S.S. MAPR

Smart Sampling & Measuring
Autonomous Platform for Rivers

Final Project Report

MEAM 445/446, MEAM Senior Design

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ABSTRACT

River ecosystems are constantly threatened by the discharge of harmful by-products and waste from industrial facilities as well as increased salinity due to agricultural residues. In order to facilitate regulation proposals, water authorities need a way to track water quality across the entire dynamic water body, through consistent and frequent measuring and sampling. The main bottleneck for these regulatory bodies is funding, which results in having limited and inconsistent coverage. Water utility providers and governmental bodies use cross-sectional metric maps and water samples to model the distribution of water quality attributes and conduct nutrient tests to facilitate important regulation proposals. However, sampling is currently only performed at the surface, leading to a lack of multi-depth data crucial for detecting contaminants and disease-causing bacteria in everyday drinking water.

S.S. MAPR addresses this need with a low-cost autonomous surface vehicle that provides frequent measurements and sampling services at varying depths up to 45 feet and 2.5 liters of water samples. Equipped with this solution, water commissions will be able to measure and sample 8 times more frequently, reduce the labor cost per trip by 67%, and reduce measuring and sampling costs by 67% and 71% respectively. Additionally, it increases the multi-depth data points per year by 260x. Given its low upfront and variable cost and faster speed, S.S. MAPR can be frequently deployed to gather measurements and samples to model water quality, ensure compliance with regulations, and quickly identify critical changes across the water body which facilitates regulation proposals.

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EXECUTIVE SUMMARY

S.S. MAPR is a low-cost autonomous surface vessel for multi-depth water quality measuring and sampling. It is able to produce one cross-sectional map in 4 hours - meaning 2,200 m across and 45 ft deep - and also collect 2.5 L of water samples. The solution is designed to lower the cost by ~70% for measuring, sampling, and labor and provide 260x more multi-depth data points per year.

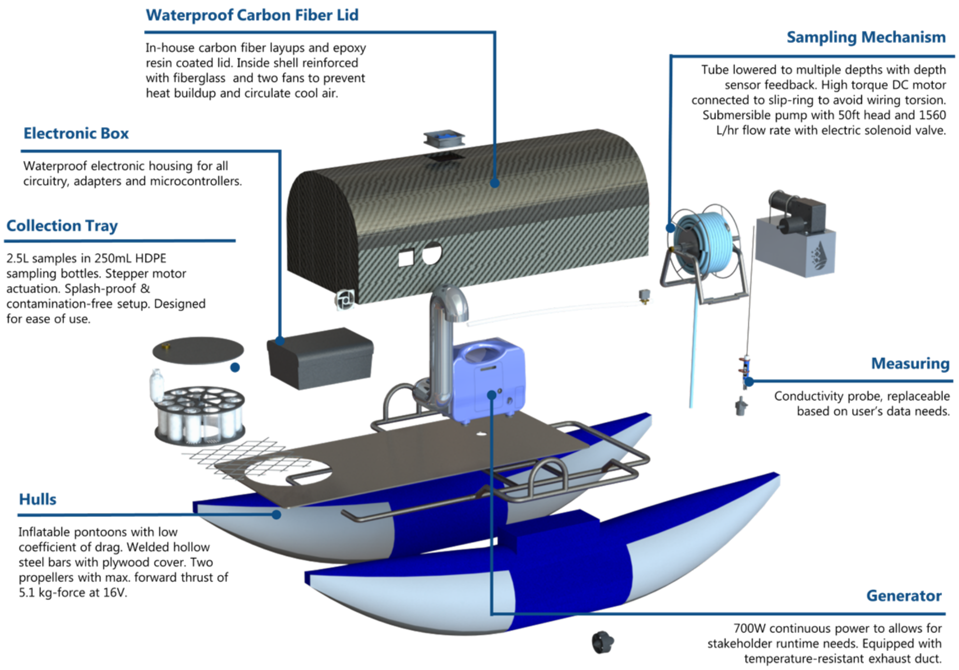


Figure 1. S.S. MAPR overview

USER EXPERIENCE

A typical day with S.S. MAPR is like this: The user, a USGS water scientist, would pack up S.S. MAPR in the back of their pickup truck and drive to the field. They pump up the pontoons of S.S. MAPR and set it ready for initialization. On their computer, they set the points the stop points that they want to sample and measure at on an easy-to-use UI. As they click the launch button, this data is transferred to the boat, and off S.S. MAPR goes! At each stop point, S.S. MAPR will pump up water and store it in scientific bottles onboard to be retrieved after the journey. Meanwhile, the probe will measure conductivity at different depths. The user can see real-time data streaming in. 4 hours later, S.S. MAPR is back with 2.5L of water samples and 100 multi-depth data points. As they pack up and go back to the office, the data is already processed and waiting for their analysis.

SUBSYSTEMS

S.S. MAPR has 3 main groups of subsystems:

1. Task functions: Sampling, Measuring and Collection
2. Control, Actuation & Autonomy
3. UX & Data Processing

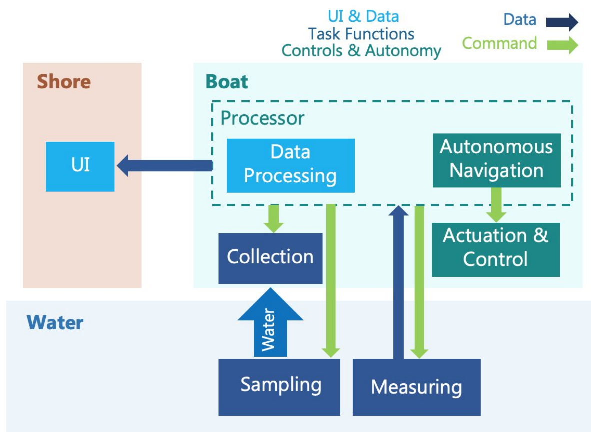


Figure 2. Subsystem Interactions

Task Functions: Sampling

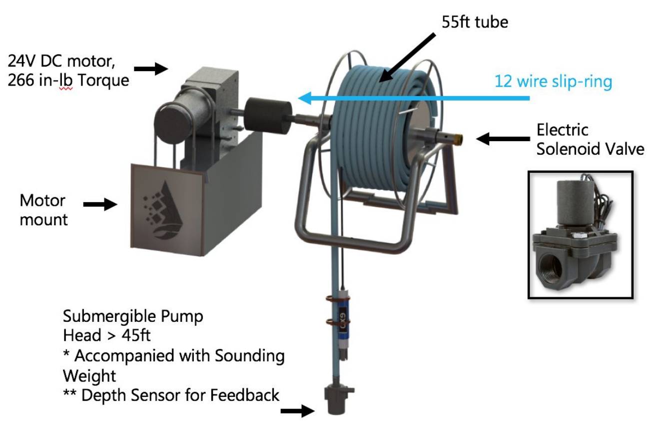


Figure 3. Sampling subsystem annotated

The sampling subsystem consists of a high torque DC motor that actuates a pulley to lower a 50-ft tube to designated depths based on the feedbacks from the depth sensor attached at the end of the tube. A submersible pump is attached to the end of the tube that pumps up the water. The water pumped up goes through the electric solenoid valve on the other side of the pulley, which is controls the flow of the water, and then goes into the collection tray through a clear tube. The quality of the depth sensor data was guaranteed with the addition of a boosting & filter circuit.

In the Design & Realization section, multiple design decisions were considered with regards to:

1. Choosing the size of the sampling tube

2. Selecting the pump based on the needed flow rate
3. Selecting a DC based on the needed torque and RPM
4. Ensuring the measuring and sampling occur with a 1m x 1m x 1m bounding box as dictated by stakeholders
5. Ensuring accurate transmission of depth sensing data using circuitry

Task Functions: Measuring

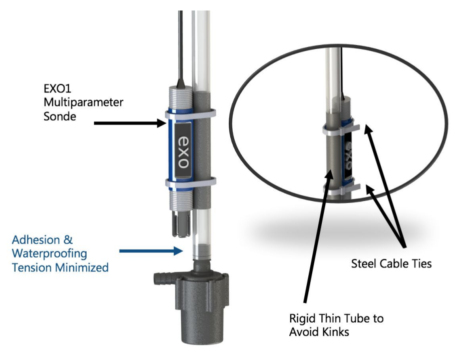


Figure 4. Measuring mechanism annotated

At the bottom of the sampling tube, S.S. MAPR holds a water quality probe and a submersible pump. The submersible pump is heavy enough to act as our sounding weight and make sure this system is driven to the bottom of the river.

Our stakeholders needs to measure different water quality attributes. We decided to use an analog electrical conductivity sensor as a proof of concept for our system. Conductivity has shown to have larger spatial variation than other metrics and the probe is relatively similar in size and usability to the existing probes of stakeholders. As a next step, the probe mount will be improved to be customizable to the sondes from users.

Task Functions: Collection

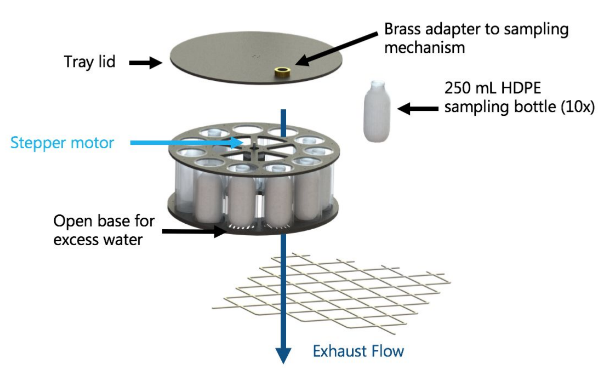


Figure 5. Collection tray annotated

The collection tray consists of a rotating tray that alternates among sampling bottles and exhaust. The tray is actuated with a stepper motor. To avoid cross-contamination, a cleaning mechanism was designed that pumps at least 3x the tube volume of water through the exhaust at each new sampling location. The tray of tubes is also closed in order to avoid splash contamination across samples. The bottom part of the rotating tray is made with a brush to lower the rotating friction while sealing the containers.

Actuation & Control

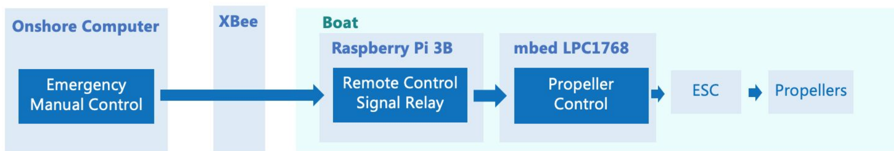


Figure 6. Remote Control Block Diagram

The user can remotely control the boat using an RF module (XBee) connected to the offshore laptop in cases of emergency. Two propellers are attached to each pontoon to actuate the boat. The propellers were selected based on coefficient of drag and our necessary runtime. As shown in Figure 6, the propellers are connected to the ESCs for controlling the speed, which in turn are connected to the microcontroller (mbed LPC1768), which takes thrusts data from the main processor (Raspberry Pi 3). The on-board computer uses XBee to communicate with the offshore laptop. The specifics regarding our choices for these electronics will be detailed in the *Design & Realization* section.

Autonomous Navigation

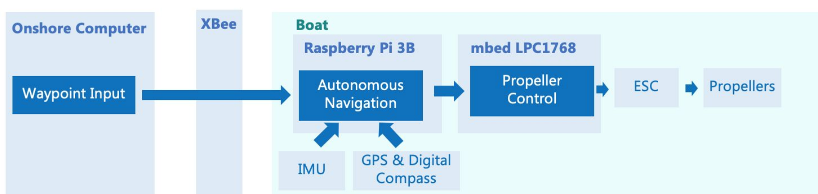


Figure 7. Autonomous Navigation Block Diagram

The autonomous navigation subsystem takes in the user-defined stop-points for the mission and autonomously drive the boat from point to point, while stopping at each stop-point and performing task functions. The autonomous navigation subsystem is mainly composed of localization and control.

For localization, we use GPS and digital compass inputs to correct for the drifting of integrating IMU inputs. All sensors are directly connected to the main on-board processor. The localization algorithm uses a Kalman Filter, which takes in the sensor inputs for action and measurement updates. The uncertainties are accounted for to generate a good estimate of the boat's location.

To ensure the boat switches naturally between path following and stopping, we designed a state machine in which the boat switches between 3 different control modes. In each mode, a PID controller takes in the angle error as well as the distance error to calculate the thrusts for turning and forward motions.

With all of these together, S.S. MAPR is able to follow a set of waypoints, stop at each point, perform tasks necessary, and continue along its way while updating its position and modifying its course all in real-time. It also autonomously drives back to the starting point at the end of the test.

UX & Data Processing

We have designed user interfaces for various parts of the experience. The first interface is used for inputting the mission, namely the start and end points and details for measuring and sampling. In Figure 8, you can see the input panel for setting surface stop points, adding depth points for each surface point and configuring measuring and sampling. The route map is generated to the left and some basic mission information is below. Once the user puts in all the information, he/she can press the blue button to start the mission.

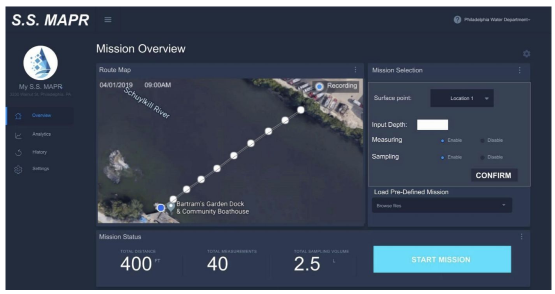


Figure 8. User Interface (Pre-Operation Mission Configuration)

Another user interface is designed for real-time updates of S.S. MAPR. As the boat is running on the river, the user can see the cross-sectional map being generated partially with real-time data start filling in the graph from the left. At the bottom, the user can see the status of water samples and the progress of the mission. If anything happens, the user can switch between manual control and the autonomous mode on the bottom right panel.

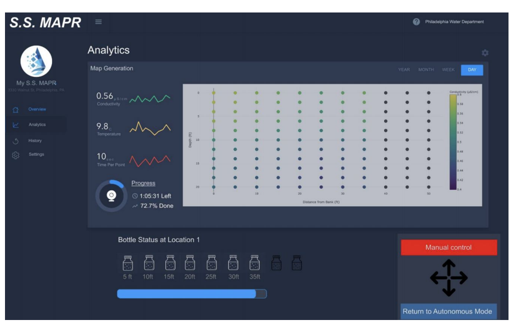


Figure 9. User Interface (Progress Update during Operation)

Power

The system is powered by an inverter gasoline generator, considering the power needs, size, weight constraints, as well as user familiarity, as specified in the technical documentation section. We proposed this in the semifinals presentation and decided to move on with it as we got more feedbacks from stakeholders and instructors. Compared with battery, this brings double the runtime at half the cost and its smaller volume fits better with the on-board components.

Gasoline generators have high requirements for waterproofing. So a waterproof lid is designed and built with in-house carbon fiber layups and epoxy resin coated lid. The lid contains two fans to prevent heat buildup and circulate cool air.

Considering the uncertainty involved with boat runs, we have built a backup battery. The system will switch to the backup battery and notify the user once the voltage provided by the generator is lower than a certain level. The backup battery powers the remote control components and is enough for the user to manually drive the boat back.

Figure 10. Dirty Hand Tools 800W Inverter Generator[1]

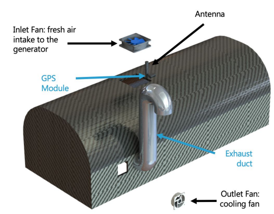


Figure 11. Ventilated Lid

VALIDATION

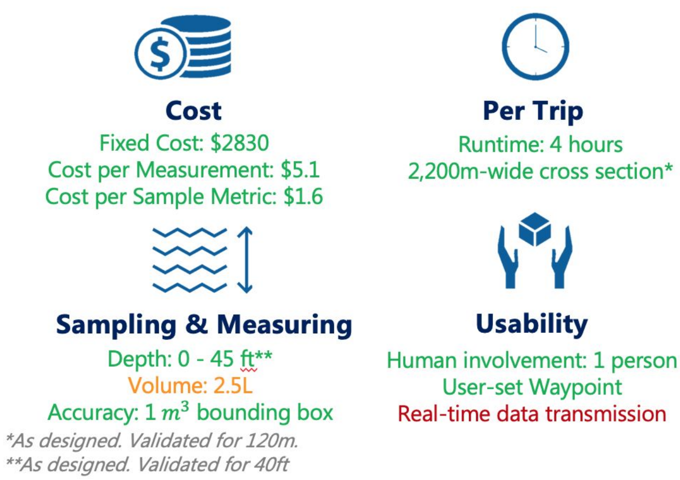


Figure 12. Key Design Goal Achievements

We conducted various integration tests at Pottruck Pool and then in the Schuylkill River at the loading dock of Bartram's Garden. S.S. MAPR was able to fill the collection tray with 10 sampling bottles of water, while measuring 100 conductivity measurements up to 45 feet deep. We first began the tests with remote control and then further proceeded to waypoint guidance.

Overall, most of the objectives we outlined were met. Figure 12 lists the achievement of key design goals. S.S. MAPR significantly lowers the fixed cost and cost needed per sampling and measuring costs. What's more, the runtime, width and depth per trip were achieved. The sampling volume of 2.5L is lower than the 8L design goal but covers the 16 most important sample metrics for our stakeholders. Expanding the sample volume will thus be a crucial next step. Last but not least, S.S. MAPR reduces the human involvement to 1 person by enabling the boat to follow user-set waypoints. Data transmission is prototyped with csv file export and real-time transmission will be developed as a next step. Details of each design goal and achievement can be found in *Objective* and *Discussion* sections.

S.S. MAPR won the Judges Choice Award in Mechanical Engineering and Applied Mechanics and won first place at the Cornell Cup for an outstanding senior design project.

STATEMENT OF ROLES AND EXTERNAL CONTRIBUTIONS

TEAM MEMBERS

Mia Mansour
Mia Mansour was the mechanical lead of the team. She set deadlines for the mechanical subteam and distributed tasks for all of the mechanical components that needed to be accomplished. In addition, she made sure the team as a whole was working hard and meeting deadlines.

Xiaoyi (Sherry) Chen
Sherry Chen was the lead for software and electronics. She designed the circuits and wrote the software that ran S.S. MAPR. She and Mia led meetings, set deadlines and made high level decisions about the trajectory of the team.

Yoon Ji (Eunice) Lee
Eunice Lee worked on mechanical design and analysis. She analyzed the various options available when choosing a propulsion system and completing fluid flow analysis of S.S. MAPR. She worked on system testing, design, waterproofing, and research.

Vanessa Howell
Vanessa Howell worked on mechanical design and analysis. She also worked on configuring and fixing all of the subsystems to the bridge of the boat. She was was instrumental in completing many prototyping and manufacturing tasks.

Quinn Wu
Quinn Wu was in charge of data collection and user interface. He also worked with Sherry in order to simulate the dynamics of the boat, which was then used to write and test the control algorithms.

Fangyi (Frank) Fan
Frank Fan was in charge of the power subsystem. He designed and assembled a battery pack to be used for S.S. MAPR.

PRIMARY ADVISORS

Dr. M. Ani Hsieh - Research Associate Professor, University of Pennsylvania
Dr. Ani Hsieh advised us heavily with water testing. The boat was tested in the Schuylkill using the permit her lab received, and she gave us access to a small pool in her lab for small scale testing if needed.

Dr. Graham Wabiszewski - Professor, University of Pennsylvania

Dr. Graham Wabiszewski advised S.S. MAPR through the entirety of the project. The team met with him frequently, and every time he was able to point us in the right direction. He helped with the high level system solution and general trajectory of the project.

Dr. Paulo Arratia - Professor, University of Pennsylvania
Dr. Arratia helped us in the initial ideation stage and the scope of doing a project related to fluids.

TECHNICAL ADVISORS

Eric Quesada - Student, University of Pennsylvania - Teaching Assistant
Eric Quesada was our teaching assistant for the class. He was constantly available whether it was guidance for mechanical design decisions or actuation and control. He was available to point us in the right direction when we were stuck and ensured that everything went smoothly throughout the year.

Nikhil Chari - Student, University of Pennsylvania - Teaching Assistant
Nikhil Chari was our teaching assistant for the class. He closely monitored our weekly progress, gave us high level strategic advice and worked closely with us on our deliverables acting as a general consultant for the team for the first half of the year.

Dr. Dhanushka Kularatne - Post Doctoral Researcher, University of Pennsylvania - Technical Advisor
Dr. Dhanushka was the post-doc in Dr.Hsieh's lab. He has helped us throughout the project with choice of electronics, control algorithm design, and software platform choices.

Yash Mulgaonkar - Research Scientist, University of Pennsylvania
Yash Mulgaonkar has provided us with extensive help in the power subsystem, electronics setup, and software questions.

Joe Valdez - Instrumentation Technician, University of Pennsylvania
Mr. Szczesniak acted as a consultant for us on the manufacturing of the system. He presented to us various design decisions that the team could pursue and aided the team in the Machine Shop.

Sid Deliwala
Sid Deliwala acted as a consultant for us on the electrical parts of the system. He has helped us with various key decisions related to the power subsystem, processor and sensor selections. He also borrowed us the power supply that empowered the demo on MEAM design day.

Anurag Makineni
Anurag Makineni helped us throughout the project with processor selection and autonomy & control algorithm.

Shreetej Reddy
Shreetej Reddy helped us throughout the project with specifically the power issue of our ODroid as well as power management and voltage regulation.

PROJECT SPONSORS

Namsoo Suk - DRBC
Namsoo Suk is the Director of Science and Water Quality Management of Delaware River Basin Commission (DRBC). He has provided us with almost all the background materials of the problem and helped us clarify the system characteristics of an ideal solution. He has also connected us with other stakeholders with similar needs.

John Yagecic - DRBC
John Yagecic is the Manager of Water Quality Assessment at Delaware River Basin Commission (DRBC). He has helped us understand the current manual sampling procedure and provided us with precious data crucial to our system design. He has also provided us with feedbacks on our design decisions.

Li Zheng - DRBC
Li Zheng is the Senior Water Resource Modeler at Delaware River Basin Commission (DRBC). He has helped us understand the water quality modeling process.

Joseph Duris - USGS
Joseph Duris is a Water Quality Specialist-Microbiologist at United States Geological Survey (USGS) Pennsylvania Water Science Center. He has been utmost helpful in helping us understand the current annual multi-depth measurement process and provided us with technical details crucial to our design. He has also provided us with feedbacks on our design decisions and helped with getting clearance for river testing.

Robert Mason - USGS
Robert Mason is Acting Chief at USGS Pennsylvania Water Science Center. He provided us with helpful insights in current depth measurement procedures.

John Jastram - USGS
John Jastram is a Water Sampling Specialist at USGS Virginia and West Virginia Water Science Center. He provided us with helpful insights in current sampling processes.

Matt Fritch - PWD
Matt Fritch is Environmental Engineer and Initiator of GreenSTEM at Philadelphia Water Department (PWD). He helped us understand the procedure needed for multi-depth sampling for bacteria tests.

Gary Burlingame - PWD

Gary Burlingame is Director of Bureau of Laboratory Services at PWD. He provided helpful insights about the current sampling practices at PWD and provided suggestions on our design choices.

Ellen Hwang - PWD

Ellen Hwang is Assistant Director of Strategic Initiatives at City of Philadelphia. She informed us of the current sensors most commonly used by water authorities.

OUTSIDE RESOURCES

We used mbed RTOS as the main library that powers the operations of our microcontroller. We used Solidworks and MATLAB for most of our analysis and simulation.

BACKGROUND

Water quality problems are very hard to fix and can easily be found out too late. Recently, Mountaire Farms, located in Delaware, was found out to have caused the nitrate pollution in its nearby rivers for decades. The company had repeatedly violated its permits for waste disposal by spraying contaminated water on hundreds of acres of farm fields. The water became unsafe to drink and led to community members facing bacterial infections and even birth defects. Additionally, industrial facilities in Pennsylvania recently have been dumping pollution into rivers for over 21 months[2] before they were found out. Lethal dissolved oxygen levels are endangering different aquatic species to the point of becoming extinct.

Other water quality threats, like the salt front, is also easily left undetected, because it mostly progresses at the bottom of the river, but sensing is usually done at the water surface. Salt front is caused by the intrusion of salty seawater into freshwater, and this can cause contamination to water sources for drinking and urban usage. However, the salt front is hard to detect because it changes with the weather and it progresses mostly at the bottom of the river, while measurements are usually taken at the water surface. All these can threaten the drinking water safety of the 1.5 million people in Philadelphia. But the river is so big and changes so dynamically that it is very hard to keep up with the water quality across the whole water body and over time. [3]

NEED

Many facilities have been polluting nearby rivers and it takes regulatory bodies 6 years[4] to collect enough data to regulate their emissions. But with ecosystems getting affected and people dying from something as fundamental as drinking water, water authorities need accurate aquatic models to facilitate regulation proposals. Unfortunately, it takes them years to gather enough data points and samples and that stalls regulation proposals.

