Sediment Sampling Autonomous Surface Vehicle

2.017: Design of Electromechanical Robotic Systems

MIT Sea Grant, Cambridge, MA 01239
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Abstract

Harmful algal blooms (HABs) occur when algae grow out of control and negatively impact their environment and/or human health. This paper focuses on the *Alexandrium* genus, which produces a neurotoxin that leads to paralytic shellfish poisoning (PSP) in humans. Some harmful algal genera including *Alexandrium* produce cysts, which are dormant stages of algae that protect the organism until favorable conditions arise for blooms. Monitoring of cyst levels in sediment during the winter can be used to forecast blooms in the following spring (Greengrove, 2015). HABs are becoming more frequent due to climate change, and current predictive models suffer from data limitations.

An autonomous surface vehicle (ASV) would remove the research bottleneck of limited data and accelerate the validation of predictive algal bloom models. ASVs are cost-effective, cover larger areas, and enable direct field sampling without chartering boats. *Twin Pickles* is our proof-of-concept catamaran ASV that was designed to collect a single soil sample and maintain stationkeeping over a given waypoint. By the end of the term, we demonstrated that *Twin Pickles* was capable of lowering and retrieving our sampler and collecting a partial soil sample. Future research is necessary to fully validate the system so samples can be used to forecast HABs.

1. Introduction & Background

Harmful algal blooms (HABs) are overgrowth of algae within a region. These blooms can lead to mass die-off events in ecosystems, and cause sickness in humans and animals who consume shellfish containing toxins. The detection of HABs is critical to protect food sources, warn consumers, and predict oxygen-depleted dead zones.

The genus *Alexandrium* contains some of the well-known and dangerous species of dinoflagellates that comprise algal blooms. Specifically in New England, *Alexandrium catenella* is of large concern because it produces saxitoxin, the neurotoxin behind Paralytic Shellfish Poisoning (PSP) (Northeast HAB, n.d.). When contaminated seafood is consumed, PSP can lead to sickness, paralysis, and death.

Alexandrium (along with several other genera of algae) have a stage in their life cycle called cysts (seen in Fig. 1) which allows them to remain dormant and wait for more favorable conditions for them to germinate. What causes cysts to germinate is not well understood, and research is unfortunately bottlenecked by a lack of data. Interest in *Alexandrium catenella* cysts is not limited to New England; studies have been conducted across the world including in China, France, and South Africa (Tang et al., 2022; Genovesi et al., 2009; Joyce & Pitcher, 2006).

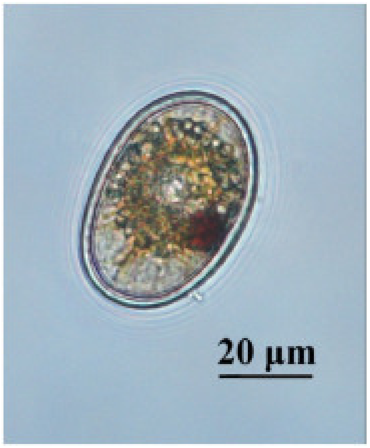


Fig. 1. *Alexandrium catenella* cyst under a microscope.

One method of sampling which is particularly bottlenecked is soil sampling, as conventional methods are currently very expensive and labor-intensive. Boats generally deploy a spring loaded claw grabber or spring loaded coring tubes. A common collection method is the Van Veen grab sampler (Woods Hole Oceanographic Institution, n.d.), but the mechanism disturbs the sediment significantly. This makes it unideal for studying cysts since the water-sediment interface tells researchers much about the time and conditions during which the cysts were deposited. National Centers for Coastal Ocean Science (NCCOS) expeditions for cyst sampling typically use a Craib Corer (NCCOS Coastal Science Website, n.d.-a) which preserves the water-sediment interface and leaves the sediment relatively undisturbed, but boat expedition costs can cost upwards of $25,000 per day (OceanInsight, n.d.), which limits the frequency at which samples can be collected.

Nonetheless, ongoing research by the Woods Hole Oceanographic Institution (WHOI), the National Centers for Coastal Ocean Science (NCCOS), and various universities are still highly reliant on sediment samples. Various projects are still in early validation stages, meaning they require a large abundance of samples to compare new developments to existing standards. A notable example is an experimental model of *Alexandrium catenella* blooms funded by NCCOS (NCCOS Coastal Science Website, n.d.-b), which once validated would be useful to many stakeholders, but relies on cyst sediment data collected once a year in a limited number of sampling locations. If we could increase the number of samples available to these research institutions, much progress could be made on these models.

Autonomous surface vehicles (ASVs) offer a promising approach to sediment sample collection, enhancing data quantity and sampling precision for researchers. ASVs are sea-surface robots gathering a variety of oceanographic data and their use could reduce expedition costs due to less crew dependency. They can operate in harsh weather conditions where manual sampling is impractical. With larger payloads and battery capacity compared to autonomous underwater vehicles (AUVs), ASVs can also harness solar or wind energy, allowing extended missions with real-time data transmission and GPS navigation for consistent location testing. ASVs expand monitoring capabilities at a reduced cost and can be repositioned swiftly to areas of interest for research or policy action. Previous unmanned vehicles, like the one with a Van Veen grabber showcased in a 2019 conference paper (Bae et al., 2019), demonstrated sediment sampling from an autonomous craft but failed to maintain the sediment-water interface (Fig. 2), leading us to explore alternative designs.

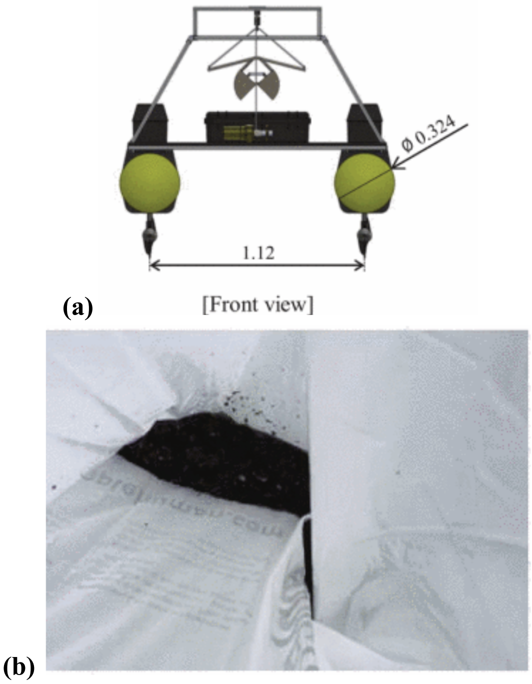


Fig. 2. (a) Model of unmanned surface vehicle shown with a Van Veen grabber for sediment collection. **(b)** Photograph of a collected sediment sample [10].

