Aquabot: An open-ocean aquaculture feeding vessel proof-of-concept

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***Abstract*—With the rapid growth in population, the need for sustainably sourced food is also growing. Open-ocean aquaculture, an innovative and environmentally conscious approach to food production, is a mainly human-powered process which leads to relying heavily on optimal conditions for service and feeding. During the manual process, crew members drive boats out to the location of the farm, reach or dive into the water to attain the necessary connections and manually pull up the heavy hoses while they are fighting the currents and waves to pull them onto the boat to finish the connection process. This is a cumbersome, expensive and potentially dangerous activity.**

Our team designed "Aquabot," an autonomous surface vessel (ASV) which automates docking, uses assisted autonomy for tube connection, and parallelizes the feed refill process. This allows automated connections to various pens, improving safety for the crew and increasing efficiency of feeding in time and cost. With a more automated docking and tube connection, the reliance on human workers decreases, putting fewer people in danger of the harsh conditions. Navigation and positioning of the ASV is possible through the use of April Tags for location determination. Mechanical mating is achieved through a mooring design which snugly fits with the ASV to prevent unnecessary movements in various directions. This design helps to decrease the effects of weather and swell conditions during docking and pumping activities.

A proof-of-concept system was designed, fabricated and tested to validate the approach. The system worked as intended, showing that the approach is functional and construction of a field-testable version is merited. It is hoped that this new system will positively impact the growth of the open-ocean aquaculture field.

***Index Terms*—aquaculture, ASV, autonomy, docking, feed pens, food sustainability, offshore, resupply, robotics**

I. Introduction

Most current food systems such as crop and livestock agriculture consume an exorbitant amount of resources and negatively impact the environment [1]. Terrestrial livestock contributes to 51% of global greenhouse gas emissions in the form of carbon dioxide, nitrous oxide, methane, and ammonia [2]. These gaseous pollutants greatly contribute to global warming, acid rain, and the general acidification of ecosystems. Livestock rearing requires an extensive amount of land for grazing and growing feed which directly leads to deforestation for pasture, water pollution from animal waste and fertilizer, and overconsumption of freshwater. Fortunately, there is a desire among consumers to move away from land-raised meats to a diet where the majority of protein comes from fish and other seafood. This trend toward seafood consumption is driven by an increase in both health and environmental awareness.

Although commercial fishing is a more sustainable alternative that does not require land, feed, or emit as much greenhouse gas, it can harm ecosystems in other ways. Without regulation, fish are overexploited and can be overfished to the point of extinction, which impacts the ocean's interconnected food web. Traditional fishing tools like trawls or dredges scrape over the ocean floor and subsequently destroy habitats such as corals and sponges [3].

Aquaculture is an underutilized method of food production that would lessen the need for conventional farming and relieve pressure on wild fish populations and ecosystems. Between the two main types of aquaculture, land-based and open-ocean, open-ocean aquaculture utilizes unused ocean space, which enables large scale fish farming without using up overexploited land resources. This aquaculture method involves a system of 4-12 pens that are usually located several miles offshore, as seen in Figure 1. The massive scale and remoteness of these setups allows for a smaller environmental impact but can also create various engineering and logistical challenges during setup and day-to-day operations such as feeding. Due to the movement of water around the open-ocean farms, any pollutants that could build up and harm the fish are quickly dissipated away from the farms which provides an advantage over on-shore aquaculture where the pens must be cleaned frequently and checked for any harmful chemicals.

Fig. 1. Open-ocean aquaculture pens with a crewed feeding vessel [4].

Certain bottlenecks in open-ocean aquaculture efficiency have thus far prevented its widespread use. As an example, one aquaculture company, Innovasea, uses large vessels with a six person team to carry out daily feedings, shown in Figure 2. These teams manually transport feed to pens, connect and pump food through feed pipes, and monitor fish satiation–which can be an all day task. In order to connect the feed pipes, some crew members are located on the mooring side and others are located on the vessel side. While these daily feedings are necessary for raising healthy fish, the process is inefficient and dangerous in bad weather conditions, in addition to requiring a lot of expensive labor.

Fig. 2. Current method used to feed fish at Innovasea's open-ocean sites [4]. Boats must send crew to manually connect feed pipes from the boat to the mooring before feeding can commence.

In order to automate these processes, our team proposes the use of autonomous surface vehicles (ASV) as an alternative to manual feed teams. ASVs have been used to replace crewed vessels for marine monitoring and are used in military applications for mine countermeasures because of autonomy's inherent mitigation of human risks and improvements in efficiency [5], [6]. For aquaculture specifically, unmanned drones and boats have been used to monitor fish, their pens, and water quality–but not deliver feed [7], [8]. A proof-of-concept ASV, called "Aquabot," has been designed and built to fill this gap and autonomously connect multiple feed pipes from boats to feed moorings in the open-ocean. Automating the process can increase efficiency by decreasing the time to make and change the feed pipe connections and can eliminate some of the harsh and dangerous tasks that are currently done by humans. Current methods do not employ multi-pen feeding (parallelization). Through our ASV, the system has been parallelized to enable simultaneous multi-pen feeding further decreasing the time to feed the entire farm. The proof-of-concept system creates automated solutions for the various activities that are required to reduce and eventually replace manual labor in the fish feeding process.

