab and shop space, and creating something which could be transported to the oyster field.

- Has to be manufacturable on a 4ft x 8ft CNC router out of 3in (7.6cm) thick foam layers.

- Generally smooth geometries for ease of composites manufacturing (fiberglass, fillers, sanding, painting)
- Fully waterproof, biofouling resistant, and corrosion resistant
- Minimize tools needed on-site for assembly and disassembly
- Small enough to fit in a cargo van for transport

4.3 General Hull Shape

Given the Oystermaran is expected to travel at slow speeds through the aquafarm, the frictional forces of baskets pressing into the hulls are significantly greater than the forces caused by hydrodynamic effects such as drag. Therefore the new hulls were designed with primarily geometric, rather than hydrodynamic, concerns in mind. The design of the new hulls is shown in Fig. 4.3. Each hull is approximately 2.1m (7ft) long including the nose, 30cm (12in) tall, and 33cm (13in) wide at its widest point.

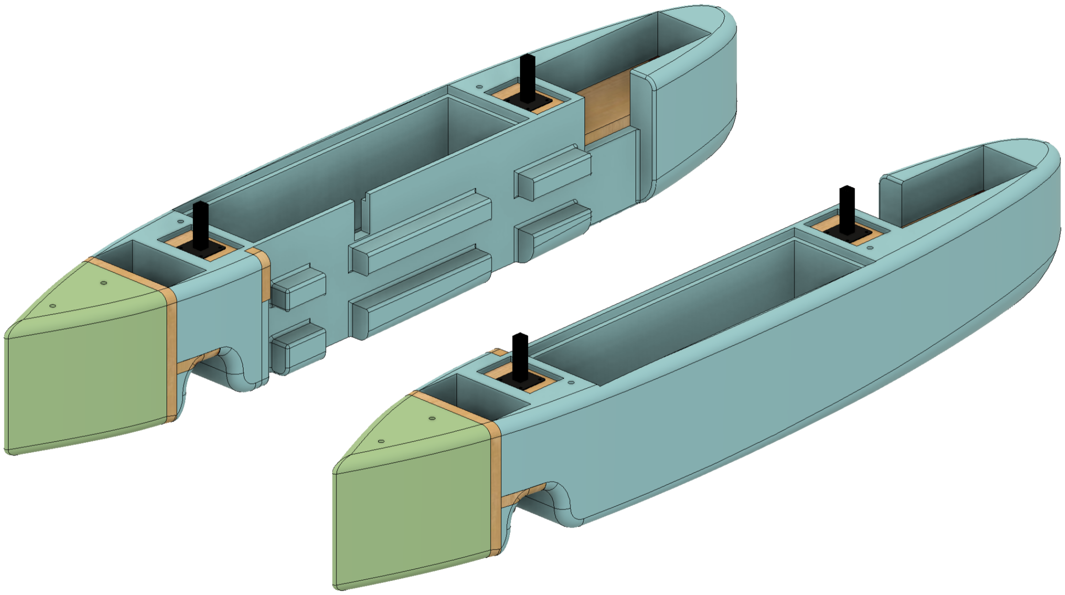


Figure 4.3: CAD of the V2 Oystermaran hulls. Blue represents the main body of the vehicle, while the noses (which can be switched out) are shown in green. Tan represents the wooden blocks used to install tee-nuts for component mounting. The small holes noticeable on the both the noses and main hulls are alignment features used in manufacturing. This image uses the baseline nose discussed in section 4.4

As the previous hulls often struggled to fit between the rows of baskets, the new hulls were designed to be as narrow as possible while accommodating the width of the battery box - the largest fixed-sized component on board. Instead of mounting components on top of the hulls, which sometimes caused snagging, each hull features a large central cavity - one of which is used for the battery and electronics storage, with the other housing and mounting parts of the bag handling mechanism. In front of and behind the central cavities are posts for mounting the frame. In front of and behind the posts are additional cavities for component mounting, electronics, and ballast.

On the inner sides of the hulls are slots for elements of the bag handling mechanism to fit into. This continues to reduce the number of extruding components field elements can snag on. The hulls have excess slots cut out of the inner edges due to testing different basket flipping mechanisms.

In total, the hulls generate a buoyancy force of 1,200N (270lbf). This is more than the combined weight of all mechanisms, so to bring the waterline to the intended level the vehicle is ballasted with lead dive weights.

4.4 Interchangeable Noses

As the 2021 Oystermaran experienced difficulties with sliding on top of baskets and with lining up the vehicle between the rows of baskets, determining the proper nose geometry that would function in the oyster array was critical to the design. The bow's ideal geometry would allow the vehicle to easily enter the array and slide each hull between a row of baskets, push baskets to either side while traveling through a line, and avoid the beaching effect where the vehicle rises up on top of the array. Designing this shape was determined to be best suited for field testing rather than in-lab testing or simulation. Therefore, the hulls feature an interchangeable nose system that can be replaced by one tool during testing to allow for experimentation with different geometries.

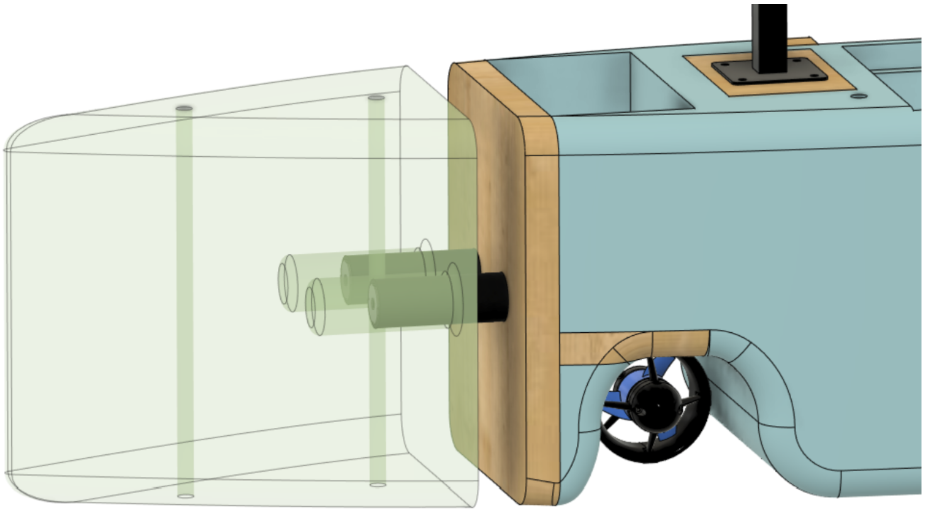


Figure 4.4: A closeup of the nose attachment and removal system. The design was made so the only tool required for replacement is a single wrench, simplifying the ability to switch noses on-site.

On each hull, the nose mounting system consists of two rubber cylinders, each with an oversized washer and flange tee-nut on the end and a bolt running through the center that can be accessed from the forward multipurpose cavity. The rubber cylinders slot into plastic

PVC pipes set inside the noses, as seen in Fig. 4.4. As the central bolt tightens, the rubber cylinders are axially compressed, expanding them outward and pressing them into reinforced slots in the noses. The resulting force of the radially expanded rubber causes a friction fit which secures the noses in place. This system allows for the noses to be exchanged while on the testing site and is achieved with all mounting hardware internal to the hulls, avoiding any disruption of external hull geometry.

In total, four nose geometries were built and tested for the Oystermaran. Three initial designs were completed and tested in both the pool and field, with a fourth and final geometry developed based on the results of testing.

4.4.1 Initial Nose Geometries

The three bow shapes which were originally built and tested are shown in Figure 4.5:

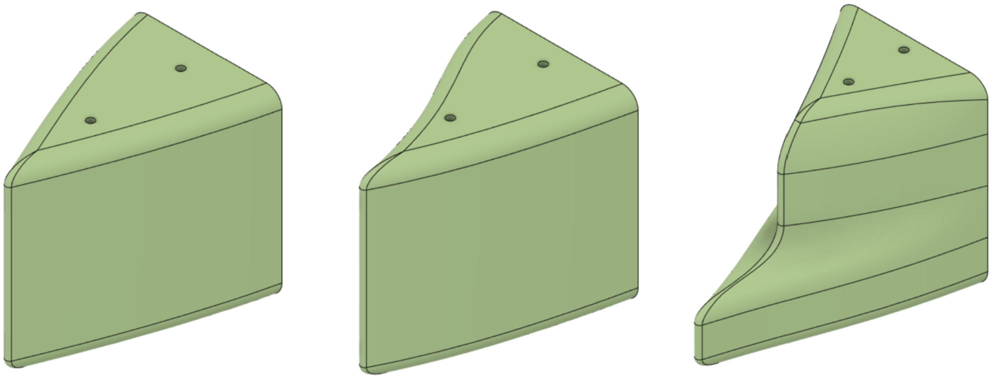

Baseline Asymmetric Guide Anti-Rising

Figure 4.5: The three initial noses

Baseline

The first bow shape, the baseline nose, acted as a control to compare the other designs to. It uses a similar geometry the V1 Oystermaran nose, with slight changes made for ease of fabrication. This nose is symmetric and follows the curves of the sides of the hulls out to their natural point.

Asymmetric Guide

The first of the experimental noses is the asymmetric guide nose. The outer edge of this nose is similar to the baseline nose, while the inner edge is concave to the center of the vehicle. The goal of the asymmetric guide nose was to counter issues with snagging and the vehicle struggling to travel directly through the row of baskets. The outer edge would force baskets on either side of the target row out of the way while using the concave inner edge to direct the central target basket to the flipping zone between the hulls.

Anti-Rising

Finally, the anti-rising nose was designed specifically to address the problem of the vehicle riding up onto the array, sliding on top of the baskets rather than between the rows. The extended portion of the nose in the front is below the vehicle's waterline, and as such it becomes difficult for the vehicle to ride on top of the baskets. The extended front of the nose instead pushes under the basket, directing baskets up and around either side of the nose. One potential concern with the design of this nose was the possibility of the extended portion becoming snagged on the horizontal pipes that hold the array in place, preventing the Oystermaran from entering the field.

4.4.2 Final Nose Geometry

Based on the results of pool and field testing (Chapter 5), a fourth and final nose was developed (Fig. 4.6). It combined the curved guiding properties of the asymmetric guide nose with the underwater point of the anti-rising nose. Additionally, it moved the points of the noses as close as possible towards the center of the hulls.

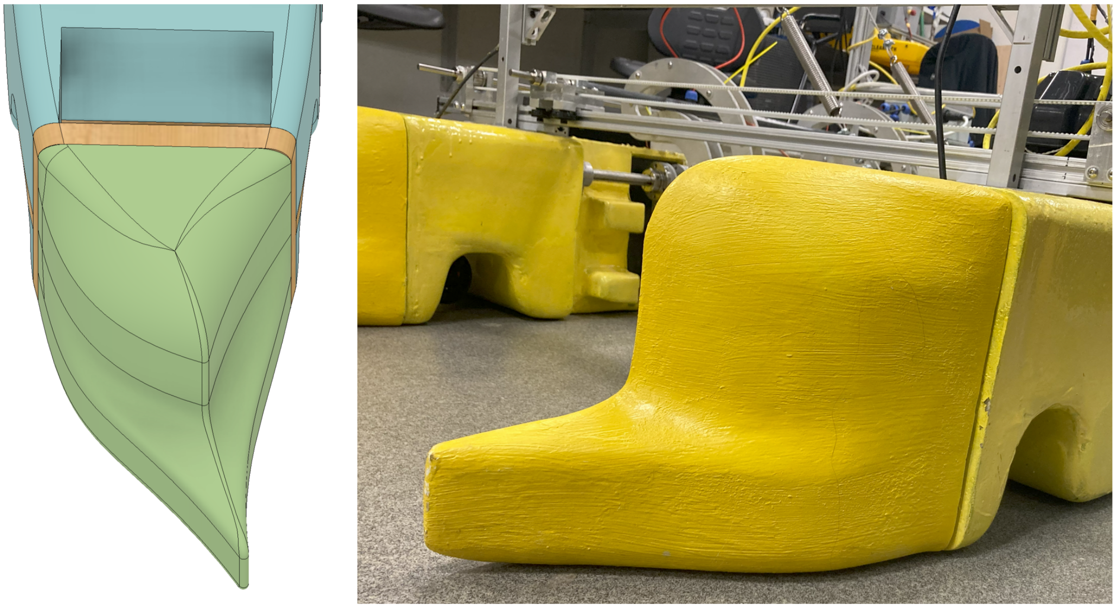


Figure 4.6: The final combination nose. In the right image the lateral thruster channel can also be seen.

4.5 Thruster Placement

The new thruster placement addresses two key issues. First, as the previous Oystermaran had difficulties where the thrusters would catch on the pipes holding an oyster array in place and prevent it form entering the array, the thrusters are now located inside a rear channel (Fig. 4.7). Unlike many hulls which taper in the back leading to the propellers, the sides of the thruster channel are covered to further protect the thrusters and prevent them from snagging any component of the array. Any losses from insufficient water flow due to the channel are considered a necessary trade-off to achieve these benefits. The channel consists of a circular profile starting on the underside of the hull and continuing upwards towards the thruster. It has a diameter of 15cm (6in), leaving a 5cm (2in) structural gap between the channel and the inside of the electronics cavity.

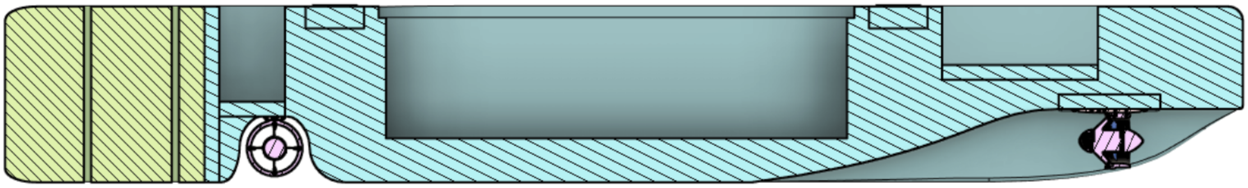


Figure 4.7: A cross-sectional view of a hull showing the thrusters (pink) and their channels, as well as the three main component cavities. The lateral thruster is to the left and rear thruster is to the right.

Additionally, to increase the vehicle's overall maneuverability, two lateral thrusters are located towards the bow. While the rear thrusters provide forward propulsion and can spin the vehicle in place, the confines of the oyster array require additional movement capability. When the original vehicle would become stuck between the rows of baskets, it could occasionally be freed by moving the vehicle back and forth until a gap in the array formed. Inspired by this, the goal of the forward thrusters is to allow the vehicle to shake side to side while in the basket array, clearing space to continue moving after it becomes stuck from baskets pressing around it. Additionally, the forward thrusters add some additional movements the vehicle can perform, such as traveling perpendicular to the hulls' orientation.

In total, the Oystermaran now features four Blue Robotics T200 thrusters: two rear thrusters and two lateral thrusters. The addition of lateral thrusters greatly increased the vehicle's ability to align with and traverse though the oyster farm.

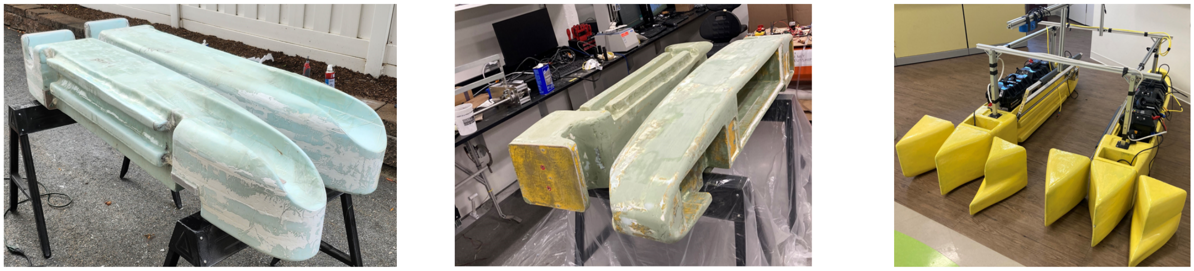
4.6 Fabrication

The hulls were cut on a large computer numerical controlled (CNC) router out of 3in (7.3cm) sheets of foam then stacked and epoxied together to form the main shape. The layers were then stacked together, guided by wooden alignment dowels, to achieve the full shape. Marine-grade wood with tee-nut inserts installed on the underside were epoxied into set cavities for component mounting. The three nose sets were manufactured in the same way, with the plastic reinforcement for the attachment mechanism added to each nose where the rubber cylinders would interface with it.

The hulls were then covered with a two-layer fiberglass wet layup and vacuum bagged. Post-vacuum, the hulls were sanded down for smoothness and all noticeable voids removed. Additional layers of fiberglass, microbead filler, and fairing compound were added for strength, waterproofing, and surface finish as required. Finally, the hulls were painted with an epoxy-based slick marine paint to discourage biological growth without bringing any biofouling-reducing toxins near the oysters. A summary of the process is shown below in Figure 4.8.

1. Cutting the foam layers

2. Stacking and gluing the foam; installing the wooden inserts using weights and clamps



3. Fiberglass applied and beginning of sanding/filling

4. Fairing compound to smooth and seal the hulls

5. The painted hulls and noses

Figure 4.8: Hull and nose manufacturing. In order: CNC machining, gluing layers and installing inserts, fiberglass, filling, painting

4.7 Vehicle Frame

The Oystermaran's frame underwent a few iterations. First, a frame made of hollow press-fit framing components was used for easy disassembly/reassembly. However, it was too wide to enter the array and an adjustable frame was made to replace it (details in Section 5.1.2). As testing revealed the precision and tuning required of the hull separation, an adjustable t-slot frame was made to replace it (Fig. 4.9. The frame mounted to the same posts as the original frame and was able to be adjusted both vertically to accommodate the flipping mechanism and horizontally to tune the spacing between the hulls. A raised top camera boom gives a wider field of view for the autonomy program to utilize when identifying and aligning on top of baskets.

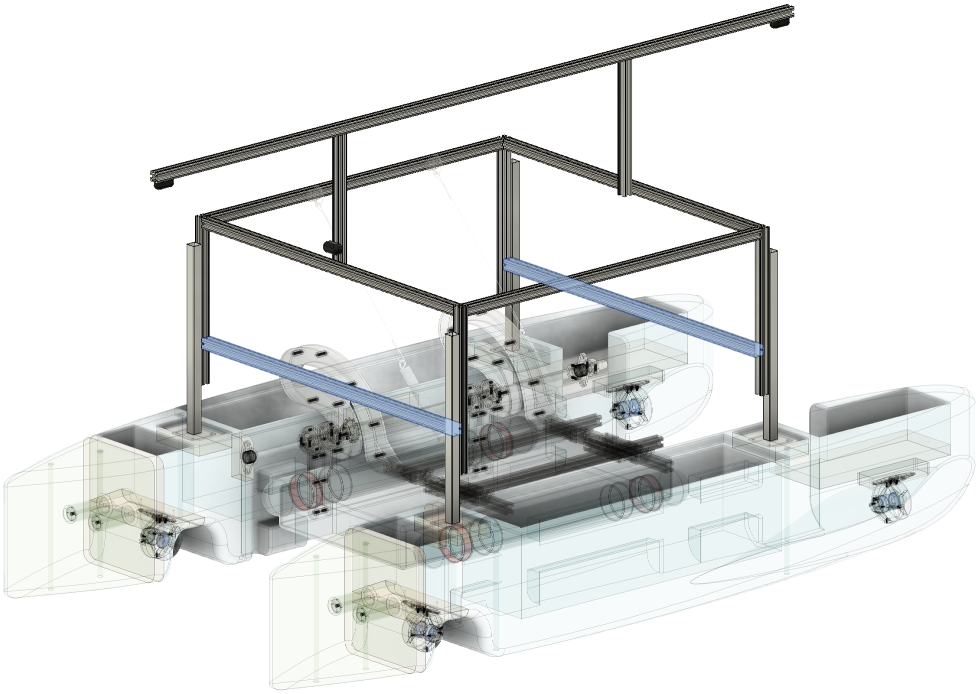


Figure 4.9: The final frame. The greyed-out cross members were added for stiffness after hull separation was determined.