The HydroNet ASV (Ferri, Manzi, Fornai, Ciuchi, & Laschi, 2015), developed by the Marine Robotics Lab at the Scuola Superiore Sant'Anna, is an autonomous catamaran built to monitor coastal water quality and collect water samples. It uses custom sensors and a novel winch system, successfully conducting long-range missions in diverse marine areas like the Marano-Grado lagoon, the Isonzo river, and the Livorno coastal region. Its successful navigation and sensor deployment along the Livorno coast prove the feasibility of designing ASVs that can follow coastlines and deploy sensors at predetermined locations.

Our project's goal is to develop a compact, autonomous surface vessel named *Twin Pickles*, designed to autonomously collect sediment samples and generate high-frequency, real-time data that will enhance our understanding of HABs by focusing on cyst germination in sediments. Twin Pickles aims to autonomously sample large areas with minimal human intervention, showcasing a scalable solution for sediment collection. This approach is expected to be more cost-efficient than traditional manual sampling methods, which are labor-intensive, fuel-demanding, and increasingly uneconomical (Sornek et al., 2022). Additionally, our ASV will be able to navigate and sample in areas that are otherwise inaccessible to larger vessels.

The development of autonomous samplers such as *Twin Pickles* could revolutionize sediment data collection by making it more affordable and efficient. In Massachusetts, the use of these samplers to detect *Alexandrium catenella* cysts could significantly benefit public health and the state's lucrative $800 million seafood industry [13]. Enhanced understanding of toxic HABs through increased data collection would allow for the improvement of predictive models, enabling earlier warnings to aquaculture operators to harvest shellfish proactively. The insights gained from research could provide actionable guidance to stakeholders including aquafarmers, beach-goers, shellfish consumers, and regulatory agencies.

2. Engineering & Environmental Challenges

Our ship faces challenges like biofouling, where marine life like algae attaches to its parts, as shown in Fig. 4, leading to potential contamination and degradation. Transporting the boat post-deployment risks spreading invasive species. The impact varies by algae type and region, affecting deployment length and maintenance. We can reduce this by using suitable materials, coatings, and rigorous post-deployment cleaning, especially for short-term missions, while also strategically choosing deployment sites.

Fig. 4. Example of biofouling on a ship. Although this is an extreme case, this demonstrates how algae can be transported by ships. As the buildup occurs on the hull and the boat moves between locations, the algae will then be dispersed into new waters, potentially contaminating them (Seosearchberg, 2021).

Our vessel can handle rough seas and currents with its Blue Robotics T500 thrusters, but sample collection requires calm weather to maintain precise positioning. While designed to travel in various conditions, sampling is done once the weather permits, even briefly. Challenges also include avoiding fishing gear in Massachusetts waters and preventing entanglement. Future models will feature an emergency release for samples to prevent disabling the vessel.

Cross-contamination of samples is a major issue. We plan to redesign the sampler for increased capacity, ensuring containers are sealed and possibly temperature-controlled for longer missions. Selecting durable, low-maintenance components is essential, yet we must consider cost to maintain affordability.

In development of the vessel and in future iterations, our primary goals include proving that our system (1) can consistently collect sediment samples (2) is user-friendly and can be deployed efficiently (3) will minimize cross-contamination during the sampling process.

3. System Design

The entire system consists of four main subsystems: the boat structure, the sediment sampler assembly, all of the electronics, and autonomy control. The boat subsystem consisted of building the hulls, frame, and deck, as well as attaching the propulsion and winch systems. The sediment sampler included the entire module that would be deployed to the seafloor responsible for the collection and storage of the sediment sample. The electronics encompassed the microcontrollers, power supplies, and wiring of all other subsystems that required power. Finally, the autonomy subsystem focused on stationkeeping and deployment of the sampler. The team divided ourselves up among these four main subsystems, with some overlap where integration was required.

3.1 Boat Structure

The goal of the boat structure was to create a modular platform that could be built in parallel to the sampling payloads, robust enough to maintain position as samples are collected, and capable of supporting the power systems for electronics and propulsion. We designed a catamaran consisting of two plastic hulls capable of supporting 350 lbs with space inside to store all the electronics. We selected a catamaran design to ensure high stability necessary for a robust system in the ocean.

To connect our two hulls, we ran aluminum tubing between them since there were existing round mounting points in each hull. An aluminum 80/20 frame mounted on top of the hulls provides structure and will also act as the support for a piece of marine grade plywood. Using 80/20 to easily mount components with relative ease of assembly. We connected the 80/20 frame to the round aluminum tubing using 3D printed spacers made of composite on the Markforged printer, as highlighted in Fig. 5.

Fig. 5. 80/20 frame and aluminum tubing connects the two hulls and provides a mounting platform for the marine plywood. The 80/20 and aluminum are connected via a custom 3D printed spacer.

The plywood was a base platform for all sediment sampling and in-situ testing systems to be mounted and deployed from. This allowed the boat and payload systems to be developed in parallel. A potential sampling configuration included a winch and pulley to deploy the payloads, a shaded region to ensure the samples are kept within a specific temperature range, and additional structural supports.

For the propulsion, we used two T500 thrusters attached to the back of the 80/20 frame facing forward and four T200 thrusters. The T200 thrusters were mounted at a 45 degree angle relative to the hull to prevent diagonal movement during station keeping while the sampling is deployed. Fig. 6 shows custom Formlabs Tough 2000 Resin for the T500 printed mounts and the Markforged composite for the T200 printed mounts.

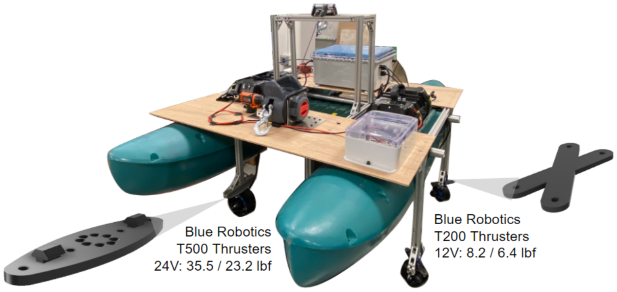


Fig. 6. T200 and T500 thrusters are connected to the 80/20 frame via 3D printed mounts.

The T500 thrusters act as the main thrusters to move between waypoints and the four T200 thrusters will be used to maintain position when the payloads are being deployed. The general simplified structure of the entire catamaran is shown in Fig. 7.

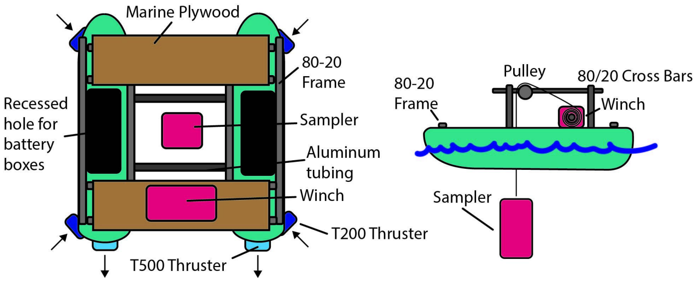


Fig. 7. Simplified diagram of our catamaran, Twin Pickles. Note the directions of the thrusters are indicated with arrows.