II. Environmental and Engineering Challenges

For an open-ocean vessel, environmental factors must be considered for successful design including: weather, moisture, and wave conditions. The weather conditions are critical to the system's operation. Foggy or rainy weather affects visibility, which limits the ability of the system to recognize the mooring. Thunder and severe storms may disturb the operation of long-distance communication. Since the vehicle is operating in the ocean, the seawater, rainwater, and moisture are threatening to the electronic devices of "Aquabot." Water resistance measures must be taken to protect all control and power systems. The most critical environmental factor that affects the ASV while underway is the wave conditions. A typical range of moderate wave height conditions is 1.0-3.0 m, and wave period of 2.5-3.2s [9]. Ocean waves make the vehicle and the mooring heave and roll in different phases, making them difficult to align and constrain. Furthermore, attaching multiple feed pipes in parallel requires the vehicle and the mooring to be stationary with respect to each other. This adds a requirement that the docking mechanism can fully constrain the ASV with little error tolerance to ensure the subsequent processes can lock and work as needed.

III. Mechanics

A. Overall Process

The entire system is composed of the following components, shown in Figure 3: support vessel, feed, pumps, hoses, ASV, mooring, and fish pen site.

The process can be broken down into the following six steps, for an explanation of how our goal fits in with our design.

1) Navigation to mooring
2) Autonomous docking
3) Feed attachment extension
4) Hose locking & pumping
5) Undocking
6) Navigation away from mooring

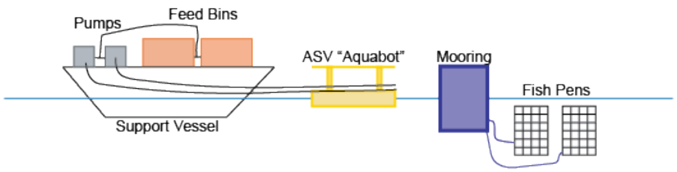

Fig. 3. The elements of the process include a support vessel, feed, pumps, hoses, ASV, mooring, and fish pen site.

First, the ASV navigates from the support vessel to the mooring autonomously or via a remote control connection. Then, once the ASV is located in the correct position, the docking pins are automatically activated to secure the ASV in the mooring and constrain it in all directions. Next, the feed attachment platform extends out to make a connection between the hoses on the boat and the mooring. The locking mechanism then clamps down to seal the connection. At this point, the feed would be sent through the system for as long as necessary to feed all the fish. Then, the process looks the same going in reverse to get the ASV back to the vessel. The locks unclamp, feed platform retracts, the docking pins are pulled in and the vehicle can be navigated back safely. This paper primarily focuses on steps 2-4: autonomous docking, feed attachment extension, and hose locking & pumping. These steps are shown in Figure 4.

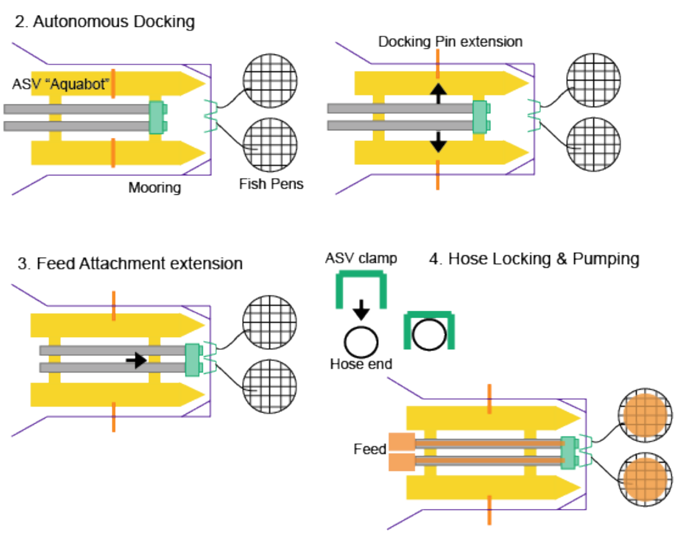

Fig. 4. Key steps outlined showing the ASV with yellow hulls entering the purple mooring. 4.2: Once inside the mooring with the docking pins aligned, the ASV autonomously docks. 4.3: The green feed mechanism extends horizontally to connect the gray hoses to the mooring. 4.4: The feed locking mechanism clamps down on the hoses and orange feed is pumped through the tubes to the fish.