Chapter 5

Maneuverability Testing and Design Iterations

As creating a vehicle whose shape allowed it to traverse in the field was one of the main goals of this vehicle, maneuverability testing began early in the process. After all, the Oystermaran cannot flip baskets if it cannot enter the field and travel down the lines. Multiple rounds of maneuvering testing were conducted, both in the pool and in the field, which allowed the team to make changes and improve the vehicle's maneuverability throughout the development process.

5.1 Pool Testing

To begin assessing the vehicle's maneuverability performance in a controlled environment, two rounds of pool testing were conducted. The goal of these tests was to qualitatively assess the vehicle's performance in a miniature oyster basket array. This allowed us to determine the viability of the key design changes, such as the inset components, side thruster performance, and varying nose geometry, in case additional changes were necessary prior to field testing.

5.1.1 Test Setup

Both pool tests were conducted in the MIT Zesiger Center Pool using oyster baskets loaned to the team by Ward Aquafarms. Baskets were set in a 3x5 basket array held in place by aluminum poles attached to the edges of the pool by rope, as seen in Fig. 5.1.

Aluminum poles simulated the securing pipes along the edges of a full oyster field which hold the array in place. The ropes allowed the team to adjust spacing between the baskets as tightening or loosening the ropes would move the anchoring poles closer or further apart. In the first round of testing, the baskets were empty and rested at a similar height in the water to a start of season oyster field. In the second round, a 3x4 array of baskets were weighted to match an oyster basket's 14kg (30lb) wet weight at the end of a growing cycle. This test was essential for nose geometry testing as the vehicle was more likely to ride on top of the baskets due to them sitting lower in the water. In both testing sessions the Oystermaran

Figure 5.1: The unweighted oyster array setup. The front holding pole and rope are both visible in the front, with the V2 Oystermaran on the left.

was remote controlled from the side of the pool and manually directed through the array. Above and below water photos and videos were recorded.

5.1.2 Overall Hull Shape Testing Results

In general, testing showed the changes made to the hulls from the previous Oystermaran significantly increased the vehicle's ability to travel through the array. As the V1 vehicle struggled to fit through the array due to its width, both in terms of the overall width and spacing between the hulls and the shape of the hulls themselves, the new design shrunk both these dimensions.

The distance between the hulls was the most significant problem with the vehicle's maneuverability discovered during testing. The vehicle's initial frame made the Oystermaran too wide to properly fit into the array, shown in (Fig. 5.2). This was due to a buffer region for the flipping mechanism included in the spacing between the two hulls, which then caused the hulls to be to far apart from each other to slide into the gaps between the arrays. To remedy this issue, the fixed frame was replaced with with an adjustable t-slot rail frame during the next round of testing. This allowed for tuning while testing, where the distance between the hulls was narrowed until they matched the gaps between the rows without becoming too narrow so a basket would become trapped between the hulls. The final width of the frame was 89cm (35in). This gives a gap of 1.3cm (0.5in) to either side of the baskets.

Components of the V1 Oystermaran also frequently caught on elements of the oyster array, leading to V2 insetting all components into cavities in the hulls. In testing, some parts of the preliminary basket flipping mechanism stuck outside the allotted space, causing

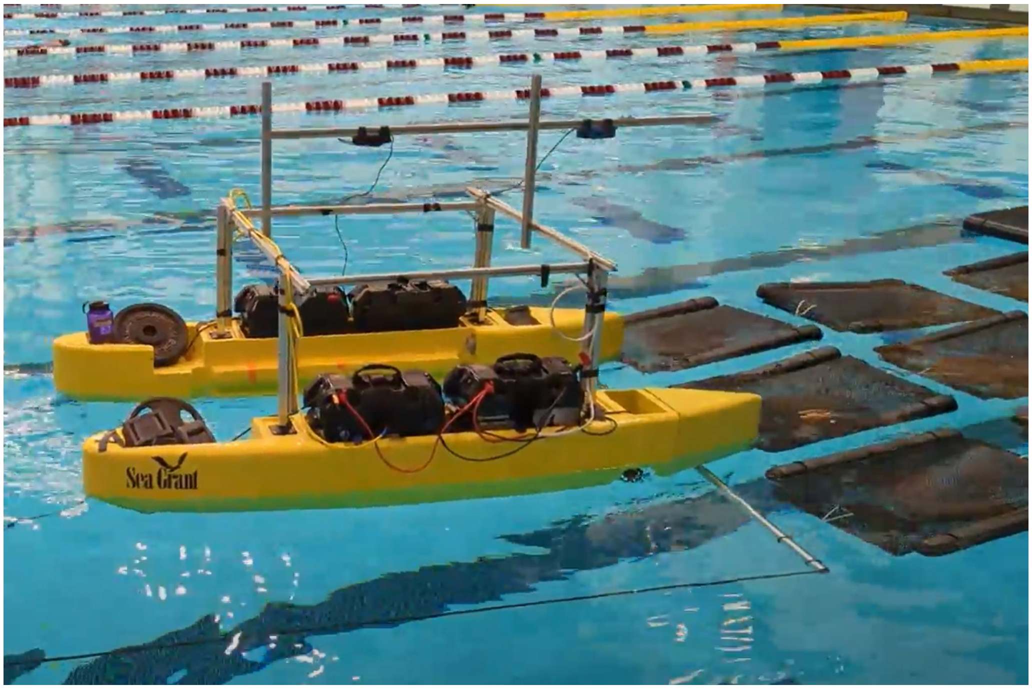


Figure 5.2: The vehicle with too large a distance between the hulls attempting to enter the array. Note how the port hull is facing directly into the middle of a basket while the starboard hull is close to the edge. Maneuvering after the geometry was tuned can be seen in section 5.1.4. Adjustable frame set to width of previous frame, baseline nose.

these components to catch on the floats of the oyster baskets and preventing the Oystermaran from moving forward. The snagging ceased to occur once said components were removed, but these results emphasized the importance of having insets as the new flipping mechanism was developed.

5.1.3 Effects of Thruster Locations and Channels

The V2 Oystermaran's thrusters are also inset, a change made after the 2021 vehicle's thrusters would catch on the pipe holding the edges of the array in place, preventing the vehicle from entering the array. Pool testing of these thruster channels had mixed results as displayed in Fig. 5.3. The rear thrusters with their fully enclosed channels were very successful. Due to the hull on either side of the thruster, they were unable to snag on any component of the array. However, the front thruster channel would occasionally catch the array holding pole and cause difficulties entering the array. The curved shape of the channel typically allowed the vehicle to continue enter the array with more power from the thrusters, but careful monitoring of this area continued throughout testing.

The second major change in regards to thrusters was the addition of lateral thrusters located towards the bow of the vehicle, an addition made as the original Oystermaran would often become stuck in the array unable to move forwards or backwards. The lateral thrusters give the vehicle an additional side-to-side movement capability intended to widen the distance between rows and allow the vehicle to continue moving after becoming stuck. During pool

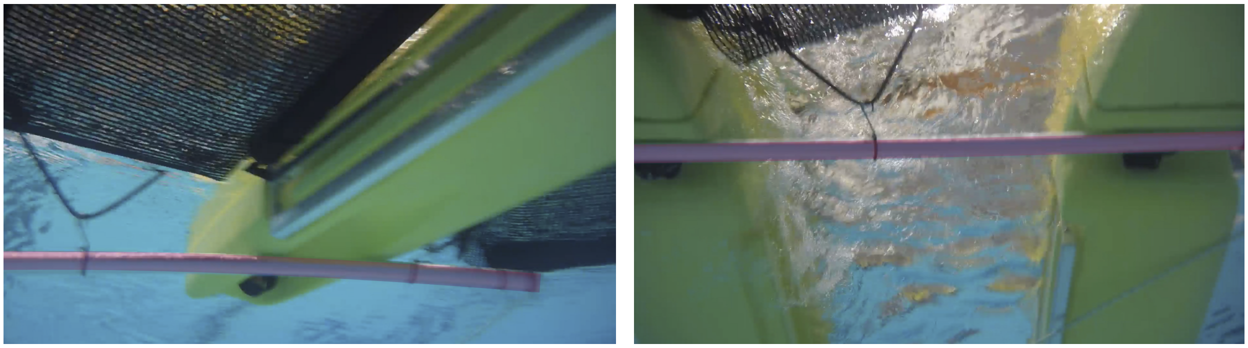


Figure 5.3: The array holding poles are highlighted in red. **Left:** the rear thruster channels force the entry pole below the vehicle, protecting the thrusters and avoiding snagging. **Right:** The same pole slightly catching on the front thruster channels.

testing the front thrusters showed remarkable performance in allowing the vehicle to enter the oyster bag array. While the testing array was too small to provide enough force to fully trap the vehicle by pressing around it, the wiggling maneuver to widen the gaps between basket rows could still be tested. This wiggling motion was extremely successful, pushing the baskets as far apart as their ropes would allow. Additionally, the wash from the thrusters aided in separating the baskets, requiring less movement from the Oystermaran to clear a path forward. Before and after photos are shown in Fig. 5.4. These benefits were barely noticeable in the full oyster field, but were still an interesting effect.

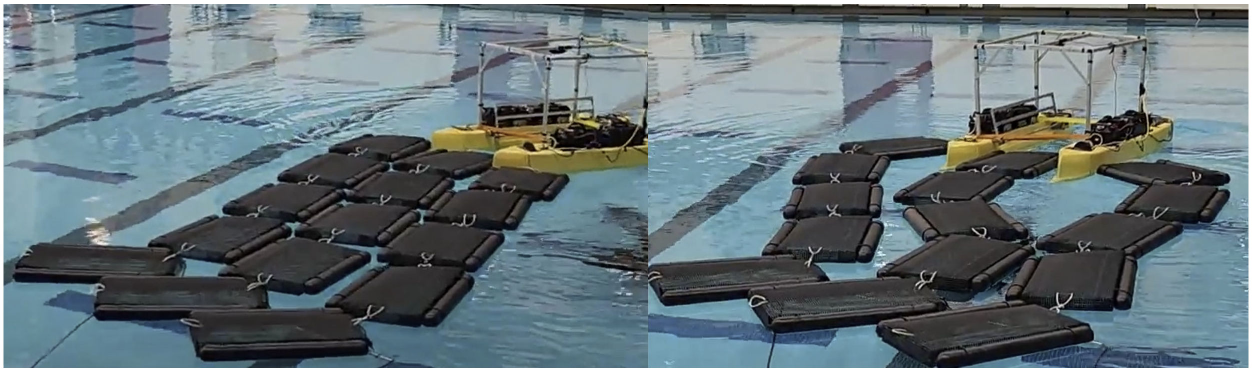


Figure 5.4: **Left:** The vehicle approaching the condensed array. **Right:** After the vehicle has performed a side-to-side maneuver. There is a significantly larger gap between the baskets, allowing the Oystermaran to more easily enter and travel through the array. Anti-rising nose.

5.1.4 Performance of Nose Geometries

The 2021 Oystermaran struggled with entering the array as well: beaching itself on top of the oyster array by riding up on top of the baskets due to its curved bows. The three initially developed nose geometries were tested in the mini-array, and with all three the Oystermaran was able to navigate through the baskets much easier than the V1 vehicle.

The first nose was the baseline nose, which acted as a control and had a similar shape to the bow of the 2021 Oystermaran, though slightly less curved on the bottom due to manufacturing constraints. This nose performed the worst out of the three and had similar issues to the original Oystermaran. Specifically, in the weighted array test setup, even with a reduced curve this nose would cause the vehicle to slide on top of the partially submerged baskets as seen in Fig. 5.5. This made it more difficult for the operator to maneuver the vehicle to enter the array. Encountering this sliding phenomenon confirmed that the rising issue with the original vehicle was due to hull geometry and not an unknown factor. Therefore, this nose provided the intended control to compare the results of the two new nose geometries.

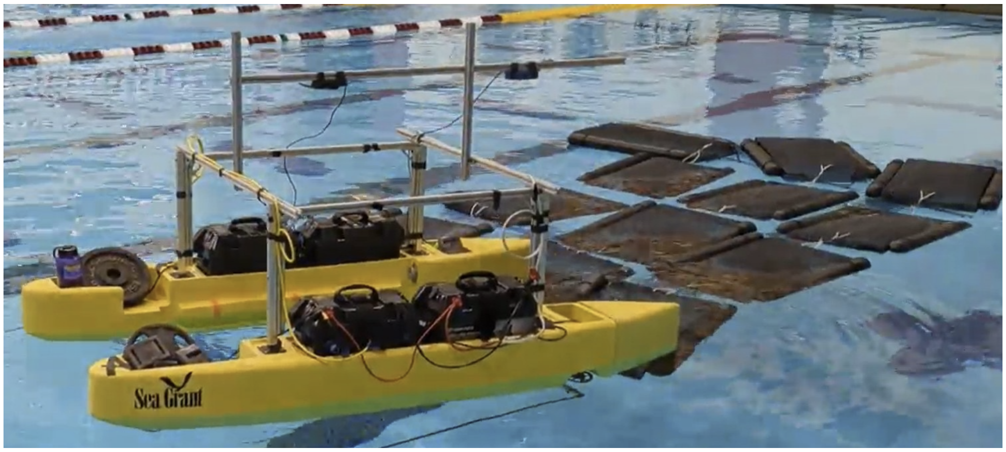


Figure 5.5: The Oystermaran attempting to enter the array, but is unable to due to the baseline nose sliding on top of the baskets.

The first of the new nose designs tested was the asymmetric guide nose, developed to solve the issue of the vehicle pushing directly into the baskets rather than the baskets being directed around the vehicle. During testing, the asymmetric guide nose cut through the array much easier than the baseline nose. As seen in Fig. 5.6, the concave curved geometry on the inside edges of the noses performed as designed and guided the target basket between the hulls. The curve gave a wider space for baskets to enter while pushing the baskets in the rows to either side of the Oystermaran away. However, when the array was weighted, similar to the baseline nose this geometry also experienced some riding-up effects and would slide on top of the baskets. The phenomenon happened less frequently than with the baseline nose, and typically the vehicle was able to slide off the baskets and continue. This is an improvement over the baseline nose which was not able to correct itself. For the final nose, the asymmetric curved guiding feature of this nose was combined with the anti-rising nose.

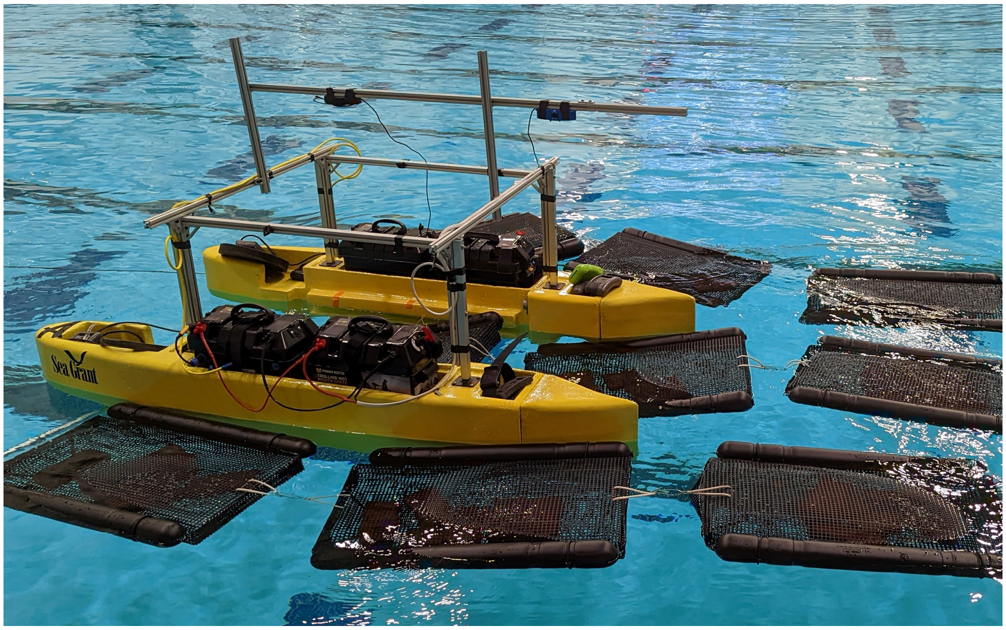


Figure 5.6: Here, while using the asymmetric guide nose the port hull can be seen pushing the central basket into position while the starboard hull pushes the exterior row away.

Finally, the anti-rising nose was developed to specifically combat the issue of riding up on top of the baskets with a point located below the water. This bow also performed as designed and no instances were recorded of the vehicle traveling on top of the baskets while using this nose, shown in Fig. 5.7. The results were better than anticipated, as prior to testing the pointed section of the nose slipping underneath the array securing pole and halting the vehicle until it reversed was a concern. However, this scenario never occurred and there were no discernible differences in navigating over the array entry pole than with the other two noses.

Figure 5.7: The hulls with the anti-rising nose traveling through the weighted array. As the pointed portion of the nose is below the water, little of can be seen in this image. An underwater photograph is displayed in Fig. 5.8

As intended, the extended lower portion of the anti-rising nose slipped underneath the baskets and prevented any sort of sliding on top of the array to occur (Fig. 5.8). The section of the nose above the water also proved extremely effective at parting the rows of baskets, quickly pushing them to either side as the vehicle progressed.

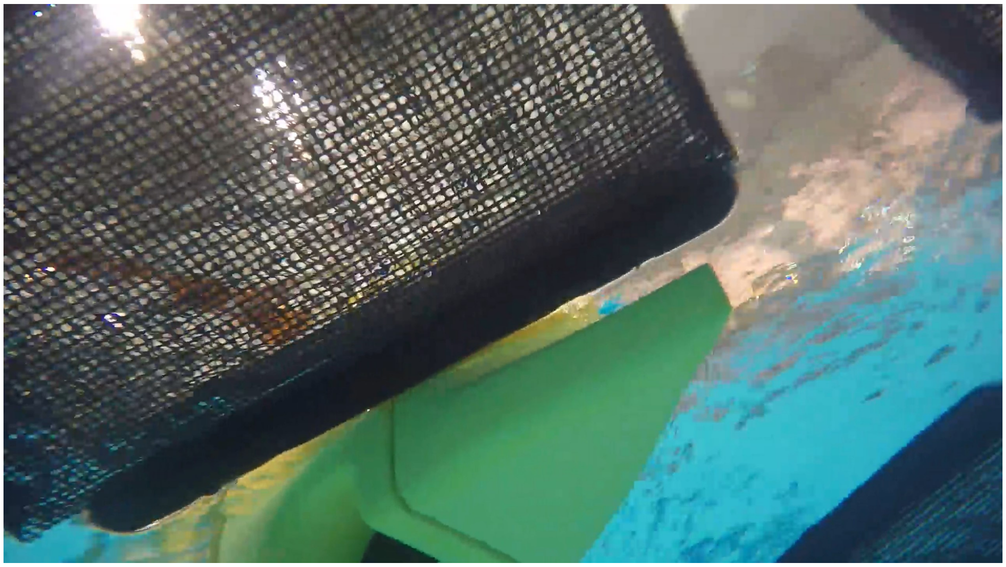


Figure 5.8: The anti-rising nose passing underneath the the edge of a basket.

The noses showed the most difference in performance while entering the array. During most trials, all three noses were able to continue through the array after entering, though both the asymmetric guide and anti-rising noses were easier for the operator to maneuver than the baseline. However, as approaching the array is expected to be a difficult task for the autonomy program, identifying which enters the array easiest in a full field is the next step in determining a final geometry. Based on this testing, the anti-rising nose will most likely be used as it eliminates the chance of the vehicle becoming stuck by resting on top of baskets. However, elements of the asymmetric guide nose could be incorporated into a final design to take advantage of its basket directing benefits.

5.2 Initial Field Testing

The team traveled to the oyster farm a total of three times during the development of the Oystermarna V2. The first test focused entirely on maneuvering, while the second tested maneuvering and the in-progress flipping mechanism, and the final trip tested the entire system.

Figure 5.9: Transporting Flippy to the oyster farm in a work boat. Note the adjustable frame and lack of flipping mechanism.