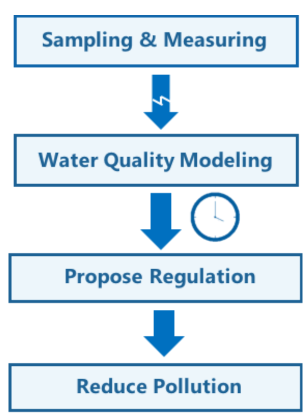


Figure 13. The process leading up to passing regulation proposals for reducing waste disposals

Currently water authorities only measure at fixed locations and sample at the surface. Our stakeholders from the United States Geological Survey (USGS) and the Delaware River Basin Commission DRBC, as well as water depths and aquaculture companies confirm that more data - especially multi-depth would be extremely valuable. Currently, there are three main sources for this. For measuring, they use fixed stations to measure continuous metrics near water surface every day, and then take multi-depth measurements once a year to take a snapshot of the river body and confirm the accuracy of the fixed point measurements. For sampling, they conduct surface sampling every month along the river in the center of the channel, which allows them to get not only more sensor measurements but also samples for nutrient and bacteria tests.[5] All the information collected are used to build and calibrate a water quality model for the spatial distribution of water quality.[6] The more frequent the actual data comes in, the more accurate this model will be, which allows them to find out chronic problems as early as possible.

Table 1. Current sampling & measuring methods are temporally and spatially limited

"We only have 1 surface sample for every 6 miles of the river." - John Yagecic	"There are only 4 water quality stations over 131 miles of Delaware River." - Joseph Duris
"The dissolved oxygen (DO) varies drastically with depths. Fish is dying because we can't closely monitor the DO levels." - Tom Frese	"Multi-depth bacteria samples are crucial to monitoring drinking water safety." - Matt Fritch

There are many existing solutions for measuring and sampling. For measuring, fixed-stations and boat runs are the most commonly used. For sampling, Van Dorn bottles, pumps and bottle samplers are usually used with boat runs. There are also drones developed by DJI that can take water samples. However, there are more and more autonomous tools that can do both measuring and sampling, such as water surface vehicles, underwater vehicles, and underwater crawlers. Instead of manually running a boat, stakeholders have the options to use autonomous vehicles. However they both require high upfront cost and they are not capable of collecting enough samples. [7][8]

USE CASES

We focus on the use cases where cheaper and denser data have the biggest impact. Specifically, we focus on water-quality modeling, which is used to detect pollution, river-bottom salt front, bacteria composition, and dissolved oxygen distribution. The more accurate the model is, the earlier water authorities can intervene issues that could affect drinking water safety, river ecosystem as well as rish farm environments.

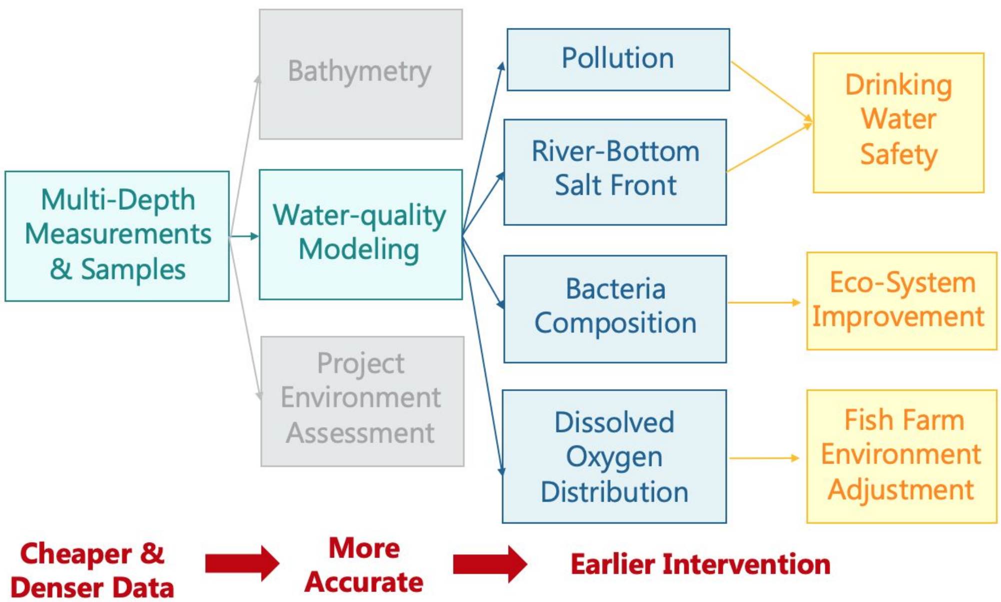


Figure 14. Simplified layout of use cases

GLOBAL IMPACT

On 28 July 2010, through Resolution 64/292, the United Nations General Assembly explicitly recognized the human right to water and sanitation and acknowledged that clean drinking water and sanitation are essential to the realisation of all human rights [9]. The Resolution calls upon States and international organisations to provide financial resources or technology transfers to help countries provide safe, clean, accessible and affordable drinking water and sanitation for all. S.S. MAPR would grant people access to a basic human right.

S.S. MAPR would help water authorities obtain more data at a lower cost. The vessel would lead to 71% of savings in cost per measurement, 67% of savings in cost per sample metric, and 67% of savings in labor cost per cross-sectional trip. Most importantly, S.S. MAPR would provide 260X more multi-depth data points per year, which would motivate regulatory bodies' to make change and pass on proposals before it's too late.

EXISTING SOLUTIONS

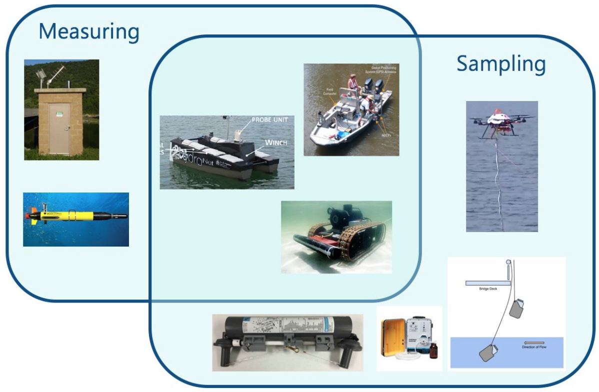


Figure 15. Categories of Existing Solutions

The most common existing solutions are the sensing stations that were mentioned before and tools designed for boat runs. There are also autonomous tools for either measuring, or sampling. Some of them can do both, like autonomous surface vessels and underwater crawlers.

Table 2. Quantitative Comparison of Existing Solutions

	Manual Boat Run	Autonomous Surface Vehicle	Autonomous Underwater Vehicle
Fixed Cost	-	$85,000	$80,000
Cost per Measurement	$18	$5.7	$6.6
Cost per Sample Metric	$4.9	$14.2	-
Man Hour per Trip	12 hr	2.5 hr	4.4 hr
Sample Metrics	41	2	0

Instead of manually running a boat, stakeholders have the option to use autonomous vehicles. However they both require high upfront cost, which is a headache of most water quality projects. What's more, they are not capable of collecting enough samples for the 41 metrics required.

In conclusion, a cheaper, more frequent multi-depth measuring and sampling solution is needed to fill this gap.

OBJECTIVES

The objective of the project is to provide water authorities accurate aquatic models to facilitate regulation proposals and reduce pollution. In order to satisfy this general goal, the solution should be able to provide denser, more frequent, and cheaper data points by sampling and measuring the water in river bodies.

STAKEHOLDER NEEDS

After careful research and analysis of current methods, the team has arrived to the following challenges:

1. United States Geological Surveying: Water quality stations have very limited coverage on the Delaware river that stretches to 131 miles
2. Delaware River Basin Commision: Water sampling also has very limited coverage on the Delaware river where 1 sample represents 6 miles of water
3. Philadelphia Water Department: Water sampling is only done at the surface although multi-depth sampling would be extremely beneficial
4. Aquasol Fish Farming Consultants: Parameters like Dissolved Oxygen (DO) vary drastically with depths and fish is dying because there are no methods to closely monitor the DO levels

Following these needs, the team has concluded that the current sampling and measuring methods are temporally and spatially limited. With that, an ideal solution has 3 key characteristics: First, it can measure and sample at varying depths with customizable locations and volumes of water. Second, it should require low human intervention and has low variable and fixed costs. Third, it should be able to measure and sample multiple times a day.

An ideal solution should be able to produce one cross sectional map of 100 data points with a runtime of 4 hours. The Schuylkill River in Philadelphia has depth of 45 ft and the sampling volume should be 10 samples of 8L total. The samples should have a process to prevent cross contamination. An ideal solution would require only 1 person to operate it which required an autonomous user-set waypoint navigation and a real-time data transmission. Given that current solutions require about 4 hours of manual data input into the database, an ideal solution should be able to process and store data more efficiently. An ideal solution would consequently decrease the fixed cost to less than $3,000, as well as decrease the variable costs to less than $18 per measurement and $4.9 per sample.

The team has arrived to the following stakeholder characteristics:

Table 3. System characteristics, as dictated by stakeholders and environment constraints[10]

Category	Metric	Design Goal
Overall System	Fixed Cost	< $3000
	Cost per Measurement	< $18
	Cost per Sample Metric	< $4.9
	Weight	153 lb
	Dimensions	2m W x 2.4m L
	Runtime	<= 4hr
Environment	Width	2200m
	Depth	45 ft
	Current flow rate	1.12m/s
Sampling & Measurin	Volume	2.5L - 8L
	Sample Metrics Covered	16 - 41
	Accuracy	1m^3 bounding box
	Location Accuracy	2m radius
	Decontamination	Rinse between samples
	Measuring Metrics	Customizable
	# of Measuring Points	100
	# of Samples	10
Usability	People Needed	1
	Data Transmission	Real-time
Control & Autonomy	Autonomy	User-set Waypoints
	Control	Manual available

These system characteristics were not arbitrarily selected. They objectives were set based on careful research of the environment, the stakeholder needs and the engineering standards. The team has arrived to the following needs:

1. The Delaware River spans a distance of 2,200m bank to bank. This environment requirement set the need for a specific control **range.**
2. The Delaware River reaches maximum depths of 45 feet. After careful water quality monitoring, the stakeholders have specified a need to monitor the changes in the water parameters up to the bed of the river. This environment requirement set the need for a specific **depth range** for sampling and measuring.
3. Fixed cost, cost per measurement, cost per sample metric should fit in the budget allocated to water-quality related projects per year and should be significantly lower than the current costs of $18 per measurement and $4.9 per sample metric.
4. Only 1 person should be needed during operations, given that over 50% of the current cost is driven by labor cost.
5. The users need to be able to select where the samples and metrics need to be collected. This requires the solution to be **waypoint**-guided with manual control available in cases of emergency.

6. The current solution employed by DRBC generates a water parameter map in under 4 hours, thus making this **time per trip** a maximum threshold for our objective.
7. The solution needs to be tailored to the users. The stakeholders interviewed use a very common pick up truck which would provide the required **dimensions** an ideal solution should stay under in order for it to be transportable and easily deployable
8. The Delaware river reaches maximum velocities of 1.12 m/s, this provided a **current flow rate** from which our objective sets a velocity of 3 knots for the system with a possibility to drive upstream
9. In order for the data to be relevant, the stakeholders require a **location accuracy** of 2m radius for the data to be beneficial to the water quality model
10. The stakeholders provided a list of 41 metrics or parameters that can be measured from sampling the water or **metrics covered**. In order to achieve all 41 metrics, 8L of samples should be collected in HDPE bottles. In order to achieve 16 metrics - the stakeholder minimum requirement - 2.5L of water should collected in 250mL HDPE bottles, which dictates both the **volume capacity** and the **number of samples**
11. The stakeholder require that the container of the samples be rinsed at least 3 teams before new samples are collected. This motivated a design of **decontamination** with an "exhaust" channel in the collection tray where excess water used to attenuate cross-contamination would be eliminated
12. The stakeholders require 10 points along the surface of the river, that is bank to bank from 0 to 2,200m, as well as 10 points in each column of water, that is from the surface to 45ft. This requires 100 **data points** of different parameters measured depending on the probe installed t a **customizable** probe mount

ENGINEERING STANDARDS

Ingress Protection

Ingress protection is divided into testing for ingress from foreign objects or liquids. As defined in international standard IEC 60529, it classifies the degrees of protection provided against the intrusion of solid objects, dust, accidental contact, and water in electrical enclosures [11]. The standard aims to provide users more detailed information than vague marketing terms such as waterproof.

The team aims to have a system that meets level 8. The electronics will need to be sealed in a container and be protected while immersed in water, because the entire system will be completely immerse beyond 1m in water. Water resistance is of crucial importance as it can cause electronic failures.

Table 4. Identification of the different levels of Ingress Protection

Level	Object Size Protected Against	Effective Against
0	Not Protected	-
1	Dripping Water	Dripping water (vertically falling drops) shall have no harmful effect
2	Dripping water when tilted up to 15°	Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle up to 15° from its normal position.
3	Spraying water	Water falling as a spray at any angle up to 60° from the vertical shall have no harmful effect.
4	Splashing water	Water splashing against the enclosure from any direction shall have no harmful effect.
5	Water jets	Water projected by a nozzle (6.3mm) against enclosure from any direction shall have no harmful effects.
6	Powerful water jets	Water projected in powerful jets (12.5mm nozzle) against the enclosure from any direction shall have no harmful effects.
7	Immersion up to 1m	Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under defined conditions of pressure and time (up to 1 m of submersion).
8	Immersion beyond 1m	The equipment is suitable for continuous immersion in water under conditions which shall be specified by the manufacturer. Normally, this will mean that the equipment is hermetically sealed. However, with certain types of equipment, it can mean that water can enter but only in such a manner that it produces no harmful effects.

Pennsylvania Waters With Special Boating Regulations

Since the team will be using our system in the Schuylkill, we must comply to the Pennsylvania Waters with Special Boating Regulations. The use of motors in excess of 10 horsepower is prohibited from Flat Rock Dam downstream to the Girard Avenue Bridge [12]. The operation of boats powered by internal combustion motors is prohibited.

The power source design is impacted by the type and horsepower limit specified in this engineering standards.

OSHA/NIOSH

According to the Occupational Safety and Health Administration (OSHA), workers must limit the weight they lift to no more than 50 pounds. When lifting loads heavier than 50 pounds, use two or more people to lift the load. The National Institute for Occupational Safety and Health (NIOSH) has developed a formula for assessing the hazard of a lifting situation. The formula looks at the following elements involved in the lift: distance the load is held in front of the body, height the load is lifted from and to, height of the load[13], frequency of lifting, the hand load coupling, and the amount of torso twisting that is involved with the load lifting motion. Using these parameters NIOSH, has established that, for occasional lifting where the load is held close to the body, with no twisting, and at about waist height and where the load has good hand holds, the typical industrial worker could lift about 51 pounds without a significant increase in risk of injury. [14]

The team planned to manufacture a system that would not exceed 3 people in order to transport the boat, giving us a maximum weight of 153 pounds.

DESIGN AND REALIZATION

SYSTEM FORM

Design

Hull

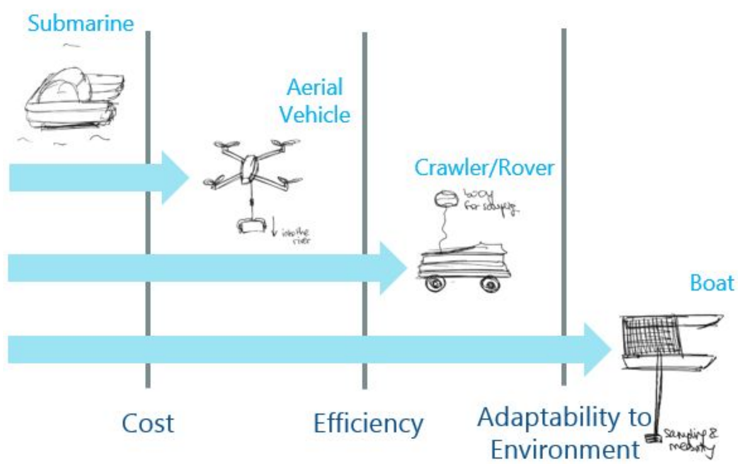


Figure 16. System Form Down-Selection

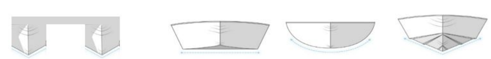
In brainstorming for solutions to our stakeholders' problems, we settled on 4 possible forms for our solution. A submarine, an aerial vehicle (or a drone), a crawler (or a rover) and finally a surface vehicle (or basically) a boat. Since cost is a big concern for our stakeholders, we ruled out the submarine solution as the price exceeds more than 50 time our customers' budget. Looking into efficiency of the sampling and measuring trips as well as power consumption, something like a drone carrying large volumes of sample screams inefficiency. Next, another important criteria is the interaction of our system with the environment of the Delaware and Schuylkill Rivers. Something like a crawler or rover with a floating buoy is very prone to collisions and entanglements at the bottom of river (especially with large mountains of silt, vegetation, algae). This leaves us with the final form of a surface vehicle – a catamaran-like boat – this is when S.S. MAPR was born.

Table 5. Detailed System Form Down-Selection

Metric	Boat	Rover	Submarine	Drone
Cost*	5	5	1	4
Efficiency	**5**	5	5	2
Deployment Regulations	5	5	4	1
Data Quality	5	4	5	3
Ease of Use	**4**	4	3	3
Obstacle Avoidance	**4**	1	3	4
Total	**56**	**45**	**40**	**44**

To make the transition to deploying S.S. MAPR easier for users, the system was had to be equal to or smaller than the current equipment in operation. Most researchers go out into the water in small motor boats that fit in a standard pickup truck. This limited the size of the vessel to a maximum of 1.75m by 2m. Further design decisions led to the final system form of a catamaran vessel. Several different shapes were evaluated based primarily on draft, which would affect the speed and propeller power, and stability which would protect the sample bottles, as shown in Table 6. Additional criteria that were considered were adaptability, amount of power required, and the turning area of the hull shape.

Table 6. Hull Shape Downselection



Metric	Weight	Multi-Hull	Flat Bottom	Round Bottom	Deep Vee
Draft	2	3	5	3	1
Stability	5	**5**	2	1	3
Adaptability	3	3	1	3	3
Power	4	3	3	3	2
Turning Area	2	**2**	5	5	5
Total		**56**	**45**	**40**	**44**

A multi-hull vessel was the most appropriate choice, as it is the most stable and has a shape that allows the sampling mechanism to be easily mounted onto without drastically altering the center of gravity of the entire system.[15]

Lid

To protect all components from splashing and consequent water damage, a rigid lid was designed to cover the entire deck, as shown in Figure 11 in *Executive Summary*. In this lid, two fans and an opening for the exhaust were included to provide sufficient air flow for the generator. To determine the flow rate needed, the heat output and air intake of the generator were analyzed.

In order to make sure that enclosing a generator in a closed space meets all safety requirements, the team has taken the following measures:

- Fresh air intake for the generator guaranteed with a 308 CFM fan
- Cooling fan guarantees lowering internal temperature and the heat generator by the body and exhaust of the generator, 72 CFM
- Exhaust duct ensures mass flow outside of the lid

Realization

Due to time and monetary restrictions, the team decided not to fabricate the hulls and purchased off-the-shelf pontoons. In order to support this decision, the following criteria were verified for off-the-shelf pontoons: Buoyancy, Von Mises Stresses, Size, Mass and Required Thrust. Another important criteria to verify is the stability of the catamaran. In order to do that, the heeling angle was calculated and plotted.

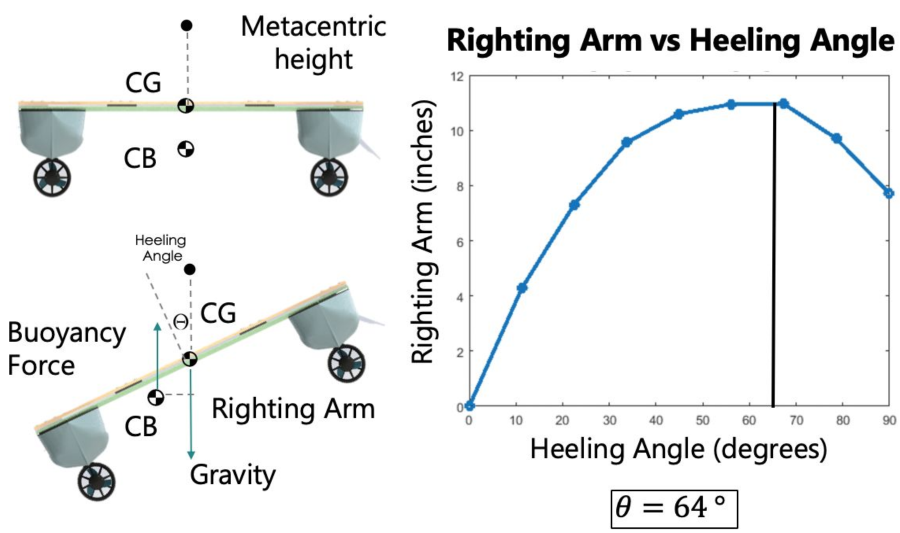


Figure 17. Stability analysis: righting arm vs heeling angle

The boat guarantees a heeling angle of which is well under the wave heights as dictated by the environment conditions.[16]

The lid was constructed out of extruded polystyrene (XPS) foam and coated with carbon fiber and epoxy resin for reinforcement. Large sheets of XPS foam were stacked and carved to obtain the general form, and then the foam was sanded to smooth out rough corners and edges. A layer of epoxy was applied then sanded in preparation for the carbon fiber. Two long sheets of carbon fiber were positioned on the foam and multiple coats of epoxy were applied and sanded for a smooth, even finish. Figure 18 shows the materials used.

Figure 18. Lid Fabrication Materials

TASK FUNCTIONS - SAMPLING

Design

An average trip across a river approximately 2,200 m wide takes water scientists four hours with current sampling methods. The goal for S.S. MAPR is to be able to collect samples and take measurements at a maximum of ten points across the river and ten points into the river, which would produce a 100-point cross sectional map. The allowable accuracy of these functions is one meter in all directions. To achieve this in an environment with currents of 1.12m/s, S.S. MAPR needs a minimum speed of 1.12m/s and to be able to reach higher speeds. With a target relative speed of 1.3m/s, the the total time for travel to each sampling point was calculated to be 47 minutes. This allows the system to execute task functions in 193 minutes. Assuming that each point along the width of the river would take the same amount of time for task functions means that there are 19.3 minutes to collect samples and take measurements at each point. These time constraints informed the team's decisions on the system design.

The team considered several mechanisms/methods for obtaining water samples. Submersible centrifugal pumps, non-submersible centrifugal pumps, van dorn samplers, and actuated syringes were assessed based on the weight, volume capacity, amount of effort required for waterproofing components, and ease of cleaning. As shown in Table 7, the submersible pump was the most appropriate choice, as this would minimize the weight of the subsystem and time for sampling, while allowing the system to collect a large volume of samples.