The goals of automating feeding and making it a more efficient process governed our design requirements. There are some design requirements such as ability to float, drive and control, and connect feed. Furthermore, it was quite challenging to match the buoyancy of the ASV on the water with the mooring to align the docking pins and the feed hoses. There are multiple subsystems on the ASV which are highlighted in Figure 5 and allowed us to achieve our goals. A catamaran design was chosen for the hulls in yellow. The electronics are at the rear of the ASV in purple. In front of that is the docking system in red. The feed system is at the front of the boat in green. On top of the crossbar is a gray box where the Raspberry Pi and camera are located. 80/20 was used to attach the subsystems because of the ability to easily adjust the placement of each subsystem relative to each other.

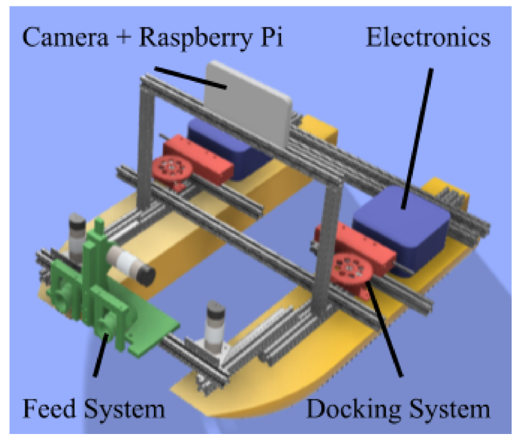

Fig. 5. CAD model of the designed ASV. Including feed attachment (green), docking system (red), electronics boxes (purple), Raspberry Pi & camera (light gray), and the hulls (yellow). The subsystems are attached to each other using 80/20 (dark gray).

B. Docking Mechanism

Once the vehicle is within roughly 2m of the mooring, it is ready for docking. The mooring shape, patterned after the stern of an articulated barge, helps the ASV drive to the general target area and roughly constrains the vehicle. The second step of docking is to constrain all remaining degrees of freedom of the vehicle to prepare for connecting the feed lines. Throughout the design process, various methods of locking to the mooring were explored. A pin and funnel locking mechanism was pursued since the funnel would account for any misalignment and help guide the pin into a constrained position.

The current mooring is shown in Figure 6 [10]. The mooring design mechanically aligns the vehicle as it drives into the target area. Foam inserts were cut to fit "Aquabot" and attached using epoxy and hot glue to a wood mooring rig which made this possible.

On the mooring side, the feed pipes to the fish pens are rigidly attached. In order to prevent pipe tangles due to environment-induced relative motion, which previously made feed parallelization impossible, the feed pipes from the support vessel will be rigidly attached to the ASV. As shown in Figure 7, there are two feed pipes which are connected through a bracket and remain attached to the ASV which will keep the lines separate and untangled.

The mooring encapsulating the ASV prevents the decoupling of feed pipes due to waves, wind, and other disturbances.

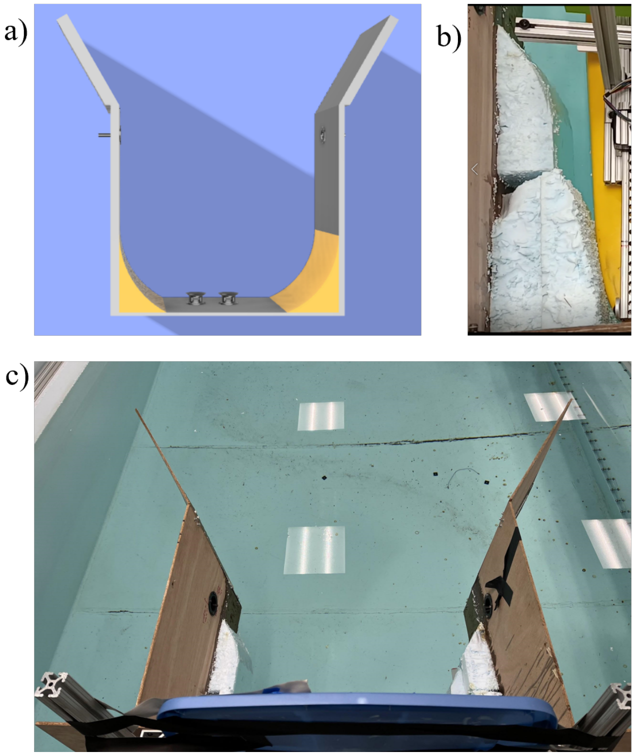

Fig. 6. When the ASV drives into the mooring, their geometries force each other into alignment. (a) CAD model of the mooring showing the funnel shape of both the overall mooring and added inserts (yellow) to align the ASV correctly. (b) Built foam inserts in the mooring shown. (c) Actual mooring funnel shape in float tank.

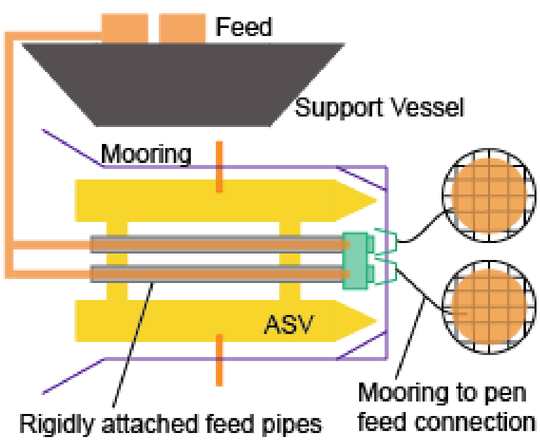

Fig. 7. Multiple feed pipes are rigidly attached to both the support vessel and the ASV, which prevents tangling as all pipes are locked into the mooring at once.