For the lowering and raising of the sample we used a handheld drill winch designed for handheld drills and attached a Black and Decker 12V Cordless Drill to the vehicle itself. Using a drill instead of a motor solved several problems for us simultaneously as we did not have to source a motor controller and motors separately, we didn't have to worry about managing acceleration rates as the motor went up to speed, and because the winch was designed for handheld drills, we knew a drill would provide sufficient torque and reasonable rotation speed at its gear ratio. We mounted the winch to the plywood deck using a laser cut ⅛" aluminum plate, and secured the drill mechanically by constraining the handle within a hole in the deck, as seen in Fig. 8.

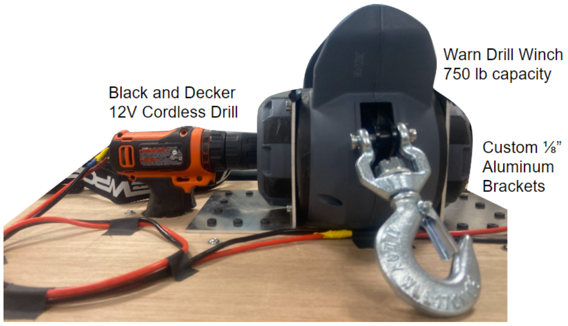


Fig. 8. Winch assembly, driven by cordless drill and attached to the marine plywood deck of the boat with custom brackets.

There are two critical design considerations for the winch system. Most importantly, the winch must support the absolute maximum expected weight of the sampling system including a large safety factor to account for the added weight of any collected water and sediment. We estimated this weight to be 50 pounds, and our system is rated to a much higher capacity. The assembly also must lift the sampler fully out of the water so as not to drag while the boat is navigating between locations. Therefore, a raised pulley frame greater than height of the sampler was attached in the middle of the boat. We built an 80/20 frame over the center of the gap in the deck where the sampler is lowered to provide a mounting point for the pulley. Finally, we mounted the electronics box and emergency stop button, and inserted the battery boxes into the recessed holes in the hulls, completing the assembly as shown in Fig. 9. Overall the entire vehicle is around 6' long, 4' wide, and 3' tall which allows it to fit within a cargo van without disassembly.

Fig. 9. Completed platform, including electronics boxes, batteries, winch, and sampling frame.

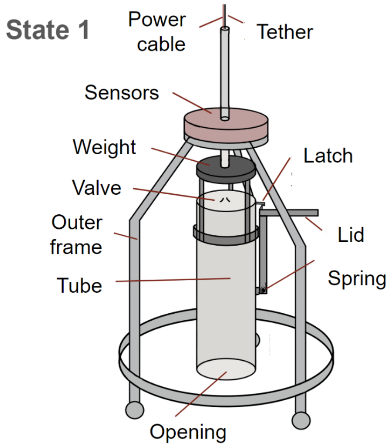
3.2 Sediment Sampling

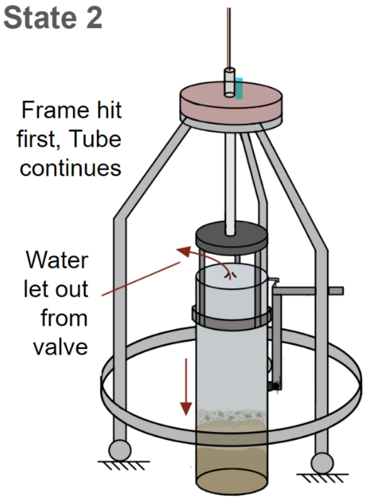
The sediment sampling subsystem in the ideal system would include the storage and collection of the samples, deployment and retrieval of the mechanisms, and in-situ sensors as an add-on. With the timeline of this project in mind, the scope of our work was limited to collecting a single sample core of sediment and water. Preserving the layers of sediment and the interface between the top layer and water is important in analysis of the sample, so our system aims to not disturb the sample as much as possible.

The basic design would include a vertical tube that collects the sample when dropped into the seafloor and an outer frame to stabilize it, as seen by Fig. 10 below. As the assembly lifts up via a tether attached to a winch on the hulls, a lid will passively swing down to secure the sample. This assembly would be deployed when the user decides to collect the sample, while the hulls of the boat remain stationary. After the sample is collected and stored, the boat can be driven back to shore and the sample sent to a lab for analysis.

The coring assembly will be lowered from the boat to the ground in order to collect a sample. Once at the ground, the outer frame will collide the seafloor first, ensuring the coring tube will be perpendicular to the ground. The weighted coring tube will then continue the drop to the ground and, using the force of its impact with the seafloor and added weights, drive itself down into the mud. The final sample must include the sediment at a depth of 0-3 cm since this is where the most recent cysts would be located, but the collected sample needs to include a deeper sediment sample to account for loss through the rest of its journey; thus the sampler aims to collect a core of about 15 cm.. The tube will be open on the bottom and be sealed on the top with a one-way valve to allow water to escape when the sample is collected, but help keep the sample locked in place otherwise. After the coring tube digs into the ground, the winch will lift the assembly, causing a passive spring-loaded sealing lid to enclose the sediment from the bottom of the tube. As it lifts up, the first iteration of our design included a latch that would open, causing the lid to swing down and secure the sample in the tube before its journey back up to the boat, as seen in Fig. 10 below.

The coring mechanism will attach to the hulls via a winch, which will facilitate dropping and raising it. When not actively collecting a sample, the coring tube is stored between the hulls of the boat above the water, so the leakage from the core is minimized as compared to storing it in the water. Since the excursion would last no longer than about three hours, the temperature difference should not significantly affect the sample.





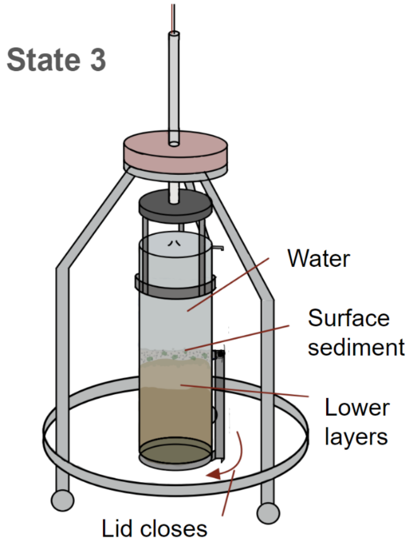


Fig. 10. Sketch of the first iteration of the sediment core sampling system. The whole assembly slowly lowers to the ground together (State 1) until they reach the seafloor. The frame contacts the ground first and provides stability, while the tube continues to fall. The tube drops to the ground with enough force to dig into the sediment (State 2), and when it lifts up, the lid swings down to enclose the sample (State 3). The cysts are located in the top layers of the surface sediment.