5.2.1 Field Test I: Maneuvering

During the first test, only maneuvering was tested and the vehicle did not have any flipping mechanism mounted (Figure 5.9). The vehicle was placed inside a work boat to take it out to the field, requiring four people to lift in/out of the boat (two on each hull). A final

Oystermaran would require fewer people and be launched from shore, with GPS navigating it to the oyster field.

Test I focused on testing the different nose designs, in particular the asymmetric guide and anti-rising noses based on their performance during pool testing. However, when faced with the even more crowded conditions of the full oyster field the noses did not perform as well and were unable to enter the oyster field at all.

Asymmetric Guide Nose

The asymmetric guide nose proved to be too wide for the full oyster field. The tips of the noses were significantly wider than the baskets, though the space between the inner edges of the hulls were barely wider than the baskets (Figure 5.10). One nose would point between the rows while the other would be facing directly into a basket. The vehicle came closer to entering the fields when the noses were turned upside down, reducing the distance between the bow points, but was still unable to enter the field.

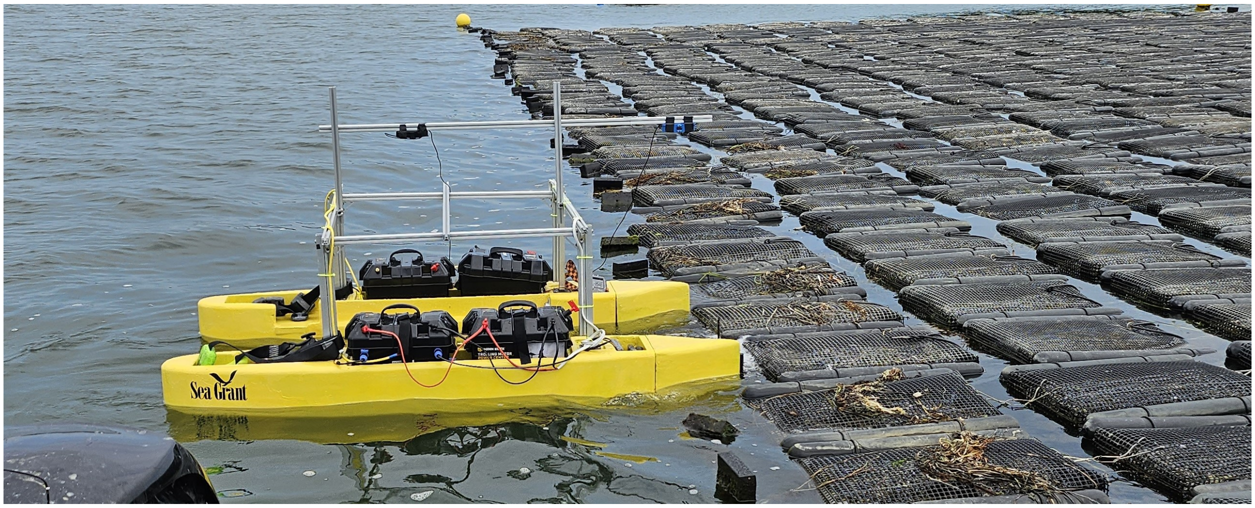


Figure 5.10: The Oystermaran was unable to enter the array using the asymmetric guide nose. As seen in the image, the points of the noses are over 1.5 basket widths apart and the vehicle is unable to nudge the points in like it did in the pool.

The poor performance of the asymmetric guide nose indicated that the vehicle's bows needed to focus on pushing other baskets away rather than guiding the target basket into the hulls. Additionally, having the points of the bows close together is essential to entering the array.

Anti-Rising Nose

The anti-rising nose performed better than the asymmetric guide nose, though improvements were still needed. The vehicle fit into the array, though separating the rows to push the vehicle in was much more difficult than during pool testing. For the most part the nose slid under the baskets like in the pool, and the vehicle partially entered the array without becoming caught on the farm's frame, resolving a major concern for this design. However, due to a thruster error the vehicle had insufficient thrust to fully enter the array against the force of baskets pushing in around it. The nose ended up riding on top of the basket a couple of times (Fig. 5.11) - precisely what it was designed to avoid. This happened infrequently and the nose points were still wider than the basket rows, indicating the issue could be resolved with a new nose design.

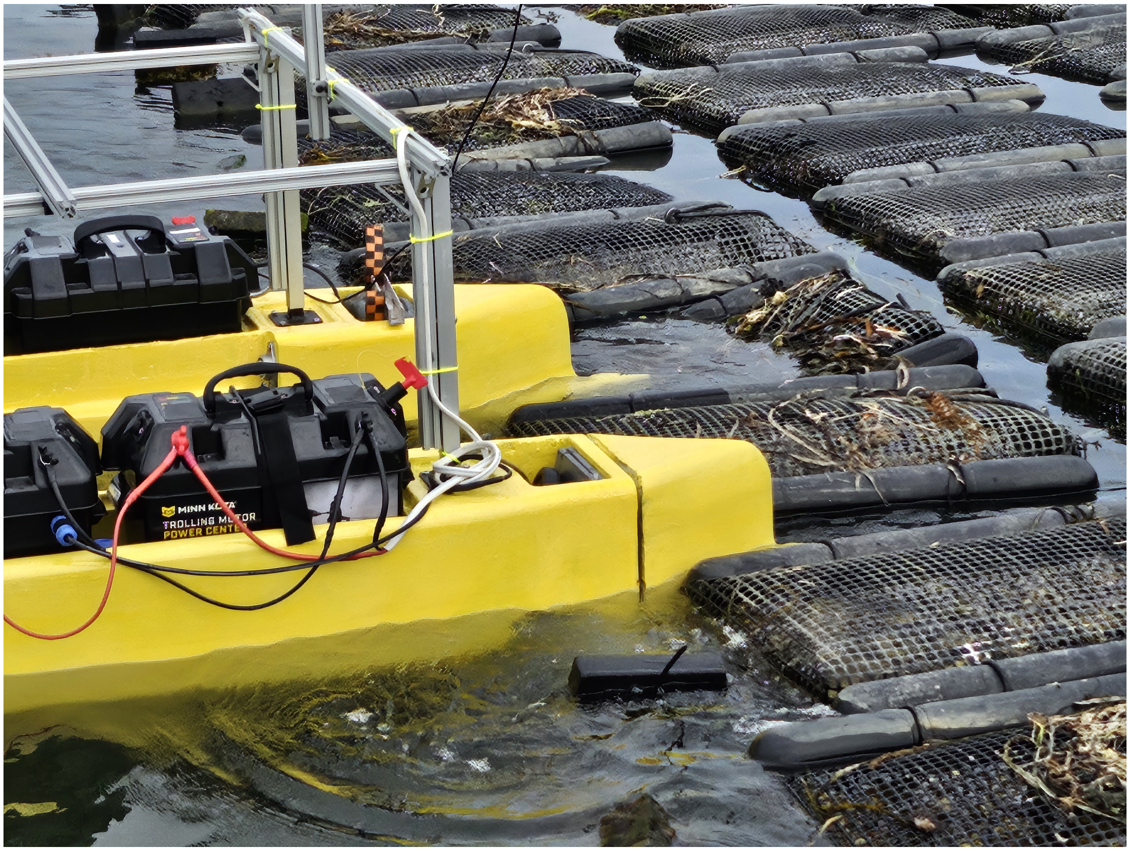


Figure 5.11: The antirising nose performed better than the asymmetric guide nose. However, you can note the spacing between the bow points still caused issues and in this case the bow slid onto the edge of the basket.

5.2.2 Thruster Biofouling

During both Field Test I and a separate in-progress test launching the boat from a beach, biofouling in the thrusters was a major problem. The thrusters would fill with seaweed and other biofouling, especially from the pipe that holds the array in place (Fig. 5.12) and reducing the thrust until the vehicle could barely move. To solve this issue, open-source thruster guards which clipped on to the thrusters were 3D printed and installed before the next test [19].

Figure 5.12: The thrusters experienced significant biofouling, much of which came from entering the array over the frame shown on the left. On the right, a rear thruster filled with seaweed.

5.2.3 Field Test II: Maneuvering

Field test II occurred late in the oyster season, and only two rows of baskets were left in the water (Fig. 5.13). As such, maneuvering was unable to be fully tested, though an initial test of both the new combination noses and and any snagging effects of the flipping mechanism (now installed) were completed.

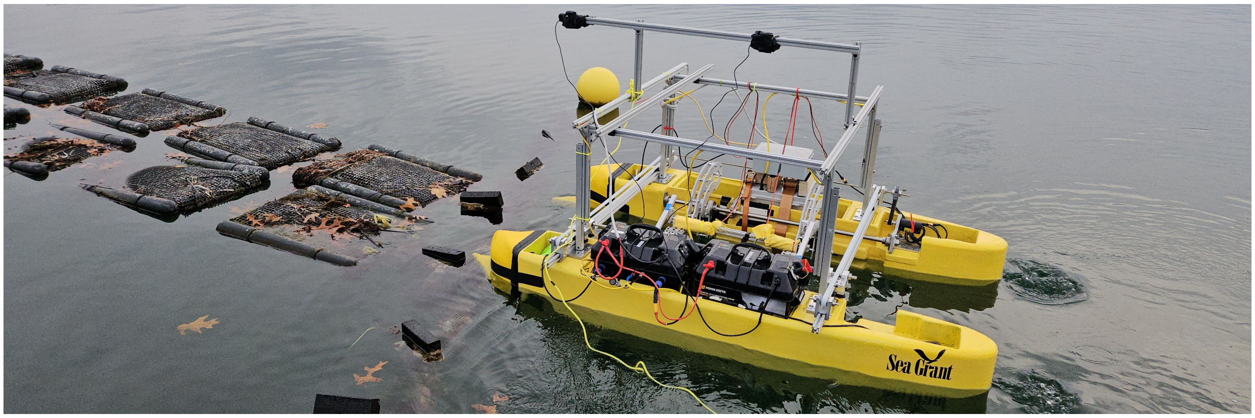


Figure 5.13: The two rows of oyster baskets. Note Flippy's the new noses and prototype flipping mechanism.

As discussed in Section 4.4.2, the combination nose combined a curve similar to the anti-rising nose with the underwater point of the anti-rising nose and brought the tips of the noses as close together as possible. The two noses surrounding a basket in the lab is shown in Figure 5.14

Figure 5.14: The combination nose shown in the lab surrounding an oyster basket. Note the points of the noses coming close to the baskets to reduce the spacing between them.

During Field Test II, the new nose was easily able to push its way between the baskets (Fig. 5.15). However, this was significantly easier to do than during Test I as there were only the two rows of baskets. The baskets were also pushed due to thruster wash, repeating a phenomenon which occurred in the pool but not before in the field before.

Figure 5.15: The vehicle successfully made it down the line of baskets, despite snagging.

However, the flipping mechanism (design in Chapter 6) snagged frequently on the baskets. This was mainly due to two causes. First, the basket grabbing "claws" were unable to fully extend straight and curled around to interfere with baskets. Second, a basket rest which did not properly fit into its inset snagged as well. The back of the basket rest interfered with the hull, preventing the arm from lowering completely and sticking out between the hulls. New claws and thinner basket rests were both installed based on results of this test.

Finally, the test was conducted using thruster cages were 3D printed using a Markforged printer with carbon-fiber imbued filament to increase their strength. The thruster cages were very successful in preventing biofouling, there was no visible fouling after the test (5.16).

Figure 5.16: A fully protected rear thruster. Visible are both the surrounding shape of the thruster channel as well as the thruster cage. Slight discoloration can be seen from testing, but no biofouling became entangled with any of the thrusters.

Results and discussion of the final field test and maneuvering effects in combination with the bag handling mechanism are in Section 7.4.

5.3 Vehicle Ballast River Test

During a test on the Charles River, the team discovered where the waterline fell on the Oystermaran had a major effect on whether or not it was able to maneuver over the baskets. If the vehicle sat too low in the water, the flipping arm would interfere with the baskets and prevent the vehicle from moving forward (Fig. 5.17). Too high, and baskets would be unable to be grabbed by the flipping mechanism. How deep the vehicle sat in the water was easily able to be changed by adjusting the amount of lead ballast weights, but this is necessary information as future vehicle iterations also need to be able to be ballasted to work with baskets at all stages in the growing cycle.

Figure 5.17: During testing of where the waterline needs to be on the vehicle for it to travel over the baskets while still being able to grab and flip them. Notice how the vehicle is higher in the water than usual.

Chapter 6

Bag Handling Mechanism Design

After the Oystermaran has navigated into the field and aligned on a basket, the bag handling mechanism itself activates to flip the basket. The aim of the bag handling mechanism was to create a reliable system that could both flip the baskets over as well as shake them to redistribute the oysters inside. This was accomplished by iterating on the previous design, which used an arm which reached between the hulls to grab the opposite edge of a basket, lift it up while tilting it back, then release it to slide into the water. While a successful proof of concept, this design was slow, unable to lift a full weight basket, concentrated oysters to one side, and sometimes the basket would fall back into its original orientation instead of flipping.

To solve these issues, a few new designs were considered (see Appendix A: Discarded Solutions for more details) but ultimately a design inspired by the one on the first Oystermaran with additional capabilities was implemented, as seen in Figure 6.1.

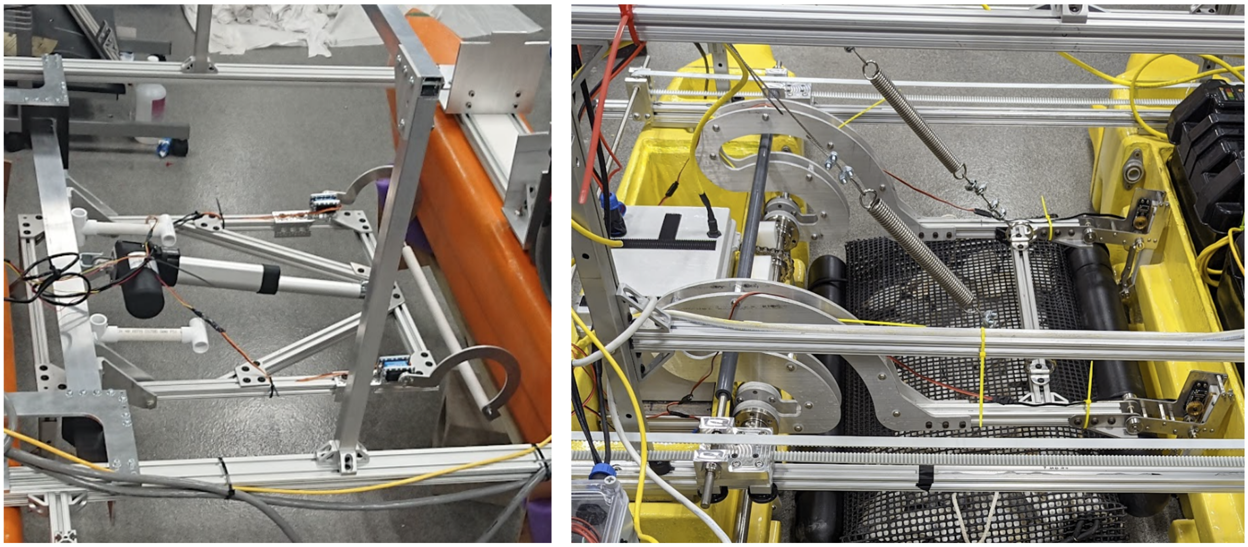


Figure 6.1: The flipping mechanisms from V1 and V2 of the Oystermaran. The new mechanism switches the linear actuator for a high-torque motor, uses linkages rather than static claws to reduce distance between the hulls, and replaces the static PVC basket pushers with an actuated beam that pushes out the underside of the basket.

6.1 Mechanism Design Overview

The flipping mechanism is mounted between the two hulls and has three submechanisms: the claw, arm, and slider (Fig 6.2). The claws grab the basket while being able to mostly flatten to avoid snagging while the vehicle is moving through the water, while the arm provides the main flipping motion. The slider sits inside of a slot in the arm during lifting, then pushes out the underside of the baskets to ensure a successful flip and shake the oysters. The three mechanisms were designed to be adjustable, with parts either able to be tuned while testing or easy to switch out based on testing results.

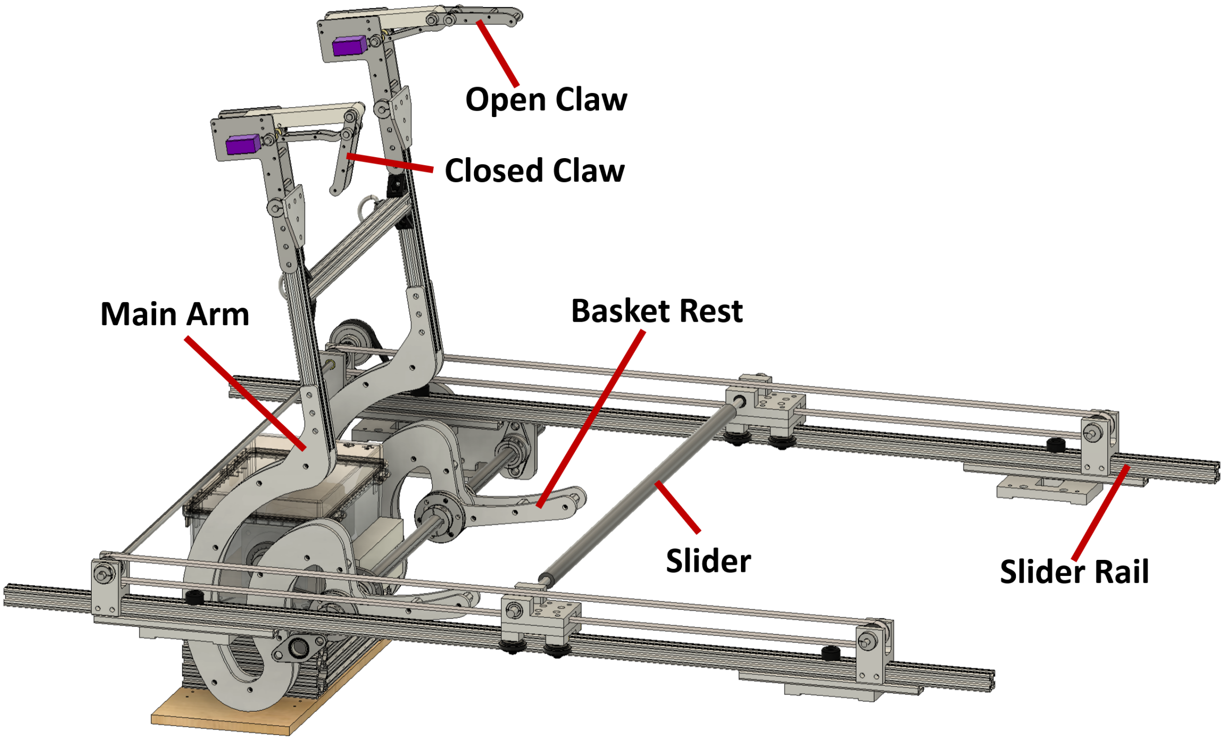


Figure 6.2: CAD of the bag handling mechanism. The claws, arm, slider, and slider rails are all labeled. Two springs which assist in the initial arm lift are not pictured.

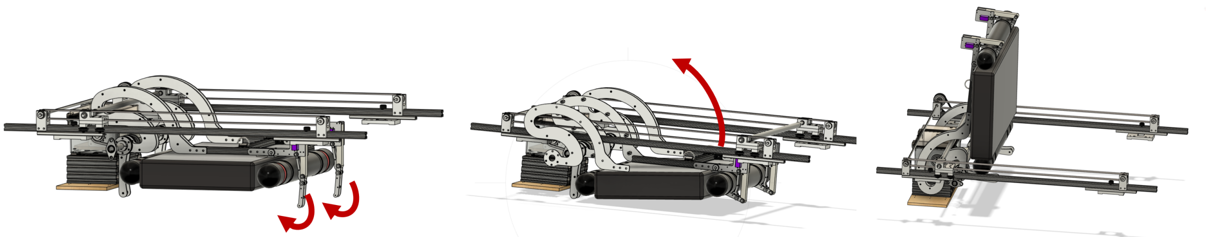
To accomplish a flip, a five-stage process is conducted as seen in Figure 6.3:

1. **Grab** First, the Oystermaran approaches a basket with its arm in the downwards position, allowing baskets to slide into the mechanism. Two "claw" linkages then activate, securing the basket tightly into the mechanism against two "basket rests" mounted to the base of the arm.