Table 7. Sampling design down-selection

Metric	Submersible Pump	On-board Pump	Van Dorn Sampler	Actuated Syringes
Weight	3	1	2	4
Required Waterproofing	4	4	4	3
Ease of Cleaning	4	4	3	2
Volume per Trip	4	3	2	1
Total	**15**	**12**	**11**	**10**

The time constraint of 193 minutes motivated the design decisions with regards to the pump flow rate and sampling tube size. In varying the tube diameter, we vary the flow rate. The decision is bounded by 3 constraints:

1. Friction: A tube of 0.5 inches or less wastes more than 50% of power due to large friction forces
2. Flow rate: given the stakeholder specific need of samples, the minimum flow rate is 3 L/min
3. Space: given the size constraint of the boat, the tube needs to be compact with a minimal radius of curvature

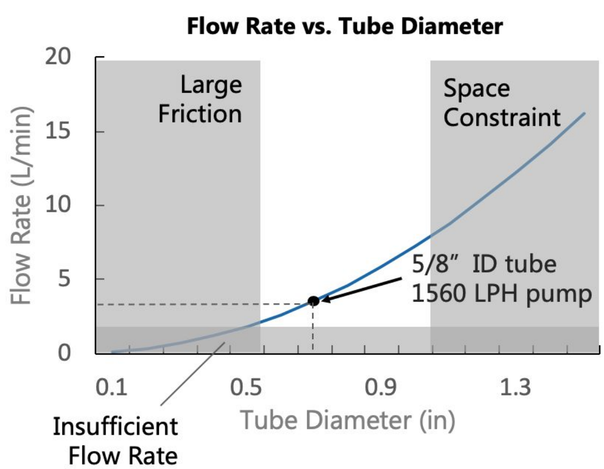


Figure 19. Tube & Pump Selection

Based on that, we chose a 5/8” ID tube. Leaving us with a flow rate of 162 LPH. Taking cost, flow rate and a minimum 45ft head into account, we selected our 1560 LPH pump

First, the minimum flow rate required would be the total volume of water passed through the system in 1.93 minutes, the time calculated for one sample. This was calculated to be 0.031L/s based on the following equation:

$$q_{min} = \frac{volume}{115.8\,s} = 0.031\ L/s \tag{1}$$

The velocity v of water inside the tube was also calculated with an assumption that friction would reduce it by 50%, and this value was 0.237 ft/s.

$$v = 50\% \cdot \frac{55\,ft}{115.8\,s} = 0.237\,ft/s \tag{2}$$

The relationship between tube diameter and volumetric flow rate is shown in equation 3, with the diameter in millimeters squared, the velocity in feet per second, and flow rate in liters per minute.

$$d^2\,(mm^2) = \frac{21.22}{v\,(ft/s)} \cdot q\,(LPM) \tag{3}$$

The pipe friction loss was calculated using the following variables:

- Reynolds number (*Re*)
- Relative roughness (*RR*)
- Swamee-Jain friction parameter (*f*)
- Darcy Friction Factor (*FF*)

The Reynolds number can be calculated using the velocity (in meters per second), tube diameter (in mm), and kinematic viscosity (in centistokes), as in equation 4, and this also determined whether the flow was laminar or turbulent.

$$Re = \frac{1000 \cdot v\,(m/s) \cdot d\,(mm)}{v\,(cSt)} \tag{4}$$

The Re values were less than 2300, which is the value at which flow is no longer laminar. The Swamee-Jain and Colebrook Equation friction parameter can be found below:

$$f = \frac{64}{Re} \tag{5}$$

$$f = 0.25 / (log_{10}\,(\frac{\varepsilon\,(mm)}{3.7 * d(mm)} + \frac{5.74}{Re^{0.9}}))^2$$

This is used in the Darcy-Weisbach equation, equation 6, to find the Darcy friction factor. The velocity (v), tube diameter (d), and gravity (g) are used to calculate the friction factor.

$$FF = 100,000 \cdot f \cdot \frac{v^2}{2\,d\,g} \tag{6}$$

With this friction factor, the pipe friction loss can be calculated using equation 7 for the tube length of 55 feet.

$$Friction\ loss = \frac{FF \cdot tube\ length}{1000} \tag{7}$$

With our pulley system, an important factor for selecting a motor is determining the amount of torque that we will need to be able to withstand. Our maximum torque will be the scenario in which we are lifting our sensors, pump, and tube vertically upward at the maximum depth. The DC motor requirements were calculated based on a static and dynamic analysis of the forces and moments:

$$\Sigma M = -\tau + 0.5\, Mp\, R^2\, \bar{\theta} + (m_t + m_p + m_s)\, g \tag{8}$$

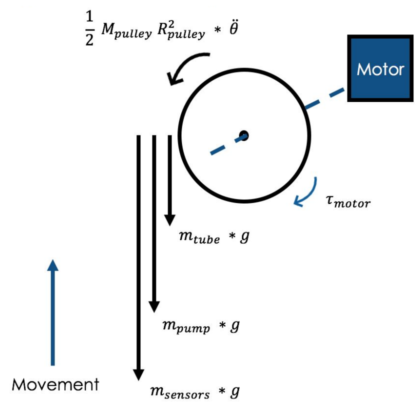


Figure 20. Motor design decision, free body diagram

Given the stakeholder time constraints, the RPM was calculated based on the allowable time for lowering and lifting the pump and probe. As for the torque, the forces were analysed in the worst case scenario where drag and weight both contribute to the torque on the motor while still allowing the later to brake at a specific depth in the column of water. After applying a safety factor of 3, the motor torque needed is at least 250 lb-in.

Realization

The sampling subsystem was tested to ensure that all ten 250mL bottles could be filled up in the 19.3 minutes calculated previously. The reel and DC motor were mounted on a test rig and the pump was lowered directly below at 5 ft intervals. At each depth, the time to fill up 250 mL was measured and found to be within 5% of the theoretical calculated values. This led to approximately six minutes at each point for ten samples at varying depth, which was significantly less than the 19.3 minutes anticipated.

The DC motor is controlled through mbed with a DC motor driver that contains a high current H-bridge with PWM speed control, as shown in Figure 21. A depth sensor is used to measure the depth of the pump, which is used as a feedback for the motor to actuate and stop. The depth sensor was designed according to the accuracy required by stakeholders, which is described in further detail in the next section.

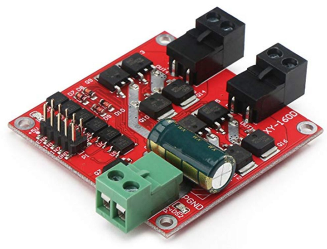


Figure 21. DC motor driver [17]

Pump and valve are controlled through a MOSFET: IRLB8721. The pump and valve positive ends are both connected to the source terminal, and the drain terminal is connected to 28V and 12V, respectively. During operations, mbed gives a high digital signal to the gate terminal to connect the drain and source terminals of the MOSFET, thus powering the pump and valve.

One issue that we ran into during implementation was that there was a significant voltage drop along the 50ft wire. We measured the resistance along the wire to be 1.5 ohm. At a current of 2.22A, this amounts to 3.3V voltage drop. So we increased the voltage input from 24V to 28V, and added a voltage regulator underwater next to the pump power input to ensure constant 24V voltage supply for the pump.

TASK FUNCTIONS: MEASURING

Design

Currently employed methods of measuring different metrics in the water are mostly multi-probe sondes. However, these the cost of these sondes far exceeded the budget of the team, and several key metrics were chosen to be measured. Out of the numerous parameters scientists measure to determine water quality, the team decided to measure specific conductivity, as it has a large spatial variation which would be easily discernible. Moreover, specific conductivity indicates salinity levels, which are causing concern as they rise at river mouths.

A very important part of the measuring function is ensuring that the probe and pump stay within a $1m^3$ cubed bounding box as instructed by our stakeholders. In terms of the vertical error, the depth sensor resolution and accuracy was selected to ensure the measurement happens within the $\pm 0.5\ m$ vertical error. However, in terms of the horizontal error caused from currents, the goal is to decrease the angle theta *(see Figure 22)* by adding a sounding weight.

$$\Sigma F_x = \frac{1}{2} \rho v^2 C_D A - T \cos(\frac{\Pi}{2} - \theta) \tag{9}$$

$$\Sigma F_y = T \sin(\frac{\Pi}{2} - \theta) - mg \tag{10}$$

$$\tan(\frac{\Pi}{2} - \theta) = \frac{mg}{0.5 \rho v^2 C_D A} \tag{11}$$

$$\pm x = \sin(\theta) * depth\ of\ pump \tag{12}$$

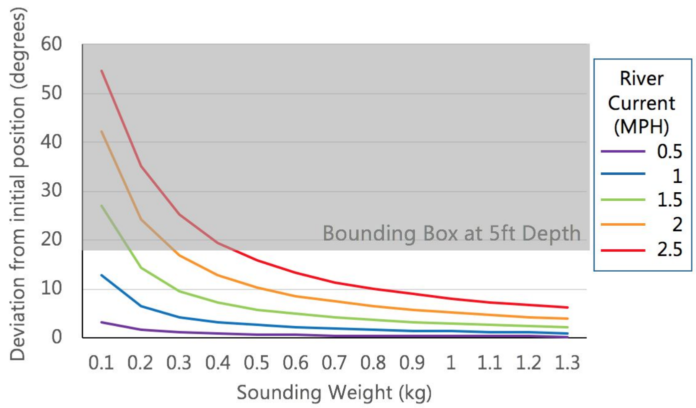


Figure 22. The position accuracy is dictated by the stakeholder bounding box

The user interface would provide the user with the needed sounding weight to stay within the threshold of error. The sounding weight selected is affected by the depth and the current.

Realization

The probe, shown in Figure 23 has 0.01mS/cm precision and accuracy of ±0.05mS/cm[18], which was verified through testing with calibrated solutions. To ensure the accuracy of the measuring and sampling unit, the required accuracy is one meter, which led to the decision to use the Blue Robotics Bar30 depth and temperature sensor. The sensor, shown in Figure 33 has 2 mm precision and ± 2mm accuracy.[19]

Figure 23. Probe and Depth Sensor

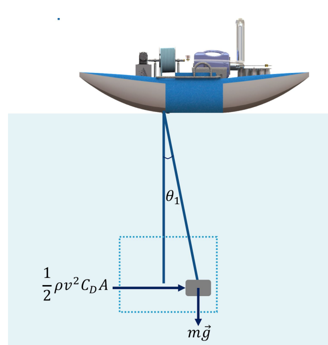


Figure 24. Bounding box required for measuring probe

The depth sensor sends back data to mbed through I2C. To ensure data quality of the depth sensor, a boosting and filter circuit was added to the I2C bus of the depth sensor, as shown in Figure 25 (a) and (b).

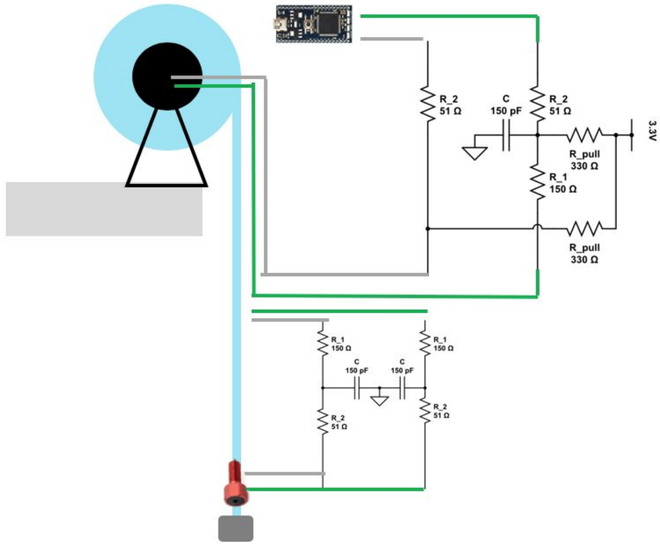


Figure 25 (a). Boosting and Filter Circuit for Depth Sensor

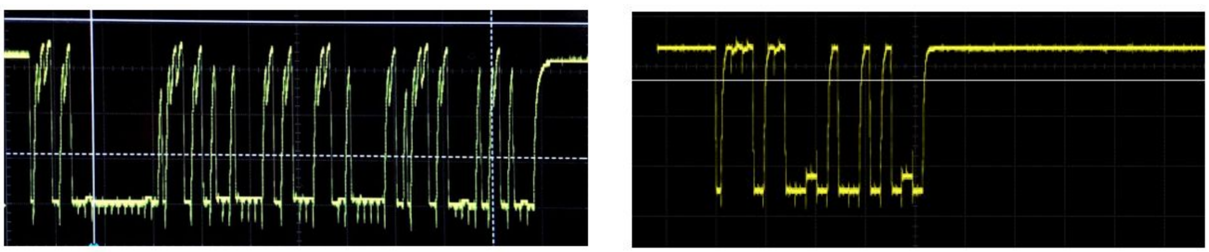


Figure 25 (b). Depth Sensor Data Transmission, with & without Boosting and Filter Circuit

During operations, the probe sends back data to mbed through analog input. It was found that mbed internal ADC was very unstable, so an external ADC (analog-to-digital converter), MCP3202, was added to reduce the noise.

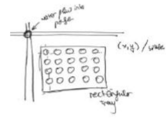
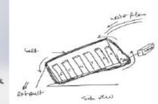
TASK FUNCTIONS: COLLECTION

Design

The system required a container to hold the water sample bottles securely in a spatially efficient manner. The collection tray would hold ten 250mL bottles and guide the flow of water into each bottle while preventing sample contamination due to open containers. Additionally, minimizing the number of actuators would reduce the weight and cost of the subsystem.

Four different configurations were considered for collection tray design, as shown in Table 8.

Table 8. Collection Tray Down-selection

				
Metric	Rotating Tray	Cartesian Tray	Incline Tray	Conveyor Tray
Cost*	4	3	2	3
Space	3	4	1	2
Free from Error	4	4	4	2
Feasibility in Time Frame	1	0	1	0
Total	**12**	**11**	**11**	**7**

**Score 5 means cheapest*

A rotating tray would require one motor and enough space for a single large cylindrical container, while a Cartesian tray would require two actuators and potentially more surface area. An inclined tray relies on gravity to guide the water into the bottles, but it would need several actuators to control the bottle openings and take up a lot of height for ten bottles. A conveyor tray was the least ideal option, as it would require a belt to move samples bottles, which was prone to contamination of samples and falling bottles.

The stepper motor was selected based on the torque required to actuate the upper tray. This of course depended on the material used, which would affect moment of inertia:

$$\tau_{motor} = (0.5\, M_{tray}\, R^2_{tray}) * \bar{\theta} \tag{13}$$

Realization

The collection tray was designed to have 11 sections total, ten for each sample bottle and one for exhaust flow. The lid is a rotating plate with a fitted brass adapter which was connected to the sampling subsystem. For each sample, the lid is positioned so that the adapter is directly above the designated bottle, and then water is pumped through the reel and valve into the bottle.

Multiple revisions were made from the initial prototype to accommodate user concerns and improve performance. The first prototype was constructed of medium density fiberboard, aluminum standoffs, and a stepper motor, as shown in Figure 26. The shortcomings of this prototype exposed the sample bottles to contamination, provided little support for the bottles when they were full, and made the tray susceptible to water damage because of the material choice.

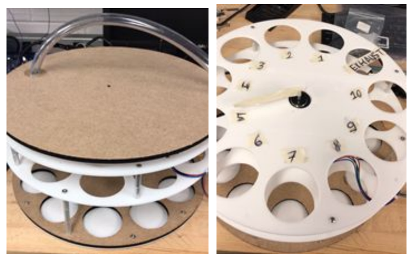


Figure 26. Collection tray first prototype

The next revision was constructed of laser-cut acrylic and polyvinyl chloride (PVC) pipes. As shown in Figure 27, the revision protected the samples from contamination by encasing the bottles in the PVC pipes, and a bottom plate with slots for excess water supported the bottles well. With an increase in the lid density, the motor experienced more stalling, so the stepper motor was replaced by a higher torque stepper motor. Finally, the tray was put over a perforated steel plate that was put over a large opening in the deck of the vessel, and the gaps between the PVC pipes were covered with a nylon tarp to prevent water from infiltrating the deck.

Figure 27. Collection Tray Second Prototype

After conducting user testing, a biggest feedback was to focus on the importance of the lock mechanism. The goal was to reduce the number of screws needed for the user to access the samples faster and more efficiently. The final revision included a simple lock mechanism that snaps in and requires no screws for access.

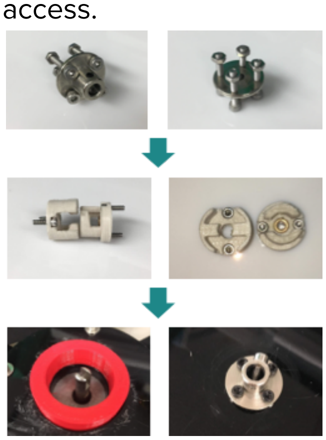


Figure 28. Lock mechanism iterations

The stepper motor is controlled by mbed through the stepper motor driver, TB6600. The motor is controlled with 1/16 microstep to ensure that it accurately reaches the designated bottle.

Figure 29. Stepper Motor Driver TB6600[20]

ACTUATION & CONTROL

Design

Processor Selection

For the overall hardware architecture, we decide to use two processors, a main computer and a microcontroller, in order to separate the more demanding computing tasks of autonomous navigation and overall mission control from the low-level motor controls, as is shown in Figure 30.

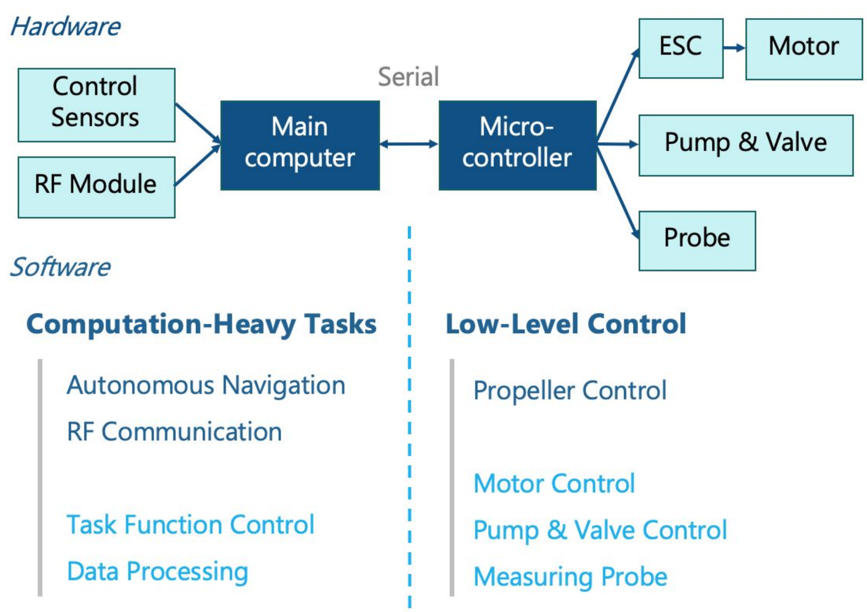


Figure 30. Overall hardware and software architecture

For the main computer, there are 4 main criteria. Most importantly, we need to lower the cost in order to hit the overall low-cost target required by our stakeholders. Aside from that, we need enough storage capacity and computing power for the autonomous navigation and control algorithm.

Table 9. Main computer down-selection

Metric	Weight	Raspberry Pi 3	ODROID XU 4	NVIDIA Jetson TX2	STM32 Micro-controller
Cost*	5	5	4	1	5
Storage Capacity	3	3	4	5	1
Computing Power	4	3	4	5	1
Power Requirement	4	5	4	3	5
Total		66	64	52	42

**Score 5 means cheapest*

We considered 4 options for the main computer, as is shown in Table 9. We used a weighted score for each criteria, with 5 being the most desirable, for down-selection.

1. **Raspberry Pi 3B**: Raspberry Pi has medium computing power (64-bit quad core processor running at 1.4GHz). It can run Linux, which means the low-level drivers have better support. Its RAM (1GB) is barely enough for real-time image processing - previous research have shown that an OpenCV deep learning project can only run on Raspberry Pi 3B at ~0.5fps.
2. **ODroid XU4**: ODroid is more friendly for image processing, which comes with Samsung Exynos5422 Cortex™-A15 2Ghz, Cortex™-A7 Octacore CPUs with Mali-T628 MP6 GPU, and a larger RAM (2GB). It's also only slightly more costly than Raspberry Pi - with a price tag of $62.
3. **NVIDIA Jetson TX2**: TX2 is super powerful with 256 core NVIDIA Pascal GPU, ARMv8 (64-bit) Multi-Processor CPU Complex and Advanced HD Video Encoders. But the cost is ~$300 at student discount.
4. **Microcontroller (STM32)**: STM32 microcontroller has enough computing power (>= 96MHz), but they don't have enough storage for image processing. What's more, since we need to configure the real-time OS on STM32, we also need to configure the low-level drivers for GPIO, Serial and sensors on our own.

We initially chose to use ODroid XU4, in anticipation of the potential need to use image-based autonomous navigation. Due to some issues found during implementation, which will be specified in the *Realization* section, we decided to switch to Raspberry Pi 3 as the main processor.

Table 10. Microcontroller down-selection

Metric	mbed LPC1768	Pixhawk	ATMega328P
# of PWM Pins	5	5	5
Library & Driver Support	5	5	2
Cost*	5	3	5
Customizability	5	3	3
Total	20	16	15

**Score 5 means cheapest*

For the microcontroller, there are 4 main criteria, as is shown in Table 6. Since the microcontroller is mainly used for low-level control, it needs to have enough PWM pin numbers. What's more, it needs to come with good library and driver support. Aside from that, we still have the cost constraint coming from stakeholders. Last but not least, customizability is considered due to the potential of switching and/or adding sensors to the microcontroller. The following microcontrollers are considered:

1. **Arduino**: Arduino comes with 6 PWM output pins which could meet our needs. With ATMega328P as the main processor on board, Arduino has 16MHz clock speed and 2KB RAM. Arduino comes with good library support. However, we need to use real-time OS to ensure low latency, and the computing power of ATMega328P puts an upper limit of how fast and accurate it runs. The real-time OS is also not very well supported for ATMega328P. As for cost, We can get it for free from Penn Detkin Lab. Arduino libraries have limited customizability.
2. **Pixhawk**: With STM32F427 onboard, Pixhawk runs at 180MHz and has a RAM of 256KB. It has 8 PWM outputs and also comes with library support for UART. What's more, it embeds IMU and GPS. Cost is $72. Customization can be achieved by modifying the existing open-source codebase, but the available documentation is limited for customization.
3. **mbed LPC1768**: It is based on the NXP LPC1768, with a 32-bit ARM Cortex-M3 core running at 96MHz with 32KB RAM. It is not as powerful as Pixhawk, but it has 6 PWM output pins and 3 Serial ports, which is sufficient for our purpose. The platform comes with many open-source libraries which are easy to customize. It costs $55, but we can get it for free from Detkin.

We used a score for each criteria, with 5 being the most desirable, for down-selection. We chose to use mbed LPC1768 as the microcontroller, given the easy accessibility, superior library supports and customizability.

Propeller Selection

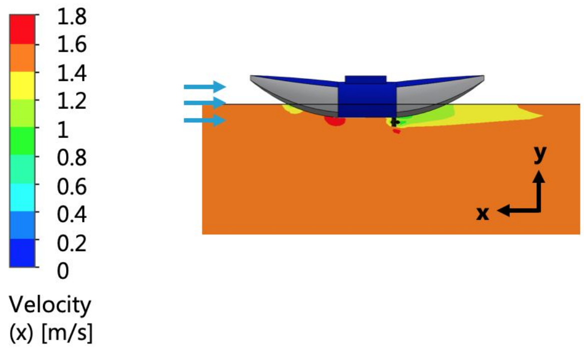
We chose between two waterproof propellers: Blue Robotics T100 and T200. In order to choose the right one, we need to quantify the required propulsion in order to meet the stakeholder target runtime requirement.

Considering the average current speed of 1.12m/s, the boat should navigate at a speed higher than river currents in the worst case scenario of driving against the current. To meet the runtime requirements from the stakeholders, the boat's relative velocity to the river should be at least 1.3m/s.

To translate the speed requirement to required propulsion, we need to use the following equation: the relationship of speed and drag.[21]

$$F = \frac{1}{2}\rho v^2 C_d A \qquad (14)$$

Where ρ is the fluid density, v is the boat speed relative to the fluid, C_d is coefficient of drag, and A is the surface area of the boat in contact with the fluid. We got a theoretical C_d of .0378 through Computational Fluid Dynamics (CFD), as shown in Figure 31. The range of C_d for typical hulls is 0.03 - 0.055.[22] This helps us confirm our simulation.



$C_d = 0.0378$

Figure 31. Computational Fluid Dynamics

Using the C_d value found and the equation, we plotted the relationship of the total thrust needed for the boat's relative velocity to the moving water, as shown in Figure 32. The green region on the right meets our requirements. Then, using the datasheets of the two propeller candidates, we found the thrusts that can be provided. The maximum thrust of two T200 is 90N, while the max thrust of two T100 is only 42N. Therefore, we chose to use 2 Blue Robotics T200 propellers.

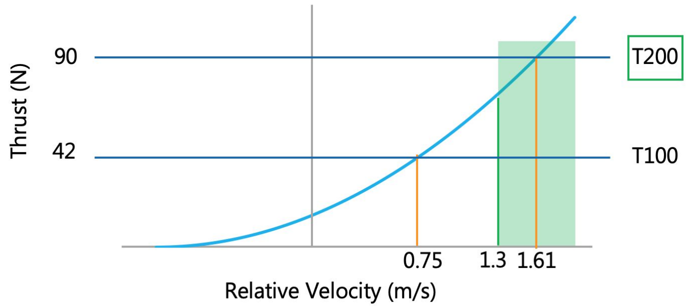


Figure 32. Total thrust vs. relative velocity to current

Remote Control Sensor Selection

The sensor for remote control was chosen based on two criteria, as shown in Figure 33:

1. Based on the width of the river sites required by stakeholders, the communication range should be at least 2200m[23], so LoRa modules are ruled out due to small range.
2. The latency for control is expected to be at most 10 milliseconds. So 4G LTE modules are ruled out due to its latency of around 100ms. [24]

Therefore, XBee is chosen given the large range and short latency. [25] [26]

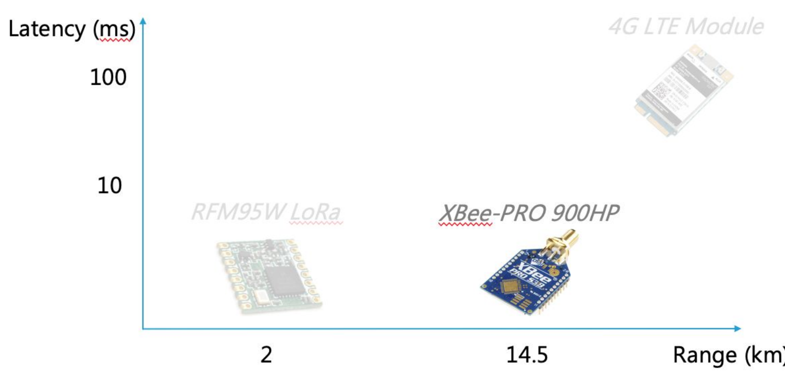


Figure 33. Remote control sensor down-selection

Realization

Benchtop Propeller Control

The remote differential control of the two propellers was implemented at benchtop. The deliverable was to use XBee to control the two propellers remotely through the laptop, and the propeller is controlled through ESC by mbed. Through this test, we were able to implement the code for each interface (XBee, main computer, microcontroller) and make sure all the interfaces in remote control work together. Figure 34 (a) shows the actual experiment setup and Figure 34 (b) shows the circuit block diagram.