The second iteration of the sampler kept the same general designs: an outer frame that hits the ground first, a weighted coring tube to collect the sample, and a passive spring actuated lid that encloses the sample. The main difference comes in how the lid is actuated and the valve on top of the tube. As depicted in Fig. 11, the revised design utilizes a compression spring that allows the lid to swing down and continues to pull it closed after the sample was collected in order to more securely enclose the sample. The lid is initially held open by a latch connected to an eye hook that is fixed to the outer frame. When the outer frame hits the ground first, the tube continues to descend, pulling the eye hook out from its preloaded position which then releases the lid to swing closed.

The valve consists of an O-ring glued to the upper face of the tube and a hinged rubber flap. This flap gets pushed open by the water flowing through it when the assembly descends and closes when it ascends, again due to the water pushing on it. The valve serves two main functions: create a suction that helps lift the sediment once the tube begins to rise up from digging into the mud, and to protect the sediment to water interface from other water or floating particles as the sample travels from the seafloor back to the boat.

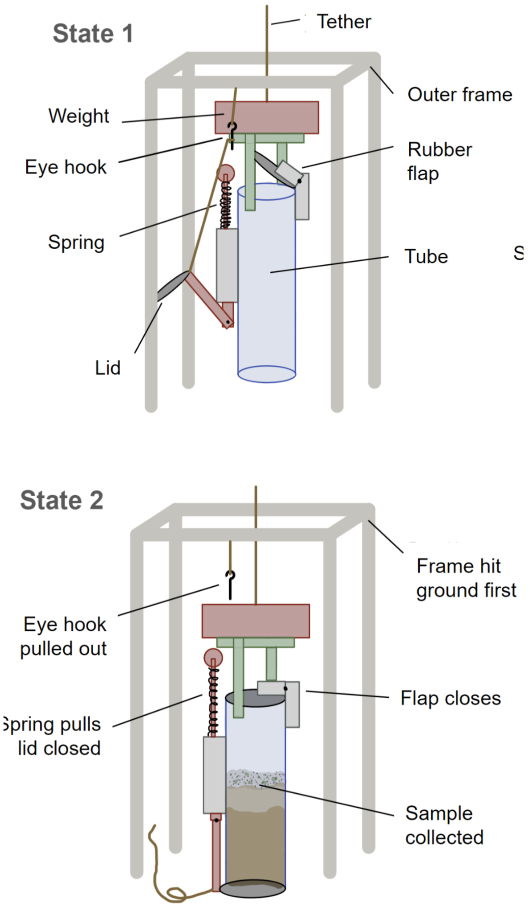


Fig. 11. Sketch of the second iteration of the sediment sampler design. The spring swings the lid down to seal the bottom of the tube and continues to pull upward, securing it in place. State 1 shows the preloaded position of the sampler, in which it gets deployed and travels to the seafloor. In State 2, the tube descends farther than the outer frame, pulling out the eye hook and closing the lid.

3.3 Electronics

In order to empower the vessel in effectively carrying out its sampling objectives, the electrical subsystem covers three main functions: navigational capabilities, station keeping and sediment sampling as shown in Appendix A. The navigation components focus on control and power to the main thrusters which are optimized for forward propulsion. The station keeping control circuit maintains vessel position during the sampling process and the Sediment Sampler control deals with every step of the sample collection process on the vehicle.

The main navigational processing and execution block is happening on a Pixhawk 6X flight controller using Ardupilot software as represented by the Pixhawk 6X block. It receives input signals for positioning data from a GPS and compass as well as an onboard inertial measurement unit. A Raspberry Pi 4 Model B is communicating with the Pixhawk through the UART protocol and remote control from a Spektrum DX8 RC transmitter is passed through to the Pixhawk via a DSMX RC receiver. On top of that, there is an arming switch and buzzer which facilitate the easy use of this system by the operator. This device will communicate directly with the main forward (T500) thruster electronic speed controls (ESCs) to relay navigational commands (Appendix A).

The station keeping control circuit and sampling mechanism will both be actuated through an ATmega328P microcontroller onboard an Arduino UNO. We have set aside 4 T200 thrusters for station keeping. Angled at 90 degrees from each other and offset by 45 degrees from the main forward (T500) thrusters, the T200 station keeping ESCs will operate under a PID controller loaded onto the ATmega328P with the IMU onboard the Pixhawk 6X acting as the input to close the control loop. When engaged, the T200 station keeping thrusters will be the only propulsors receiving signals in order to simplify the control scheme. Likewise, when remote or point-to-point control is active and the vessel is navigating to waypoints using its main forward (T500) thrusters, the station keeping (T200) thrusters will be inactive. This is accomplished via a 5V DC relay which is powered and controlled by the Raspberry Pi 4 which switches the all clear signal between the two EV200AAANA contactors which give power to each respective thruster circuit. By default, given that the main power switch is on, the T500 contactor is receiving power, turning on the internal solenoid switch to pass 24V DC to the T500 ESCs. The T200 contactor circuit is connected to the normally open relay terminals, so that upon receiving a switching signal from the Raspberry Pi, it will switch off the T500 main navigation thrusters and activate the T200 stationkeeping contactor circuit.

For the motors used in the sampling mechanism, we used a 12V DC brushed motor within the body of a Black and Decker cordless drill combined with a handheld winch system with an internal high gearing. To run the drill motor, we used a separate, dedicated arduino, receiving minimal directional and enabling signals from the Raspberry Pi, to control a MD25HV Cytron 25 Amp 7-58V high voltage motor driver.

The entire system will run off of a configuration of two high capacity 12V Absorbent Glass Mat (AGM) batteries wired in series to allow for untethered operation of the thrusters and all other subsystems. The main bus will first go through a main power switch and a power monitor hooked up to the PX4 before it reaches the thrusters. From there we will step down the voltage to 12V (using a DC-DC converter for their efficiency) in order to power our sensor array and the Raspberry Pi (albeit through the use of a battery eliminator circuit for the Pi). While we initially planned on powering our winch motor off of the 12V buck converter supply, our DC-DC converters were unable to meet the power draw requirements to start the drill up from stall, so we instead had to pull directly from one of our 12V AGM batteries.

3.4 Autonomy

There will be 5 key components of autonomy: waypoint finding, object detection, seafloor perception, stationkeeping, and sampler deployment. For the full autonomous system, the boat will be able to autonomously navigate to a series of waypoints and collect samples at each location. Once the boat is deployed on a mission, it will be able to autonomously perform these tasks for missions lasting roughly an hour, with the option to override with manual control depending on the mission specifications. Implementing a fully autonomous system that can sample at multiple waypoints per mission was not implemented on the first vehicle iteration but will be an integral part of the full system.