In designing the mooring and tandem system, both hydrostatics and wave forces were considered [11]. As shown in Figure 8, a funnel and pin configuration was used to prevent unwanted movement in the x, y, and z directions and eliminate any potential load on the feed pipe connections. Since the final version will need to be capable of operating at up to 3m wave height conditions, the mooring has some additional space in the z direction to prevent relative heaving between the ASV and mooring. This mechanism increases the efficiency of the feeding process by decreasing the need for manual labor in addition to enabling parallelization.

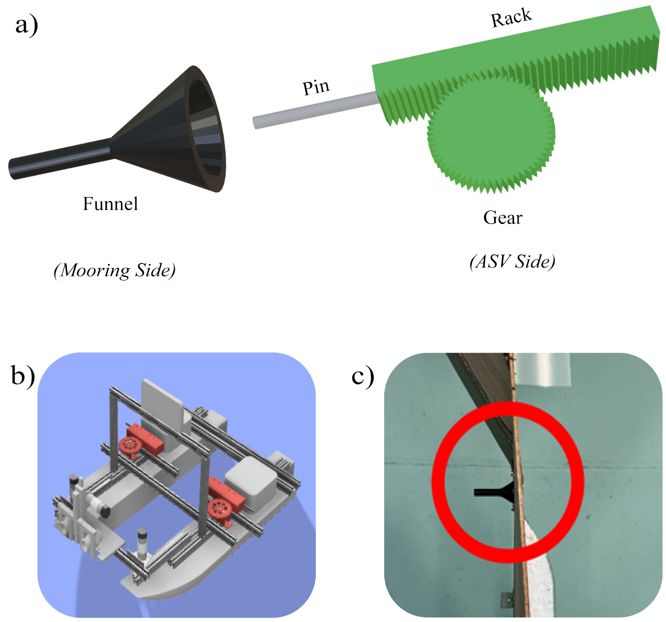

Fig. 8. Pins extend from the ASV's sides via rack and gear system shown in (a)(b) and fit into tapered funnels in the mooring (c) to lock in. This prevents unwanted movement and external forces from damaging feed pipe connections between the ASV and mooring when locked in.

The funnel and rod locking mechanism is controlled by two servos connected to a 10cm diameter gear that drives a rack. The teeth are large enough to prevent slipping on the rack and pinion system and the rods are able to extend 18cm to secure inside the funnels.

C. Feed Attachment

After stably docking our ASV to the mooring, we deploy our feed system shown in Figure 9 to be able to pump the feed slurry into the mooring.

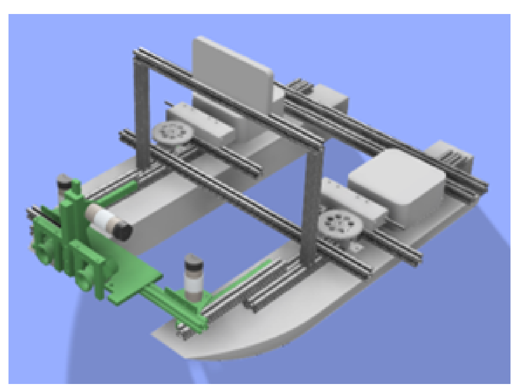

Fig. 9. CAD of the ASV in gray with feed attachment mechanism in green at front.

One major requirement for the feed attachment is functionality for protruding and retracting the feed attachment mechanism to avoid interference with the docking process. Another requirement is to maintain a pressure seal for pumping the feed through. The final requirement is that it must be possible for autonomous attachment. Therefore, it is desirable to limit the degrees of freedom of the system. It is assumed that after docking, the feeding hoses on the mooring and ASV are aligned.

1) Horizontal Extension: To satisfy our protrusion and retraction functionality, we created a two rack and pinion system rigidly attached with an 80/20 bar as circled in Figure 10. We connect both motors to the same controller such that they will have the same revolution speed. The whole extension and retraction of the horizontal motion process takes approximately 15 seconds.

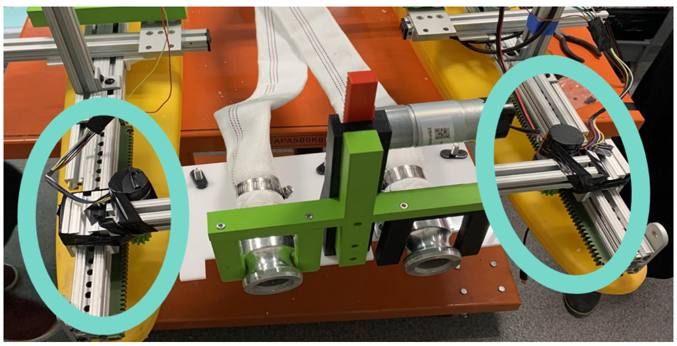

Fig. 10. Closeup image of ASV on feed attachment mechanism. Rack and pinion system as well as motors which powers the motion circled on each side.