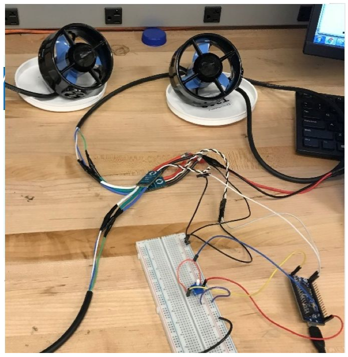


Figure 34 (a). Experiment Setup

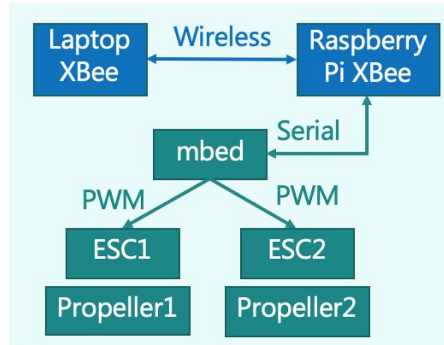


Figure 34 (b). Circuit Block Diagram

Pool Remote Control

After benchtop propeller control, we put the subsystem in a waterproof electronic box, put it on the boat and tested it during the weekly Pottruck Pool tests from Jan.31 to Feb.21. Through those tests, we were able to identify many implementation issues related to the system and improve the reliability and robustness. During the last pool test, we finished the final prototype of the actuation & control subsystem and confirmed its reliability. We also tuned the PWM levels needed for the boat to drive in a straight line, which was later used for the implementation of Autonomous Navigation subsystem.

Four main implementation issues were encountered and solved during the implementation stage:

1. **Electronic wirings & organization**: During the first pool test, one of the biggest issues was that there were many wires and components in the electronic box, and they got entangled together very easily which led to many unnecessary debugging. Starting from the second test, we fixed the components to the box, soldered almost all permanent connections, and used molex to a perfboard for all components that needed to be removed from the box for development. During the third test, we further improved it by adding a laser cut mount and fixated the pin assignments for left and right propellers to facilitate the debugging process.
2. **XBee inconsistency and code robustness**: The XBee communication was very unstable at first due to the loose connections of the adapters used and the incomplete messages that could lead the programs to crash. We fixed this by including a message check procedure at the receiving end and by fixing the XBee to the adapter.
3. **Main processor switch**: We initially used ODroid XU4 as our main processor in anticipation of the potential need for image processing. However, during the implementation stage of the power source, we found that ODroid has very high requirements for startup voltage stability, and it also has high power needs (5V, 4A at startup). We fixed that by setting the voltage regulator output to be slightly higher than 5V. During the second test, however, a small fluctuation in the startup voltage burned the ODroid module. After that, we decided that Raspberry Pi is a better option for the prototype given that we decided not to use camera as the sensor input. It's also designed to be more robust during startup stage and it has a lower power need (5V, 0.5A). Therefore, we switched to Raspberry Pi after the second test.

Propeller Mount

The propellers were first attached to the boat by sewing them to the boat. This was the simplest way to attach the propeller to the soft pontoon body. We had planned to test the remote control in Pottruck Pool starting Jan.31 so this was set up in order to be ready for the test and figure out any issues that might come up with this design.

After the first Pottruck Pool test, we realized that the propeller would bend backwards due to the soft connection with the pontoon body, as shown in Figure 35 (a). So an acrylic board was added at the bottom of each pontoon to support the propeller mount. Subsequent tests confirmed that the propellers maintain vertical to the connection surface during actuation (Figure 35 (b)).

Figure 35 (a).
Propeller Position with Soft Mount

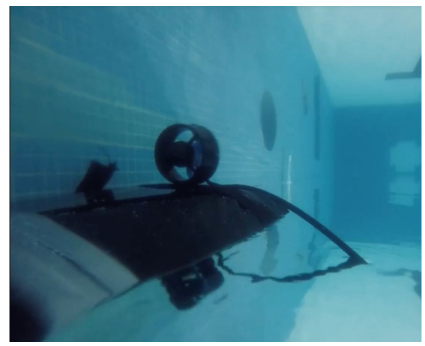


Figure 35 (b).
Propeller Position with Acrylic Mount

AUTONOMOUS NAVIGATION

Design

Localization Sensor Selection

For the localization mechanism, there are 5 main criteria: cost, feasibility, computing power & pre-processing, accuracy, environment knowledge.

1. The first two criteria come from stakeholder needs.The cost of the sensor needs to lie within the low-cost requirement of our stakeholders, and the sensor should be feasible to use at the designated sites from stakeholders.
2. The last three criteria come from implementation needs. The computing power and preprocessing need to be feasible for our main computer, while achieving sufficient accuracy and environment knowledge to localize. Specifically, the localization and control accuracy required by stakeholders is within 10m radius around the target point.

We use inertial navigation system (INS) as the foundation for localization. INS is a navigation aid that uses a computer, motion sensors (accelerometers), rotation sensors (gyroscopes) to continuously calculate by dead integrating the orientation and the velocity (direction and speed of movement) of a moving object without the need for external references. It has been widely used for boat localization since WWII.

However, a stand-alone INS suffers from drifting. We need other sensor inputs to correct for the drifts over time. We considered 3 sensor options. A weighted score for each criteria, with 5 being the most desirable, is used for down-selection, as is shown in Table 11.

1. **GPS + Digital Compass**: GPS is the most commonly used input to calibrate INS, used to correct for the accumulated translation error of INS. Digital compass, or magnetometer, is used to correct for the accumulated rotational error of INS with the actual heading of the boat. Based on previous research, an INS-based GPS-aided navigation system, with integration done with Kalman Filter, can achieve an accuracy of 0.5m in still water surface, while a GPS + IMU + Digital compass navigation system, with integration done with Kalman Filter, can achieve an accuracy of 3m in strong wind conditions[27]. Both of these lie within the required accuracy, with a combined cost of <$50.
2. **RTK GPS:** RTK GPS involves a GPS module on boat and an onshore base station. It can achieve an accuracy of <1cm, but it comes at a price tag of $600+. [28]
3. **Stereo vision**: Stereo vision has been used to correct for INS and GPS data by matching static hazards with fixed labels on a reliable pre-provided global map. This is commonly used in maritime environments, where an updated global map like Digital Nautical Chart is readily available. However, for the sites that S.S. MAPR will operation in, such maps aren't available, and there are also fewer fixed obstacles to correct for GPS/INS input. What's more, stereo-vision-based localization requires large amount of computing power to reach the accuracy required, and the cost is usually $300+.

GPS + digital compass was finally chosen as the correction input to the INS due to its superior cost and amount of computing power needed.

Table 11. Localization sensor downselection

Metric	Weight	GPS + Digital Compass	RTK GPS	Stereo Camera
Cost*	4	5	1	1
Feasibility	3	4	4	2
Computing Power & Pre-Processing	5	5	5	1
Accuracy	3	3	5	3
Environment Knowledge	2	2	2	5
Total		70	65	34

**Score 5 means cheapest*

Localization Algorithm Design

The localization algorithm is implemented with a Kalman Filter. The uncertainty of each sensor input is accounted for in order to generate a good estimate of the boat location. Specifically, the filter first takes in linear acceleration and angular velocity data from IMU and conducts an action update to generate a priori state estimates. To correct for the drifting that could happen in action updates, the position and heading data from GPS and digital compass data is incorporated in the measurement update, which outputs the updated state and covariance. These two results are fed back to the filter to form a loop. Figure 36 shows the algorithm flowchart.

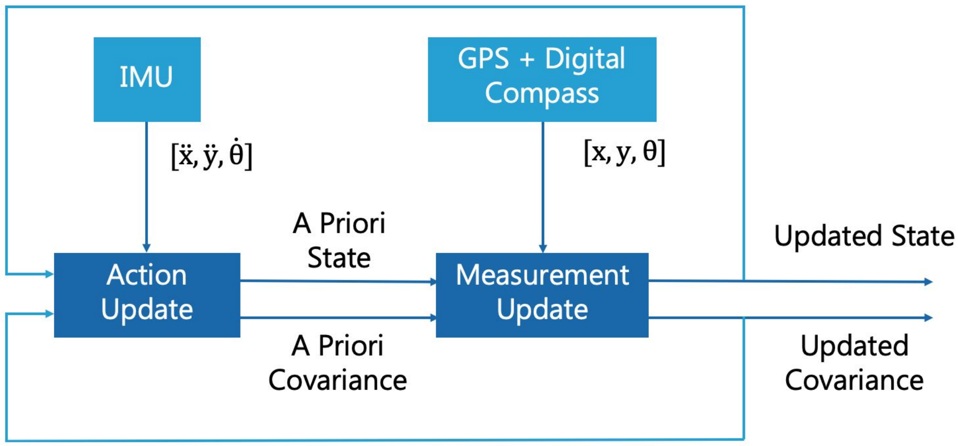


Figure 36. Localization algorithm flowchart

The control system is modeled as a linear system:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k+1) + \epsilon \\ z(k+1) &= Cx(k+1) + \delta \end{aligned} \tag{15}$$

Where x is the state of the system, z is the measurement of the system, $\varepsilon \sim N(0, R)$ is the error in action update, $\delta \sim N(0, Q)$ is the error in measurement update. Specifically:

$$\begin{aligned} x(k+1) = \begin{bmatrix} x_w(k+1) \\ y_w(k+1) \\ \theta_w(k+1) \\ \dot{x_w}(k+1) \\ \dot{y_w}(k+1) \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 & T_s & 0 \\ 0 & 1 & 0 & 0 & T_s \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_w(k) \\ y_w(k) \\ \theta_w(k) \\ \dot{x_w}(k) \\ \dot{y_w}(k) \end{bmatrix} + \begin{bmatrix} \frac{1}{2}T_s^2 & 0 & 0 \\ 0 & \frac{1}{2}T_s^2 & 0 \\ 0 & 0 & T_s \\ T_s & 0 & 0 \\ 0 & T_s & 0 \end{bmatrix} \begin{bmatrix} \ddot{x_w}(k+1) \\ \ddot{y_w}(k+1) \\ \dot{\theta_w}(k+1) \end{bmatrix} + \epsilon \\ z(k+1) = \begin{bmatrix} z_x(k+1) \\ z_y(k+1) \\ z_\theta(k+1) \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_w(k+1) \\ y_w(k+1) \\ \theta_w(k+1) \\ \dot{x_w}(k+1) \\ \dot{y_w}(k+1) \end{bmatrix} + \delta \end{aligned} \tag{16}$$

During action update, the IMU input $u_w(k+1)$ is used to update the estimated state $\widehat{x}(k+1)$ and covariance $\Sigma(k+1)$:

$$\begin{aligned} \hat{x}(k+1) &= A\hat{x}(k) + Bu_w(k+1) \\ \Sigma(k+1) &= A\Sigma(k)A^T + R \end{aligned} \tag{17}$$

where:

$$u_w(k+1) = \begin{bmatrix} \ddot{x_w}(k+1) \\ \ddot{y_w}(k+1) \\ \dot{\theta}(k+1) \end{bmatrix} \tag{18}$$

During measurement update, the GPS and digital compass input $z(k+1)$ is used to update the estimated state $\hat{x}(k+1)$ and covariance $\Sigma(k+1)$:

$$
\begin{gathered}
K(k+1) = \Sigma(k)C^T(C\Sigma C^T + Q)^{-1} \\
\hat{x}(k+1)' = \hat{x}(k+1) + K(k+1)(z(k+1) - C\hat{x}(k+1)) \\
\Sigma(k+1)' = (I - K(k+1)C)\Sigma(k+1)
\end{gathered} \tag{19}
$$

where:

$$
z(k+1) = \begin{bmatrix} x_w(k+1) \\ y_w(k+1) \\ \theta(k+1) \end{bmatrix} \tag{20}
$$

In both action update and measurement update, the sensor uncertainty is accounted for using a covariance matrix. The matrices are initialized using the variance values shown on the datasheets. Additionally, the sensors have bias at 0 measurements which need to be subtracted from measurements. The IMU bias values were measured by placing the IMU flat on the table with the z value equal to 9.8m/s. The GPS and digital compass bias values were measured by comparing against the values output from an iPhone compass.

Control Dynamics

The dynamics of the boat is analyzed in order to design the control algorithm, as shown in Figure 37. There are 2 main types of forces: thrust (T) and drag (D). In Figure x, X_W, Y_W and θ_W refer to the world frame, while X_B, Y_B and θ_B refer to the boat frame. T_L and T_R refer to the thrusts of the left and right propellers, respectively. D_x, D_y and D_θ refer to the drag in the X_B, Y_B and θ_B direction. b refers to the distance from the center of gravity to each pontoon. v_c refers to the river current.

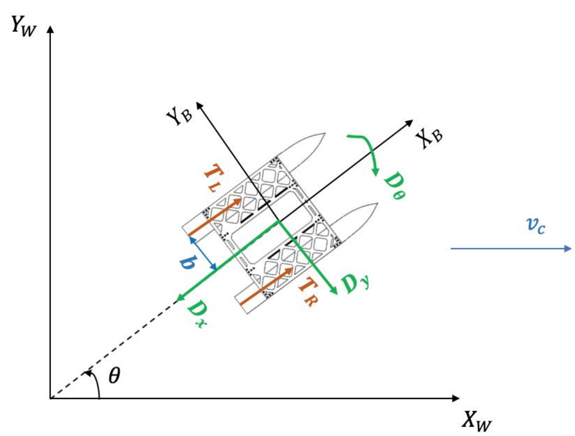


Figure 37. Dynamics Analysis

$$\begin{cases} \Sigma F_x = T_L + T_R + C_1(\dot{x_b} - v_c\cos(-\theta))^2 = m\ddot{x_b} \\ \Sigma F_y = C_2(\dot{y_b} - v_c\sin(-\theta))^2 = m\ddot{y_b} \\ \Sigma M_z = b(T_R - T_L) + C_3\dot{\theta_b}^2 = I\ddot{\theta_b} \end{cases} \Rightarrow \begin{cases} \ddot{x_b} = \dfrac{T_L + T_R + C_1(\dot{x_b} - v_c\cos(-\theta))^2}{m} \\ \ddot{y_b} = \dfrac{C_2(\dot{y_b} - v_c\sin(-\theta))^2}{m} \\ \ddot{\theta_b} = \dfrac{b(T_R - T_L) + C_3\dot{\theta_b}^2}{I} \end{cases} \quad (21)$$

The forces are analyzed along the X_B, Y_B and θ_B directions, as shown in equation (21).

Along X_B, there are thrusts and drags. The drag is modeled according to equation (14) with $C_1 = \frac{1}{2}\rho C_d A$ and the velocity in the equation uses the relative velocity of the boat to the water. $\ddot{x_b}$ refers to the linear acceleration and $\dot{x_b}$ refers to the linear velocity along the X_B axis. m refers to the mass of the boat. Along Y_B, there is only drag, similar to the previous case.

Along the θ_B axis, there are torques M_z caused by the thrusts and the rotational drag. The counterclockwise direction is considered positive direction. $C_3 = \frac{1}{2}\rho C_{ang} A$, as illustrated in equation (22), where ρ is the fluid density, ω is the boat angular velocity relative to the fluid, C_{ang} is rotational coefficient of drag, and A is the surface area of the boat in contact with the fluid.

$$F_{ang} = \frac{1}{2}\rho\omega^2 C_{ang} A \quad (22)$$

I is the momentum of inertia, as shown in equation (23) where C_4 refers to the proportion of mass that is b distance away from the center of gravity.

$$I = C_4 m b^2 \quad (23)$$

Then the values from the boat frame is converted to the world frame with a rotation matrix:

$$\begin{bmatrix} \ddot{x_w} \\ \ddot{y_w} \\ \ddot{\theta_w} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \ddot{x_b} \\ \ddot{y_b} \\ \ddot{\theta_b} \end{bmatrix} \quad (24)$$

This dynamics model is used to design the control algorithm and also used later in the simulation.

The linear and rotational coefficients of drag in the equations above are confirmed with experiments at Penn Pottruck Pool, as detailed in the Validation & Testing section.

Control Algorithm

There are two constraints for the control algorithm:

1. It's important for S.S. MAPR to keep itself at the same place during the operation of task functions. So the algorithm should both drive the boat and keep it at the same place as needed.
2. It should be able to control both forward and turning motion of the boat.

From the dynamics, we designed the PID control algorithm, as illustrated in Figure 38. We first calculate the angle error $\Delta\theta$ between the boat heading and the target, and then get the distance error from the boat position (x,y) to the target position (x*, y*). These two errors are fed into two

PID control loops. The first control loop represents the thrusts needed for the forward motion. It uses the distance error to calculate the sum of the two thrusts needed. The second loop represents the thrusts needed for the turning motion. It uses the angle error to calculate the difference of the right and left thrusts.

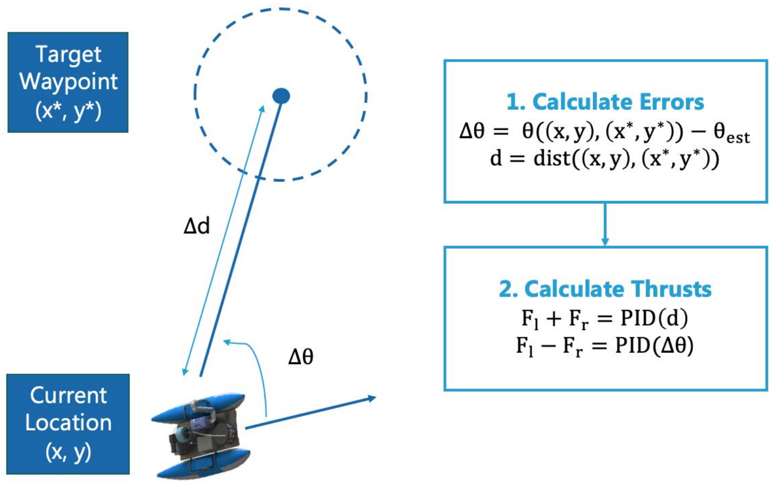


Figure 38. PID control algorithm illustration

To achieve constraint 1, i.e. to realize both path tracking and stop-point stabilization, we designed 3 control modes, as illustrated in Figure 39.

1. In the first mode, the boat is ready to leave from one stop point to the next, and the main goal is to correct the boat heading. Tuning of the PID is focused on twist control, and linear control is just used to cope with current drift. The first mode is switched to second mode if the moving average of the past 10 angle errors are smaller than a threshold.
2. In the second mode, the boat points at the next stop point and the main goal is to move closer to the next stop point. Tuning of the PID is focused on linear control, while keeping twist control to the minimum. The second mode is switched to third mode if the moving average of the past 10 distance errors are smaller than the 2m boundary.
3. In the third mode, the boat is within the 2m radius of the target stop point. The main goal is to keep itself within the 2m radius. The PID is focused on linear control, because turning should be kept to minimum to prevent disturbing the underwater equipment during task function. The maximum thrust is also limited to prevent over-reaction. The third mode is switched to first mode once the task function is finished.

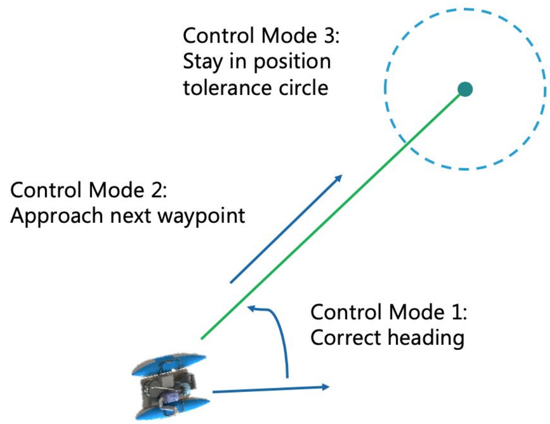


Figure 39. Control Modes

Realization

Simulation

The control algorithm is tuned in simulation with MATLAB, due to its easy transferability to our the implementation language on Raspberry Pi, Python. Simulation waypoints are chosen based on the testing site, Bartram's Garden Boat Dock, and the river current speed is also integrated into the simulation. The GPS, IMU and digital compass sensor inputs are simulated using a Gaussian distribution with the mean as the "real state" in the simulation and the covariance approximated with the values on the data sheets. Figure 53 shows the simulation output with waypoints, the boat trajectory and the localization output of the estimated locations.

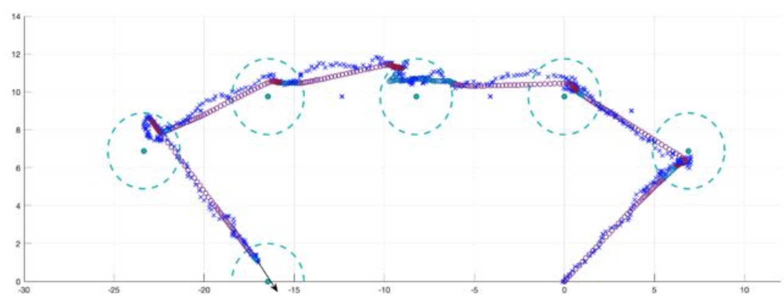


Figure 40. MATLAB Simulation Output

Implementation Platform

We first implemented the localization algorithm and a basic PID controller in MATLAB. Then we improved the control algorithm with the three-stage control mode and implemented it in MATLAB. After that, we tuned the parameters in MATLAB with the waypoints selected based on the testing site and probabilistic sensor inputs. The parameters could let the boat follow a pre-set path of waypoints and stop at each stop point. The codebase was then converted to Python, which was used for testing.

Localization Testing

We initially tested the localization algorithm on campus with the GPS and IMU data. However, the GPS input data was very noisy due to the disturbance from surrounding buildings. So we had to test localization on the boat on open water. This could have a big impact on our timeline. Luckily, the river localization test went well. The results have been shown in the performance evaluation section.

Control in High Currents

The boat runs autonomously in low current speeds. During one of the autonomy tests, the boat suffered from significant drifting due to the high current and wind speed on that day. We have consulted Prof.Kothmann about this issue and set it as a next step to tune the control parameters in order to cope with this situation.

UX & DATA PROCESSING

Design

User Interface Downselection

During operations, the user will use a user interface to turn on / off the boat, receive data, track progress, and control the boat in manual mode in cases of emergency. There are 5 main constraints for the user interface. First, it should be easily used by 1 person, given the stakeholder requirements. Second, it should be portable given that it will be operated outdoors. Third, it should be easy for the user to interface with the boat through the UI. Fourth, it should be able to achieve easy drive control. Fifth, it should be able to easily and reliably receive data from the boat and store it locally as a format that is easy to export to existing databases.

We considered three different options and scored them against each criteria, with 5 being the most desirable, as shown in Table x. In the end, a web-page based laptop UI is selected. An XBee receiver will be attached to computer in order to communicate with the boat.

Table 12. User Interface Downselection

Metric	Laptop/Web	Tablet	Mobile
Ease of Use	4	5	3
Portability	3	4	5
Interface with Boat	5	2	2
Drive Control	4	3	3
Data Storage	5	2	2
Total	**21**	**16**	**15**

User Interface Design

The functionalities required by the UI is listed below:

1. Before mission:
    a. Input start and end points (click and drag functionality with longitude and latitude when hovered over).
        i. Way to localize and re-correct with actual boat's position from GPS.

b. Input number of points on surface and depth spacing desired (scale drag functionality).
    i. Way to load in average depths at each point from past surveys.
    ii. Way to detect depth at each surface point to set final depth point.
c. Multi-select functionality for points desired for water sampling.
d. Generate mission with points selected. Estimate time and power needed.