For our proof-of-concept deployment, the primary focus is on performing just stationkeeping and sampler deployment autonomously. The boat will be manually driven to a location within the user's line of sight that is suitable for sampling though visual depth and topological data information transmitted back from the bottom-sensing sonar. Once the user triggers a signal to start sampling, the vehicle will autonomously maintain that position and begin the sediment sampling process. Once the full sample, retrieval, and storage process is finished, control will return to the user.

The proof-of-concept system has 2 main modes: the manual control mode and the stationkeeping mode. A Raspberry Pi acts as the boat's primary microcontroller, running processes and performing computational logic to control the boat. The control block diagram is shown in Fig. 12.

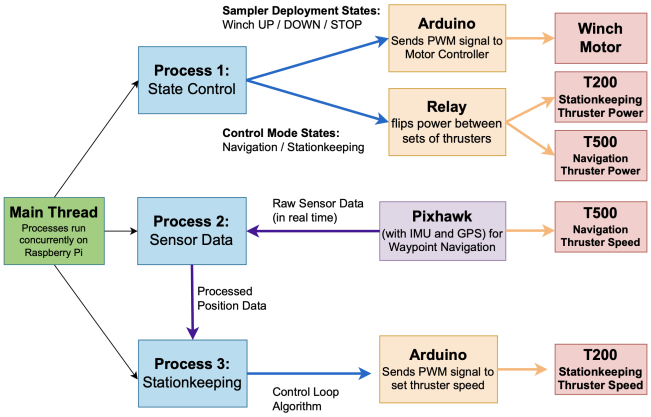


Fig. 12. Control Block Diagram depicting the flow of signal between the computational logic performed in processes run on the Raspberry Pi and Arduino microcontrollers, Pixhawk, and relays that interface directly with the motors.

The manual control mode uses Ardupilot's RC control to allow the user to drive the vehicle from a base located within line-of-sight. The built-in autonomous waypoint navigation can also be used. The fully autonomous version can use a fish finding sonar to detect suitable sampling locations before attempting to sample. Whenever the user triggers sample collection mode, the control mode state will transition into deployment mode and stationkeeping mode. The RasPi does this by sending a signal to the relay which flips power between the navigation thrusters and stationkeeping thrusters.

The stationkeeping mode involves a feedback control algorithm using input data from an IMU (inertial measurement unit) to determine how the thrusters should oppose drift caused by currents in the water or wind. The IMU is zeroed at the location where stationkeeping mode is triggered, and a moving average filter and coordinate transform is applied to process the raw data. We determined that additional processing such as a low-pass-filter would be necessary to improve IMU data quality. Additionally, data from the GPS can be used to improve data accuracy and minimize drift over longer periods of time. In high wind situations, an anemometer can measure the direction of the wind which will help optimize the orientation of the boat based on the best directions to point the thrusters relative to the wind. Stationkeeping mode continuously actively adjusts the boat position until deployment is finished.

The starting point for the feedback control algorithm is a PD control loop based directly on the IMU data. This was implemented by calculating error from the current position from the IMU and a reference saved at the time of initiation. That error is then multiplied by the proportional control gain. The same is done with the derivative of the error and the derivative control gain. These values are summed and the resulting command value is appropriately scaled to a thruster command. Testing and optimizing the algorithm was beyond the scope of what we had time to implement in the initial prototype, but next steps would include developing a model for the boat and tuning gain values.

Once the boat is stable in stationkeeping mode, the deployment mode sequence will run - it consists of a finite state machine with the various stages of deployment and collection and feedback control depending on what is required by the mechanism. The proof-of-concept deployment sequence consists of an up, down, and stop state determined by remote user input. Depending on which stage of the process it is in, the Raspberry Pi sends digital signals to an Arduino, which generates PWM signals for a motor controller. This motor controller makes the winching mechanism to raise, lower, or stop the sampler. Once finished sampling, the boat returns to navigation mode.

4. Testing and Results

There are three primary subsystems needed for the product to be viable: the control system, the sediment sampler deployment system (henceforth referred to as the deployment system), and the sediment sampler. Each subsystem underwent various stages of testing and development.

The testing of the control scheme involves the testing of the propulsion system and its interaction with the Ardupilot and Pixhawk. There are two main tests that were done in regards to the control scheme: that of waypoint navigation as well as station keeping. The deployment system testing tested its ability to properly deploy and retract through remote commands. The sediment sampling mechanism testing tested its sampling capabilities.

Minimal performance needed for the end product would be a functioning control system, deployment system, and sediment sampler. The control system should allow for stationkeeping and following of remote controlled inputs; the deployment system should allow for the deployment of the sediment sampler; and the sediment sampler should allow for the retrieval and storage of samples for testing.

4.1 Quality Tests

There are two major quality tests for the controls system. The waypoint navigation quality was assessed through river testing. The boat was put on the water and driven to various locations using navigational controls. The station keeping protocol was not able to be tested for the boat and future testing criteria will be discussed in the later section.

The deployment system was assessed by how well it could both deploy and retract a 45 pound weight. This weight was chosen as the actual sampler is much lighter.

The sediment sampling mechanism's quality was determined by how well it holds and preserves samples during a mission. The transportation and preservation tests were done separately.

4.2 Testing of Control Scheme

The control scheme's navigational control was first fully tested in the river, but the data and electrical connections underwent several out of water tests to ensure functionality. The station keeping scheme underwent many iterations in terms of both hardware and software. In terms of hardware, initially an Adafruit 16-Channel PWM Servo Hat was used for PWM control of the stationkeeping T200 thrusters. While initially promising, while integrating software to run the thrusters, the PWM signal was not sent consistently. This issue prevented any proper station keeping to be developed, resulting in the Servo Hat being replaced by an Arduino module. By replacing the Servo Hat, consistent PWM signals were able to be sent to the thrusters. In terms of software, various tests were done in order to properly connect the thrusters as well as them to work with a PD controller. These tests included testing the output of the IMU data from the Pixhawk while *Twin Pickles* was out of the water, testing different control schemes and various inputs for PD control, and software integration testing.

4.3 Testing of Deployment System

One critical subsystem of the boat structure is the winch mechanism which raises and lowers the sampling system. Within the lab, the winch was first tested by directly powering the drill motor with a 12V lead acid battery. After successfully lifting 10 lbs, a 45 lb (20.4 kg) weight was then tested to validate the system (Fig. 13). Once it was determined that the system could lift the maximum expected weight of the sampler, a control system was implemented for the field test.