2) Sealing the Feed Attachment: Our seal was inspired by a standard firehose connector, but with a different locking mechanism. This involves the custom female sleeve, located on the mooring, and the male groove hose, which is an industrial standard and located on the ASV as shown in Figures 11 and 12. The custom female sleeve has a funneled end that allows the hose to have some small adjustments when entering the mooring side.

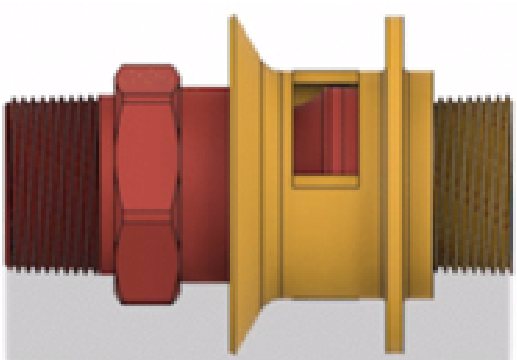

Fig. 11. CAD of sealing process: groove male side (left, red) and custom female sleeve (right, yellow).

When the male groove hose enters the female side, our custom-designed clamper will seal these two entities together and the hoses are ready for pumping. The sealing process is

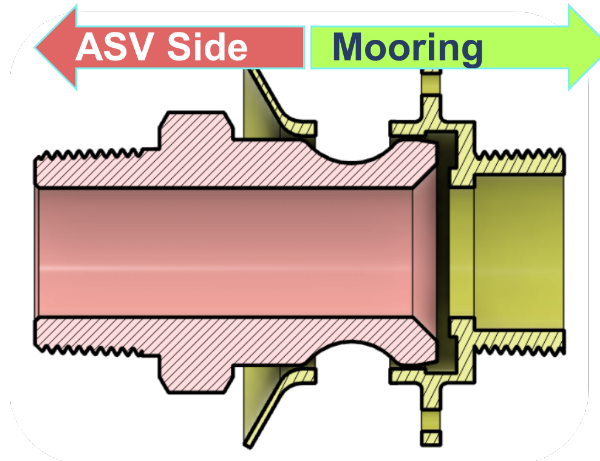

Fig. 12. CAD cross-section of the male (left, red) and female (right, yellow) coupling.

outlined in Figure 13. The clampers are tapered at the end to allow some compliance if the groove is not completely aligned.

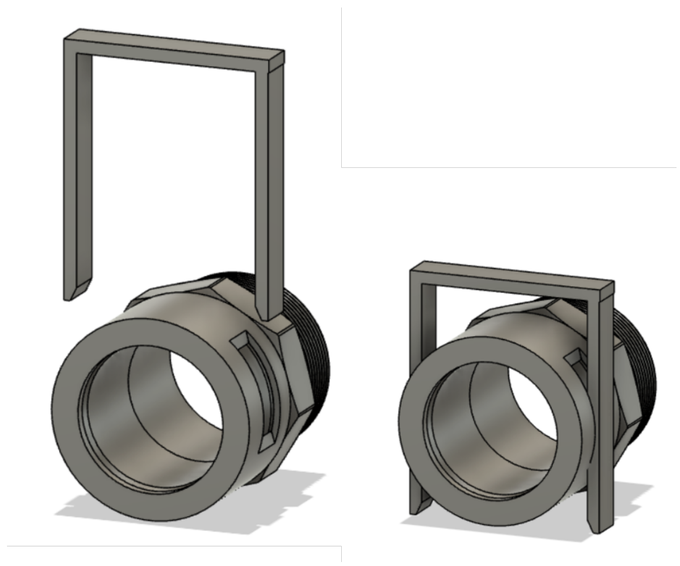

Fig. 13. CAD of single tube attachment method. A U-shaped clamper with two tapered rod ends inserts on both sides of pipes.

3) Parallelization: To test parallelization, we created a T-structure for clamps that is rigidly attached to a rack and pinion. On each side of the T, there is a clamper, allowing for the sealing to happen in parallel and only requiring one motor; the CAD is shown in Figure 14.