2. **Lift** The main arm lifts up, carrying the basket out of the water and tipping it backwards slightly.

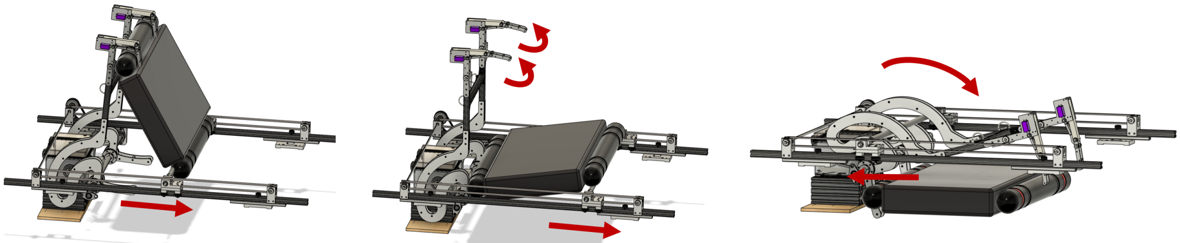
3. **Push** The pushing beam, or "slider" moves out from its resting position in the arm and forces the underside of the basket onto it and off the basket rests. The claws maintain their grip and rotate passively as the base of the basket is pushed out.

4. **Release** The claws release the top of the basket to drop it onto basket rests, shaking the oysters in the process. The slider finishes its path, moving out from under the basket to drop the basket into the water.
5. **Reset** The slider then retreats back into the arm. The arm lowers and the vehicle can continue to the next basket.



1. Claws close around basket

2. Arm lifts basket up



3. Slider pushes basket out

4. Claws open; slider continues; basket falls and oysters shake

5. Slider retreats, arm goes down; system resets

Figure 6.3: The five step flipping process: grab, lift, push, release, reset

6.2 Subsystem Requirements

6.2.1 Functional Requirements

Using lessons learned from a scale model and general requirements from the user and the operating environment, a summary of the bag handling mechanism's functional requirements are as follows:[1]

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[1] Background calculations used Roark's Formulas for Stress and Strain [20] and Shigley's Mechanical Engineering Design [21]

Category	Key Functional Requirements	Design Parameters
Claw	Tightly hold top basket float	Must be able to provide 250N to holding the mechanism in place 6.3.1
	Rotate top float as basket is pushed by slider	Passive rotation link with hard stop
	Slot inside of space on opposing hull	Fit in a bounding box of 8cm (3.2in) wide, 23cm (9in) tall, and 4.4cm (1.75) deep
Main Arm	Transfer the full 200 Nm basket lifting torque to the arm shaft	Chain and sprockets used with shaft supports, maximum stress of 310Pa well under 304 SS limit of 215MPa[22]
	Arm can reach across the basket and between the hulls even as frame distance changes	T slot rails allow a total of 9cm (3.5 in) adjustability
Slider	Ability to adjust forward/back spacing between slider rails	4 mounting locations rails can be switched between
	Torque requirement to push basket between hulls	4.8Nm minimum motor torque, assuming a 300N basket and a 16mm mechanism
	Energy requirement to push basket between hulls	270J (300N moving 0.9m)
	Slider beam should deform less than 2cm under weight of basket	With a 1.1cm (7/16in) diameter 316 Stainless Steel beam, the deflection is 1.2cm [23]

Table 6.1: Bag Handling Mechanism Functional Requirements

6.2.2 Subsystem Constraints

Due to the hulls being manufactured for a previous version of the bag handling mechanism (A.2), the preexisting hull cavities and mounting locations provided the main design constraints. Although new component insets between the hulls could be cut out, the old ones were still there and influenced where changes could be made. Most importantly, this design was heavily constrained to where it could mount and secure into the hulls. This, and other main constraints facing the bag handling mechanism's design, are listed below:

- Components should secure to existing mounting points
- Minimal carving away of existing hulls to preserve anti-snagging and waterproofing
- All actuators must be waterproof or secured in a waterproof enclosure

- Made out of corrosion resistant materials (6000 or 3000 series aluminum for large components, stainless steel, brass, and water swelling resistant plastics. Stainless steel fasteners, or zinc-coated carbon steel in non-submerged areas.)
- For speed of manufacturing and the ability to adjust and re-make parts as needed, all components must either be off-the-shelf, milled aluminum or plastic, or 2D manufactured (waterjet, laser cut)

6.2.3 Scale Model

To test the idea for the arm/slider combination mechanism and help in determining detailed requirements, a 1:10 scale model was first created (Fig 6.4). The model allowed basket manipulation testing before investing the time and effort into building a full-scale mechanism. This was especially important to learn how hardware representing oysters would slide around inside the baskets.

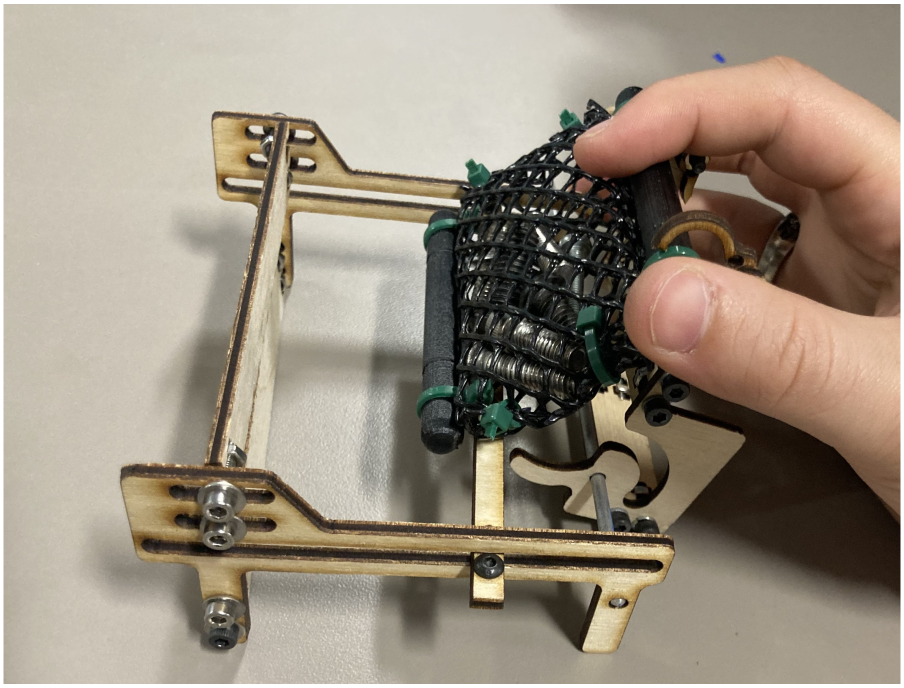


Figure 6.4: A 1:10 scale model of the flipping mechanism, made out of laser cut plywood.

The scale model resulted in a few key lessons:

- The claws which grab the basket must be able to hold on to the baskets as the slider actuates. If they do not, the basket slips out of the mechanism prematurely and back into its original orientation rather than flipping.
  - To allow for both a secure grip and for the basket to move with the slider's motion, the claws need to rotate with the basket while remaining closed around the basket float. This would be difficult to synchronize while under controller testing, so should happen using a passive link.

- For the basket to be properly secured in the mechanism as well as to allow a platform for the basket to fall onto during the release stage, basket rests attached to the main arm are needed. However, the size of the basket rests means the vehicle must travel through the array with the arm in the "down" position.

- Gravity is generally sufficient to redistribute the oysters if the slider is located above the basket rests. However, if oysters fail to redistribute sufficiently, the slider can move back and forth to shake the basket and oysters.

- Occasionally the slider can get stuck at the intersection between the mesh basket and the float, and thus needs a rolling component.

- Basket floats did not get stuck in the slider gap in the arm and baskets slid down to the basket rests as intended, resolving an initial concern with this design.

- The exact dimensions of components were very precise for what worked, which set the system requirement of having an adjustable design.

The success of the scale model in shaking the components inside the basket and manipulating the model baskets as intended resulted in the team deciding to move forward with this general mechanism design. Manipulating the model and watching how baskets responded to varying inputs helped inform the functional requirements for the final mechanism.

6.3 Claw Linkage

In the five-step flipping process, the first item to actuate is the claw (Fig. 6.5). The claw holds the baskets during the main lift of the arm as well as during the pushing step of the flipping process. Having the mechanism tightly hold the basket floats and support their weight was essential as premature release of the claw causes baskets to slide down back into their original orientation.

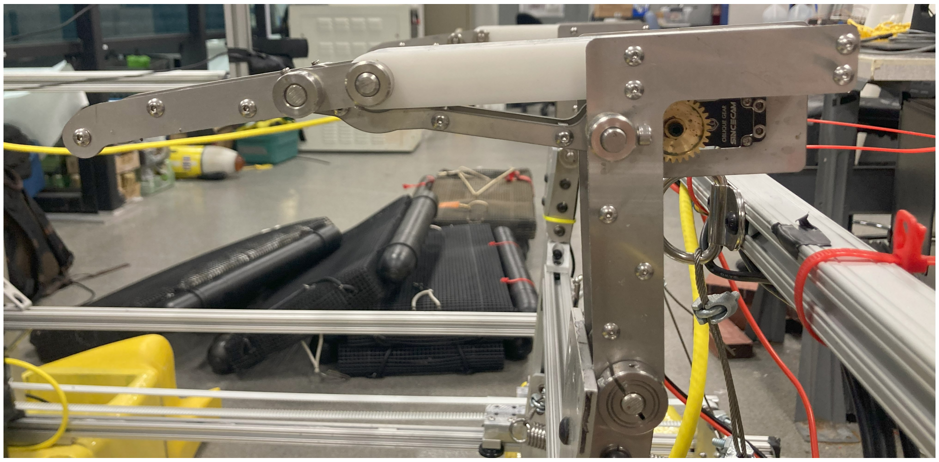


Figure 6.5: The final claw mechanism, made of made of a custom 4-bar linkage with an unpowered hinge to allow it to rotate passively with the basket.

However, having a one-piece curved claw requires space for the claw to circle around the basket float to grab it. As pool and initial field testing showed the importance of narrowing the distance between the hulls, the claw needed to be able to wrap around the basket float to grab while avoiding snagging and keeping the spacing between the hulls 63cm (24.8in) apart. A custom 4-bar linkage was used to meet the constraints of creating a mechanism that could slot into spaces in the hulls while meeting the other requirements.

The main motion of the linkage required it to go from a mostly flat orientation to one curved around the basket float (Fig. 6.6). Making a linkage to accommodate this constraint was accomplished via a "pushing" member of the linkage which would actuate linearly to force the base of the linkage out. The inner link member also pushes against the basket, securing the basket into position in the arm.

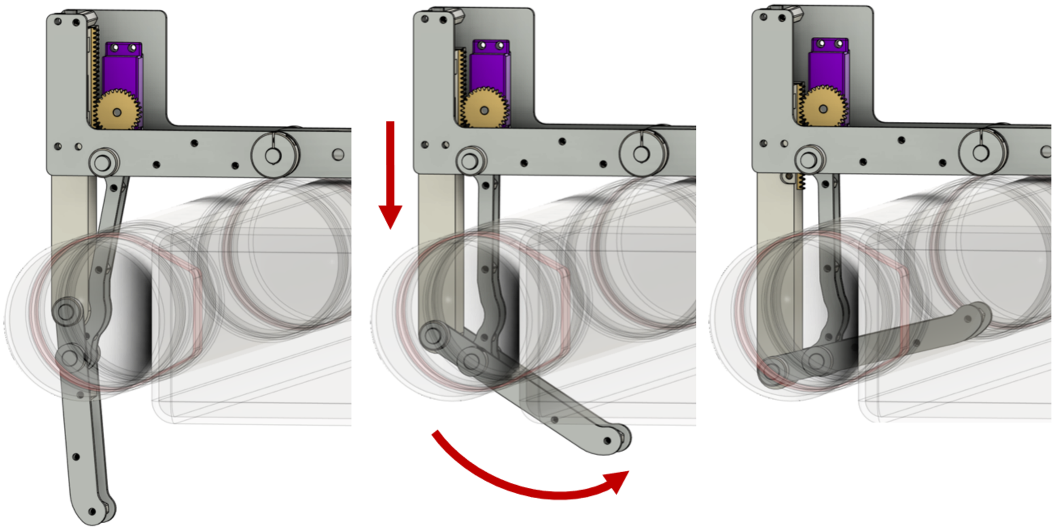


Figure 6.6: The motion of the claw linkage, showing the full range of motion. The open position, left, fully slots into the hulls and is what allows the vehicle to approach baskets without snagging. The claw begins to actuate, center, by the "pushing" beam actuating via a rack and pinion. On the right, the claw is fully gripping the basket.

6.3.1 Linkage Force Analysis

Calculations for the claw were completed by modeling it as a static system of members, similar to a truss, as depicted in the free body diagram in Figure 6.7. Analysis was done in the "closed" position of the claw to determine the maximum forces to hold the claw in place when secured around a basket.

The FBD was inputted into MATLAB as a system of equations and force required at each joint calculated. Using the required forces, each link was then represented as a beam undergoing bending and axial loading using calculations from Roark's Formulas [20]. The required thickness of each beam was calculated, taking into consideration that there would be in total four of all the metal hinged elements and two of the plastic "pushing" member.

The calculations determined that to save space on beam size and thickness, 3mm (0.12in) 304 stainless steel sheets could be used for the hinged links and thicker acetal plastic for the

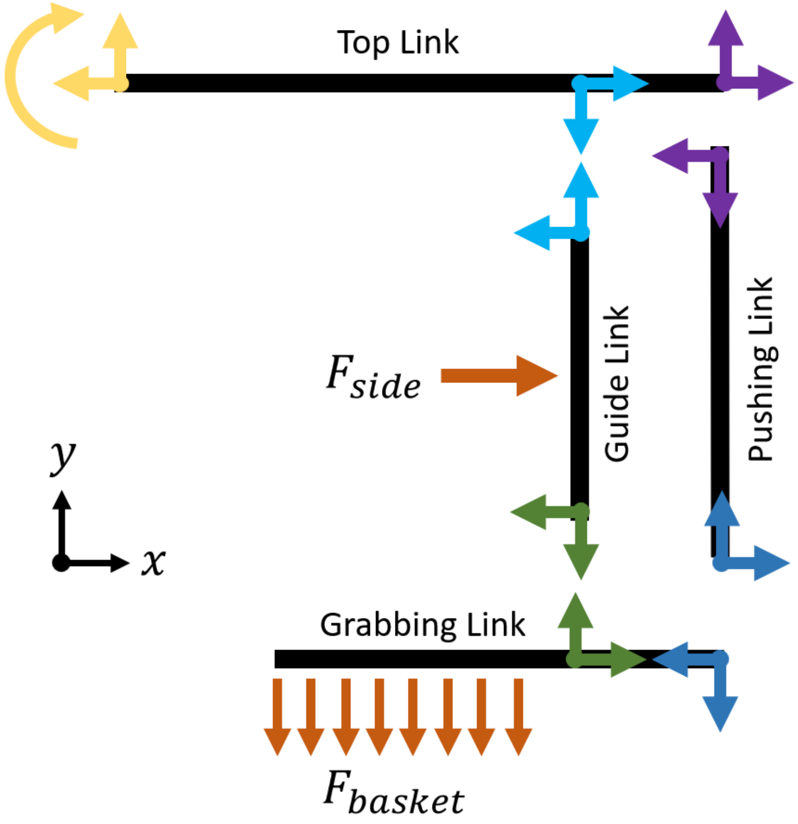


Figure 6.7: A free body diagram of the claw mechanism. $F_{(}basket)$ represents the main force of the basket on the linkage, while $F_{(}side)$ represents the force applied to the guiding link due to it pressing in to the basket. Reaction forces and moment are colored.

pushing link. The lengths of each link were set by geometric constraints, while the widths were calculated assuming a 300N load in y and 200N in x. The final widths and safety factors of each beam are listed below in Table 6.2:

Beam	Width	Maximum Stress	Safety Factor
Top	2.5cm	47MPa	4.5
Guide	0.7cm	68MPa	3.2
Pushing	1.3cm	14MPa	4.8
Grabbing	1.5cm	53MPa	4.0

Table 6.2: Calculated widths, maximum stress, and safety factor for each link

High safety factors were chosen for the top and grabber links to accommodate for mounting holes, alignment with the t-slot rail, and because the wider beams fit with the chosen shaft collars. The pushing link's shape was designed to fit best with the other beams and hold the gear rack, with the stress calculated to ensure acetal could be used.

The force required to hold the pushing link in place is 250N, and the minimum travel required to get the linkage motion to be 2.8cm (1.1in). A servo motor was chosen to power the claw for its high torque:weight ratio and easy availability of waterproof servos. Brass servo gears are also easily accessible, and to select between servo torques and gear sizes calculations were completed per Chapter 13 in Shigley's [21]. Using a 24mm diameter 0.8 mod gear with 30 teeth on a 6.8N servo motor, the maximum transmittable force is 542N, well above the required amount. While undergoing the 250N load, the gear teeth experience a maximum stress of 150MPa, which is high but within the range of brass[24] and no other materials were available within the time frame. Spare gears were purchased in case of yield.

The chosen servo motor has a range of 180°, with a 24mm diameter gear this gives a total range of 3.77cm (1.5in), above the 2.8cm (1.1in) minimum requirement. This slightly larger range of motion allows the claw to push strongly against the basket and secures the edge of the linkage around the edge of the float as shown in Figure 6.8.

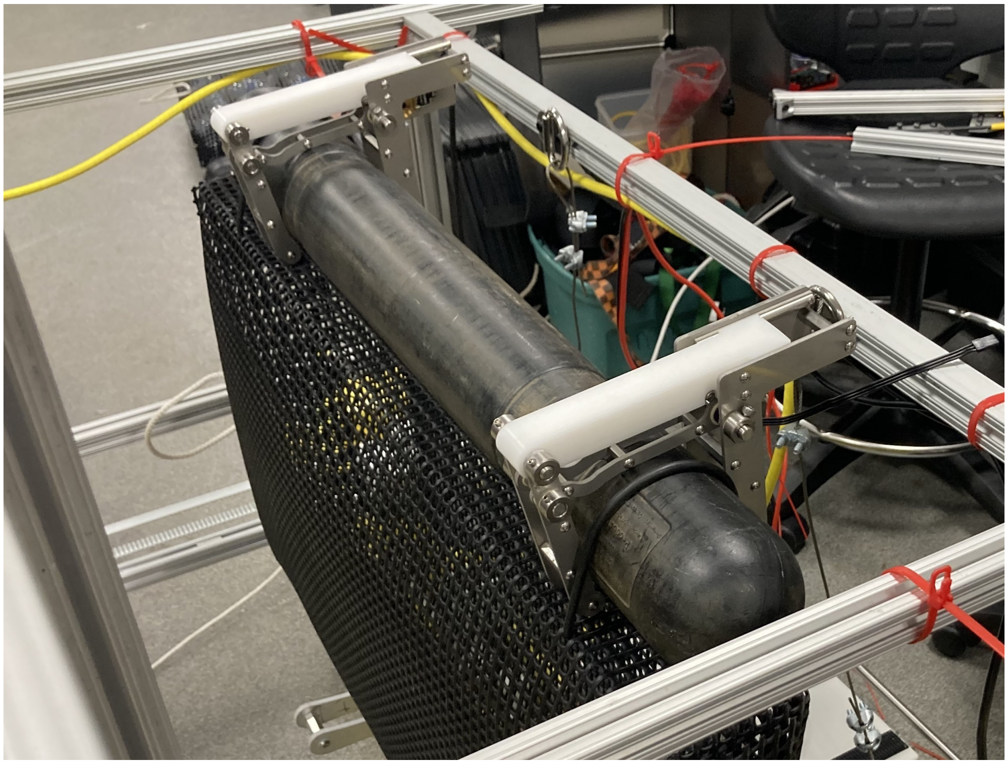


Figure 6.8: The claw closed tightly around a basket. Note how the edge of the claw tucks in around the float between it and the main basket.