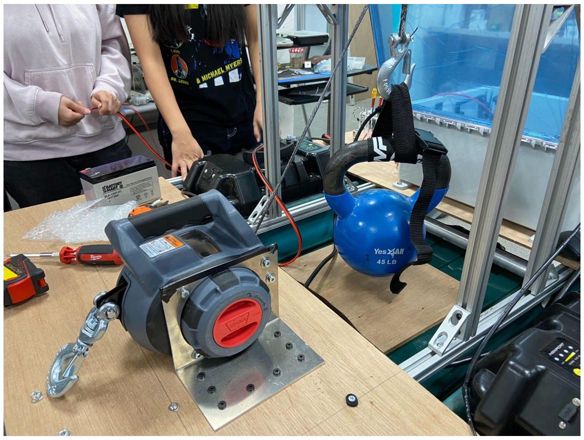


Fig. 13. The winch system doing a test deployment with a 45 lb weight

There were two winch-sampler integrated tests, one in the test tank and the other in the Charles River. While lowering and raising the sampler in the test tank went smoothly (Fig. 14a), field testing was not as successful (Fig. 14b). While we anticipated the frame to realign itself as it was raised, when it was being pushed by currents in the river, the frame would sometimes continue to rotate. The diagonal top length of the frame is larger than the gap between the plywood sheets so it would sometimes catch on the wood and we would have to briefly lower and raise the frame again. In the future, widening the gap between the plywood sheets or making a cylindrical frame would eliminate this issue. Though the winch was slow, no slipping or additional strain was observed when raising the frame in water compared to testing in air.

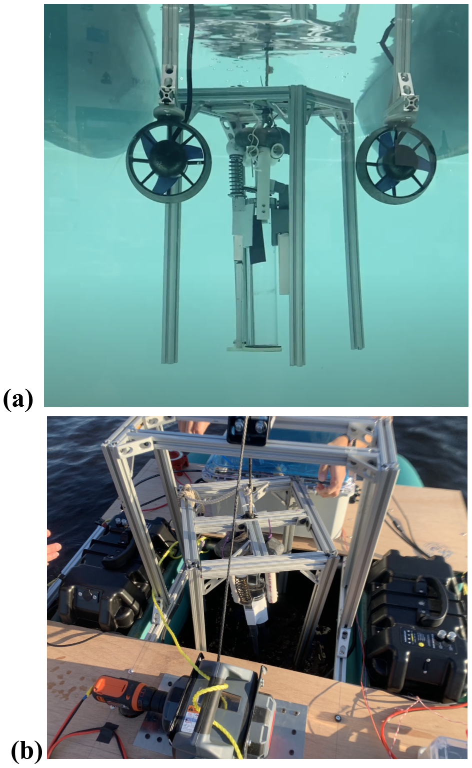


Fig. 14 (a) Successful test of winch system in Sea Grant tank. **(b)** River testing of the winch system, where currents rotated the sampler which caused the frame to catch on the plywood.

4.4 Testing of Sediment Sampler

Two prototypes of the sediment sampler were built and tested. The first consisted of two torsional springs that would snap the cap closed, while the second used a linear spring that is initially compressed and is released in the process of sealing the sample into the tube. The second prototype was designed after preliminary testing of the first prototype revealed critical problems with the design.

Since the torsional springs in the first prototype were most compressed (and capable of generating the most force) when the cap was in the fully open position and the least compressed when the cap was closed. This meant that, when the cap was closed, there was very little keeping it in place. During testing, the mud passed through the gap between the tube and cap. This gap couldn't be reduced because there had to be enough clearance for the cap to rotate from the side to the bottom. Since these issues were fundamental to the design of the sediment sampler, it was determined that a new system would need to be designed and built from scratch. It is important to recognize that the second prototype was built with the knowledge gained from the first. It was not an upgraded version of the first one.

The second prototype was much more promising. After weeks of manufacturing, it was first tested in Sea Grant's test tank without any mud. The test showed the mechanism worked as expected when exposed to zero resistance from mud/sediment. We quickly moved on to testing in buckets of mud collected from the Charles river, which would also be our final test site. During this test the mechanism was manually deployed and triggered. The sampler was collecting some mud but the mechanism was not properly sealing the sample due to a misalignment of the cap with the tube (Fig 16). Additionally, the components used to transfer the force from the spring to the cap were not toleranced tightly enough, which caused the cap to be slightly loose when fully capped. This also allowed mud to escape from the tube.

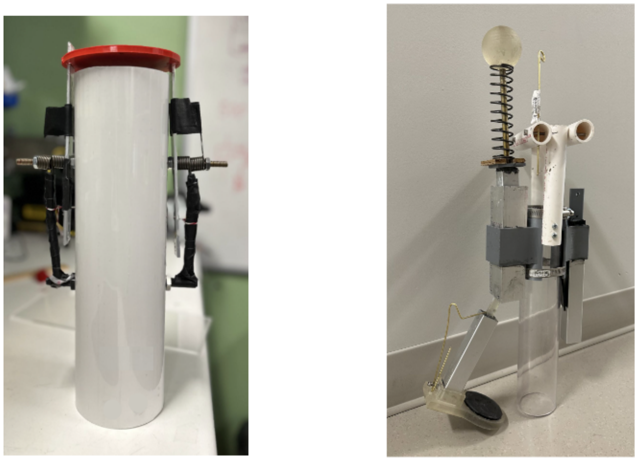


Fig. 15. First prototype of the sediment sampler (left) and revised second prototype (right).

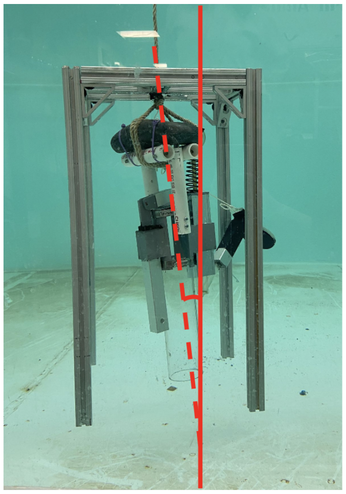


Fig. 16. Image displays testing of the version two of the sampler in the test tank. Red annotations point out the angle of descent of the sampler and its deviation from the vertical.

A third system was manufactured based primarily on the second prototype. This version consisted of a very similar setup but with tightly toleranced components and new parts. The new setup was able to seal much more firmly than the prior two and eliminated all of the issues noticed previously. With its completion, the next test happened at the MIT Sailing Pavilion where the sampler was deployed by hand to the bottom of the river. Over the course of multiple attempts, mud was not able to be collected. This was due to several issues noted during the tests. The sampler did not sink vertically due to uneven weighting and interference with the water as exemplified in Fig. 17. When it reached the bottom, this likely caused the system to tip over to lay horizontally along its side instead of sinking straight down into the mud. This uneven sinking also caused failures in the trigger mechanism since the pin needed to be pulled vertically upward instead of at an angle. Another failure occurred when the system was successfully triggered, but the force of the lid snapping closed and the subsequent force from the spring caused the new 3D printed components to snap. This was unfortunately a critical error that prevented any further testing with this system since there was not a way to make these components large enough to handle these forces without constructing a completely new version.