2. During mission:
    a. Real-time status of boat position, heading, speed.
    b. Real-time status of boat action (monitoring, sampling, driving, etc.)
    c. Real-time update of time and power left.
    d. Real-time data transmission and map generation.
3. Finish mission:
    a. cross-sectional water data plots with hover functionality
    b. Information of each sample
    c. Button to export data and save locally

Realization

We designed the UI and data processing back in December, based on the preliminary design of the remote control and autonomous navigation subsystems.

Then we built the backend of UI from Mar.17 to Mar.25. At this time, the codebase for task functions, remote control and autonomy were almost finished, so we discussed and designed the overall software architecture, which is specified in *Appendix: Software*. This led to the work over the week to write the code to manage map generation and task functions.

From Mar.25 to Apr.7, we designed a UI based on the functionalities and feasibility to integrate with backend codebase. we have prototyped the UI with InVision, as shown in Figure 8 and Figure 9 in the *Executive Summary* Section. Special care have been taken to minimize the number of clicks needed for data inputs and control. For example, the mission can be pre-configured and loaded into the interface, and the manual control is only one click away, which is easy to access in cases of emergency. We have asked for feedbacks from stakeholders. As a next step, we will implement the frontend UI and integrate it with the backend.

In hindsight, the decision to use MATLAB to implement autonomy dragged down the progress of implementing the backend in Python, especially the backend needed to control the task functions and map generation. This left us with almost no time to implement the UI. For future improvement, we should aim to build the software stack in the final language as early as possible, so as to eliminate any problem that might come up.

POWER

Design

The power source needed is constrained by the total power needed and the working environment of the system. Hence, we first calculated the power needed, and then down selected among different power sources.

Power Calculation & Power Budget

The total power needed is calculated based on the following steps.[29]

1. The voltage levels of each power rail is calculated from the maximum component voltage needed
2. The total capacity needed is calculated by multiplying the quantity, voltage, current and runtime percentage of each component, and then level up by 20% to account for the power loss during DC-DC conversion.

The power budget is shown in Figure 41, and the details are listed in Table 13.

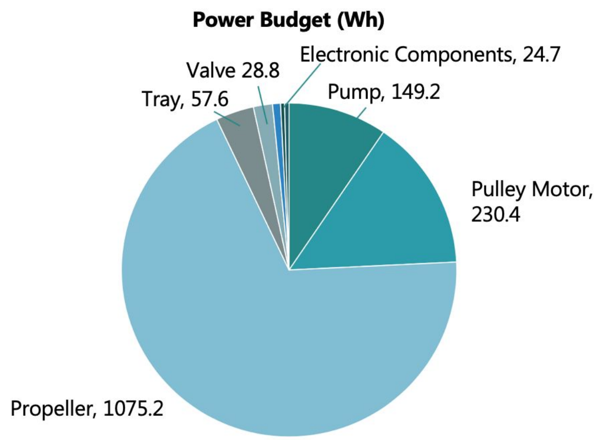


Figure 41. Summarized Power Budget

The total power needed is 391W, amounting to total capacity of 1566 Wh with the required 4 hour runtime.

Table 13. Detailed Power Budget

Component	Quantity	Supplied Voltage (V)	Max Current (A)	Avg. Current (A)	Runtime	Power (W)	After DC-DC 20%
Pump	1	28	3.6	2.22	50%	31.08	37.30
Pulley Motor	1	24	6.3	2	100%	48	57.6
Propeller	2	16	25	7	100%	224	268.8
Tray Actuation	1	16	2	0.75	100%	12	14.4
Valve	1	12	0.5	0.5	100%	6	7.2
Raspberry Pi	1	5	0.5	0.5	100%	2.5	3
mbed	1	5	0.25	0.25	100%	1.25	1.5
GPS	1	5	0.02	0.02	100%	0.1	0.12
GPS antenna	1	5	0.01	0.01	100%	0.05	0.06
Conductivity probe	1	5	0.1	0.1	100%	0.5	0.6
IMU	1	5	0.01	0.01	100%	0.05	0.06
depth sensor	1	5	0.00125	0.00125	100%	0.00625	0.0075
XBee	1	3.3	0.215	0.215	100%	0.7095	0.85
						Power (W)	**391.49**
						Total Capacity (Wh)	**1565.98**

Power Source Down-selection

There are three main constraints for the power source:

1. It should be able to provide the total power needed. The total power needed is 391W for 4 hours, which is 1565Wh in total.
2. It should fit within the weight and size limit of the boat.
3. It should lie within the cost limit required by stakeholders

Two types of options are considered: Batteries and gasoline generator.

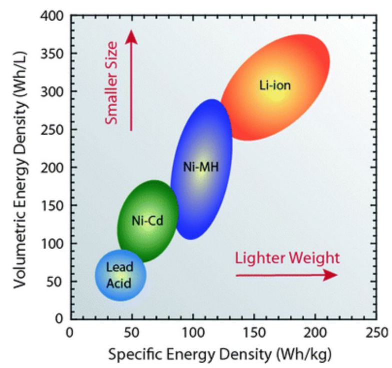


Figure 42. Battery density comparison[30]

Among all the battery types, the size and weight are the two main concerns. We compared the volumetric energy power density and the specific energy density of Lead Acid, Ni-Cd, Ni-MH and Li-ion batteries, as shown in Figure 42. Li-ion battery has the smallest size and lightest weight, so it's chosen as a candidate. We then calculated the cost, weight and size required of a lithium battery to achieve our power needs and compare it against the gasoline generator. The results are shown in Table 14 and Figure 42.

Table 14. Comparison of gasoline generator and Li-ion battery

	Cost	**Weight**	**Size**	**Recharge / refuel**	**User Familiarity**
LiPo	$800	8kg	18.5 x 18.1 x 1 in	2.5hr	Low
Gasoline	$350	10kg	17 x 9 x 14 in	5min	High

A gasoline generator uses gasoline as the fuel to generate electricity. It has higher power density than batteries and also much cheaper. More importantly, our stakeholders currently use gasoline powered engines for sampling and measuring boat runs, and they are more familiar with gasoline generators than with batteries.

Putting the two in comparison, gasoline generators are significantly cheaper than Li-ion batteries, and they are easy to refuel and the users are also more familiar with them. However, they are slightly heavier than batteries. In contrast, Li-ion is considered a cleaner power source compared with gasoline generators, but its high price tag and long charging time makes it unfavorable.

In the end, we chose gasoline generator as the main power source. We chose the Dirty Hand Tools 104609 800W Inverter Generator shown in Figure 10 (in *Executive Summary* section).

To meet the different voltage requirements of each component, we use AC-DC adapters to convert the 110V 60Hz AC output of the generator. In particular, we selected the open-frame adapter shown in Figure 43(a) for the propeller, because open-frame adapters are rated for continuous power output, which is crucial for propellers. Closed-frame adapters are used for the other components. Figure 43(b) shows an example of the closed-frame adapters used.

Figure 43(a).
Open-frame AC-DC Adapter [31]

Figure 43(b).
Closed-frame AC-DC adapter [32]

Backup Battery

To account for the case where the generator runs out of power, we plan to add a backup battery that will keep powering the propellers and electronic components that will enable the user to manually drive it back. Based on the down-selection results in the previous section, LiPo battery is chosen as the battery type. The battery voltage is 16V, designed for the propeller, and the capacity is 275Wh, which is enough for the propellers and all the electronic components needed for remote control to operate for an hour. The number of cells in series is calculated based on the voltage needed, and the number of cells in parallel is calculated based on the capacity needed. The configuration is 5 cells in series and 5 cells in parallel, amounting to a total weight of 1.25kg.

Due to the customized voltage level and capacity needed, the battery pack is assembled using individual NCR18650B batteries to ensure the lowest cost. The pack is equipped with a Battery Management System board to ensure equal charging of each individual battery cell, and the output voltage is leveled down to 5V using a power distribution board for the electronic components. What's more, for safety reasons, we decided to not solder any battery; instead, we used the the DIY Battery Kit by Vruzend. The components used are listed in Figures 44 to 47. [33] [34] [35] [36]

Figure 44. NCR18650B

Figure 45. Battery Management System

Figure 46. Power Distribution Board

Figure 47. Vruzend Battery Pack DIY Kit

Realization

After the power subsystem was designed, the power subsystem implementation was broken down into two main parts: the first part was building the backup battery. The battery assembly was prioritized due to the testing limitations at Pottruck Pool to battery source. The second part was the implementation of the generator power source.

Battery Implementation

During the first stage (Jan.20 - Feb.3 , Feb.19 – Mar.1, Mar.10 - Mar.17), we designed the circuitry needed for the battery, specifically, the battery management system (BMS) and the power distribution unit (PDU). After consulting many instructors, we decided to purchase off-the-shelf BMS and PDU that fits the need of our system. We then calibrated the PDU and also built the 5V battery needed by the electronics for testing at Pottruck. Then the 16V backup battery was assembled and tested during the remote control river test.

Shortly after the 5V battery was built, we realized the difficulty of soldering the batteries directly, and
were strongly suggested by an advisor to switch to the Vruzend battery kit to ensure safety. This switch helped us to accelerate the progress of assembling the battery afterwards, but it also led to some connection issues.

It's worth mentioning that, after making the decisions to use off-the-shelf BMS, it took two weeks for the board to ship from China. The development for power subsystem was almost stopped at this time, which led us to have to use an off-the-shelf battery for the tests at Pottruck. In hindsight, we should have finished the design for the battery subsystem and sent out all the orders before winter break to avoid the long shipment time.

Gasoline Generator Implementation

During the second stage (Mar.10 - Apr.4), the weight tolerance of the boat was tested at Pottruck Pool for the generator. 100lb of weight was placed on the boat to simulate the total weight of all components including the gasoline generator, and the boat was driven in a straight line at Pottruck Pool to verify that it could reach the maximum velocity required. This experiment guided our gasoline generator purchase decision.

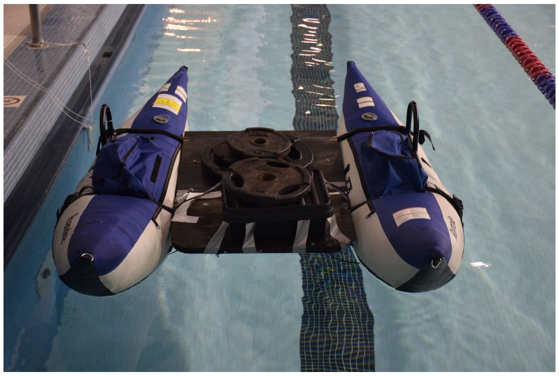


Figure 48. Weight Tolerance Pool Test

The waterproofing, heat dissipation and exhaust mechanisms on the lid for the gasoline generator was designed and discussed with instructors after a couple gasoline generators were selected and provided a range of weight and volumes. We also designed the power distribution mechanisms and consulted the instructor team for feedback. After all those, we sent out the orders for the generator and adapters Mar.17, and the next few weeks were spent on building the waterproofing lid for the generator, setting up the generator at Bartram's Garden, and setting up the inlet and cooling fans needed for the generator on the lid. Last but not least, the generator was tested as the power source during the week of Mar.26 to Apri.4.

FINAL SYSTEM EMBODIMENT AND FUNCTION

Task Functions

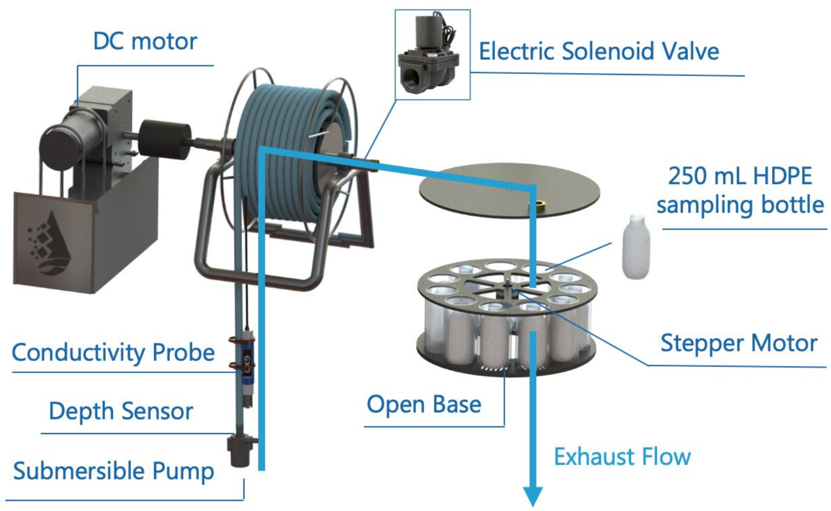


Figure 49. Task Function - Mechanical Parts Overview

During operations, the DC motor actuates the pulley to lower the 50-ft tube to designated depths based on the feedbacks from the depth sensor attached at the end of the tube. A submersible pump is attached to the end of the tube that pumps up the water. The water pumped up goes through the electric solenoid valve on the other side of the pulley, which is controls the flow of the water, and then goes into the collection tray through a clear tube.

The collection tray consists of a rotating tray that alternates among sampling bottles and exhaust. The tray is actuated with a stepper motor. To avoid cross-contamination, a cleaning mechanism was designed that pumps at least 3x the tube volume of water through the exhaust at each new sampling location. The tray of tubes is also closed in order to avoid splash contamination across samples. The bottom part of the rotating tray is made with a brush to lower the rotating friction while sealing the containers.

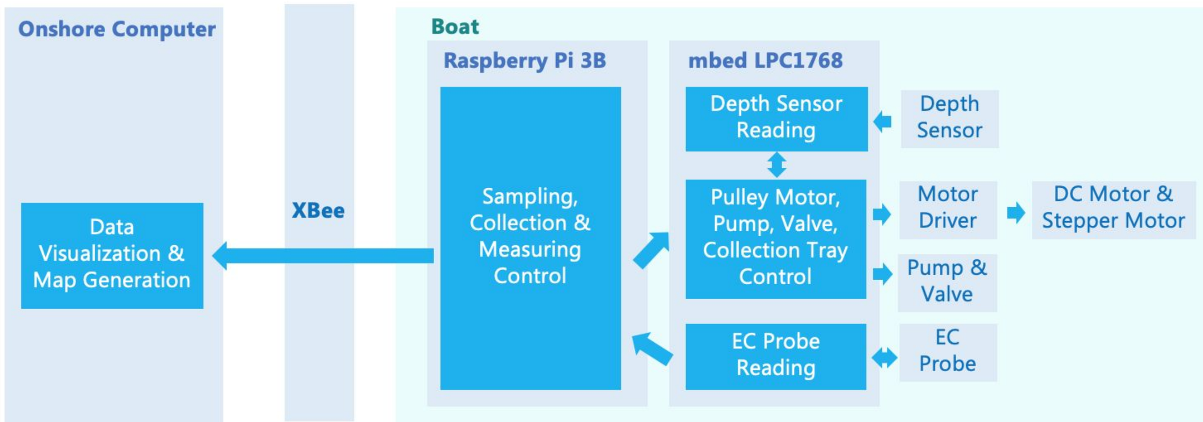


Figure 50. Task Function - Electrical Parts Overview

Task function components are mainly controlled by the Raspberry Pi and mbed onboard. As the system initializes, the task function specifications are sent to Raspberry Pi. Then the task function control module in Raspberry Pi coordinates with the navigation module to decide when to start a task. Once a task start signal is sent to mbed, mbed controls the DC motor to lower the pulley, pump up water, and read data. At the end of each task, data is sent back to Raspberry Pi, which stores the data as well as sends it back to the user interface.

Autonomy & Control

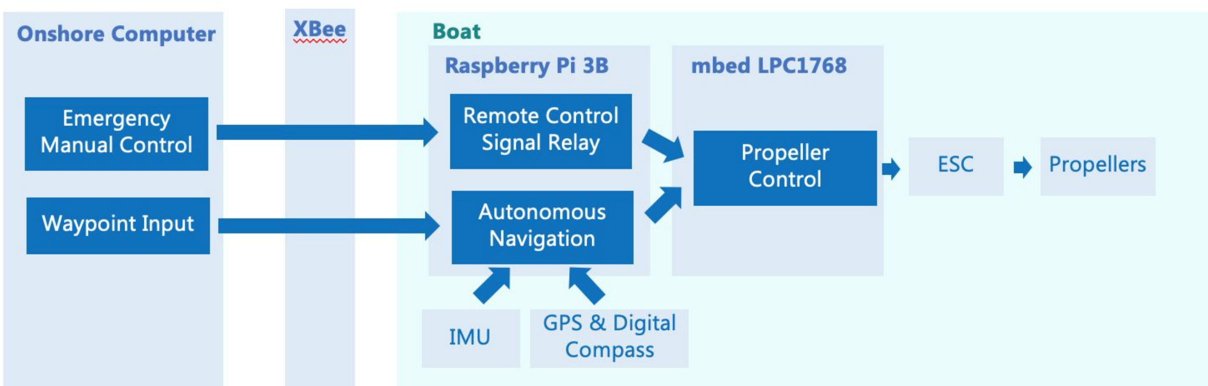


Figure 51. Autonomy & Control Overview

There are two main control modes: manual control and autonomous navigation. The former is used for boat deployment and in cases of emergency. The user can remotely control the boat using an RF module (XBee) connected to the offshore laptop. The boat is actuated by the two propellers attached to each pontoon. As shown in Figure 51, the propellers are connected to the ESCs for controlling the speed, which in turn are connected to the microcontroller (mbed LPC1768) taking over serial from the main processor (Raspberry Pi 3).

The autonomous navigation subsystem takes in the user-defined stop-points for the mission and autonomously drive the boat from point to point, while stopping at each stop-point and performing measuring and sampling at selected depths. The autonomous navigation subsystem is mainly composed of localization and control. During operations, the localization algorithm takes in IMU, GPS & digital compass data and generates a good estimate of the boat location. Then the control algorithm takes in the user-set waypoints and output of the localization algorithm to output thrusts. The thrust data is sent to mbed, which controls the propellers through an ESC.

User Experience

During operations, the user unloads the boat to the dock, turns on the generator, and uses the electricity from the generator to pump up the boat. Then they can deploy the boat in the river and use the user interface to put in the locations and depths at which they wants to sample and measure from. Once they click on the blue button, off S.S. MAPR goes! When S.S. MAPR is running on the river, the user can get real-time updates from the boat through the user interface. If anything happens, they can switch to manual control mode and control the boat on the user interface with keyboard. 4 hours later, S.S. MAPR will be back with the data points and samples. The data is already processed and stored in their laptop, and they just need to export the csv file to start the analysis.

VALIDATION AND TESTING

We conducted a wide range of tests during and at the end of the implementation process. For each subsystem, we will first introduce the key performance measures for each subsystem, and then describe tests for both design improvements and performance validation.

TASK FUNCTIONS

The performance of our sampling and measuring subsystems were evaluated by the depth that our system could reach, and time taken to collect a set of data for one cross-sectional map. In the fall, the team tested the pump and collected data for calculations to characterize our pump and completed the assembly. After conducting several more tests and integrating with the rest of the system, we tested in the river to pump actual samples.

In comparison with existing autonomous solutions, S.S. MAPR is not only able to collect and measure water samples near the river floor but is also able to collect a larger volume (2.5L) of water, compared with the 1L samples provided by existing autonomous surface vehicles. This allows our stakeholders a more diverse and larger range of data points to analyze.

Performance Measures

Performance Measure 1: Volume Collected

Another differentiating characteristic of S.S. MAPR is that it can provide a much larger volume of multi-depth samples which will lead to a larger number of sample metrics. From our design, the collection tray can hold 10 bottles of 250mL samples. Comparing against the sampling metric table provided by our stakeholders, S.S. MAPR samples can provide 16 sample metrics, which is 8x of those provided by other autonomous surface vehicles. However, current manual boat runs can take 22 sample metrics from the surface samples. Thus, increasing sampling volume is one of our next steps.

Table 15. Comparison of Sampling Volumes with Existing Solutions

	S.S.MAPR	Autonomous Surface Vehicle	Stakeholder Boat Runs
Sample Metrics	16	2	41*
Multi-depth sampling volume	2.5L	1 L	0 L
Man Hour per Trip	4 hr	2.5 hr	12 hr

**Surface Samples Only*

Performance Measure 2: Depth Reached

The reeling mechanism was designed to reach depth up to 45ft. In order to validate that, the sampling mechanism was tested in a dry environment. The purpose of this test was twofold: (1) ensure the motor runs with the predicted RPM that will ensure lowering and raising the pump within the time window dictated by the stakeholders, (2) validate the elasticity of the tube at high axial tensile stresses that would be exerted with the pump and probe dangling.

Figure 52(a). Reeling mechanism test in a dry environment

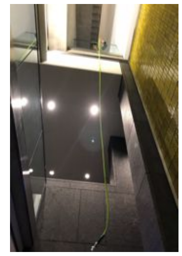


Figure 52(b). Initial pump characterization test

In parallel to that, the selected pump was characterized in order to confirm the specifications of flow rate and head. The time a pump needs to travel 50 ft of tube and fill up 250mL is a particularly important datapoint to predict how much time each sample would need in the column of water (for a total of 10 samples per column).

At first, the pump was only able to pump from 30 ft depth. This was because, a 60 foot wire was extended from the deck of the boat to the end of the tube to power the pump and the probe. The wire has a very large resistance, which caused the pump to experience a 4V voltage drop that reduced its performance (flow rate). A larger supply was consequently required to ensure the pump performs at said flow rate at lower than 30ft. For this reason, the team switched to a 28V voltage supplied by an adapter from the gasoline generator. The 28V is voltage regulated to 24V to the pump, which ensured that it receives the full 24V as required on the datasheet.

In the end, the pump was able to fully function at 40ft.

Performance Measure 3: Timing of Water Collection

The data collected in the initial pump characterization test (see figure 19), was then used as an input to predict the time per sample and verify that we are well under stakeholder time of 19.3 minutes per column.

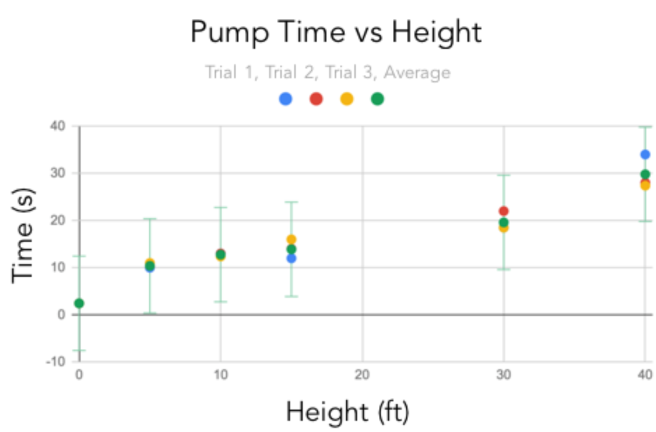


Figure 53. Experimental data for pump characterization test

Following this first draft of timing, a basic algorithm was developed in the most time efficient way to perform the task functions:

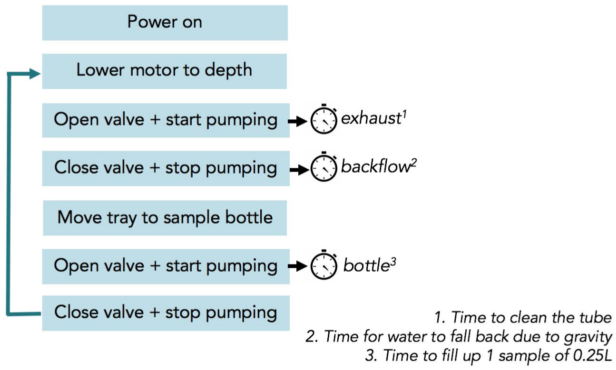


Figure 54. Task Functions control algorithm and timing

The above listed control algorithm was used as a skeleton of the code for the Task Function Control, as detailed in *Appendix: Software*.

With that, the second timing test was performed in the Engineering Building:

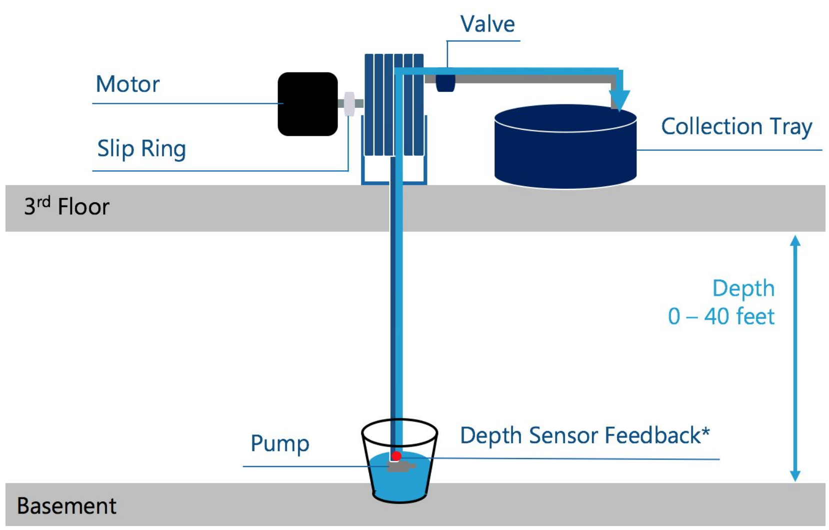


Figure 55. Task Functions integration test and timing

With this set up, the pump was lowered from the surface (3rd floor) to 40 feet (basement) and the water was pumped from a bucket up to the collection tray. For each sample, the team recorded the time to fill up 250mL HDPE bottles at each depth. This experimental value has been compared to the theoretical times calculated.