6.3.2 Additional Claw Design Elements

To complete the claw design, these features gave it a smooth and reliable motion.

Guide Rails

A set of 1/4in (6.35mm) 304 stainless steel hemispherical guide rails set the linear motion of the rack and pinion (Fig. 6.9). The semicircle shape is also in the acetal pushing beam, and provides a smooth surface and point of contact to guide the motion of the link. The rails are mounted on additional rail spacers, which provide distance between the pushing beam and the inner edges of the linkage to ensure the pushing beam and side panels do not rub against each other and add excess friction to the system.

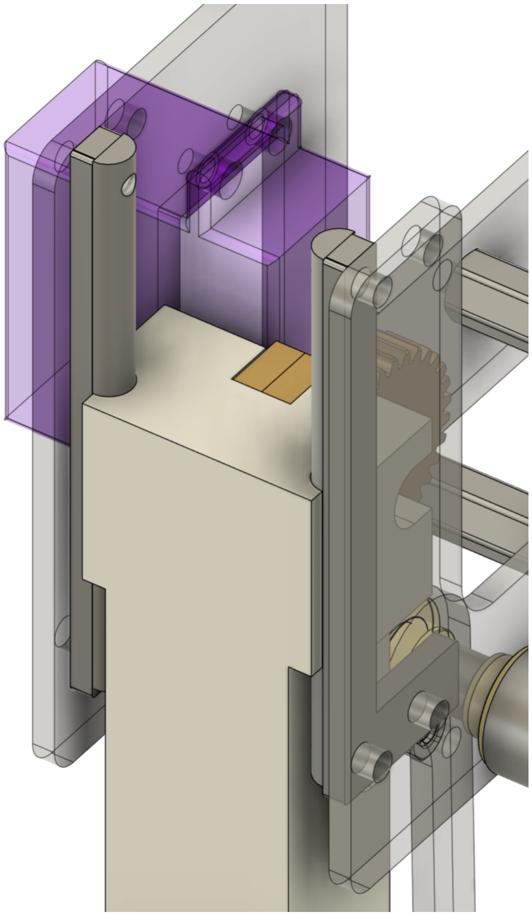


Figure 6.9: The two guide rails on the claw. The rail slot on the acetal pushing beam is slightly wider than the rail itself, allowing for slight misalignment.

Hardstops

Two hardstops (Fig. 6.10) prevent the pushing beam from running off of the rails in case of an error by the servo motor. One of the connecting standoffs doubles as the top hardstop, while a ledge extending from the top of the pushing beam hits a base section on the rail spacers to prevent further downwards motion. Additional hardstops, mounted on the guiding link, also stop the grabbing link from overextending to a singularity point and risk the mechanism flipping around.

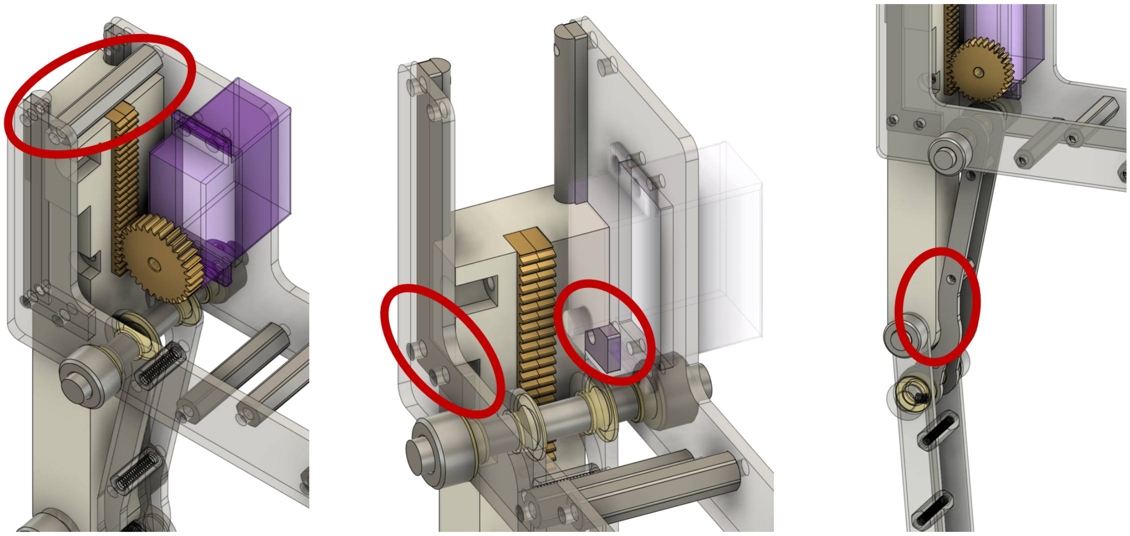


Figure 6.10: Three hardstops prevent the pushing link from falling off the claw in case of servo error and keep the link to its intended motion.

Passive Rotation

To allow the claw to swing with the basket, a 8mm (0.315in) shaft is located where the claw meets the arm. The weight of the claw pulls it against a hardstop when not grasping a basket. When the slider is pushing the basket, however, the claw rotates with the changing angle of the basket to maintain its tight grip without requiring an additional actuator or carefully timed controls scheme (Fig. 6.11).

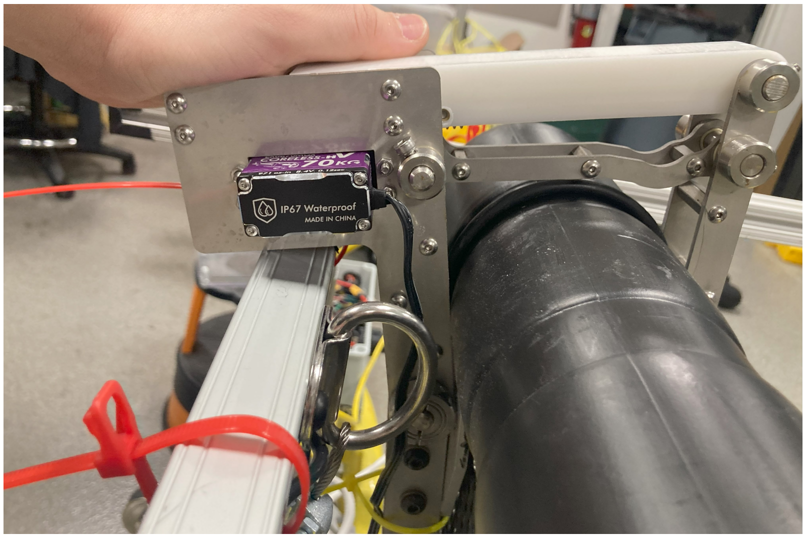


Figure 6.11: The claw being held back into its rotated position. In this image the claw interferes with the frame, though the frame can be either raised to be above the claw or lowered so it rotates above.

Bushings

To ensure smooth rotary motion, plastic bushings are added to any places where metal would be moving against metal. Every motion interface on the shafts is a plastic/stainless combination to reduce total system friction.

Spacers

To properly constrain the system, spacers are added between links to restrict the linkage to rotary motion and prevent any side-to-side slop (Fig. 6.12).

Figure 6.12: The inside of the claw, where the spacers which constrain the links to rotary motion can be seen along the shafts next to the guiding link.

6.4 Main Arm

After the claw has grasped a basket, the arm lifts the basket out of the water. To accomplish this while maintaining the adjustability required by the prototype and lift the heavy baskets on a long lever arm, a system of waterjet 2D parts mounted to t-slot rails powered by a strong motor was designed (Fig. 6.13).

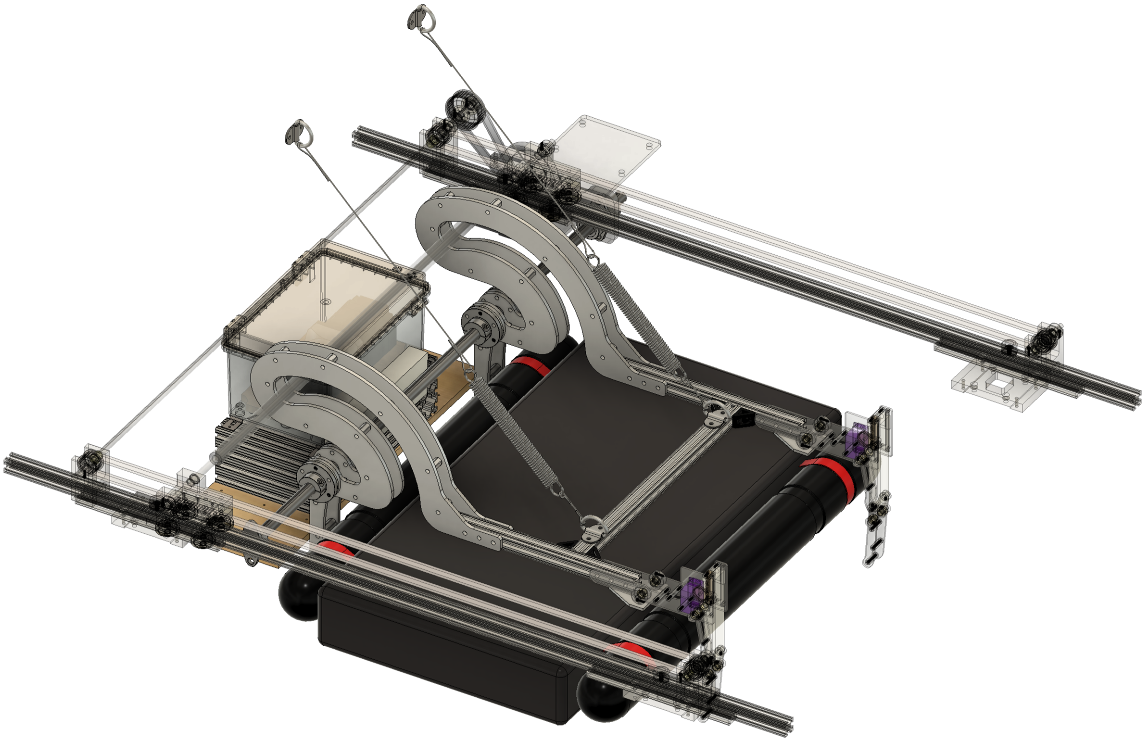


Figure 6.13: The main arm mechanism. The base of the arm has a curved shape cut out of it for the slider to sit in while the arm rotates, as well as allowing the arm to rotate around the inner edges of the hulls.

The arm needed to be adjustable in multiple directions (Fig. 6.14). The distance it could reach across the hulls needed to be able to be adjusted as the distance between the hulls continued to change, while the distance between the two main beams themselves had to move in case of interference with the camera's view of the baskets. T-slot rails accounted for flexibility in both directions. After initial rounds of testing and finalization of the arm spacing, these additional degrees of freedom were removed in favor of a simpler design.

At the base of the arm, a separate basket rest is attached (Fig. 6.15). It serves two purposes: first, baskets are pushed into the basket rest by the claw to secure the arm's hold on the basket. Second, when during the fourth flipping stage when the baskets are released, one side of the basket drops down onto the basket rests to shake the oysters. The basket rest is separate from the main arm piece so it could be switched out without re-machining the entire arm base based on testing results.

The basket rests are part of a series of components which attach to the arm and shaft. The arm and basket rest are directly attached to each other and to a stainless steel flanged

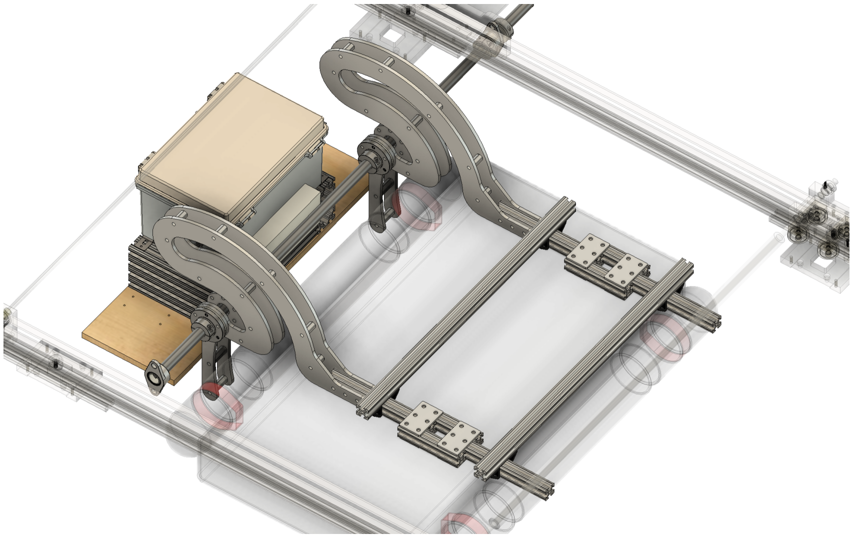


Figure 6.14: The first version of the arm, in which both the distance between the two arm beams and the total length of the mechanism could be adjusted.

clamping shaft collar. The aluminum is separated from the stainless steel by an acetal spacer to prevent the aluminum from corroding. Two of these assemblies, mirrored to each other, make up the end of each arm. The assembly can also be seen in Figure 6.15.

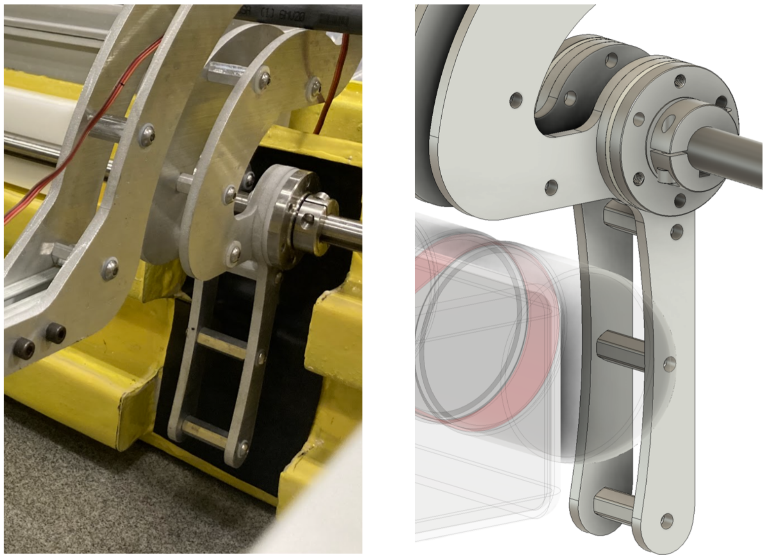


Figure 6.15: The final design of the basket rest mounted to the arm. The stackup of pieces to attach the arm to the shaft is also visible.

6.4.1 Structural Analysis

Due to the nonstandard shape of the arm bases, Finite Element Analysis (FEA) was conducted to finalize the shape of the arm bases. Due to their large size to accommodate the slider beam and based on FEA results, the arm bases were made of 6.35mm (1/4in) 6061 aluminum.

A mesh convergence study was done, and FEA completed on one arm as seen in Figure 6.16. FEA aided in tuning the dimensions of the arm base, with a force of 240N applied to the end of the arm to represent the chance of oysters being shifted to one side of the basket. The arm has a maximum stress of 124MPa and a safety factor of 2.2 with a maximum deflection of 20mm (0.79in) at the claw end.

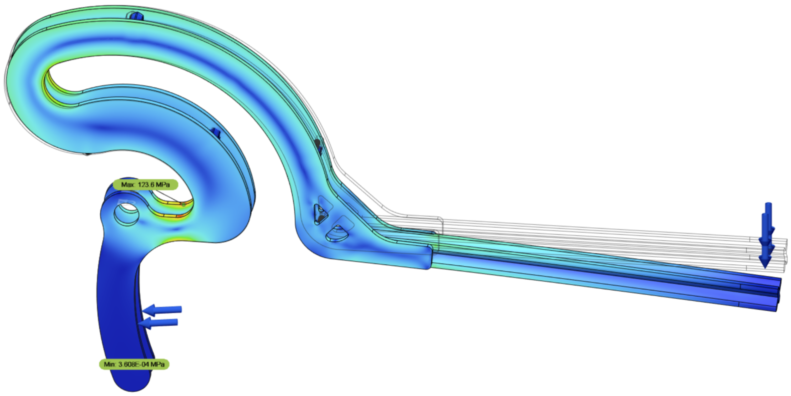


Figure 6.16: FEA of the arm. The locations of highest stress are near where the arm attaches to the drive shaft and towards the back where the arm curves to fit the slider and move over the hull wall into the interior.

6.4.2 Power Transmission

To determine the torque requirements for the arm motor, the simplified FBD in Figure 6.17 can be used.

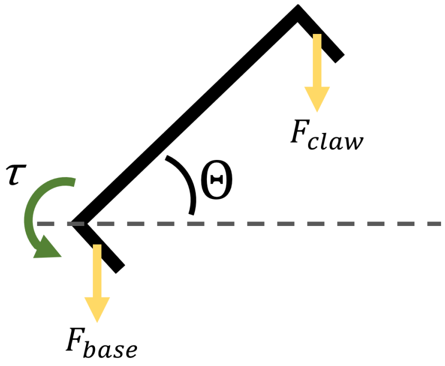


Figure 6.17: A simple free body diagram of the arm showing the basket applying forces to both the claw end and the basket rests, as well as the angle the arm makes with the horizontal plane.

The torque required to move the arm changes with the angle θ of the arm to the horizontal, and the arm requires more torque to move the smaller θ is. However, the center of mass is not necessarily in the center of the baskets since the oysters can shake around inside. In a worst-case scenario, almost all the oysters are towards the claw and very few towards the basket rest when flipping begins. As seen in Figure 6.18, if the oysters start towards the claw, the torque required is significantly more than if modeling the basket with the center of mass at the geometric center of the basket. Assuming a 0.6m (27in) length arm reaching across the baskets with 90% of the weight starting at the claws, the following figure is generated:

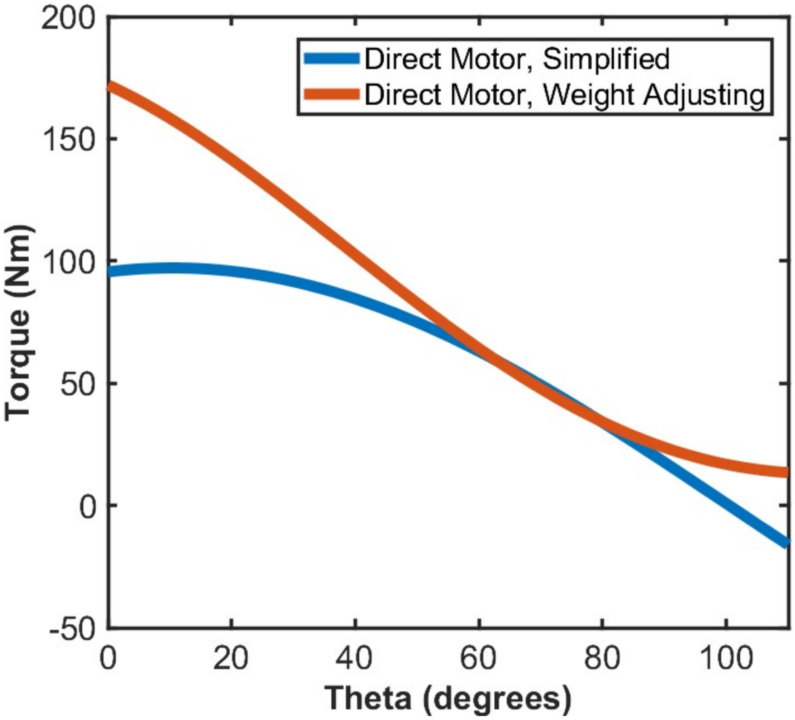


Figure 6.18: Torque required to move the arm assuming either oysters located at the center of the basket or shifting from the claw side to the basket rest side.