4.5 Testing of Final Integration

For final integration testing. all subsystems with the exception of the PD station keeping control scheme were brought together. The first test occurred in the indoor testing tank within the Sea Grant facility, as shown in Fig. 17. This test was primarily to validate the integration of the deployment system with the sediment sampler and radio control of the T500 thrusters. The second test occurred at Magazine Beach on the Charles river (Fig. 18). The integration of the deployment system with the sediment sampler was again validated on the water. In this test, the navigation control was also validated with the combined weight of all subsystems present. All systems that were present operated within the expectation of the minimal product.

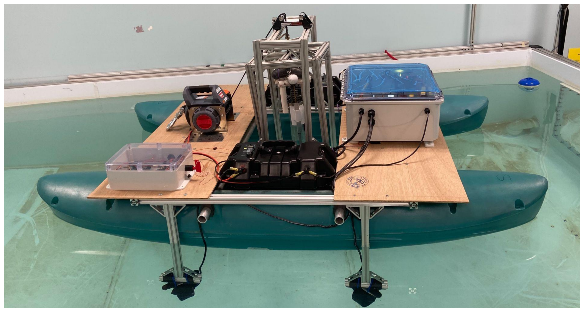


Fig. 17. The fully integrated system during indoor tank testing

Fig. 18. The fully integrated system during outdoor river testing at Magazine Beach

5. Failure Modes and Major Challenges

Some of the primary conditions factoring into our design lay outside of our control and include weather, water conditions, bottom hardness, and cyst concentration. Therefore, we tried to make our system robust enough to function even when the environment is not similar to that of testing or if it doesn't match the expected state.

Reviewing potential failure modes and their effects revealed weaknesses for several key aspects of our proposed system and allowed us to ideate solutions to shore up said weaknesses. One of the first potential failure modes would be the lack of power for any given piece of equipment on the vessel. In the absence of power, the respective equipment will not function and sample collection will not be possible. Furthermore, if this is due to the battery running low, it could permanently damage the battery and even pose a further safety hazard to the operation crew. In our case, we had to temporarily power our Raspberry Pi with its own dedicated battery during field testing and when it died, it disabled our ability to send signals to our winch motor. Our initial failure mode was that the computer was unable to boot up, so we added the battery, but to address our secondary hardware failure, we can use the dedicated battery as a buffer and give the Raspberry Pi power through it.

A sampler malfunction or inaccurate feedback signal readings are also two occurrences we expected to come up in the deployment process. This could be caused by anything from a wired connection coming loose to a piece of adrift debris clogging our sampling mechanism. If the feedback signals are inaccurate, leading to incorrect interpretation of the state of the sampler, then this error could incur a damaging response from the system leading to mechanical failures or electrical overload. In the case of our testing, the sampler sometimes changed orientation drastically as it was reeled back up into *Twin Pickles*. As a result, it would get caught on the deck and the winch motor would stall as it exerted large amounts of force into pulling the deck up from the boat. Luckily, we caught this in action and were able to stop the winch before it did any permanent damage. As mentioned earlier, future improvements include widening the gap between the plywood sheets or making a cylindrical frame to guard from mechanical overload scenarios.

We also wanted to be cognizant of entirely external physical failure modes. For example, if our vessel were to incur hull damage from rocks, debris, or other objects, the boat could become unstable, and the sample collection apparatus could be disrupted or destroyed. Or, if further environmental factors such as wind, waves, or currents are more extreme than our vessel can handle, then the stability of the catamaran could be compromised, leading to difficulty in sample collection and potential damage to electro-mechanical equipment or the vehicle itself. To combat this we designed *Twin Pickles* with a wide 4 foot beam given the other dimensions and attempted to keep the center of gravity low by placing the 50 pound AGM batteries inside the hulls. General sampling equipment malfunctions, such as the faulty loading of the sampling mechanism or a broken tether, were also expected, though should pose less of a risk to the vehicle's integrity and operation team. In a few instances, the equipment did not function as intended, leading to incorrect or incomplete sample collection, but this was apparent upon the vehicle's return and before proceeding we ensured that it posed no potential hazards.

One of the immediate concerns when sending out an unmanned vehicle is always loss of communication between the operator or other support team members and the vessel. In this case, the remote operation team would be unable to communicate with the vehicle, leading to potential safety concerns and loss of equipment. Many of the failure modes can trigger loss of communication, particularly any water leakage or flooding of the catamaran, electronics compartments or wires themselves. Inadequate waterproofing can cause a small short that could bring down our communication connection even if it is a relatively contained short with only a few fried components. If the battery were to short sufficiently it may consequently explode, which has the potential to make the vehicle unrecoverable. Therefore, we implemented overcurrent protection in the form of a 200A circuit breaker. Despite this, we did run into several occasions where we lost communication with our vehicle, both via our 2.4 GHz connection to the Raspberry Pi or radio control transmitter and our 915 MHz serial mission data connection. In cases that were isolated to one form of communication loss, we were able to diagnose the issue and decide the next course of action from there. However, at the end of one of our field tests with the full system, we lost all three communication lines with the vehicle and had to use a tether to bring *Twin Pickles* back in. In this case, we used a tether to guard from this communications hazard, but in the future we can address this with more advanced and effective antennas with optimized placement.

Other methods we came up with to address our major challenges include the reinforcement of the hulls and installation of protective equipment to reduce the risk of damage to the vehicle or operators to quell physical hazards. Additionally, the use of advanced weather forecasting and monitoring systems helped us to predict and avoid adverse weather or other environmental conditions during our field testing which would have otherwise led to several failure modes. However, even if these conditions are encountered, implementing robust communication systems as mentioned before will ensure to the best of our ability that the operation and support team can stay in contact with the vehicle at all times and can coordinate necessary actions in case of an emergency. For the future of the *Twin Pickles* system, implementation of these mitigation strategies in parallel to our critical vessel elements will serve as a bulwark to expected and future challenges.

6. Future Work

More tests need to be performed in order to better understand and improve the *Twin Pickles* vessel for further development.

6.1 Stationkeeping System

In order to make *Twin Pickles* run fully autonomous missions, a more complex state machine will need to be implemented. The boat will start in navigation mode, and navigate to the first waypoint, determining suitable sampling locations using onboard sensors (refer to section 6.3: Sensor Additions). Once a location has been determined, it will trigger stationkeeping mode to stabilize position and the sampler deployment sequence will start. After the sample is successfully retrieved, the boat returns to navigation mode and proceeds to the next waypoint.