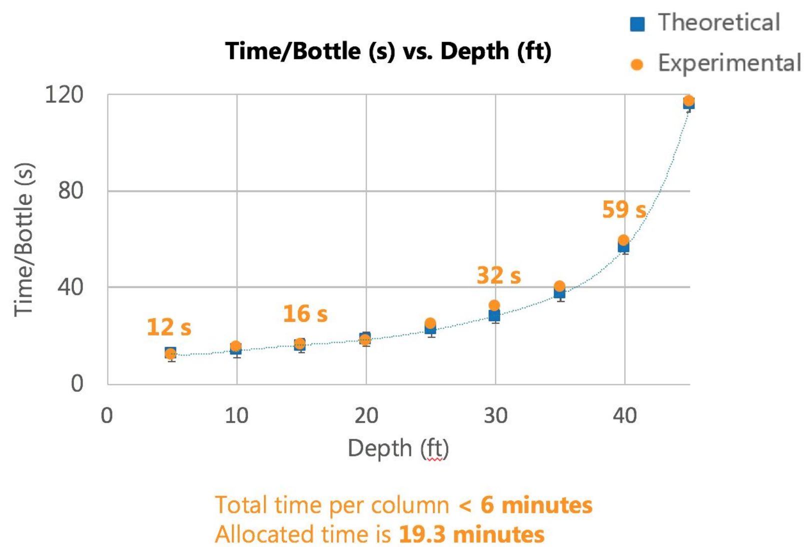


Figure 56. Comparison of theoretical and experimental times to fill up sampling bottle

The theoretical values above were estimated based on the pump specification sheet. They were adjusted for a specific duty cycle, efficiency and tube friction that was deduced from our Reynolds number and friction factor of the Darcy Weisbach Equation for head loss and the friction parameter of the Colebrook Equation, Swamee-Jain.

With these comparisons, the total time per column is 72% lower than the stakeholder maximum time limit. This leaves us with enough time to cycle exhaust, clean the tube and adjust the pump from depth to the depth.

Performance Measure 4: Number of Metrics Measured and Final Map Product

An important criteria that needs to be tested is the delivery of a cross-sectional map to the stakeholders. This requires a 100 point map generated using the probe on S.S. MAPR for either temperature, conductivity, or dissolved oxygen levels in the river. This requires the system to be tested in the Schuylkill river and the data points be generated under 4 hours to meet the stakeholder time requirement.

Performance Measure 5: Data Accuracy - Horizontal Bounding Box

The stakeholders require the probe and pump to stay within a $1\ m^3$ box. Horizontally, high currents in the river will tend to deviate the probe and pump from the zero-current vertical position and outside of the bounding box. In order to test the data accuracy, the deviation from the vertical was plotted for different values of river current, and a sounding weight mass is provided for the user to counteract any deviation and stay within the bounding box. In order to test the effectiveness of the sounding weight, the depth sensor values were used to verify the angle of deviation.

Performance Measure 6: Data Quality - Vertical Bounding Box

One issue that arose during the integration test is the data quality issue. The 60 foot wire that was extended from the boat deck to the probe leads to corruption in the data quality of the depth sensor and the conductivity probe. A booster and filter circuit were implemented and tested with oscilloscope to ensure the data quality.

Tests

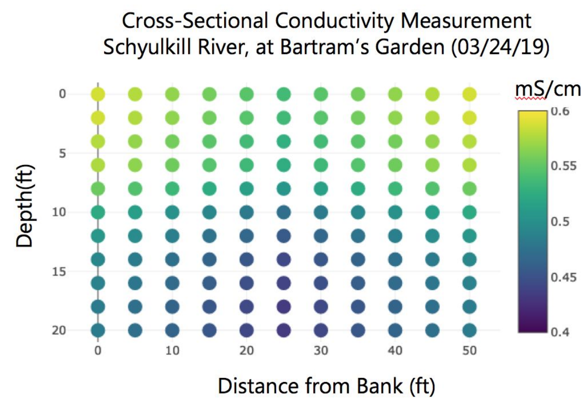
Collection Tray Test

Test Objective	1. To ensure the quality of the samples: by avoiding splashing and cross contamination 2. To guarantee ease of use for the user
Location	Penn Engineering
Test Setup	Water was pumped from a bucket up to the collection tray, sitting on a table.
Test Process	With this setup, the pump was turned on and off to see the splashing of the water and to make design decisions with regards to ease of use. The water was running constantly as the tray rotated from bottle to bottle.
Test Result	A new locking mechanism was implemented to ensure easy access to the sampling bottles and and extra layer of foam was added to the output of the tube in order to prevent splashing.

Sampling Test

Test Objective	1. Timing of Water Collection
Location	Penn Engineering & Schuylkill River
Test Setup	The collection tray, motor and pulley were located on the 3rd floor of a stairwell. The pump was lowered from the third floor to the basement, collecting water in buckets at varying heights.
Test Process	With this set up, the pump was lowered from the surface (3rd floor) to 40 feet (basement) and the water was pumped from a bucket up to the collection tray. For each sample, the team recorded the time to fill up 250mL HDPE bottles at each depth. This experimental value has been compared to the theoretical times calculated.
Test Result	The data collected in the initial pump characterization test, was then used as an input to predict the time per sample and verify that we are well under stakeholder time of 19.3 minutes per column.

Measuring Test

Test Objective	1. Create a 100 point Cross Sectional Map
Location	Schuylkill River
Test Setup	The junction box that includes the booster circuit, filter circuit and voltage regulator, was sealed with marine silicone and covered with epoxy resin to ensure it was waterproof under a column of water of 45ft. The pump was also supported with the necessary sounding weight for the river current to ensure that the measurements are within the horizontal bounding box dictated by the stakeholders.
Test Process	The measuring subsystem collected measurements at 10 different locations and 10 different depths. The test spanned 50 ft from the bank and 20 feet into the river.
Test Result	Multiple water samples were collected and a conductivity map was generated for the stakeholders, as shown in Figure 57.  *Figure 57. Cross sectional map generated*

ACTUATION & CONTROL

Performance Measures

Performance Measure 1: Communication Range

The range of communication with S.S. MAPR is a key performance metric. This is to ensure that the user can control the boat across the cross section. Based on our measurement of the river sites required by stakeholders, we determined that the communication range should be at least 2200m, given the width of the sites where S.S. MAPR will be deployed.

Performance Measure 2: Actuation against River Current

Given the average river current of 1.12m/s at the required river sites, the actuation system should be able to drive the boat against river current at the desired relative speed of 1.3m/s.

Tests

Benchtop Differential Remote Control

Test Objective	1. To ensure that the remote control and propeller control components have been set up correctly. 2. To quantify the time delay in remote control.
Test Setup	1. Laptop: a. 1 XBee is connected through USB. The antenna has been installed. b. The keyboard rc control program is running. 2. Raspberry Pi: a. 1 XBee is connected through USB. The antenna has been installed. b. Mbed is connected through USB to TTL converter (5V, GND, TX, RX) c. Remote control command relay program is running. 3. Mbed: a. Two propellers are connected to ESC. The propellers have to be placed in a water bucket during the test. Running in air will cause damage to the propeller b. The 2 ESC are connect to mbed and the power source (16V). Power source is off at the beginning. c. Remote control receiver and propeller control program is running.
Test Process	1. Turn on power supply. 2. Send keyboard command on laptop. Check that the corresponding propeller is turning. 3. Time the time delay between keyboard command and propeller reaction. Notice: The propellers run very fast in the bucket and they might spill water out. Keep the PWM command to the minimum during testing.
Test Result	1. The two propellers successfully ran. 2. Time delay between command sending from the laptop to propeller actuation is between 0.1s and 0.2s.
Conclusions & Implications	1. The code for interfacing among main computer, microcontroller and propellers ran reliably in the lab setting. 2. The time delay should be taken into account in control algorithm design.

Remote Control Pool Test

Test Objective	1. To ensure the reliability of the remote control system. 2. To test and improve the robustness of the propeller mount. 3. To find the straight-line PWM control level through experiments.
Location	Penn Pottruck Swimming Pool
Test Setup	1. Boat: a. The boat is pumped up and attached to a tether. The tether is crucial to any water test to ensure safe retrieval of the boat if the remote control doesn't work. b. Raspberry Pi, mbed, XBee and all connections have been set up in the electronics box and the box is closed. c. The battery is placed in the electronics box. d. A Go Pro is attached to the boat bridge and lowered underwater to "see" the propellers. 2. Laptop: a. 1 XBee is connected through USB. The antenna has been installed. b. The keyboard rc control program is running. c. VNC into Raspberry Pi to monitor normal operation of the program 3. Raspberry Pi: a. 1 XBee is connected through USB. The antenna has been installed. b. Mbed is connected through USB to TTL converter (5V, GND, TX, RX) c. Remote control command relay program is running. 4. Mbed: a. Two propellers are connected to ESC. The propellers have to be placed in a water bucket during the test. Running in air will cause damage to the propeller b. The 2 ESC are connect to mbed and the power source (16V). Power source is off at the beginning. c. Remote control receiver and propeller control program is running.
Test Process	1. Reliability of remote control system: a. Connect the battery to power on the electronics b. Send keyboard command on laptop. Check that the corresponding propeller is turning. c. Push the boat into water. Send keyboard commands again to drive the boat forward, backward, left turn and right turn. 2. Robustness of propeller mount: a. After confirming the boat drives in the water, the Go Pro video is reviewed to check if the propellers are fixed to the pontoons. 3. Straight-line PWM control level

<table>
<tr><td></td><td>a. After confirming the robustness of propeller mount, drive the boat forward and backward with the same PWM levels. Tune the PWM levels until the boat moves in a straight line in the still pool water and its distances to both sides are constant. Record that data.</td></tr>
<tr><td>Test Result</td><td>1. Reliability of remote control system:
a. During the first few tests, there were issues related to connections that led to significant onsite debugging. After organizing the electronics box and fixating the wirings, we managed to start the remote control system within 2min with no debugging.
b. Initially, the remote control system would crash and restart due to invalid packages received. After adding a message format check on the receiving end, the system was able to function well for the entire duration of testing.
2. Robustness of propeller mount:
a. During the first test, the propellers would bend towards the back due to the soft connection to the pontoons. The problem was solved after an acrylic board was added to the connection, as shown in Figure 35 (a) and (b) in Design & Realization Section.
3. Straight-line PWM control levels: The values were obtained for driving the boat in a straight line. Depending on different PWM levels, the left PWM is consistently smaller than right PWM by about 10%.</td></tr>
<tr><td>Conclusions & Implications</td><td>1. A reliable remote control subsystem was built, improved and ready to be used in future river tests.
2. The propeller mount fit the needs of accurate control.
3. The PWM control level values corrects for the minor differences in propulsions potentially caused by propeller mount asymmetry and individual differences in propeller quality. The data was later integrated into control algorithm and we could be confident about the expected straight-line actuation performance.</td></tr>
</table>

Experimental Confirmation of Coefficients of Drag

<table>
<tr><td>Test Objective</td><td>To experimentally confirm the theoretical coefficients of drag obtained through CFD.</td></tr>
<tr><td>Location</td><td>Penn Pottruck Swimming Pool</td></tr>
<tr><td>Test Setup</td><td>1. Same as remote control pool test.
2. Set two markers, 25 ft apart, from close to the end of the lane.</td></tr>
<tr><td>Test Process</td><td>1. Linear coefficient of drag: the boat was driven in a straight line from the beginning of the lane and reached constant velocity after the boat head reaching the first marker (Figure 58). Measure the time needed</td></tr>
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to travel from the first to the second marker. Measure three values at each PWM level and take the average. Both forward and backward values were taken.


Figure 58. Linear coefficient of drag experiment

2. Rotational coefficient of drag: the boat was rotated and reached constant angular velocity. Measure the time needed to rotate 5 full circles. Both clockwise and counterclockwise values were taken.

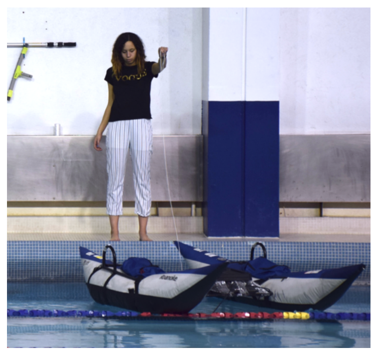
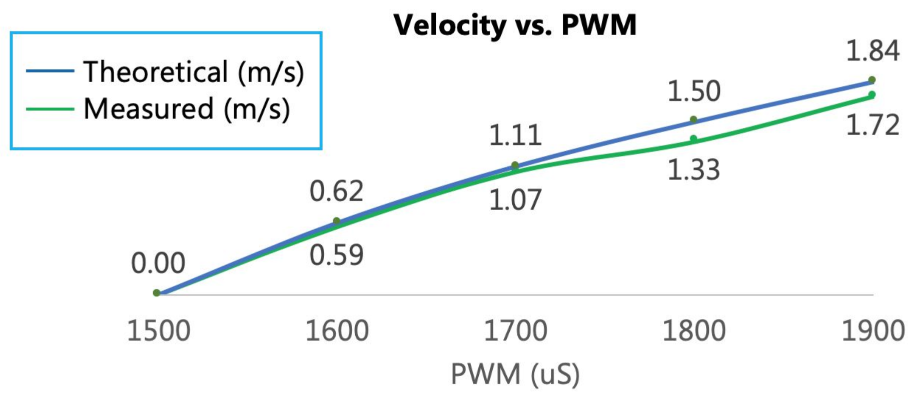
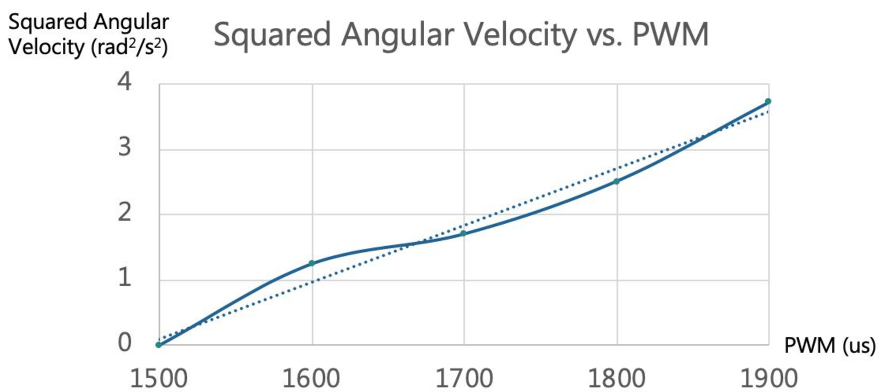



Figure 59. Rotational coefficient of drag experiment
</td>
</tr>
<tr>
<td>Test Results & Analyses</td>
<td>
1. The theoretical thrust values at each PWM level were found in the documentation of the propellers.
2. Linear coefficient of drag was calculated as: $C_d = \frac{2F}{\rho A v^2}$, where ρ is the density of water, v is the average speed measured at each PWM level, and A is the surface area of the boat in contact with water, which was measured to be 0.64 m^2. The measured and theoretical data are shown in Figure 59. The linear coefficient of drag was measured to be $C_d = 0.034$.
</td>
</tr>
</table>

	 *Figure 60. Measured and Theoretical Velocity vs. PWM Levels* 3. Rotational coefficient of drag was calculated as: $C_{ang} = \frac{2F}{\rho A \omega^2}$, where ρ is the density of water, ω is the average angular velocity measured at each PWM level, and A is the surface area of the boat in contact with water. The rotational coefficient of drag was measured to be $C_{ang} = 0.031$  *Figure 61. Squared angular velocity vs. PWM*
Conclusions & Implications	1. From the measured values, we calculated $C_d = 0.034$. This value is close to the theoretical $C_d = 0.0378$ previously derived from CFD. 2. The rotational coefficient of drag was measured to be $C_{ang} = 0.031$ This value is also close to the theoretical $C_d = 0.0378$, which was expected. 3. The measured values were both close to the theoretical values, which confirmed our CFD results. Those values were later used in control algorithm design.

Wireless Communication Range Test

Test Objective	To experimentally confirm the range of wireless communication of the 2 XBee is at least 2200m as required by design constraints.

Location	Bartram's Garden on Schuylkill River Boat Dock
Test Setup	1. Laptop 1: a. 1 XBee is connected through USB. The antenna has been installed. b. The keyboard rc control program is running. 2. Raspberry Pi: a. 1 XBee is connected through USB. The antenna has been installed. b. Remote control command receiving program is running. 3. Laptop 2: a. VNC into the Raspberry Pi b. This laptop is carried by tester 2 together with the Raspberry Pi 4. A tape measure is held by tester 1. 5. Tester 1 and 2 communicates through phone call. Notice: the test should be carried out in an open space with little disturbance to the wireless communication (metal, building, moving objects, etc.)
Test Process	1. Tester 1 marks the starting point on Google Maps. 2. Tester 1 holds Laptop 1 and keeps moving away from Tester 2, while tester 2 keeps updating tester 1 through phone whether the communication is still functional. 3. While moving away, tester 1 keeps measuring the distance from the starting point with tape measure. 4. Once tester 1 measures that he/she is 2200m away from tester 2, he/she marks the stopping point on Google Maps to confirm the measured distance. Tester 1 also confirms with tester 2 that the communication is still functional.
Test Result	The wireless communication was still functional at the required distance of 2200m.
Conclusions & Implications	We confirmed that the wireless communication of the 2 XBee sensors could reach the required range by our stakeholders.

Remote Control River Test

Test Objective	1. To confirm the robustness of remote control in river environment. 2. To confirm the straight-line PWM levels obtained from the pool test. 3. To measure the maximum speed against the river current.
Location	Bartram's Garden on Schuylkill River Boat Dock
Test Setup	1. Boat: a. The boat is pumped up and attached to a long and strong tether. The tether is crucial to any water test to ensure safe retrieval of the boat if the remote control doesn't work. b. Raspberry Pi, mbed, XBee and all connections have been set

<table>
<tr><td></td><td>up in the electronics box and the box is closed.
c. The 16V battery is placed in the electronics box.
2. Laptop:
a. 1 XBee is connected through USB. The antenna has been installed.
b. The keyboard rc control program is running.
c. VNC into Raspberry Pi to monitor normal operation of the program
3. Raspberry Pi:
a. 1 XBee is connected through USB. The antenna has been installed.
b. Mbed is connected through USB to TTL converter (5V, GND, TX, RX)
c. Remote control command relay program is running.
4. Mbed:
a. Two propellers are connected to ESC. The propellers have to be placed in a water bucket during the test. Running in air will cause damage to the propeller
b. The 2 ESC are connect to mbed and the power source (16V). Power source is off at the beginning.
c. Remote control receiver and propeller control program is running.
5. Drone:
a. The drone is flied up with the camera pointing downwards.</td></tr>
<tr><td>Test Process</td><td>1. Reliability of remote control system:
a. Connect the battery to power on the electronics
b. Send keyboard command on laptop. Check that the corresponding propeller is turning.
c. Push the boat into water. Send keyboard commands again to drive the boat forward, backward, left turn and right turn.
2. Straight-line PWM control levels: Use the straight-line PWM values previously obtained during pool test to drive the boat against river current. Observe from real-time drone video to ensure that it's running in a straight line parallel to the boat dock
3. Maximum Relative Speed: Drive the boat against river current at maximum PWM level from a little beyond one end of the boat dock to the other end, to make sure it reaches constant speed once it hits the start of the dock. Measure the time. Confirm that the boat is driving in straight line and the time measured from the drone video.</td></tr>
<tr><td>Test Result</td><td>1. The remote control system was able to start and operate without debugging.
2. Straight-line PWM control levels changed a little bit due to the flowing water. The values were tuned.
3. Maximum relative speed: 1.5m/s against river current. The current speed on testing day was 1.1m/s.</td></tr>
</table>

Conclusions & Implications	1. The remote control subsystem was proved to be able to operate robustly in river environment. 2. Straight-line PWM control levels were collected and later integrated into control algorithm simulation. 3. The maximum speed against the river current meets the 1.3m/s required by our stakeholders.

AUTONOMOUS NAVIGATION

Performance Measures

Performance Measure 1: Localization Accuracy

The accuracy of GPS input is rated to be 10m, but the localization algorithm should achieve an accuracy of at most 1 m in order to achieve the control accuracy of staying within a 2m radius circle as required by our stakeholders.

Performance Measure 2: Steady-State Control Boundary

One of the most important KPI for the autonomous navigation subsystem is the range within which S.S. MAPR could hold itself against currents during task functions. After discussion with key stakeholders, we determined that to achieve reliable data and water samples, the radius of drifting should be no more than 2m.

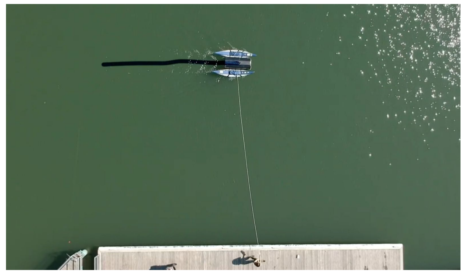
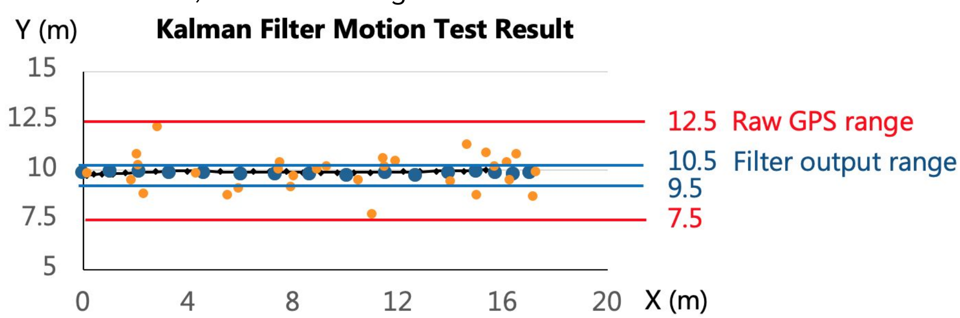
Performance Measure 3: Path Following and Stopping

S.S. MAPR should be able to both follow a set of stop points and stop at each point for task functions, as part of the key functionality.

Tests

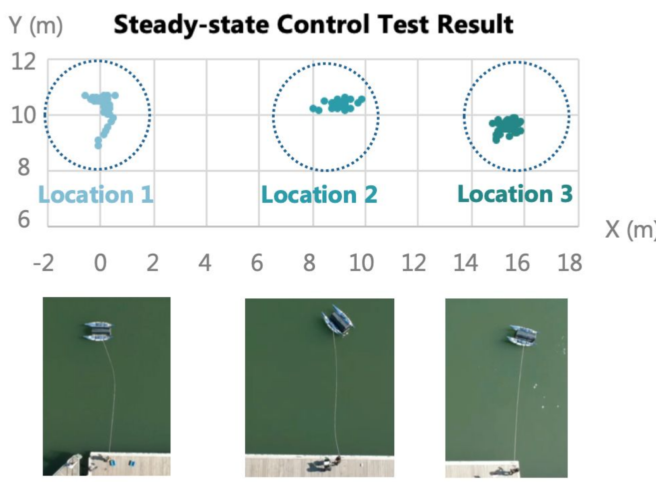
Localization River Test

Test Objective	To experimentally confirm the range of localization algorithm output lies within the 1m accuracy required for precise control.
Location	Bartram's Garden on Schuylkill River Boat Dock
Test Setup	1. Same as remote control river test 2. IMU, Digital Compass and GPS were connected to Raspberry Pi, and the localization algorithm was running on Raspberry Pi. The sensor input data and localization results were recorded and saved on Raspberry Pi.
Test Process	The boat was driven in a straight line, and the drone records the trajectory of the boat.

Test Results & Analyses	1. The trajectory of the boat was extracted from the drone videos using MATLAB and plotted. The range was found through the plot, as shown in Figure 62.  *Figure 62. Localization River Test Trajectory Extraction* 2. The recorded GPS data and localization outputs were plotted. The range was also found through the plot. The raw GPS data was measured to have an accuracy range of 5m, but the filter output is within 1m, as shown in Figure 63.  *Figure 63. Localization River Test Data Result*
Conclusion	The localization algorithm can reduce the noise in raw sensor data and the output lies within the required accuracy for precise control.