D. Hull

The hull was inspired by the Oystermaran Team at MIT Sea Grant who built a mechanism for flipping oyster cages in the water [12]. There is a catamaran set up with electronics boxes on each side and an 80/20 frame for the base. From here all of our subsystems were added and the spacing was adjusted to make everything fit. The feed attachment mechanisms needed to be at the very front of the boat to attach to the mooring. The

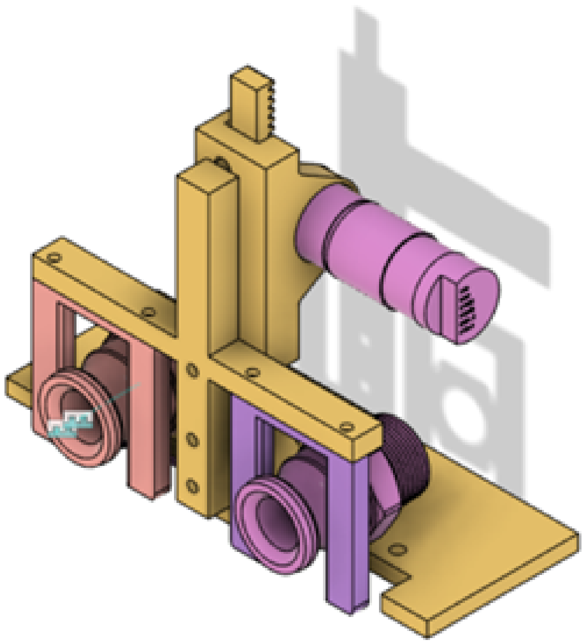

Fig. 14. CAD of parallel tube attachment mechanism. On each side of the T-bracket, there is a clamper which seals each hose to the mooring via one motor attached to the rack and pinion on the T-bracket.

docking pins should be as close to that position as possible for stability. Having two main subsystems which needed to be at the front made it difficult to balance and prevent pitch rotation, given the relatively small hulls used. The electronics were moved back to try and help the weight, but ultimately a counterweight was added on the back to pitch the boat closer to level as shown in Figure 15 with the counterweight circled in red. This counterweight helps to protect our subsystems and to improve our maneuvering.

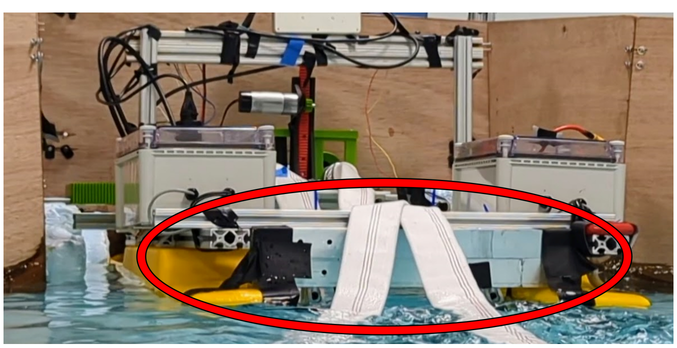

Fig. 15. View of back of ASV driving into mooring. Two hulls with water-tight electronics boxes, one on each side. In the middle there are bars connecting the two hulls which are the provided counterweights (circled in red) to pitch the boat closer to level.

IV. Electronics

The electronics for the ASV are configured to support two T200 thrusters, an Arduino, a Raspberry Pi, 2 servos, and 3 DC motors. These are run by a 12V battery with a DC-DC converter used to provide the 5V power source for the Arduino. Electronic speed controllers (ESCs) were used to moderate the speed and position of the two thrusters, 2 servos, and 3 DC motors. The controllers are housed in a water-tight compartment, and the hobby-grade motors that were used were waterproofed to prevent issues when testing in the float tank. The electrical infrastructure for the controller and two thrusters was built from the Oystermaran team's chassis [12]. The feed attachment mechanism uses a motor encoder to control exactly how far the horizontal platform extends and retracts. The vertical locking mechanism currently uses a timer to control its movement, but in the future this threshold would be replaced with another motor encoder and/or limit switches for better accuracy.

V. Algorithms and Control Systems

Once the ASV is within roughly 2m of the feed mooring, an operator can use a remote control to drive the ASV into the mooring (later versions can be autonomous). The vision system on the ASV will then autonomously dock and create a secure connection between itself and the mooring. After secure docking, the operator sends a command to start the feed attachment process.

A. System Flow

Figure 16 depicts the sequencing of controls in our feed process. There are three types of steps: autonomous, assisted, and manual. Autonomous steps are red and performed completely by the system on its own. Assisted steps are yellow, and the operator would send a signal via the wireless connection between a laptop and Arduino to prompt these steps. Finally, manual steps are white.

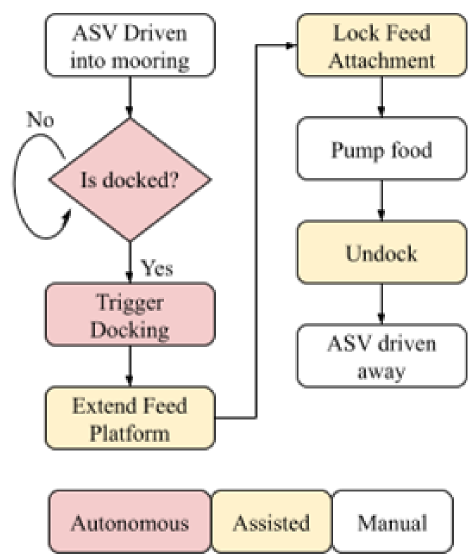

Fig. 16. Controls flowchart with autonomous tasks highlighted in red, assisted tasks highlighted in yellow, and manual tasks in white.