This results in an almost about 170Nm torque requirement at startup - however, this value drops off as θ decreases. To meet this requirement, a two part solution was developed. To provide the majority of the torque, a 4Nm motor with a 50:1 gearbox was used, giving a total 200Nm of torque. To aid in lifting the baskets initially, two springs run between the arm and the frame so the motor pulls against the springs when going down the last few degrees of motion but is assisted by the springs while lifting baskets. The complete system can be seen implemented in Figure 6.19.

Two 2.6kN/m (15lbf/in) springs are used to provide a counter to the basket's weight and aid the motor on startup. These springs were chosen as based on their mounting position they can provide a 130Nm counter-torque to the arm assuming they have initially been stretched 10cm (4in). The springs are attached by stainless steel cable to both the arm and frame. The cable is connected using wire rope clamps, allowing for adjustment of how much the springs extend when the arm is lowered and therefore how much spring force is applied

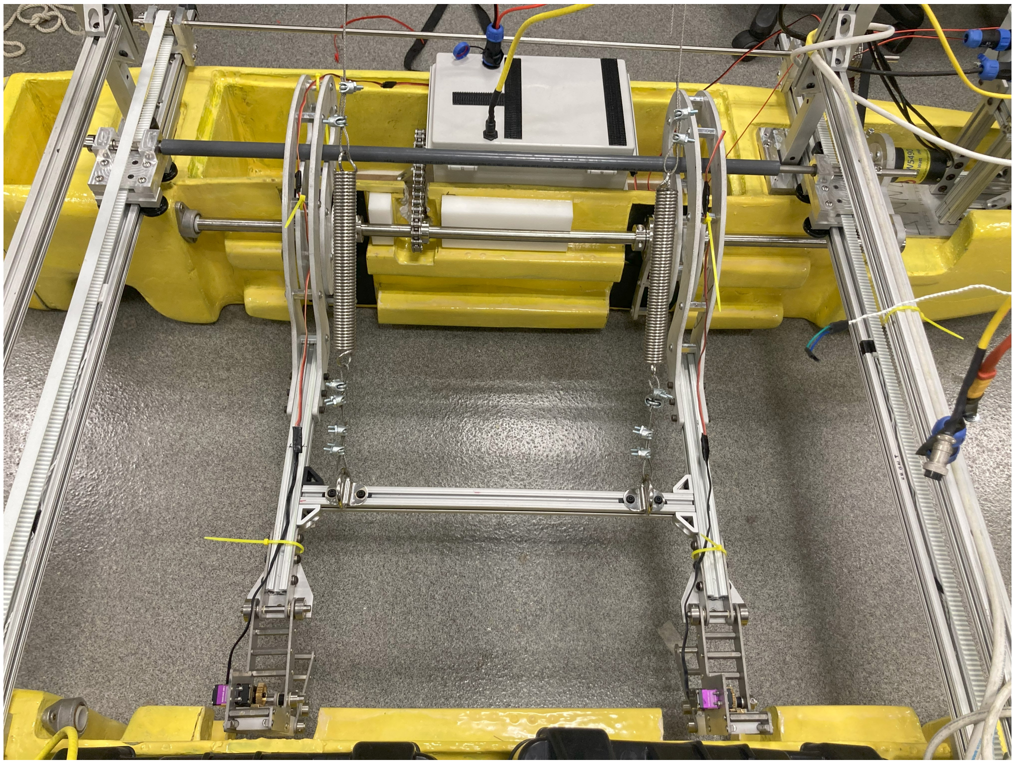


Figure 6.19: The full arm, motor, and springs installed on the vehicle.

to the system.

As finding a waterproof motor that met the torque requirements was difficult, a NEMA stepper motor and gearbox were purchased and mounted in a waterproof box. The motor and surrounding enclosure were too large to fit in the motor mounting section towards the rear of the vehicle and instead had to be mounted in the center. The inside of one hull, initially intended for electronics, was repurposed to house the motor and the arm when it tips back. Initially a friction fit frame and ratchet strap setup was implemented, but was replaced with a wooden platform with tee-nuts epoxied into the center of the hull. A box made of 5x10cm (2x4in) aluminum extrusion with t-slot rails was attached to the tee nuts for mounting the motor, allowing it to slide within the hull to tension the chain which .

To transfer motion from the motor to the drive shaft, a chain was used for its high torque and power transmission, anti-slip properties, and ability to accommodate more misalignment in tensioning than a timing belt (Figure 6.20). Due to the motor's mounting in the center of the hulls, the chain had to be connected in the center of the drive shaft rather than at the end and custom acetal support bearings were installed to the shaft could withstand the force being pulled on the chain without bending.

To source the chain basic stress/strain calculations were conducted to determine the applicable chain size. A 40B series chain and sprockets made of 304 stainless steel due to ease of availability and high safety factor for the applied loads. The fatigue life of the chain system is estimated to be 5,000 hours ([21], Section 7-15).

Figure 6.20: The arm motor, chain, drive shaft, and support bearings.

6.5 Slider Beam

The final subechanism of the basket flipper is the slider, which pushes out the underside of the basket (Fig. 6.21). The basket continues to rest on the slider for the next steps of the flipping process, as it pushes one side of the basket under the other to flip it. Once the claws release and the basket drops, shaking the oysters, the slider pushes the basket end out further then retreats back into the arm, forcing the basket to drop into the water. A belt and rail system was chosen over a linear actuator to push the undersides of the basket for its simplicity in providing the required motion.

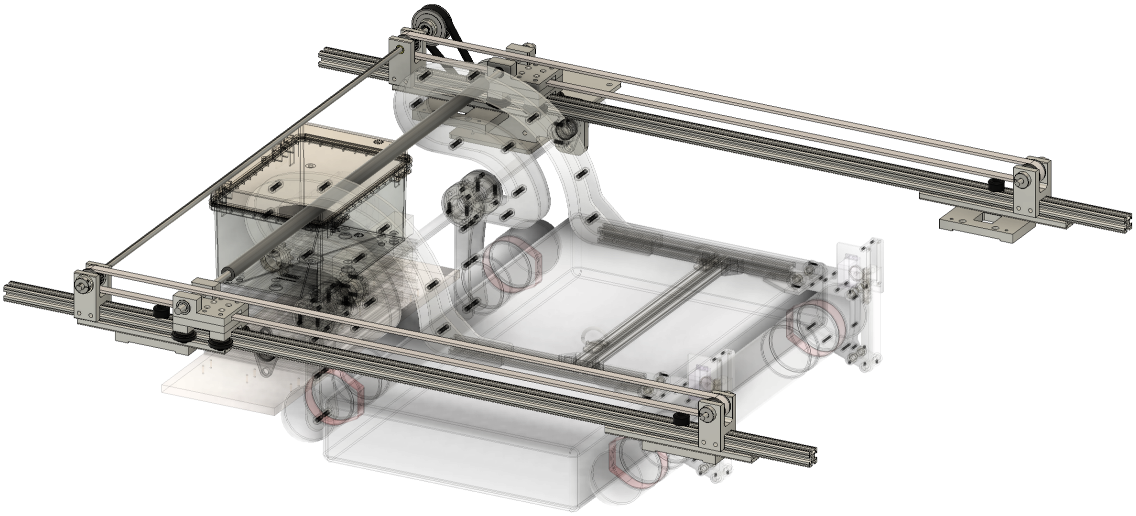


Figure 6.21: The slider system. Driven by two synchronous pulleys, the slider beam pushes the underside of the basket to increase flipping success rates. While the basket is resting on the slider and basket rests, the slider can also move back and forth to aid in shaking

6.5.1 Motion Analysis

To push a 300N basket with a 32mm (1.25in) timing pulley, 4.8 Nm of torque is required. To meet this requirement, a 4.5Nm waterproof DC motor is used with a 2.5:1 gear ratio to increase the provided torque to 11.25Nm.

A 10mm (0.4in) 304 stainless steel drive shaft powers two synchronous timing pulleys (Figure 6.22) to drive two belts which connect to the slider. Assuming 8s to run the slider, the required power for it to travel the full 0.9m across the rail is 34W. Using chapter 17 of [21], for the slider's requirements a minimum 9.6mm (0.38in) belt is needed. To meet this requirement the system uses 15mm S5M timing belts.

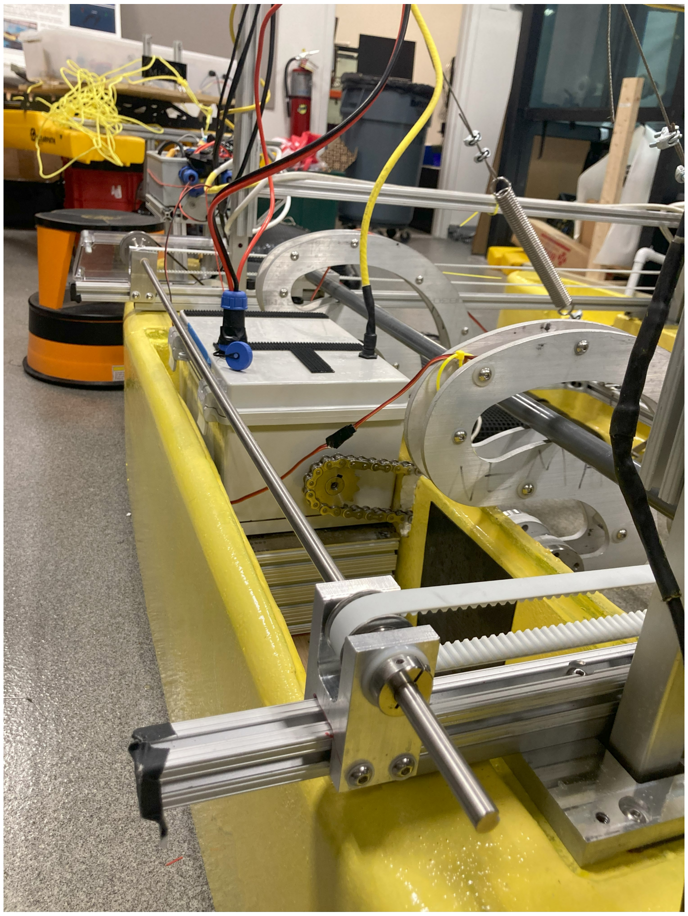


Figure 6.22: The slider pulleys mounted on their drive shaft. The drive shaft is keyed, with keys constraining the rotational motion and shaft collars constraining linear motion alon the shaft.

6.5.2 Additional Slider Design Elements

Rails and Rail Mounts

To mount the sliders to the hulls, adapter plates were made that mount on top of the frame posts, securing both the frame and slider into the hulls (6.23). Half-size t-slot rails bolt in to the adapter plates, allowing the main slider rails to slide and mount to the half-sized rails, keeping the vehicle's ability to fine-tune the distance between the hulls. There are two sets of mounts, one set each towards the forward and rear of the vehicle. Each set has two possible rail mounting locations, giving a total of four possible rail mounting locations and three options for spacing between the rails. As there was a chance of the rails interfering with the ropes which chain the baskets together, testing these options was essential to determining the balance between rope interference and ease of vehicle alignment. The closer together the rails are, the easier it is for the ropes chaining the baskets together to pass underneath the rails. However, bring the rails too close together and it becomes extremely difficult for the autonomy program to be able to line up the basket due to the limited area for lifting without hitting the rails. Both the pulley drive shaft and the slider beam itself were oversized to the widest rail configuration and still function for the smaller ones by adjusting the shaft collar locations.

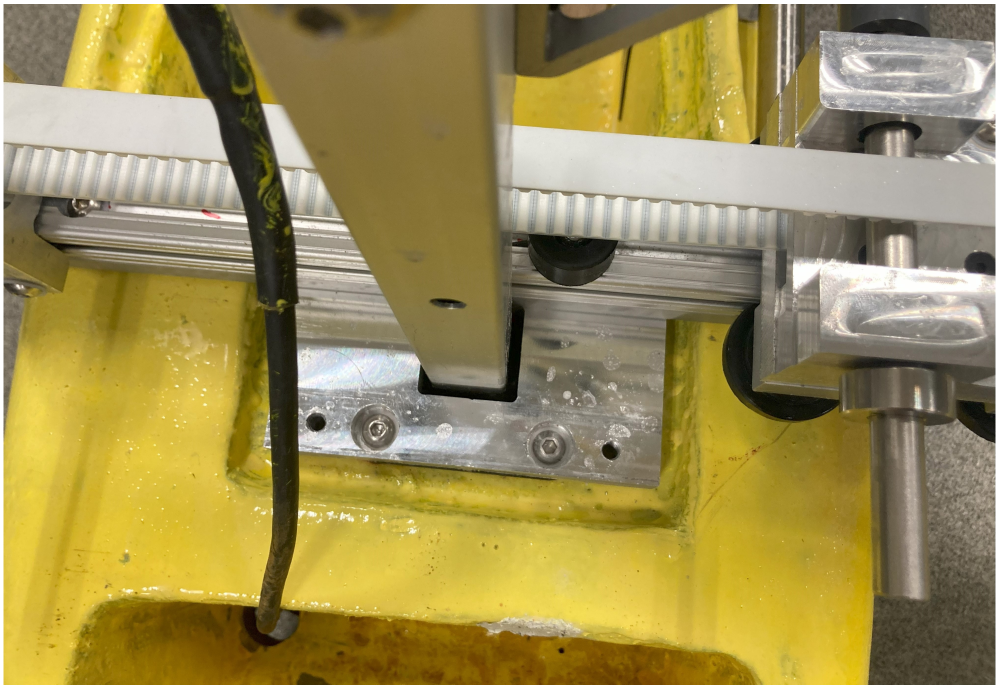


Figure 6.23: The rail mounts for the slider beams, which mount to the hulls around the frame posts. In this image, the slider is mounted to the inner mounting location with the tapped holes for the outer configuration visible.

Slider Carriage

The slider carriage rolls along the slider t-slot rails and clamps to the timing belt to achieve the linear motion. Rubber bumpers mounted to the rails provide mechanical hardstops for the carriage's motion.

The carriage assembly is comprised of a 3-part stack of wheels, base plate, and top plate. The wheels are off the shelf components which are designed to slide in the t-slot rail, and are spaced apart on the mount to prevent binding of the wheels on the rail and maintain smooth motion. The bottom plate attaches the wheels and top plate, while providing a surface for the belt to be clamped to. The top plate has the toothed profile of the S5M belts bolted into the underside, which maintains a tight grip on the two ends of the pulley belt as it is pressed into the bottom plate. The slider beam itself is mounted into two slots on the top plate. The two carriage tops were machined at the same time out of the same piece of stock to keep them identical in their vertical heights to ensure the slider was even and reduce misalignment in the system.

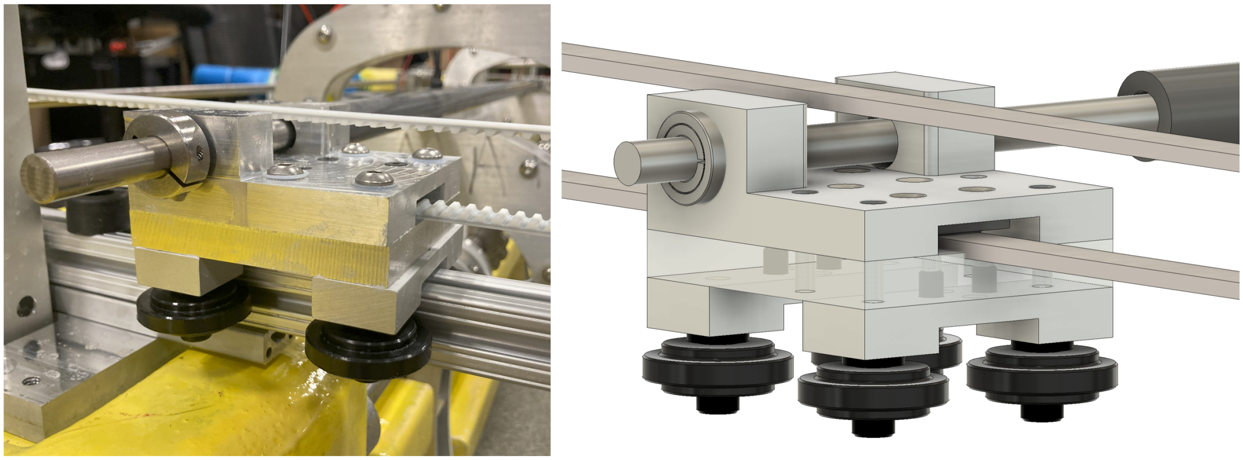


Figure 6.24: The carriage which controls the slider motion. Made of two custom pieces, wheels attach to the bottom while the belt is clamped in between and the slider beam attaches to the top. A rubber hardstop can be seen behind the carriage in the left image.

Slider Beam

The slider beam itself is made of a 7/16in (1.1cm) 316 stainless steel shaft. A PVC plastic sleeve surrounds it, which can roll under the baskets to reduce both friction and snagging.

Pulley Mounts

To mount the pulleys on the rails, custom pulley mounts were machined of 6061 aluminum. The mounts allow for adjusting the position on the pulleys on the rails to tension the belts and ensure alignment of the two carriages as well as the drive shaft.

Rather than having a second continuous drive shaft, on the electrical hull two idler pulleys are mounted on separate shafts (Fig. 6.25). The pulleys have bearings inside to allow them to freely spin and provide the other mounted end to the belt.

Motor Mount

To power the slider, a motor is located towards the rear of the vehicle. It is is mounted to a piece of 1/2in (12.7mm) 6061 aluminum and connected to the drive shaft via another belt, which is connects two pulleys together and increases the drive shaft torque. To tension the belt, a simple flexure allows the motor to rotate closer and farther to the drive shaft then clamps the motor in place.

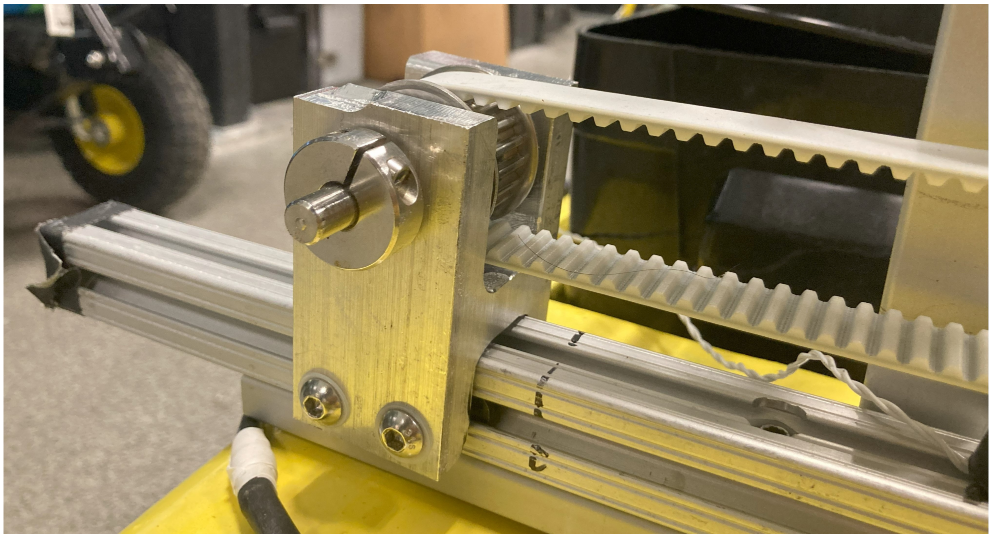


Figure 6.25: The idler pulley mounts.

Figure 6.26: The motor mount, which allows for tensioning of the drive belt. It also mounts the arm drive shaft, which can be noticed on the left.

Chapter 7

Full System Testing, Results, and Discussion

Testing of the full system occurred in a few main stages. The first major test of the entire system occurred during Field Test II. Adjustments and improvements were made to the design based on the results of the field test. To determine the performance of the final design, testing was conducted in both the lab and a river test. Finally, the vehicle was taken to the oyster farm to assess the completed system.

7.1 Field Test II: Full System

Field Test II was the first test of the entire Oystermaran V2. It was conducted late in the oyster season on two rows of baskets to for the team to understand the state of the vehicle and what changes would need to be made for final testing. For the mechanical system, the goal of Field Test II was to test the updated nose design (as discussed in Section 5.2.3) and gather initial results from the flipping mechanism.