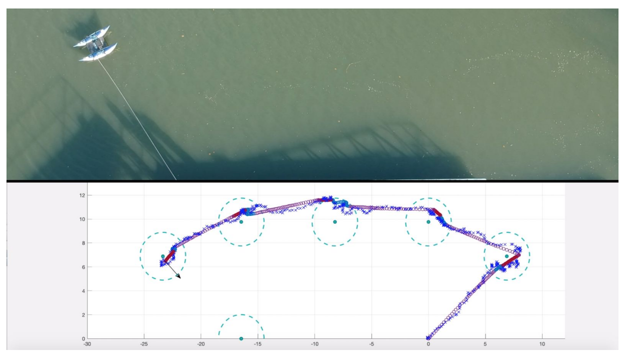
Steady-State Control Boundary River Test

Test Objective	To experimentally confirm the range within which the autonomous navigation algorithm was able to keep the boat still.
Location	Bartram's Garden on Schuylkill River Boat Dock
Test Setup	1. Boat: a. The boat is pumped up and attached to a long and strong tether. The tether is crucial to any water test to ensure safe retrieval of the boat if the remote control doesn't work. b. Raspberry Pi, mbed, XBee and all connections have been set up in the electronics box and the box is closed. c. The 16V battery is placed in the electronics box. 2. Laptop: a. 1 XBee is connected through USB. The antenna has been installed.

	b. The keyboard rc control program is running. c. VNC into Raspberry Pi to monitor normal operation of the program 3. Raspberry Pi: a. 1 XBee is connected through USB. The antenna has been installed. b. Mbed is connected through USB to TTL converter (5V, GND, TX, RX) c. GPS, IMU and digital compass is connected through RX/TX and I2C. d. Autonomous navigation, remote control program is running. 4. Mbed: a. Two propellers are connected to ESC. The propellers have to be placed in a water bucket during the test. Running in air will cause damage to the propeller b. The 2 ESC are connect to mbed and the power source (16V). Power source is off at the beginning. c. Remote control receiver and propeller control program is running. 5. Drone: a. The drone is flied up with the camera pointing downwards.
Test Process	The boat was driven to 3 different locations and switched to autonomy mode for 20 min. The drone records the trajectory of the boat.
Test Results & Analyses	The trajectory of the boat was extracted from the drone videos using MATLAB and plotted. Then the 2m boundary was also plotted around each selected stop location. The test setup and results are shown in Figure 64.  *Figure 64. Steady-State Control Boundary Test Setup & Result*
Conclusion & Implications	The boat can hold itself within the 2m radius required by stakeholders at a current speed of 1.1m/s on the testing day, which is close to the maximum

	speed we designed for. This shows that the steady-state control result from the localization and control algorithm meets the design requirements.

Path Following and Stopping River Test

Test Objective	To experimentally confirm that: 1. The boat can follow a path as defined by several waypoints. 2. The boat can switch naturally between path following and stopping.
Location	Bartram's Garden on Schuylkill River Boat Dock
Test Setup	Same as Steady-State Control Boundary River Test
Test Process	1. The boat was initialized with a set of waypoints. 2. The boat was placed at the starting point and switched to autonomy mode.
Test Results & Analyses	1. The boat was able to follow the waypoints and stop at each point. 2. The trajectory of the boat was extracted from the drone videos using MATLAB and compared against the simulation results, as shown in Figure 65.  *Figure 65. River Path-Following Test & Simulation Comparison*
Conclusion & Implication	1. The localization & control algorithm was able to switch naturally between path following and stopping as desired. 2. Given the restrictions on tether length, the stop-points distances in this test were about 8m. Further tests for this functionality will include stop-points that are farther apart with longer stopping time requirements.

UX & DATA PROCESSING

Performance Measures

Performance Measure 1: Functionalities Covered

The most important measurement of the user interface is that the user is able to perform all the necessary actions during the boat run through the interface.

Performance Measure 2: Ease of Use

Due to the constraint of having only 1 operator during the boat run, the user interface needs to be very easy to understand and use. The number of clicks and typing needed is minimized and measured. We also asked for feedback from stakeholders.

Tests

Functionality Test

Test Objective	To confirm the user interface contains all required functionalities during boat operations, by simulating an actual sampling and measuring boat run as a water scientist from USGS.
Location	Bartram's Garden on Schuylkill River Boat Dock
Test Setup	1. Same as the steady-state control boundary test 2. Mbed is connected to pulley motor, pump, valve, collection tray. The task function control thread is running on mbed. 3. The task function control thread is also running on Raspberry Pi and the laptop.
Test Process	All the functionalities were performed through the keyboard interface, from setting waypoints, tasks, and sending them to the boat, to launching the boat, tracking the boat run progress, all through the keyboard interface.
Test Result	All functionalities required during boat operations were included in the UI design.
Conclusion & Implication	Due to time limit, we weren't able to implement the user interface, but we have implemented all the backend functionalities. The next step would be to implement the UI that connects with all backend functionalities.

Ease of Use Test

Test Objective	To confirm the user interface was easy to understand and use in an outdoors context.
Test Process	1. Count the number of clicks and typing actions needed to configure a test. The worst case scenario was used: 100 measuring points, 10 samples. 2. Send the UI design prototypes to 3 stakeholders from USGS, DRBC and PWD. Ask if they could understand how to use it without a tutorial. Ask for any additional functionalities they want.
Test Result	1. The task configuration takes 50 clicks and 10 typing actions to configure the maximum number of samples and measurements. If using a predefined mission file, only 3 clicks are needed. During boat

	operation, no click is needed to see the measurement and sampling updates, 1 click is needed to get detailed information of each sample, and only 1 click is needed to switch between manual control and autonomous mode. 2. Stakeholders were able to understand the interface without a tutorial. However, 2 stakeholders suggested that joysticks are easier for manual control compared with keyboards.
Conclusion & Implication	1. Given that the main advantage of the UI is the small number of clicks needed for predefined mission file, we need to design this process as very user-friendly as well. 2. Based on stakeholder feedback, adding compatibility with joysticks is set as a next step.

POWER

Performance Measures

Performance Measure 1: Runtime

The key performance indicator of power subsystem is the required runtime of 4 hours. This was tested in full system test, detailed in next section. This is required by our stakeholders. This will put S.S. MAPR similar to existing autonomous water surface vehicles solutions, which have runtime ranging from 4hr to 6hr [37], while autonomous underwater vehicles have a runtime of 8-10 hr. [38]

Performance Measure 2: Refueling Time

Given the stakeholder need for daily measurements, the power source should have a short refueling or recharging time. Currently, our stakeholders use gasoline motor, which has a short refuel time.

Tests

Runtime Test

Test Objective	To confirm the gasoline generator can provide power for the system over the required runtime of 4hr.
Location	Bartram's Garden on Schuylkill River Boat Dock
Test Setup	1. Same as UI functionality test. 2. Fill the generator tank.
Test Process	The boat was initialized with 10 waypoints and generated a cross-sectional map. The boat was run consecutively for 4 hours. At the same time, the generator was running to provide power for the whole system.

Test Result & Conclusion	The generator was able to provide power for the required runtime of 4hr.

Refueling Time Test

Test Objective	To test the refueling time needed for the generator
Location	Bartram's Garden on Schuylkill River Boat Dock
Test Process	Stop the generator. Let it cool down. Pour in gasoline. Restart the generator. Time the whole process.
Test Result & Conclusion	The refueling time was measured to be 5 min, including the time needed to restart the generator. Compared with existing solutions, S.S. MAPR has the shortest refueling time because all other solutions choose to use LiPo batteries and have a long charging time.

Battery Voltage & Current Discharge Test

Test Objective	To confirm the voltage and current discharge of the backup battery.
Test Setup	Charge the 5S battery to full
Test Process	The voltage of the assembled battery was measured. What's more, a load with similar resistance level as the propeller was attached to the battery. The current discharge was measured.
Test Result	The battery voltage was 18.2V and the current discharge reached 7A, which is the average current of the propeller. The battery was later used in the river remote control test to power the propellers and it worked as desired.
Conclusion	The backup battery met the design requirements of powering the actuation subsystem.

OVERALL SYSTEM

Performance Measures

Performance Measure 1: Cost

One of the key differentiation from existing autonomous solutions is the low fixed and variable cost.

Regarding fixed cost, the cost of the prototype is $2830, by adding up all the components used on the final prototype. Note that this is a very conservative estimate as the material cost will go down significantly for manufacturing. This fixed cost gives S.S. MAPR a significantly price advantage over existing autonomous surface vehicles, which cost $85,000, and autonomous underwater vehicles, which cost $80,000.[7][39]

The variable cost is then calculated by including the labor cost and material cost required for each boat run with S.S. MAPR compared with other autonomous solutions. Using the current budget for measuring and sampling by our stakeholders per year, we were able to calculate the maximum frequency at which our stakeholder will be able to measure and sample with S.S. MAPR. Then we estimate the number of sample metrics and measurements that S.S. MAPR can provide per year and use that to derive the variable cost per sample and measurement to be $1.6 and $5.4, which are both ~70% lower than the current variable costs. The detailed calculations are included in *Appendix: Performance Measures*. The comparison results with existing solutions are shown in Table 16.

Table 16. Comparison with current solutions and existing autonomous solutions

	S.S.MAPR	Stakeholder Boat Runs	Autonomous Surface Vehicle	Autonomous Underwater Vehicle
Fixed Cost	$2830	/	$85,000	$80,000
Cost per Measurement	$5.1	$18	$5.7	$6.6
Cost per Sample Metric	$1.6	$4.9*	$14.2	/**

**Surface Samples Only*

***Sampling Volume = 0*

Performance Measure 2: Weight & Size

Another key constraint of S.S. MAPR is its size and weight. The vessels dimensions were restrained by the size of a standard pickup truck. The final dimensions were 2.4m x 1.4m x 0.7m. The final size was guided by this restraint as well as maximizing for space on the boat for subsystems and buoyancy of the entire system.

The National Institute for Occupational Safety and Health (NIOSH) has developed a formula for assessing the hazard of lifting a heavy load [40]. The formula looks at several elements including: distance the load is held from the body, height the load is lifted from, and frequency of lifting. Using these parameters, NIOSH has established that for occasional lifting, the max a worker can lift is 51 pounds or about 23 kg. The Occupational Safety and Health Administration (OSHA) also claims that lifting loads heavier than 50 pounds will increase the risk of injury. With this knowledge, our goal was to minimize our weight to only be lifted by 2-3 people. The final weight was 63 kg, requiring 3 people to lift the vessel into the pickup truck.

Tests

Full System Test

<table>
<tr><td>Test Objective</td><td>To confirm the system works together to finish the required functionalities.</td></tr>
<tr><td>Location</td><td>Bartram’s Garden on Schuylkill River Boat Dock</td></tr>
<tr><td>Test Setup</td><td>1. Same as UI functionality test.
2. Fill the generator tank.

Figure 66. Full System Test</td></tr>
<tr><td>Test Process</td><td>The boat was initialized with 10 waypoints. The boat was tasked to generate a cross-sectional map with 100 data points and collect 10 samples from river bottom. The boat was run consecutively for 4 hours. At the same time, the generator was running to provide power for the whole system. The whole process was controlled through the keyboard interface.</td></tr>
<tr><td>Test Result</td><td>The boat generated the cross-sectional map with 100 data points and collected 10 samples within 4 hours, powered by gasoline generator. The result has been shown in Figure 57.</td></tr>
<tr><td>Conclusion & Implication</td><td>Due to the limit of tether length, the furthest distance we could set for the boat was 50 ft away from the river bank. Further tests should include a longer tether to fully test the capability of the boat.</td></tr>
</table>

DISCUSSION

TARGET VS. ACCOMPLISHED PERFORMANCE

S.S. MAPR meets almost all of the objectives we defined per our stakeholders' needs, as shown in Table 17.

Table 17. Detailed Design Goal Achievements

Category	Metric	Design Goal	Result
Overall System	Fixed Cost	< $3000	$2,830
	Cost per Measurement	< $18	$5.10
	Cost per Sample Metric	< $4.9	$1.60
	Weight	153 lb	138 lb
	Dimensions	2m W x 2.4m L	2.4m W x 1.4m L x 0.7m H
	Runtime	<= 4hr	4hr
Environment	Width	2200m	2200m*
	Depth	45 ft	45ft**
	Current flow rate	1.12m/s	1.12m/s
Sampling & Measuring	Volume	2.5L - 8L	2.5L
	Sample Metrics Covered	16 - 41	16
	Accuracy	1m^3 bounding box	1m^3 bounding box
	Location Accuracy	2m radius	2m radius
	Decontamination	Rinse between samples	Rinse between samples
	Measuring Metrics	Customizable	Electric Conductivity
	# of Measuring Points	100	100
	# of Samples	10	10
Usability	People Needed	1	1
	Data Transmission	Real-time	Export csv file
Control & Autonomy	Autonomy	User-set Waypoints	User-set Waypoints
	Control	Manual available	Manual available

**as designed. Validated for 120m*

***as designed. Validated for 40ft*

For the overall system, we were able to achieve all the cost metrics with a fixed cost under $3000 as well as the variable costs for measurements and samples. System weight is 138 lb, which lies within the maximum weight for 3 people to carry. The dimension of the boat fits in the pickup truck as designed, and the runtime is 4 hours, which lies within the maximum runtime required.

As for environment constraints, we were also able to achieve the 2,200m-wide cross section and 45 ft depth objective. The boat has been tested to be able to achieve the control goals in the current flow rate of 1.12m/s.

Considering sampling & measuring, we able to reach the minimum volume of 2.5L, 10 samples that can cover the 16 most important sample metrics required by stakeholders. For location accuracy, we were able to achieve our desired accuracy within a 1 m^3 bounding box, and the steady state control was able to hold within 2m radius. The decontamination process meets current stakeholder process standards. For measuring, we were able to measure 100 electric conductivity points, which needs further improvement to be able to customize for the user's probes.

From the usability and autonomy side, S.S. MAPR only needs 1 person to set it up and run it as well as provides the functionality for users to set their own waypoints. In addition, manual control is available as required. What needs to be improved on is the real-time data transmission during mission operation, given that the current implementation needs the user to export csv files.

RECOMMENDATIONS

In order to increase the number of parameters S.S. MAPR can obtain, the volume of samples collected should be increase from 2.5L to 8L. This will increase the parameters from 16 to 41. In order to accommodate for a larger number of samples, a couple changes should be implemented. Given that S.S. MAPR would need to carry heavier loads, the thrust and buoyancy needed will increase. In order to accommodate for a larger number of bottles, the carousel design needs to be replaced by a cartesian placement where each bottle has a specific coordinate instead of an angle - still using a stepper motor.

In order to enable users to use their own probes with the measuring mechanism on S.S. MAPR, a probe mount will be designed and attached to the end of the tube where the electric conductivity probe is currently located.

In order to realize the real-time transmission functionality, an ACK mechanism needs to be implemented in the laptop-Raspberry Pi transmission to ensure reliable data transmission. The current spinning lock mechanism that is used to control access to the shared serial communication channel also needs to be improved to be more robust. Last but not least, a program needs to be implemented on the laptop to receive the data, confirm the accuracy, store it in csv file and generate a plot in real time.

Some further improvements have been considered:

In order to adapt S.S. MAPR to any river topography, the system should be adaptable to varying depths. Currently, the depth of the river is input from USGS and DRBC databases. These values are then used as a maximum threshold communicated to the depth sensor. Alternatively, a sonar sensor unit would be placed with the pump to measure the maximum attainable depth at each point and set that is the varying maximum threshold.

S.S. MAPR communication micro-controller was carefully down selected to ensure the highest communication range: the XBee offers 120m of range. Since this range is not fully reliable given the noise that might interfere with the signal, the goal is to increase the range with the use of improved antennas and reach 2,200m which is the bank to bank distance needed.

In order to improve the ease of use for the stakeholders, the pump and probe should be easily accessible. Instead of dangling under the boat, an elevated platform can be incorporated to the pulley to elevate the components.

The autonomy of S.S. MAPR should be improved to accommodate for high river current situation. A possibility is to add pure pursuit to the control algorithm. This allows the boat to follow the path without overshooting and thus will allow it to respond to changes brought by high current more quickly.

BUDGET, DONATIONS, AND RESOURCES

SOURCES OF FUNDING

Table 18. List of Funding Sources

Source	Date	Amount
School Funding	September 2018	$2,460.00
Cornell Cup	March 2019	$1,000.00
Berkman Innovation Fund	March 2019	$1,000.00
Total		**$4,460.00**

BUDGET BY SUBSYSTEM

Task Functions

Table 19. Task Functions Budget

Subsystem	Item	Unit Cost	Qty	Total Cost
Task Functions	Pulley + Motor	$542.00	1	$542.00
	Slip Ring	$170.00	1	$170.00
	Tube	$40.00	1	$40.00
	Pump	$56.99	1	$56.99
	Empty Bottles	$14.00	2	$28.00
	Tray PVC	$15.62	1	$15.62
	Tray Motor + Shaft Coupler	$25.00	1	$25.00
	Electric Solenoid Valve	$32.95	1	$32.95
	Hose Adapters	$9.63	6	$57.80
	Acrylic 1/8 inch	$27.63	2	$55.26
	Acrylic 1/4 inch	$54.29	1	$54.29
	Marine Sealant	$16.97	1	$16.97
				$1,094.88

The main drivers of costs for the Task Functions are the DC motor, the slip ring and the pump:

1. The DC motor requirements were calculated based on a static and dynamic analysis of the forces and moments. After applying a safety factor of 3, the motor torque needed is 250 lb-in, which will only be achieved with a motor in the $500 range.
2. The choice of slip ring was motivated based on the number of wires needed as well as the output shaft of the motor. Given the configuration of the motor-pulley, a regular slip-ring cannot provide the solution. For this reason, the team has invested in a through bore slip ring, which raised the cost to above $100. Given that the depth sensor requires 4 wires, the pump requires 2 wires and the conductivity probe requires 3 wires, the best option was a 12-wire through bore slip ring.
3. The pump selection was based on two constraints: (1) the required time per sample, and (2) the depth basic and reach goals of our stakeholders. Based on limited options, the only pump that fits our need costs around $60.

Hull & Lid

Table 20. Hull & Lid Budget

Hull	Pontoon	$253.00	1	$253.00
	Plywood	$14.98	1	$14.98
				$267.98
Lid	Carbon Fiber & Fiberglass	$103.00	1	$103.00
	Foam	$69.33	1	$69.33
	Epoxy Resin + Hardner + Compound	$157.00	1	$157.00
				$172.33

The costs for the hull and lid are listed in Table 20.

Due to time and budget restraints, the team decided to purchase off-the-shelf pontoons to focus team efforts on engineering the core task functions of S.S. MAPR. Fabrication of the hulls out of polystyrene foam and fiberglass coating would have taken approximately two months, and the estimated cost of the materials was $600. The pontoons cost $250, fit in the back of a pickup truck, and could support up to 159 kg of payload, which was greater than the weight of the systems onboard the vessel.

The main drivers for the costs of the lid are the materials. Based on the material down-selection and optimizing for weight, the choice of carbon fiber coated foam made the most sense:

Table 21. Lid fabrication down-selection

Metric	Polystyrene Foam with Carbon Fiber	Fiberglass	Gel Coated Polystyrene Foam
Cost of materials	$ 500	$ 500+	$ 400
Density (lb./in^3)	0.0016	0.055	0.0016*
Estimated weight	5 kg	9 kg	6 kg

Electronics

Table 22. Electronics Budget

Propulsion	Propeller	$194.00	2	$388.00
				$388.00
Power	Gasoline generator	$212.00	1	$212.00
				$212.00
Electronics	GPS + antenna	$56.86	1	$56.86
	Raspberry Pi	$40.00	1	$40.00
	IMU+compass	$16.89	1	$16.89
	Voltage regulators	$12.00	1	$12.00
	XBee	$47.00	2	$94.00
	XBee adapters	$14.00	2	$28.00
	USB to TTL adapters	$25.00	1	$25.00
	Microcontroller - MBed	$54.95	1	$54.95
	Conductivity sensor probe	$82.95	1	$82.95
	Depth + temperature sensing	$68.00	1	$68.00
	Underwater cable	$49.99	1	$49.99
	sensor BNC cable	$9.99	1	$9.99
	Motor drivers	$31.99	1	$31.99
	28V adapter	$54.00	1	$54.00
	24V adapter	$15.00	1	$15.00
	18V adapter	$15.00	1	$15.00
	16V adapter	$11.00	1	$11.00
	12V adapter	$9.80	1	$9.80
	Waterproofing	$18.50	1	$18.50
				$693.92

The electronics budget is shown in Table 22. The main drivers of costs for the electronics are the propellers, the gasoline generator, the conductivity sensor probe, and the depth + temperature sensor.

The two propellers were chosen to be Blue Robotics T200. The main reason to use this is due to their waterproof design and good support for customization for boat projects. Also, the two propellers have been widely used in previous boat projects here at Penn and this could provide us with much help from people who have worked with them.

The gasoline generator was chosen based on the power and size requirements. This inverter generator was the one with the least power that could cover all our power needs with a light weight and small size. We were also limited by the horsepower limit of Penn in order for us to be able to store and test the generator on campus, and this generator, with a horsepower of 1.25HP, lies within the limit.

The conductivity sensor probe was chosen based on the needs of stakeholders as well as prototyping needs. Specific conductivity indicates salinity levels, which is one of the metrics that water scientists want to track because it indicates the salt front location. What's more, it has a large spatial variation which would be easily discernible for the final deliverable. This probe was also chosen due to its good customer support from DFRobotics for DIY projects, which saved us previous setup time.

Last but not least, the Blue Robotics BAR30 depth + temperature sensor was chosen given its high precision of 1mm for depth which is required by our stakeholders. More importantly, this sensor is waterproof. Our alternative would be to purchase the breakout board of BAR30 sensor and seal it on our own, which might lead to many waterproofing concerns. Therefore, this sensor was chosen in order to save time to focus on the more important development challenges.

OTHER RESOURCES

We have used the tools, materials, testing equipments from PACE Lab, General Motors Lab and Detkin Lab. We have also borrowed the battery charger from ModLab through Prof.Yim.