The motivation behind this flow was to ensure that the ASV is stable relative to the mooring before attempting to attach the hoses and pump feed. To make the ASV stable, the process starts from a large scale with the funnel-shaped mooring beginning to constrain the ASV, then autonomously identifying when the ASV should extend its docking mechanism, which fully constrains the ASV to be stable relative to the mooring. Once the ASV is safely docked, then it is assumed that the ASV and mooring move together, so it would be safe to begin the feed attachment process, which has a small tolerance for misalignment.

B. Autonomy

We used AprilTags as our visual fiducial system for autonomous docking. Created by the April Robotics Laboratory at the University of Michigan, April Tags function as simplified QR codes to enable quick and long range detection [13]. Figure 17 provides a visual of an April Tag detection. Once an April Tag is detected, its ID number, center, and position are available for computations. From the positional information, the translation and rotation of the tag relative to the camera can be extracted. Figure 18 shows our system with a Raspberry Pi and camera mounted on top of our ASV, along with 3 April Tags on the mooring.

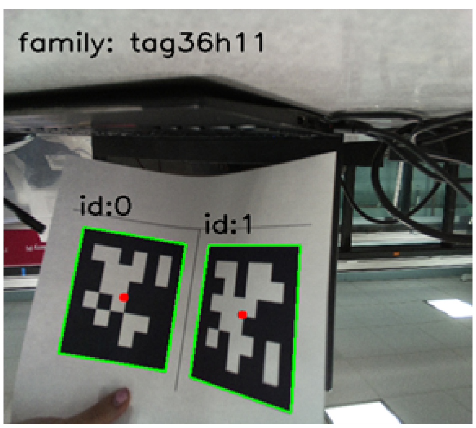

Fig. 17. Raspberry Pi detected two April Tags and identified their family, id, centers, and corners. Positional information was also detected but not shown in this figure.

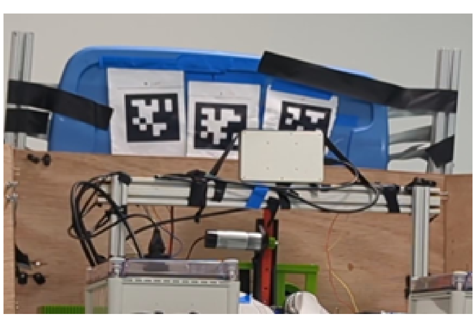

Fig. 18. Raspberry Pi is mounted on the top of the ASV looking at three April Tags on the mooring.

C. April Tag Docking Algorithm

With April Tag detection, we created an algorithm for determining if the ASV is docked (displayed in Figure 19). After the Raspberry Pi detects an April Tag, there are 3 criteria that must be met before determining that the ASV is docked.

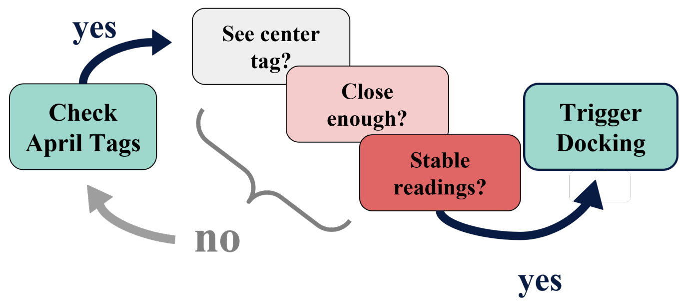

Fig. 19. April Tag Autonomous Docking Algorithm listing the 3-step criteria to trigger docking.

1) *The center tag must be detected.* If the camera cannot see the center tag, then the ASV and mooring are severely misaligned and the system should wait before attempting to dock.
2) *The camera must be close enough to the tag.* When properly docked, the ASV and camera are within the experimentally determined distance threshold.
3) *The readings of the center tag must be stable.* If the position of the center tag is recorded to be very different frame to frame, then the ASV is likely still navigating into the mooring. Once the ASV is not moving, the readings should be stable. This threshold was also determined experimentally.

Once these 3 conditions are met, the Raspberry Pi automatically sends a signal to the Arduino to trigger the docking mechanism.

D. Wireless Communication

For safety and control of the ASV, it was important to develop wireless communication between the Arduino and a laptop. The Digi XBee Radio Frequency modules worked well for this purpose, as one can be mounted to an Arduino shield and the other can plug into a USB port on a computer. Through this connection, messages could be sent and received on both sides. Our messages can be grouped in three categories: stop, mechanism triggers, and custom motor control. We chose a single letter stop command for operator simplicity. There are two letter triggers to deploy and retract each mechanism, following a preset step of commands. For more flexibility, there are built-in custom messages to provide complete freedom over all of the motors, servos, thrusters, and thresholds used in mechanism commands.