This first iteration of the flipping mechanism had some major issues which prevented a full analysis of the mechanisms. The documented problems and the solutions implemented to solve them are described in Table 7.1, and a picture of the vehicle during the test is shown in Figure 7.1.

Issue	Cause	Solution
Vehicle snagging on baskets, making maneuvering down the row difficult	Initial claw design (Appendix A.4) was unable to fully slot into designated inserts	Total claw redesign. Final design described in Section 6.3
Claws unable to grab baskets	Vehicle too high in the water, plus	Total claw redesign. Final design described in Section 6.3
Arm unable to fully lower	Interference between basket rest and hull	Thinner basket rest manufactured and installed
Arm unable to lift basket	Force of basket causes movement of the friction fit and ratchet strap motor mount, causing the chain to skip. Once the arm started going up, it would usually continue.	Permanent motor mounting solution made of installed wood with tee-nuts to bolt in the motor platform. Springs installed to aid with initial loading.
Slider shook and did not run	Controller error	Debugged in lab

Table 7.1: Documented Problems and Solutions from Field Test II

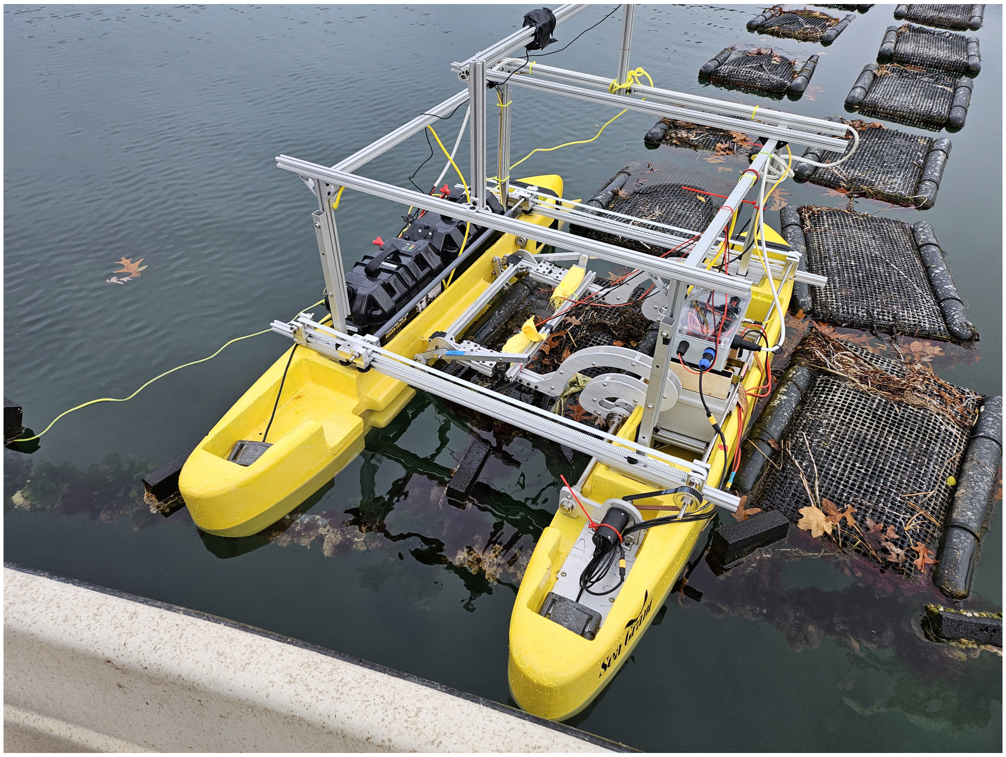


Figure 7.1: The vehicle and flipping mechanism during Field Test II. Note the mechanism is slightly raised, though it was unable to travel higher than this.

7.2 River Test

To assess the success of the arm and maneuvering fixes, a test was conducted in the Charles River off of Magazine Beach in Cambridge, MA. This section summarizes the results of that test as well as smaller scale lab testing done in preparation for the river test.

7.2.1 Successes and Shortcomings

Snagging

During this test, the vehicle experienced very little snagging. The new basket rests allowed the arm to fully descend while still providing a large curved surface to aid in grabbing and holding the baskets. Temporary passive claws were used during this experiment, which also did not snag like the old vehicle. Once the waterline was adjusted as discussed in Section 5.3, the vehicle glided over the baskets.

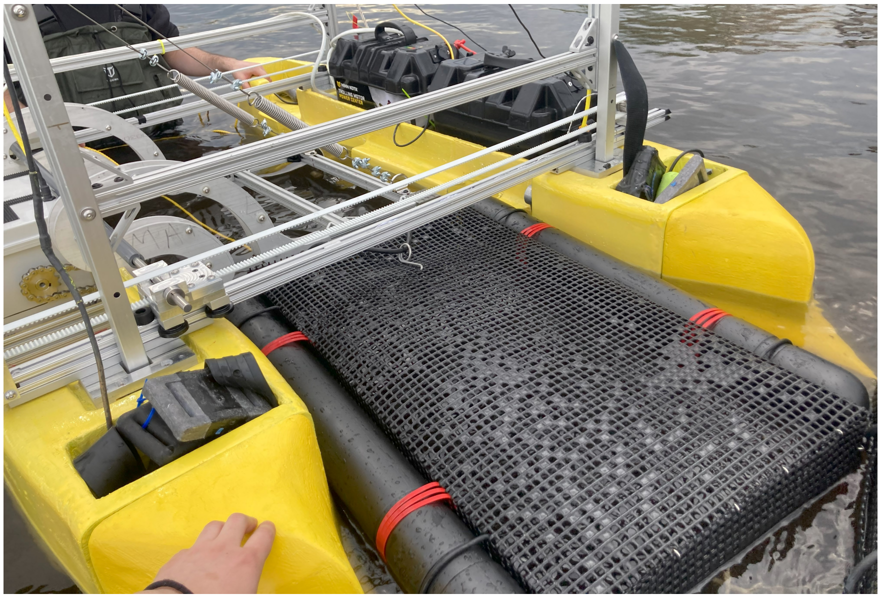


Figure 7.2: Full system testing in the Charles river.

Arm Torque

For this test, two solutions had been implemented to aid the arm in lifting the baskets. Both solutions had moderate, though not full, success. The arm was able to lift significantly more weight than the previous iteration and operated as intended for lighter weight baskets. However, for heavy baskets the same error occurred where the motor mounting components would start to bend, causing the motor to pull itself towards the arm rather than spinning the shaft and eventually cause the chain to skip. This also meant the springs were not able to be pulled to their full intended distance as the motor was unable to provide sufficient torque.

When this error happened, the entire base platform the motor rests on would lean towards the arm. The motor platform is attached to the retrofit wooden hull mount with 6 aluminum gusseted brackets, which deformed to allow the motion. Given the difficulties of motor mounting, the struggles with arm torque can be considered a side effect of retrofitting the hulls to accommodate the new flipping mechanism. The next iteration of the Oystermaran would have proper mounting for the motor installed from the beginning, eliminating this problem. Going forward, this was considered a known issue unable to be resolved for the remainder of testing covered in this thesis.

Slider

The other primary shortcomings discovered during this test were in regards to the slider. During flipping, the basket ropes would get caught around the slider rails - during previous testing, the ropes connecting the baskets appeared long enough to accommodate for the slider beams. More information about the slider and rope tangling/interference is discussed in Section 7.3.4

7.3 In-Lab Flipping

With all solutions implemented, in-lab testing was conducted to determine the overall performance of the flipping mechanism. This allowed the team to closer analyze the performance of each step of the flipping process, acknowledging new issues will arise once testing is conducted in the water. Flipping testing was conducted with a basket filled with oyster shells to analyze shaking. The ropes attaching the baskets together were lengthened beyond their original position to accommodate the slider.

7.3.1 Step 1: Grab

The first step, grabbing the basket, was extremely successful. The final claw mechanisms worked smoothly and reliably to secure around the basket floats (Fig 7.3).

7.3.2 Step 2: Lift

After a basket is grabbed, the arm lifts it up. How snugly the basket fits into the mechanism is dependant on the positioning of the arm t-slot rail, which has a few centimeters of travel in and out of the arm base. This allowed the team to experiment with how tightly to fit the basket into the mechanism. Too short, and it becomes difficult to maneuver the vehicle into the basket due to the lack of wiggle room. Too long, and during lifting the basket slips and falls off the basket rests as shown in Figure 7.4. However, even when that occurred the claws maintained a tight grip on the basket, a major success for the submechanism.

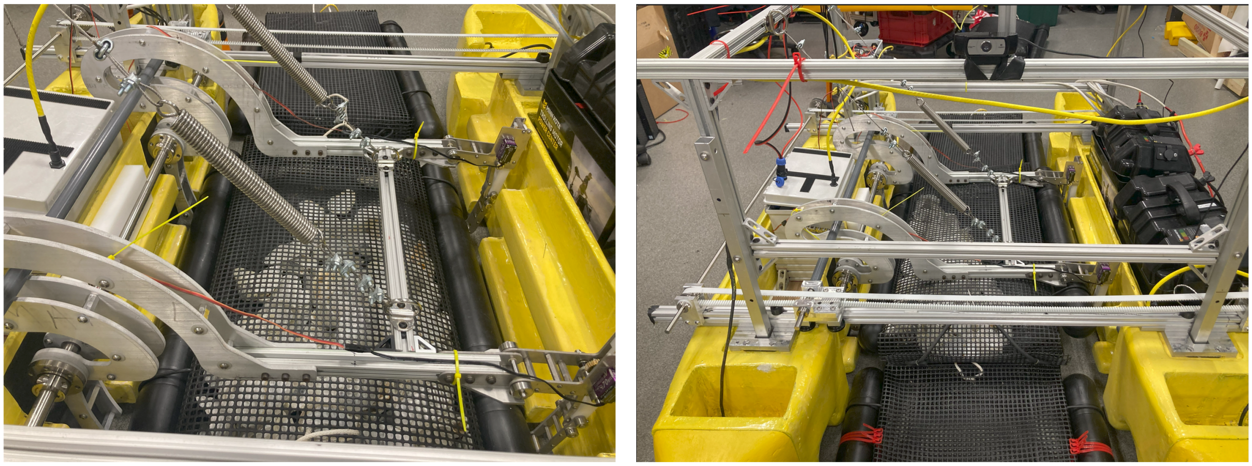


Figure 7.3: Grabbing the basket. On the left, the claws are open with baskets passing underneath while on the right the claws have closed around and secured the target basket.

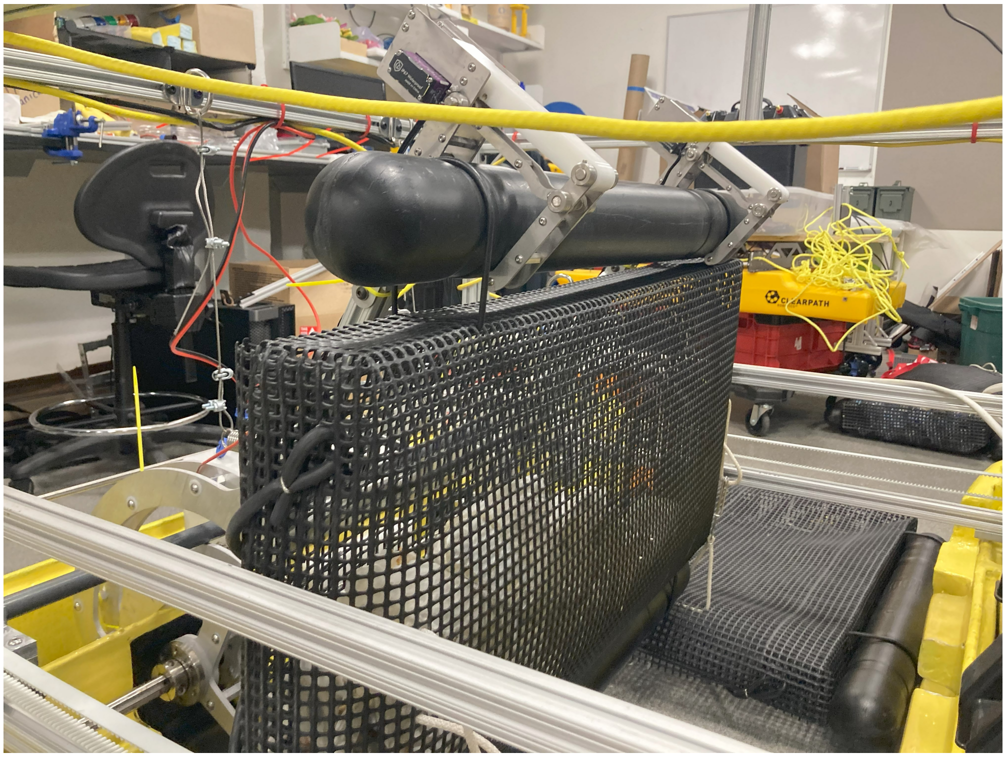


Figure 7.4: The claws alone holding the basket up after it has slipped off the basket rest due to too long of an arm.

When the distance is set properly, the arm easily lifts up the basket to complete Step 2 as pictured in Figure 7.5.

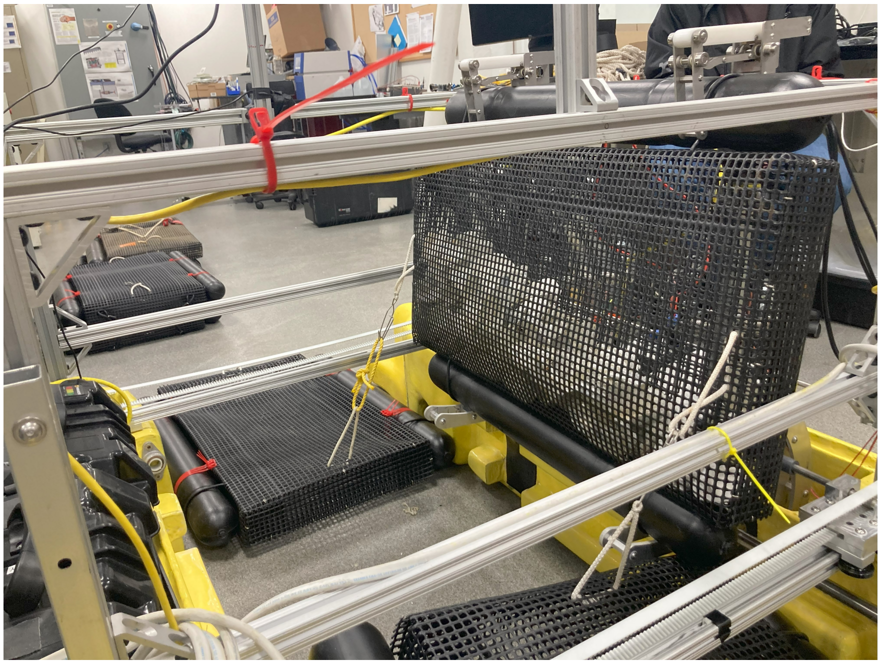


Figure 7.5: The basket fully lifted. Note that all oysters have gone to one side of the basket.

7.3.3 Step 3: Push

After the basket is lifted, the slider emerges from the inside of the arm to push the basket (Fig. 7.6). The slider motor continued to have control issues and will need either additional sensing/feedback or be entirely replaced. However, even with the control issues the slider was able to push out the underside of the basket on its own and was manually aided for completing the remainder of the push. The plastic sleeve on the slider worked as intended, and the slider easily rolled under the basket without getting caught.

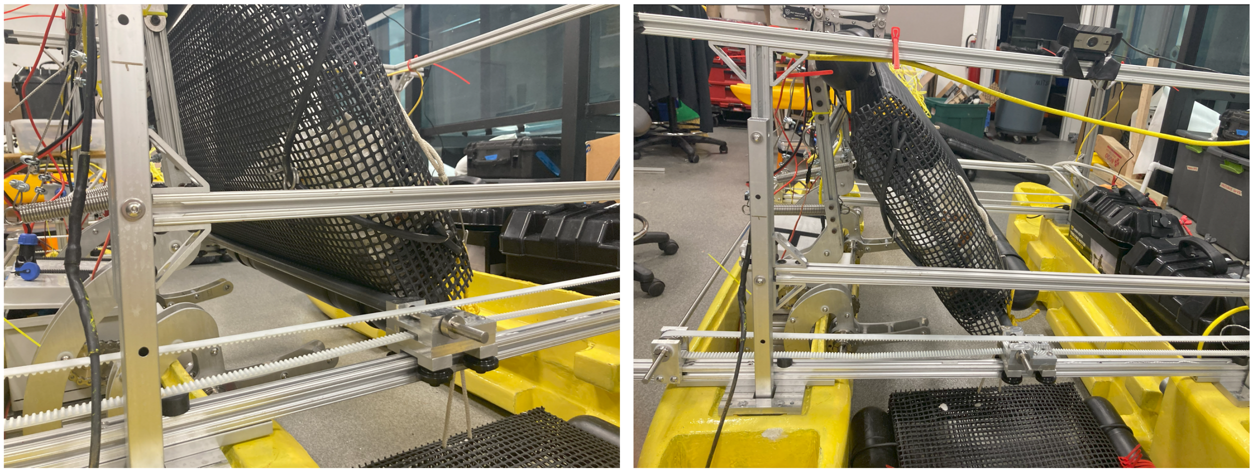


Figure 7.6: **Left:** The underside of the slider just after removing the basket from the basket rests. **Right:** The slider halfway across its rail, the end of the pushing step

7.3.4 Step 4: Release

During Step 4, the basket is placed into the water in its flipped orientation. However, testing revealed the exact order of motions taken between the arm and the slider are key to a successful flip.

The first substep is releasing the claws, which causes the basket to slide down along the arm while continuing to rest on the slider (Fig. 7.7).

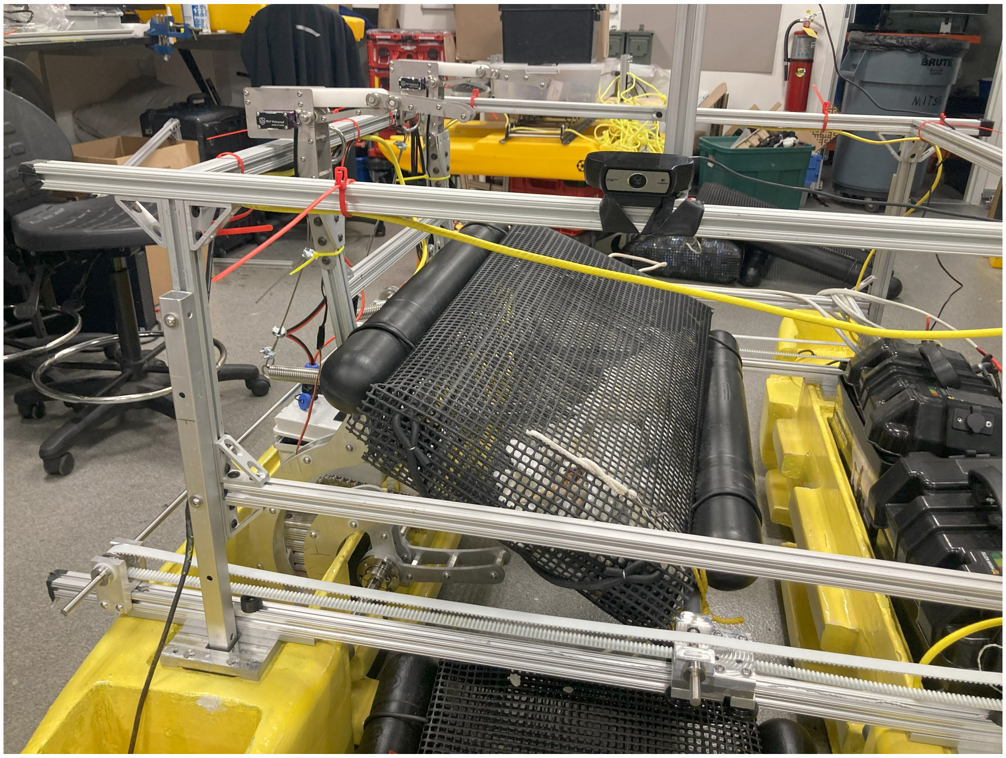


Figure 7.7: Opening the claws to release the basket.