Future testing and development is especially true in the instance of the station keeping. Proper testing of the current system must take place as the PD controller was not finished in time. The criteria for which the system will be evaluated on will be how well it keeps the vessel in place using Pixhawk data. In terms of future development of the station keeping control scheme, there are many ways to improve the current system. Most importantly, a proper model needs to be determined for the control scheme and plant. This process can be done either through more practical tests in the river or, less ideally, through an assumed approximate model. Along with this, other types of controllers could be tested along with the system, such as adding an integration element for a PID system, the exploration of Lead-Lag controllers, or even nonlinear control. Proper controls analysis must be done for the properly modeled system and improved control scheme. This will allow for appropriate gains to be determined as the current method is simply based on rough estimations.

6.2 Sediment Sampler

Future versions of the sediment sampler will need to take into account the need for a greater number of samples, temperature controlled storage, a variety of sediment types and bottom environments, and a more robust system design. The current version of the sampler is primarily constructed from 3D printed components. In order to successfully collect samples, we determined that these parts will need to be custom machined from aluminum or stainless steel. In addition to being able to withstand the loads of sample collecting, constructing these components from stronger metals will allow for repeated use over long periods of time. They will also be able to be used with much rockier sediment types, which would likely destroy the current system.

A later iteration on this project should include adding in-situ sensors to the subsystem that travels to the bottom of the ocean in order to collect basic water data, such as temperature, pH, and oxygen level. These values would help determine the water conditions at the locations of the samples, which would be useful in determining the possibility of an algae bloom occurring in the near future. A power cable would be connected to the tether along its length that pulls the core such that the two wires do not become intertwined.

Additionally, a storage system and switch between collection apparati to acquire multiple samples at different locations would be included in the final version in order to be of most use to scientists. There are two main options for this design: switching could occur at the surface or at the floor. At the surface, this would entail a mechanism that could attach and detach the end of the winch to each individual tube. The sensors would stay on the winch so they could take measurements with the collection of every sample. The benefits of this design include minimizing movement of already procured sediment samples, a consistent weight traveling vertically through the water, only the sensors requiring power, and keeping the collected samples out of the water and at a more consistent temperature. A cooling system could also be implemented to keep the samples very close to the temperature they were collected at.

The alternate option is to include all of the samples in the payload that goes down to the bottom every time. A mechanism to switch between which sample collides with the floor would also damp the rest of the samples so as not to disturb them. This design would allow the entire sediment sampling system to function largely independently of the boat, so that users could easily add this subsystem to their own vehicle. Issues could arise since the weight of the payload would increase over time as more samples are collected and there would be some jostling of the previously collected samples. The cores would be kept at a lower average temperature compared to storing in open air, since they would spend more time at the bottom of the ocean, but would undergo frequent temperature changes from traveling between the surface and floor multiple times in the span of a few hours.

6.3 Sensor Additions

To further improve the vessel, there are several additions that could be added to better its sampling capabilities, such as a bottom-sensing sonar system as well as an object avoidance system. The bottom-sensing sonar interface system would collect topological data of the seafloor, and the object avoidance system would collect data about how far objects are from the vessel. The bottom-sensing sonar's data would then be used to determine whether or not the sediment sample collector can be deployed or not; for this system, the only sensor used would be a fish finder such as the Humminbird Helix 7 Chirp Mega bottom-sensing sonar. The object avoidance system's data would be used to help with waypoint finding and station keeping; the sensors needed would be a camera and a combination of an IMU and a Time-of-Flight sensor for a lidar system. This combination of sensors allows for orthogonal sensing, meaning that errors in one sensor can be more easily determined.

The quality tests of these two subsystems would be similar to the testing of other subsystems. The bottom-sensing sonar interface's quality would be determined by how well our algorithm detects and transmits proper ground data. It would be tested against at least three different underwater terrains of known topology. Each resulting scan would be compared to the true environment; if the system accurately replicates the true environment and can detect a flat ground, the bottom-sensing sonar system would have passed. The object avoidance system would undergo a series of tests in which various large objects are brought in front of sensors. If the system is able to properly report the distance from the object, the object avoidance system has passed.

7. Other Applications of an Autonomous Soil Sampler

Even though the main purpose of the *Twin Pickles* was for the detection of cysts in bodies of water, autonomous soil sampling could prove useful in a variety of different contexts. For example, soil samples are also useful to study ecosystem health and marine geology, which is especially turbulent considering human activities such as dredging, aquaculture, and restoration often disturb the soil on the ocean floor. It might also serve useful in monitoring heavy metals and pollutant levels within the soil. In particular, as there are now around 14 million tons of microplastic on the whole ocean floor (Barrett et al., 2020), soil sampling could give further information about how microplastics travel in ocean currents and settle in the ocean.

Conclusion

Algal blooms have devastating consequences worldwide, especially on seafood consumers and industry. In Massachusetts, the harmful algae *Alexandrium catenella* can lead to Paralytic Shellfish Poisoning as well as mass die-off events from oxygen depletion in water. As a major seafood producer, significant effort has been devoted to detection networks, but a need remains for a forecasting model. As part of the natural lifecycle, *Alexandrium* forms dormant cysts in the winter which can be used to predict bloom levels in the following spring. A strong predictive model could warn aquafarmers to pull or relocate their stock, and inform regulators when areas are safe to reopen. However, significant amounts of sediment samples are required to validate predictive models. Autonomous collection of sediment samples with a surface vehicle would empower researchers and accelerate the timeline in which a model would be implemented.

ASVs are more flexible and less costly than boat expeditions. With larger payload and battery capacity than AUVs, ASVs are better suited for collecting and transporting sediment samples. And by remaining on the surface, they can transmit near-real time data and communicate with GPS for a simpler control and monitoring system. The ASV will be equipped with a core-sampler which preserves the sediment and sediment-water interface, unlike other grabber methods including Van Veen samplers.

The ASV we built ultimately had some subsystems that functioned well and others that require improvements. The hulls and winch proved they could lift the expected weight of the sampler through the water, but the sediment sampler itself was unable to successfully collect a valid sample. Improvements should be made to make it more stable and consistent in its deployment, though the actuation of the closing mechanism worked as desired. The stationkeeping and general movement of the ASV needs further testing and validation. Future work on the system could improve each of the subsystems as well as include additional abilities such as collecting multiple samples and storing them. Nonetheless our work served as a proof of concept that this system is possible and could be very useful in a variety of contexts.

Finally, a variety of research applications beyond HABs also rely on sediment samples, and have already expressed interest in our vehicle development. A future extension would be communicating with other researchers to determine their needs, and see how this sediment-sampling ASV could be adapted for other projects.

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Appendix A. Electronics block diagram that depicts the flow and routing of supply power and signals throughout the electrical subsystem on the vehicle. Color key in the bottom right defines which components pertain to each respective function of the electrical subsystem.