VI. Results

Throughout the design process, engineering decisions were made to minimize the amount of human involvement required in the aquaculture feeding process. This meant that the ASV should require minimal human engagement during the following steps:

1) Navigation to mooring
2) Autonomous Docking
3) Feed attachment extension
4) Hose locking & pumping
5) Undocking
6) Navigate away from mooring

During this process dry land testing and controlled float tank testing were performed to validate the designs and receive valuable feedback with each iteration. Land testing was done with the ASV on a lifted platform (Figure 20). When testing an early docking mechanism iteration, the servos were not able to produce enough torque to drive the gears, and informed the larger servos used to compensate in the final design. Land testing also helped establish thresholds for feed attachment extension and retraction.

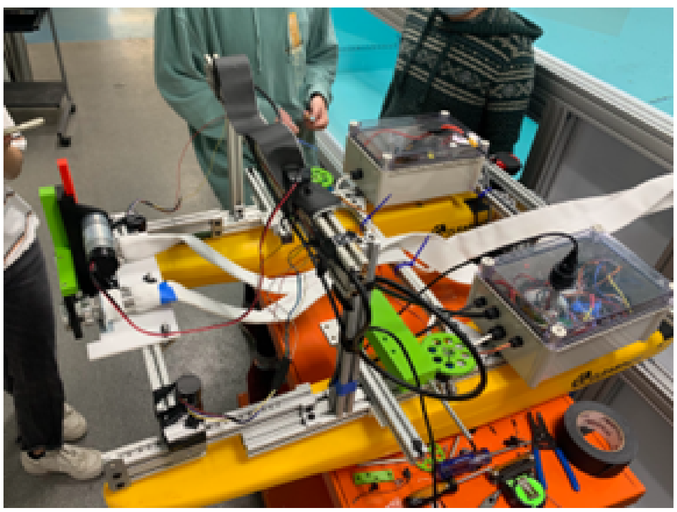

Fig. 20. Dry land test performed on an elevated platform. This gave space for the docking pins and feed attachment to be tested quickly in a controlled environment.

Float testing helped us evaluate the vehicle's functions in a 7x3m pool. During float tank testing, the pins were able to hit the funnel 60% of the time, improving as the RC driver got better at aligning the vehicle with the mooring buoy. We were also able to validate that we had a watertight seal by successfully pumping water through our connected feed attachment. Our final system test showed the ASV go through the entire feeding process using RC to control the thrusters and trigger the docking and feed attachment mechanisms. We were able to validate the autonomous April Tag docking system separately. Given the success of the autonomous docking algorithm, the entire process can likely be fully automated in the future.

VII. Conclusion

The overall system met the main goals of autonomously docking, attaching the feed hoses in a water tight seal, and demonstrating that this could work for multiple hoses simultaneously. There is a patent pending for this work, and we are excited to see how the design will evolve further. This work is just the first step in a much longer design process of creating autonomous vessels to assist in open-ocean aquaculture processes.

A. Future Work

A more finalized version should demonstrate larger scale and robustness, both internally in design and externally with varying weather and lighting conditions. While our proof-of-concept showed two hoses, a system at scale would likely require at least ten. In terms of robustness, the custom pieces should be machined or made sturdier than the 3D prints used in our design. An important next step would be to test in a larger tank using a wave generator, and eventually testing the system in both the calm and more turbulent conditions in rivers or oceans, perhaps day or night. Future tests should also pump feed pellets along with the water and use sensors to test the pressure drops to check for significant loss. Another possibility could include multiple types of feed pellets and independent feed rates for individual pen needs. For each subsystem, there are also improvements to be made.

1) Docking and Mooring: For the mooring, the whole configuration should float on its own and fit even better with the vehicle. Floatation would require a significant modification of the experimental mooring, as the current version was rigidly attached to the edge of the float tank and weighted to tilt backwards (to balance out the foam). The mooring should be designed to completely mold the outer edges of the final ASV hull geometry to ensure a tighter fit. There is also potential in increasing the radius for both funnels, giving a larger tolerance when dealing with larger navigation errors.

2) Feed Attachment: There are several opportunities for mechanical improvements and more rigorous testing. A single motor and linkage would improve the horizontal platform performance. Larger funnels on the custom hose sleeve would provide a greater error tolerance for pipe connection. To create a tighter seal and withstand more flow, a diagonal cut out on the custom female side of the hose attachment could force the male side forward and further into the mooring. Conversely, a change to the clamping finger geometry could also facilitate better clamping. It would be useful to test the final design under a flow rate closer to industry standard of 180 gallons per minute, as the test pump used only had a maximum of 41 gallons per minute.

3) Controls: The autonomous capabilities can be expanded. By combining GPS with the April Tags positional information, the ASV should be able to autonomously navigate itself into the mooring. With robust docking and feed attachment mechanisms, it should also be able to trigger and run the entire process autonomously. Moving food through the system would likely stay a manual decision for timing, but the docking and connections could be fully autonomous. In the future, with more sensors in the system, "Aquabot" could be a fully autonomous feed resupply vehicle.

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