From this stage, the slider continues along its path as much as the chaining ropes will allow. However, if the slider completely passes underneath the basket and drops the slider side of the basket, the ropes which tie together the baskets wrap around the slider, entangling it (Fig. 7.8).

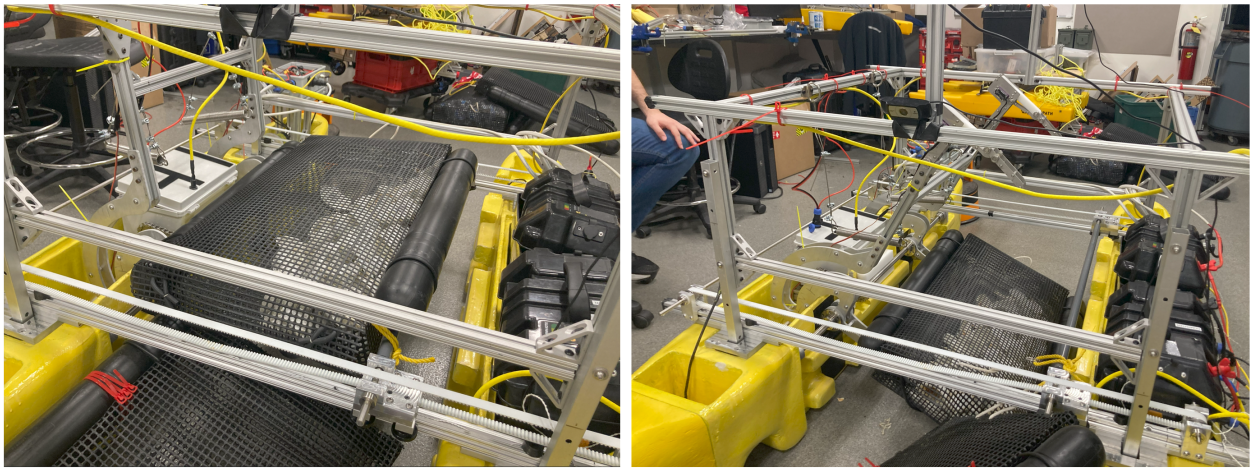


Figure 7.8: The rope holding the baskets together becoming entangled around the slider. This occurs when the slider moves out from under the basket, wrapping the rope around in the process.

To prevent this from happening, the slider must retreat back into the arm to drop the slider side of the basket. During this process both the basket rest and slider can shake to jostle the oysters inside of the basket, and the basket is lowered back down, flipped, with the oysters redistributed (Fig. 7.9).

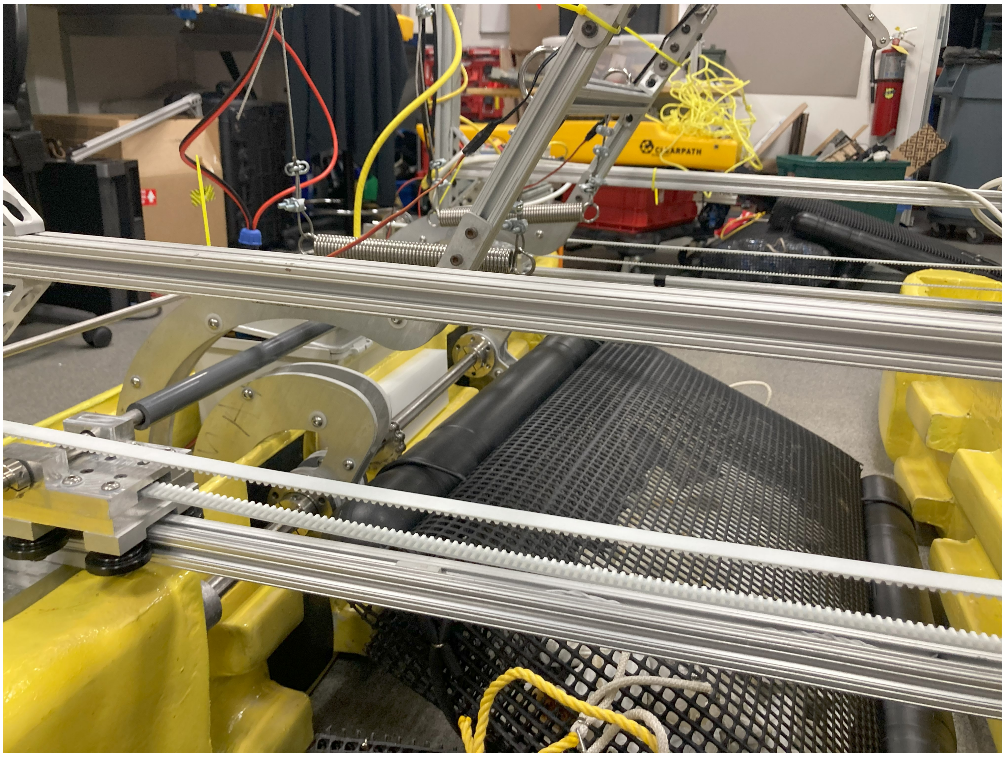


Figure 7.9: After being jostled by the slider and basket rest, the basket drops via the slider retreating into the arm. Note the more even distribution of oysters inside the basket than in Fig. 7.7 due to shaking.

7.3.5 Step 5: Reset

Finally, the arm lowers, also lowering the basket edge still on the basket rest. The claws retreat to their insets, and the flipping process is complete (Fig. 7.10).

Figure 7.10: The open claws sliding back into their insets around the basket. the arm is low enough that the basket is already laying on the floor after being flipped.

Overall, the flipping mechanism showed itself to work well in the lab. Baskets could be successfully flipped and shaken. There are is still tuning required, but testing showed this to be a mechanically viable solution to handling and maintaining oyster baskets.

7.4 Field Test III

Beyond lab testing, a final field test was conducted to test the vehicle's performance. During Field Test III the baskets were too heavy for the Oystermaran to lift with the current arm motor limitations. However, Field Test III was still useful for confirming maneuverability results, testing grabbing baskets with the redesigned claw, and practicing entering the array, aligning, and preparing to flip.

7.4.1 Test Setup

Just like the other field tests, the team traveled to the oyster farm on the workboat. Conditions included a strong current, very light rain, and heavy baskets - not pleasant for the vehicle or the farmworkers, but within standard for Cape Cod (Fig. 7.11).

Figure 7.11: The team heading to the oyster field. Note the waves, which made the process more difficult than previous tests.

7.4.2 Test Results and Discussion

Maneuvering

Geometrically, maneuvering was a major success (Fig. 7.12). The vehicle pushed into the array much easier than prior tests by using the combination noses, and snagging was infrequent. The vehicle never ended up on top of the array and was able to make it past the field frame. Full maneuvering testing could not be conducted due to a low voltage issue with the thrusters, and the vehicle struggled when facing the current and would often be dragged by the current away from the target basket when entering the array. However, within the realm of what the thrusters could do, the vehicle successfully accomplished all the maneuvering targets of guiding itself into the field and easily driving over baskets.

Flipping

As stated above, the baskets were too heavy to flip. However, the team practiced grabbing the baskets. Further low voltage issues cause the claws to shake quickly actuate up and down, but when electrically functioning it was easy to grab the basket and lift it slightly out of the water before the motor bending was triggered.

Dan was consulted about the issue with the slider requiring longer ropes than are currently standard to function. His response is longer ropes are feasible, but adding that kind of slack to the array puts greater strain and more wear on field components - a tradeoff farmers

Figure 7.12: The Oystermaran in the array. Maneuvering was generally successful, though still required some effort to enter between the rows.

would have to choose to make if the Oystermaran becomes an accessible vehicle with that constraint.

Waterproofing and Flooding

For fast transport around the field, the vehicle was dragged next to the workboat. During this process, water entered all cavities on the boat and the two central cavities for mounting the mechanism and electronics had to be bailed out. The boat did not sink, but a future iteration which has to handle waves should have a lid over any sealed cavity or a built-in way to drain water.

Overall, this test showed that the vehicle has a way to go - especially electrically. However, it also showed that the mechanical system is viable and essentially complete. Everything left mechanically is tuning and small adjustments which will be conducted as the vehicle continues to be tested and improved.

Chapter 8

Conclusion

Development of new aquaculture technology is essential for farmers, consumers, and the environment. However, aquaculture often operates in spaces where it is difficult to implement new technologies and instead relies on manual labor. The Oystermaran project is working on creating a USV for high density flip-bag oyster farming, a common practice in New England but lacks any existing technology.

The goal of the mechanical design for Oystermaran V2 was to create a prototype vehicle to be used for testing and further development of the Oystermaran concept. Building off lessons from a 2021 vehicle, the Oystermaran V2 set out to redesign the hulls to increase vehicle maneuverability so an autonomy program could be created rather than relying on fine manual adjustments. A redesigned bag handling mechanism was also created to grab, flip, and shake the oysters to improve the oysters' growth and allow biofouling to flake off in the sun.

A prototype vehicle was successfully created, tested, and iterated on. Rounds of testing led to the development of a bow shape which aided in pushing the vehicle into the array. Inset thrusters and mechanisms prevented snagging on any element of the array, and an adjustable frame allowed for tuning and determining of the ideal spacing between the hulls. A full flipping mechanism was designed and tested, also operating using an adjustable design to allow for fixing of issues as they arose. The mechanism was shown to successfully flip and shake baskets in the lab environment and is easily able to load baskets into the mechanism in the field, showing promise for fully flipping in the field.

Future Work

Even with the vehicle's successes, there are still significant areas for improvement. When looking at the next steps for the mechanical design of the Oystermaran, they include:

- The interference between the slider beam and the oyster basket ropes needs to be addressed. Possibilities include moving the position of the slider rails, improving the timing of mechanisms in the flipping process, and extending the ropes between the baskets.
- Ideally, the motor mount will be improved and the vehicle will be able to flip heavier baskets. Given the motor is currently bending multiple aluminum gussets, the next solution to try is machining stainless steel brackets to attach to the base plate and the motor stand.
- The flipping process should be fine-tuned, both for the timing of the mechanisms and the adjustable dimensions of the arm and slider.
- Resolve electrical and power issues, including raising thruster voltage to 24V for additional thrust, fixing or replacing the slider motor, and solving jittery control of mechanisms.

Eventually, a version 3 of the Oystermaran may be created. To create a fully finalized prototype, the following would need to be taken into consideration:

- Stiffening of the vehicle. Sometimes the aluminum shifts and bends, and while t-slot rails are excellent for prototyping and adjustability they also lead to components shifting. Using the final dimensions, a precise vehicle could be made without these drawbacks.
- New hulls designed for the functioning flipping mechanism. Proper mounting locations for all the motors and mechanisms rather than retrofit plates and adapters, insets designed and tuned for the mechanisms, and either lids or drains for enclosed hull cavities.
- Bigger and more powerful thrusters to provide more thrust for days with significant wind and current.

In Conclusion

Overall, the Oystermaran V2 is a mechanically viable vehicle which accomplished its goal of being an easy to adjust vehicle to tune parameters as new information is learned. The Oystermaran V2, aka "Flippy 2" is ready to continue testing and iteration as the electrical and autonomy systems progress towards a complete prototype.

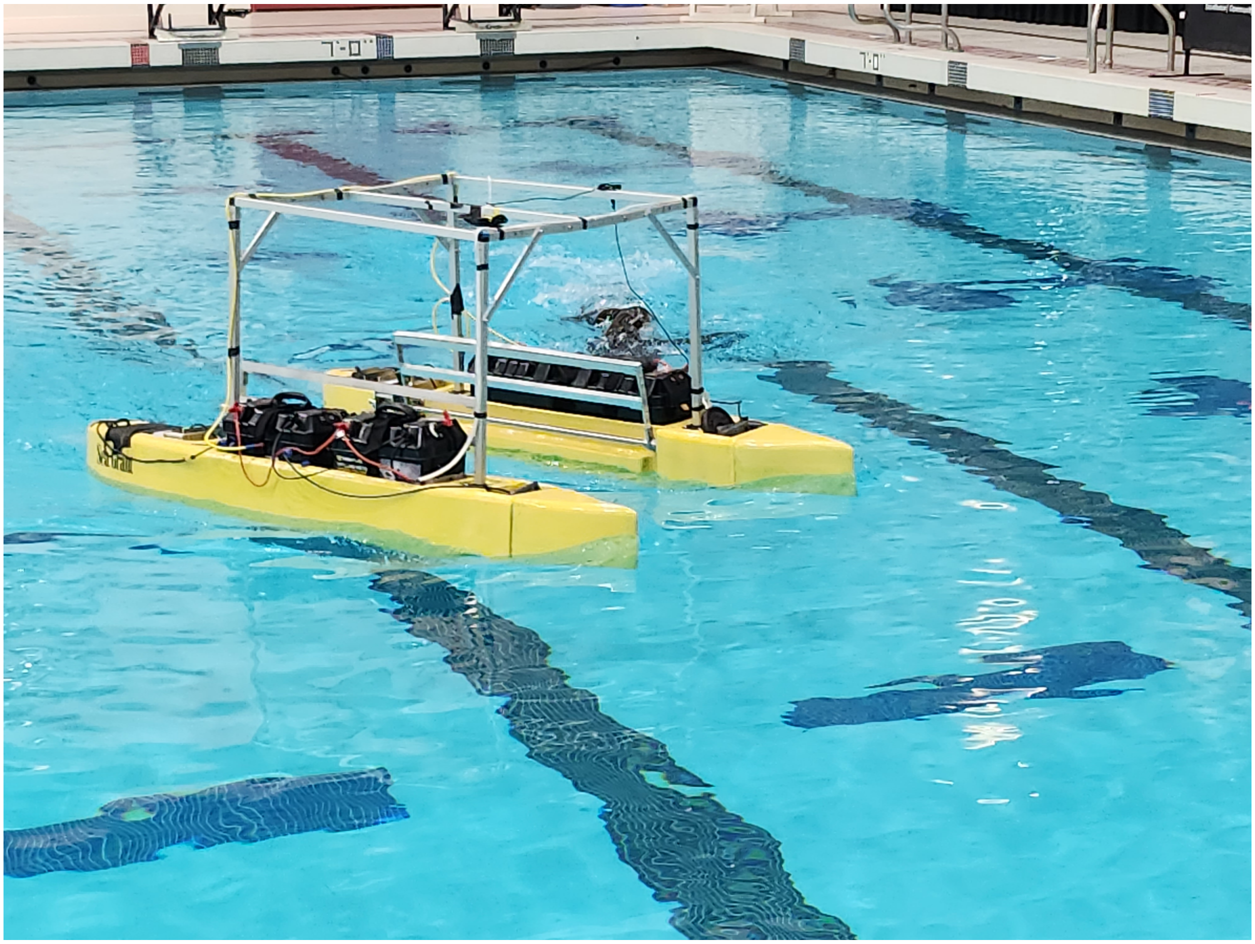
Figure 8.1: Oystermaran and oyster farm

Appendix A

Discarded Solutions

A.1 Easy Disassemble Frame

A snap-together frame for easy vehicle transport. Testing with this frame resulted in learning about the importance of vehicle adjustability and fine-tuning the gap between hulls. Plus, the frame was not stiff enough as the plastic joints would bend. Below is a photo of an early iteration of the V2 Oystermaran, showing both the first frame and flipping mechanism.



A.2 Dual Arm Flipping Mechanism

Before the team realized shaking was a requirement, a prototype flipping mechanism made of two symmetric arms to flip baskets without interfering with the central basket chain at all was designed and prototyped. It was designed by undergraduate researchers (UROPs) in the lab and built by UROP Sebastián Monsalvo. Testing revealed the mechanism turned baskets on their side rather than flipping them.

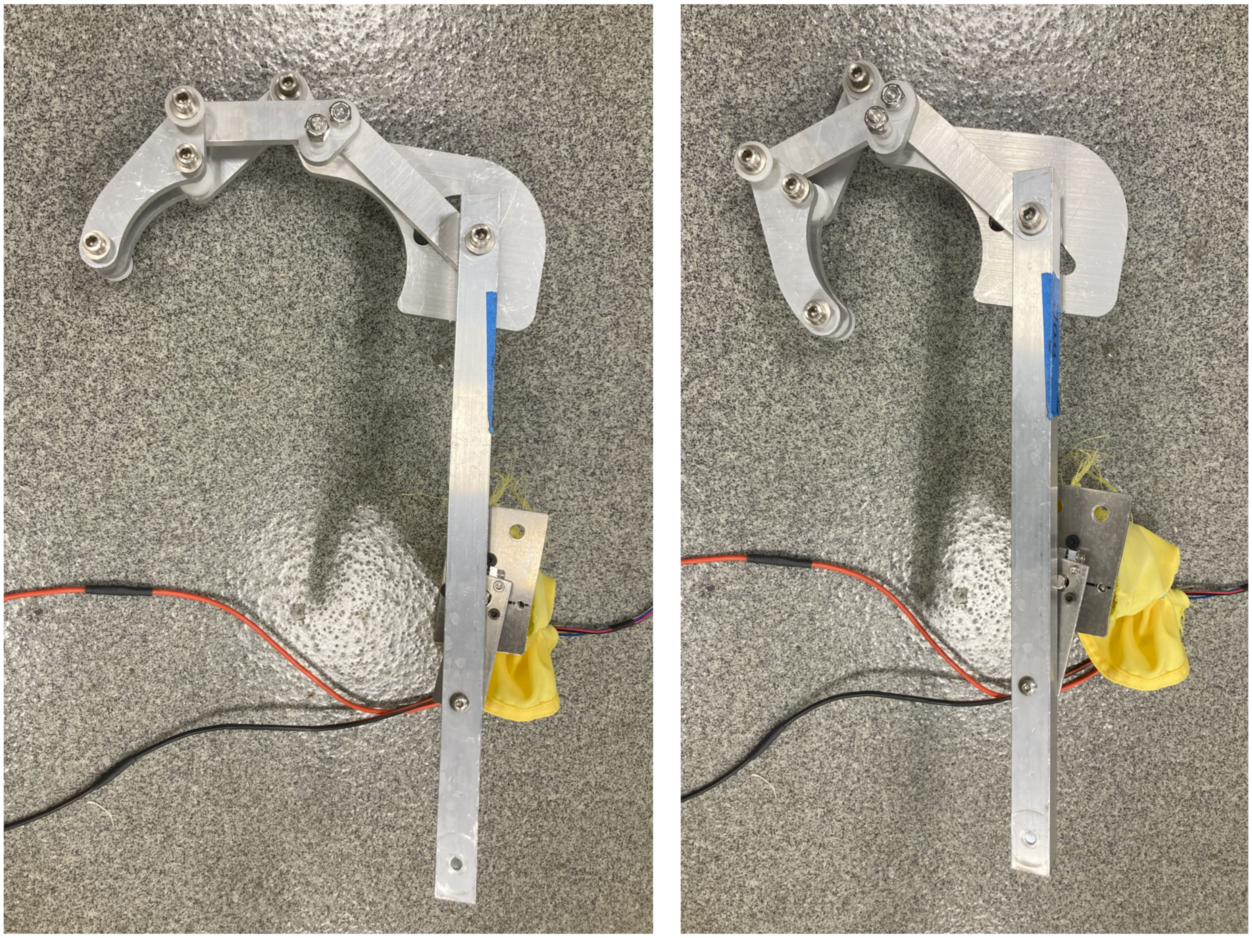
A.3 Considered Flipping Mechanisms

After discarding the dual arm mechanism, multiple new mechanisms were ideated. These included:

- A helix similar to the FlipFarm Heli-cat (before realizing the force it took to run baskets through the helix)
- A path of rollers like a conveyor belt
- A big rotating circle baskets could slide into

A.4 "Finger" Type Claw Linkage

The original claw linkage for the bag handling mechanism, designed and prototyped by Sebastián. Issues with constraints and overall slop in the mechanism as well as friction meant it did not actuate its full intended range of motion. This caused the linkage to be unable to grab and hold tightly to baskets and caused problems with snagging as it could not fully retreat into its inset.



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