GLOSSARY

Variables:

q_{min} Minimum flow rate required by the stakeholders
d Diameter of the tube
Re Reynolds Number
f Swamee-Jain friction parameter
FF Darcy Friction Factor
RR Relative Roughness
ΣM Sum of the moments
ΣF_x Sum of the forces in x direction
ΣF_y Sum of the forces in y direction
R Radius of the pulley
τ Sampling motor torque
$\bar{\theta}$ Angular acceleration
Mp Mass of the pulley
m_t Mass of the sampling tube
m_p Mass of the pump
m_s Mass of the conductivity sensor
g Gravitational acceleration
ρ density of the water at STP conditions
v current velocity
C_D coefficient of drag
A profile area of the pump and conductivity probe
F_D Drag force exerted on the pump and conductivity probe
T Tension on the tube
θ Angle of deviation of the pump and conductivity probe due to current
M_{tray} Mass of the collection tray lid
R_{tray} Radius of the collection tray lid
T_L Thrust left
T_R Thrust right

Acronyms:

CG Center of gravity of the boat
CFM Cubic Feet per minute
PWM Pulse Width Modulation
ID Inner Diameter
SS MAPR Smart Sampling & Measuring Autonomous Platform for Rivers
DRBC Delaware River Basin Commission
USGS United States Geological Survey
PWD Philadelphia Water Department
DO Dissolved Oxygen
UX User Experience
ESC Electronic Speed Controller
LPH Liters per hour
RPM Revolutions Per Minute

Definitions:

Buoyancy Force Upward force exerted by a fluid that opposes the weight of an immersed object
Cross-Section A cross-sectional map is a profile map from bank to bank of the river in x and from surface to bottom of the river in y
Aquaculture the rearing of aquatic animals or the cultivation of aquatic plants for food
Exhaust Exhaust time to clean the tube and cycle water 3 times
Backflow Time for the water to fall back from the surface of the boat to the pump due to gravity
Bottle Time to fill up one 250mL HDPE bottle

REFERENCES

[1] "Dirty Hand Tools 104609 800W Inverter Generator." [Online]. Available: https://dirtyhandtools.com/wp-content/uploads/2014/12/800W-1200W-2000W-Inverter-Generator-Op-Manual-Rev-C-lowres.pdf. [Accessed: 07-Apr-2019]

[2] M. Lauria, "Mountaire Farms' troubles mount as company is hit with lawsuits over water pollution claims," *delawareonline*, 28-Jun-2018. [Online]. Available: https://www.delawareonline.com/story/news/local/2018/06/28/mountaire-farms-faces-new-lawsuit-water-contamination/723535002/. [Accessed: 23-Apr-2019]

[3] J. M. And and M. Murray, "Delaware's dirty water," *delawareonline*, 28-Feb-2014. [Online]. Available: https://www.delawareonline.com/story/tech/science/environment/2014/02/28/sunday-preview-delawares-dirty-water/5903237/. [Accessed: 23-Apr-2019]

[4] "Delaware Riverkeeper Network Comment." [Online]. Available: http://www.delawareriverkeeper.org/sites/default/files/Press%20Release%20DRBC%20DO%20Comment%204%204%202017.pdf. [Accessed: 07-Apr-2019]

[5] K. A. Oberg, S. E. Morlock, and W. S. Caldwell, "Quality-Assurance Plan for Discharge Measurements Using Acoustic Doppler Current Profilers,", 2006. [Online]. Available: https://pubs.usgs.gov/sir/2005/5183/index_toc.html. [Accessed: 07-Apr-2019]

[6] Delaware River Basin Commission, "Water Quality Programs of the Delaware River Basin Commission." [Online]. Available: https://www.state.nj.us/drbc/library/documents/WQBooklet_final_print.pdf. [Accessed: 07-Apr-2019]

[7] FIZZ Marketing and Communicatie, "Oceanalpha USV M40 | Geo-matching.com." [Online]. Available: https://geo-matching.com/category/usvs-unmanned-surface-vehicles/m40. [Accessed: 07-Apr-2019]

[8] "YSI EcoMapper AUV | RATES, Research Applied Technology Education Services," *rates*. [Online]. Available: https://www.rates.ventures/ysi-ecomapper-auv. [Accessed: 07-Apr-2019]

[9] "International Decade for Action 'Water for Life' 2005-2015. Focus Areas: The human right to water and sanitation" [Online]. Available: https://www.un.org/waterforlifedecade/human_right_to_water.shtml. [Accessed: 23-Apr-2019]

[10] "River Conditions & Recommendations - Upper Delaware Scenic & Recreational River (U.S. National Park Service)." [Online]. Available: https://www.nps.gov/upde/planyourvisit/river-conditions.htm. [Accessed: 07-Apr-2019]

[11] "IP Rating Chart | DSMT.com," *DSMT.com*. [Online]. Available: http://www.dsmt.com/resources/ip-rating-chart/. [Accessed: 18-Oct-2018]

[12] "PA Waters with Special Boating Regulations." [Online]. Available: https://pfbc.pa.gov/spbtregsx.htm. [Accessed: 18-Oct-2018]

[13] "Ergonomics eTool: Solutions for Electrical Contractors - Materials Handling: Heavy Lifting," 05-Feb-2013. [Online]. Available: https://www.osha.gov/SLTC/etools/electricalcontractors/materials/heavy.html. [Accessed: 12-May-2019]

[14] "NIOSH Lifting Recommendations," *NIOSH*. [Online]. Available: https://www.osha.gov/SLTC/etools/poultry/additional_material/niosh.html. [Accessed: 12-May-2019]

[15] A. F. Molland, S. R. Turnock, and D. A. Hudson, *Ship Resistance and Propulsion: Practical*

Estimation of Ship Propulsive Power. Cambridge University Press, 2017.
[16] "River Conditions & Recommendations - Upper Delaware Scenic & Recreational River (U.S. National Park Service)." [Online]. Available: https://www.nps.gov/upde/planyourvisit/river-conditions.htm. [Accessed: 07-Apr-2019]
[17] "DC Motor Driver," *Amazon*. [Online]. Available: https://www.amazon.com/DROK-Controller-Regulator-Industrial-Optocoupler/dp/B06XGD5SCB/ref=sr_1_6?keywords=motor+driver&qid=1557586153&s=gateway&sr=8-6. [Accessed: 12-May-2019]
[18] DFRobot, "Gravity: Analog Electrical Conductivity Sensor /Meter V2 (K=1) – DFRobot." [Online]. Available: https://www.dfrobot.com/product-1123.html. [Accessed: 11-Dec-2018]
[19] "Bar30 High-Resolution 300m Depth/Pressure Sensor," *Blue Robotics*, 26-Jan-2016. [Online]. Available: https://www.bluerobotics.com/store/sensors-sonars-cameras/sensors/bar30-sensor-r1/. [Accessed: 11-Dec-2018]
[20] "TB6600 Stepper Motor," *Amazon*. [Online]. Available: https://www.amazon.com/STEPPERONLINE-1-0-4-2A-20-50VDC-Micro-step-Resolutions/dp/B06Y5VPSFN/ref=sr_1_4?keywords=stepper+motor+driver&qid=1557586507&s=gateway&sr=8-4. [Accessed: 12-May-2019]
[21] "The Drag Coefficient." [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/dragco.html. [Accessed: 23-Apr-2019]
[22] V. Stejskal, "Kayak design comparison - wave and viscous drag." [Online]. Available: http://www.oneoceankayaks.com/kayakpro/kayakgrid.htm. [Accessed: 23-Apr-2019]
[23] "USGS Current Conditions for USGS 01477050 Delaware River at Chester, PA." [Online]. Available: https://waterdata.usgs.gov/pa/nwis/uv/?site_no=01477050&PARAmeter_cd=00065,00060,00010. [Accessed: 23-Apr-2019]
[24] "Why do mobile networks have high latencies? How can they be reduced?," *Server Fault*. [Online]. Available: https://serverfault.com/questions/387627/why-do-mobile-networks-have-high-latencies-how-can-they-be-reduced. [Accessed: 23-Apr-2019]
[25] "RFM95_96_97_98W LoRa." [Online]. Available: https://cdn.sparkfun.com/assets/learn_tutorials/8/0/4/RFM95_96_97_98W.pdf. [Accessed: 23-Apr-2019]
[26] "DIGI XBEE-PRO® 900HP Datasheet," *Digi International*. [Online]. Available: https://www.digi.com/pdf/ds_xbeepro900hp.pdf. [Accessed: 11-Dec-2018]
[27] "Autonomous navigation of a small boat using IMU/GPS/digital compass integration - IEEE Conference Publication." [Online]. Available: https://ieeexplore.ieee.org/document/6549924. [Accessed: 23-Apr-2019]
[28] "Real-Time Kinematic (RTK)," *NovAtel*. [Online]. Available: https://www.novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/real-time-kinematic-rtk/. [Accessed: 23-Apr-2019]
[29] "What to consider when choosing batteries for a project?," *Electrical Engineering Stack Exchange*. [Online]. Available: https://electronics.stackexchange.com/questions/9389/what-to-consider-when-choosing-batteries-for-a-project. [Accessed: 23-Apr-2019]
[30] L. L. C. Keith Araujo-Epec, "Battery Comparison of Energy Density - Cylindrical and Prismatic Cells." [Online]. Available: https://www.epectec.com/batteries/cell-comparison.html. [Accessed: 23-Apr-2019]

[31] "Regulated Dc Power Supply 18v 27.8a 500w Switch Switching Led Driver Transformers 110v 220v Ac-dc Smps For Light Cnc Stepper - Buy Power Supply,18v 27.8a 500w Switch Switching,220v Ac-dc Smps Product on Alibaba.com," *www.alibaba.com*. [Online]. Available: https://www.alibaba.com/product-detail/Regulated-DC-Power-Supply-18V-27_60781802604.html?spm=a2700.7724838.2017115.24.4c0f649dEt4DnL. [Accessed: 23-Apr-2019]
[32] "24V 6A Power Supply." [Online]. Available: https://www.amazon.com/ZCPlus-Universal-Adapter-Transformer-Computer/dp/B07C5P6NNS/ref=sr_1_3?keywords=24v+6A+power+supply&qid=1553003785&s=gateway&sr=8-3. [Accessed: 23-Apr-2019]
[33] "Original 100% New Lithium Ion Rechargeable Battery Ncr18650b 3.7v 3400mah - Buy Ncr18650b 3400mah,Ncr18650b,18650b 3.7v 3400mah Battery Cell Product on Alibaba.com," *www.alibaba.com*. [Online]. Available: https://www.alibaba.com/product-detail/Original-100-New-Lithium-ion-Rechargeable_60434821256.html?spm=a2700.supplier-normal.35.14.382c599dltkoBd. [Accessed: 11-Dec-2018]
[34] Banggood.com, "7S Cells 4.2V 20A Balancing Li-ion Lithium 18650 Battery Protection Board," *www.banggood.com*. [Online]. Available: https://usa.banggood.com/7S-Cells-4_2V-20A-Balancing-Li-ion-Lithium-18650-Battery-Protection-Board-p-1063304.html. [Accessed: 27-Jan-2019]
[35] "5A DC-DC Adjustable Buck Converter 4~38v to 1.25-36v." [Online]. Available: https://www.amazon.com/Adjustable-Converter-1-25-36v-Efficiency-Regulator/dp/B079N9BFZC/ref=sr_1_3?ie=UTF8&qid=1548533096&sr=8-3&keywords=dc%2Bdc%2Bvoltage%2Bregulator%2B5a&th=1. [Accessed: 27-Jan-2019]
[36] "VRUZEND DIY Battery Kit." [Online]. Available: https://vruzend.com/. [Accessed: 26-Feb-2019]
[37] "The HydroNet ASV, a Small-Sized Autonomous Catamaran for Real-Time Monitoring of Water Quality: From Design to Missions at Sea - IEEE Journals & Magazine." [Online]. Available: https://ieeexplore.ieee.org/document/6960116. [Accessed: 23-Apr-2019]
[38] "Autonomous Underwater Vehicle for water quality, currents, bathymetry, and sonar imagery | ysi.com." [Online]. Available: https://www.ysi.com/ecomapper. [Accessed: 23-Apr-2019]
[39] "YSI EcoMapper AUV | RATES, Research Applied Technology Education Services," *rates*. [Online]. Available: https://www.rates.ventures/ysi-ecomapper-auv. [Accessed: 07-Apr-2019]
[40] "NIOSH Lifting Recommendations." [Online]. Available: https://www.osha.gov/SLTC/etools/poultry/additional_material/niosh.html. [Accessed: 04-Feb-2019]

APPENDIX: BILL OF MATERIALS

FINAL PRODUCT

Subsystem	Item	Unit Cost	Qty	Total Cost
Task Functions	Pulley + Motor	$542.00	1	$542.00
	Slip Ring	$170.00	1	$170.00
	Tube	$40.00	1	$40.00
	Pump	$56.99	1	$56.99
	Empty Bottles	$14.00	2	$28.00
	Tray PVC	$15.62	1	$15.62
	Tray Motor + Shaft Coupler	$25.00	1	$25.00
	Electric Solenoid Valve	$32.95	1	$32.95
	Hose Adapters	$9.63	6	$57.80
	Acrylic 1/8 inch	$27.63	2	$55.26
	Acrylic 1/4 inch	$54.29	1	$54.29
	Marine Sealant	$16.97	1	$16.97
Hull	Pontoon	$253.00	1	$253.00
	Plywood	$14.98	1	$14.98
Lid	Carbon Fiber & Fiberglass	$103.00	1	$103.00
	Foam	$69.33	1	$69.33
	Epoxy Resin + Hardner + Compound	$157.00	1	$157.00
Propulsion	Propeller	$194.00	2	$388.00
Power	Gasoline generator	$212.00	1	$212.00
Electronics	GPS + antenna	$56.86	1	$56.86
	Raspberry Pi	$40.00	1	$40.00
	IMU+compass	$16.89	1	$16.89
	Voltage regulators	$12.00	1	$12.00
	XBee	$47.00	2	$94.00
	XBee adapters	$14.00	2	$28.00
	USB to TTL adapters	$25.00	1	$25.00
	Microcontroller - MBed	$54.95	1	$54.95
	Conductivity sensor probe	$82.95	1	$82.95
	Depth + temperature sensing	$68.00	1	$68.00
	Underwater cable	$49.99	1	$49.99
	sensor BNC cable	$9.99	1	$9.99
	Motor drivers	$31.99	1	$31.99
	28V adapter	$54.00	1	$54.00
	24V adapter	$15.00	1	$15.00
	18V adapter	$15.00	1	$15.00
	16V adapter	$11.00	1	$11.00
	12V adapter	$9.80	1	$9.80
	Waterproofing	$18.50	1	$18.50
		Total Cost		**$2,829.11**

ALL EXPENSES

Category	Items	Date	Amount
Boat	Plywood + Spray Paint	2/28/2019	$21.20

Boat	Waterproof tarp	3/2/2019	$8.95
Boat	screws for frame	3/2/2019	$9.47
Boat	Epoxy putty	3/18/2019	$39.99
Boat	Epoxy Resin	3/23/2019	$116.57
Boat	McMaster border for lid	3/25/2019	$80.94
Boat	Latches	3/29/2019	$19.98
Boat	Waterproof box for electrical	2/15/2019	$24.37
Cover	XPS Foam and glue	3/12/2019	$69.33
Electrical / Control	Stepper motor driver	2/11/2019	$13.59
Electrical / Control	1m XBee antenna extension	3/24/2019	$6.99
Electrical / Measuring	Coax Seal	2/17/2019	$9.50
Electrical / Measuring	10ft BNC cable	3/22/2019	$5.35
Electrical / Measuring	Pressure sensor	3/25/2019	$17.99
Electrical / Navigation	Digi XBee-PRO 900HP (S3B) DigiMesh, 900 MHz, 250 mW, RPSMA, 200 Kbps	11/29/2018	$141.00
Electrical / Navigation	Antenna 860-960MHz GSM 2dBi Omni Directional Dipole W/ RP-SMA (waterproof & not waterproof)	11/29/2018	$26.34
Electrical / Navigation	GPS breakout module	11/29/2018	$41.86
Electrical / Navigation	GPS antenna & uFL to SMA cable (for GPS antenna)	11/29/2018	$21.72
Electrical / Navigation	Odroid	12/06/2018	$79.89
Electrical / Navigation	5V/4A Power Supply for ODroid	12/22/18	$15.95
Electrical / Navigation	Hose	12/17/18	$34.85
Electrical / Navigation	Pulley for hose + leading tube	12/17/18	$63.39
Electrical / Navigation	Adapter male-female	12/17/18	$10.73
Sampling Mechanism	Pump	12/17/18	$56.99
Electrical / Navigation	2 Adapter and Stepper Motor	12/21/2018	$36.41
Electrical / Navigation	Valve	12/21/2018	$40.20
Electrical / Navigation	DFRobot Analog Electrical Conductivity Meter (With Temperature Compensation)	12/17/2018	$82.95
Electrical / Navigation	BNC extension cable 50ft	12/17/2018	$9.99
Electrical / Navigation	Adafruit (PID 3387) 9-DOF Accel/Mag/Gyro+Temp Breakout Board - LSM9DS1	12/17/2018	$16.89
Electrical / Navigation	Blue Robotics T200 Thruster + ESC	12/17/2018	$388.00

Electrical / Navigation	Blue Robotics depth & temperature sensor	12/17/2018	$68.00
Electrical / Navigation	Pontoons	1/2/2019	$180.62
Electrical / Navigation	Motor	12/22/2018	$481.00
Electrical / Navigation	PVC pipe	1/11/2019	$15.62
Electrical / Navigation	Adapters & shaft coupler	1/11/2019	$20.12
Electrical / Navigation	New adapter	1/11/2019	$13.45
Electrical / Navigation	New adapter and bottles	1/21/2019	$48.73
Electrical / Navigation	sealant	1/21/2019	$17.99
Electrical / Navigation	USB to 4 TTL converter	1/22/2019	$11.99
Electrical / Navigation	Moyina USB to TTL Adapter	1/1/19	$12.99
Electrical / Navigation	Waveshare XBee USB Adapter	1/1/19	$13.99
Electrical / Navigation	Waveshare XBee USB Adapter	1/8/19	$13.99
Electrical / Navigation	Raspberry Pi Case	2/10/19	$5.68
Electrical / Power	gasoline generator	3/17/2019	$212.00
Electrical / Power	120V AC -> 28V adapter	3/19/2019	$53.41
Electrical / Power	120V AC -> 24V adapter	3/19/2019	$15.00
Electrical / Power	120V AC -> 16V adapter	3/19/2019	$11.00
Electrical / Power	gas can	3/19/2019	$19.00
Electrical / Power	SAE10w-30 Engine Oil	3/19/2019	$9.00
Electrical / Power	120V AC -> 18V adapter	3/19/2019	$15.00
Electrical / Power	12V 5A adapter	3/23/2019	$9.80
Electrical / Sampling	100ft 8 conductor 22 awg cable (shipping excluded)	2/19/2019	$43.00
Manufacturing	carbon fiber	3/14/2019	$198.00
MEAM generator	Duct interface	3/20/2019	$14.03
MEAM generator	Fan 305 CFM	3/21/2019	$25.83
Power	24V BMS board	1/27/19	$10.81
Power	16V BMS board	1/27/19	$10.06
Power	Voltage regulators	1/27/19	$12.00
Power	Plastic battery holders	1/27/19	$11.00
Power	2 more Backup LiPo packs	2/5/19	$45.98
Power	Backup LiPo pack and 18/12 AWG wires	2/5/19	$37.95
Power	18650 battery kit	2/15/2019	$29.99
Power	H1 Bridge motor driver	2/15/2019	$18.99

Propellers	Thread, belt, buckles	1/24/19	$46.31
Sampling Mechanism	Motor Brackets	2/6/19	$8.47
Sampling Mechanism	waterproof	2/8/19	$13.23
Sampling Mechanism	Submersible Pump #2	2/9/19	$35.00
Sampling Mechanism	black tube as cover	3/12/2019	$23.99
Sampling Mechanism	waterproof box for voltage regulator	3/12/2019	$20.09
Sampling Mechanism	black tube as cover	3/20/2019	$22.99
Sampling Mechanism	Slip Ring (cheap)	3/21/2019	$44.52
Sampling Mechanism	Slip ring	3/23/2019	$191.85
Tray + meam generator	Velcro, duct tube, grill plate	3/20/2019	$37.71
Electrical / Control	propeller extension cord	3/30/2019	$20.00
Measuring	Blue Robotics depth & temperature sensor	3/25/2019	$77.00
Testing	UHaul	04/04/2019	$47.17
Demo	Fisherman hats	04/06/2019	$50.95
Electrical / Control	ANtenna extension	03/24/2019	$6.99
Measuring	Pressure sensor	3/26/2019	$17.99
Electrical / Control	XBee	4/12/2019	$46.99
Demo	Fish Tank	4/16/2019	$22.37
Demo	Round pan	4/16/2019	$7.58
Crate	Wood	4/18/2019	$107.98
Total			**$4,066.58**

APPENDIX: PERFORMANCE MEASURES

OVERALL

Calculation for Cost

Current Sampling Trip	
# of people	4
Time (min)	360
Total labor cost (contractor)	$2,545
Boat rental	$ 3,255.00
Filter + Vibrio	$ 500.00
Total Cost per trip	*$6,300*
# of samples	22
Volume per sample (L)	8
Time per location (min)	16.36
Travel time per location (min)	5
# per year	12
Data points per sample	41
Time per sample (min)	**11.36**
Cost per sample metric	**$ 4.85**

Current Cross-Sectional Measurement Trip	
# of people	2
Time (min)	360
Total labor cost	0
Boat rental	$ 1,800.00
Total Cost per trip	*$ 1,800.00*
# of measurements	100
# of locations	10
# of multi-depth data points	*90*
# per year	1
Cost per measurement	**$18**

* based on DRBC cost breakdown

SSMAPR	
# of people	1
Labor cost per hour	65
Time (min)	240
Labor Cost per trip	$ 260.00
Gasoline per trip	$ 5.00
Filter + vibrio cost	$ 500.00
Allocated fixed cost	$ 5.40
Total cost per trip	**$ 770.40**
# per year	100
# of samples	10
Volume per sample (L)	0.25
Time per sample (min)	5
Data points per sample	16
# of under surface samples	9
# of multi-depth data points from samples	*144*
Average time per measurement (min)	1
# of measurements	100
# of multi-depth measurements	*90*
Total # of multi-depth data points	**234**
Time per column (min)	15
Cost per sample metric	**$ 1.61**
Cost per measurement	**$ 5.14**

Cost projection for DRBC with SSMAPR	
Current budget per year in sampling & measuring	**$77,400.00**
# per year possible for SSMAPR	100
SSMAPR fixed cost	$ 2,700.00
# of service years	5
Allocated fixed cost per trip	$ 5.40

Cost & Labor Analysis	
Cost Saving per sample metric	**66.91%**
Cost Saving per measurement	**71.47%**
Labor Saving	**66.67%**

Multi-depth Data Points	
Current annual multi-depth data points	90
Annual multi-depth data points with SSMAPR	23400
Increase in multi-depth data points	**260**

Cost Comparison with Other Autonomous Solutions

SSMAPR	
# of people	1
Labor cost per hour	65
Time (min)	240
Labor Cost per trip	$ 260.00
Gasoline per trip	$ 5.00
Filter + vibrio cost	$ 500.00
Allocated fixed cost	$ 5.40
Total cost per trip	**$ 770.40**
# per year	100
# of samples	10
Volume per sample (L)	0.25
Time per sample (min)	5
Data points per sample	16
# of under surface samples	9
# of multi-depth data points from samples	*144*
Average time per measurement (min)	1
# of measurements	100
# of multi-depth measurements	*90*
Total # of multi-depth data points	**234**
Time per column (min)	15
Cost per sample metric	**$ 1.61**
Cost per measurement	**$ 5.14**

Cost projection for DRBC with SSMAPR	
Current budget per year in sampling & measuring	**$77,400.00**
# per year possible for SSMAPR	100
SSMAPR fixed cost	$ 2,700.00
# of service years	5
Allocated fixed cost per trip	$ 5.40

Multi-depth Data Points	
Current annual multi-depth data points	90
Annual multi-depth data points with SSMAPR	23400
Increase in multi-depth data points	**260**

Autonomous Surface Vehicle	
# of people	1
Labor cost per hour	65
Time (min)	150
Labor Cost per trip	$ 162.50
Filter + vibrio cost	$ 500.00
Allocated fixed cost	$ 186.81
Total cost per trip	**$ 849.31**
# per year	91
# of samples	10
Volume per sample (L)	0.1
Data points per sample	2
# of under surface samples	9
# of multi-depth data points from samples	*18*
# of measurements	100
# of multi-depth measurements	*90*
Total # of multi-depth data points	**108**
Cost per sample metric	**$ 14.16**
Cost per measurement	**$ 5.66**

Cost projection for DRBC with SSMAPR	
Current budget per year in sampling & meas	**$77,400.00**
# per year possible for ASV	91
fixed cost	$ 85,000.00
# of service years	5
Allocated fixed cost per trip	$ 186.81

Multi-depth Data Points	
Current annual multi-depth data points	90
Annual multi-depth data points with ASV	9828
Increase in multi-depth data points	**109.2**

Autonomous Underwater Vehicle	
# of people	1
Labor cost per hour	65
Time (min)	264
Labor Cost per trip	$ 286.00
Filter + vibrio cost	$ 500.00
Allocated fixed cost	$ 205.13
Total cost per trip	**$ 991.13**
# per year	78
# of samples	0
Volume per sample (L)	0
Data points per sample	0
# of under surface samples	0
# of multi-depth data points from samples	*0*
# of measurements	100
# of multi-depth measurements	*90*
Total # of multi-depth data points	**90**
Cost per sample metric	**/**
Cost per measurement	**$ 6.61**

Cost projection for DRBC with SSMAPR	
Current budget per year in sampling & meas	**$77,400.00**
# per year possible for AUV	78
fixed cost	$ 80,000.00
# of service years	5
Allocated fixed cost per trip	$ 205.13

Multi-depth Data Points	
Current annual multi-depth data points	90
Annual multi-depth data points with AUV	7020
Increase in multi-depth data points	**78**

Sampling Metric Table

Parameter Groups	Parameters	Holding Time	Bottle	Preservation/Storage	Transport
Routine & Expanded Nutrients	Alkalinity (Titrimetric, pH 4.5)	14 days	2 L HDPE	Cool, ≤ 6°C	Ice
	Ammonia as N, Dissolved	28 days	2 L HDPE	Field-filtered (0.45 um), Cool, ≤ 6°C, HNO_3 to pH <2	
	Carbon, Organic - Dissolved (DOC)	28 days	40 mL Amber Glass VOA vial	Field-filtered (0.45 um), Cool, ≤ 6°C, HCl to pH < 2	
	Carbon, Particulate	28 days	1 L HDPE	Filter onto glass fiber (0.7 um pore size), store at -20°C	
	Chloride, Total	28 days	2 L HDPE	None required	
	Hardness as CaCO3	6 months	2 L HDPE	H_2SO_4 to pH < 2	
	Nitrate as N, Dissolved	48 hours	2 L HDPE	Field-filtered (0.45 um), Cool, ≤ 6°C	
	Nitrate/Nitrite as N, Dissolved	28 days	2 L HDPE	Field-filtered (0.45 um), Cool, ≤ 6°C, H_2SO_4 to pH < 2	
	Nitrite as N, Dissolved	48 hours	2 L HDPE	Field-filtered (0.45 um), Cool, < 6°C	
	Nitrogen, Dissolved, Alkaline Persulfate	28 days	2 L HDPE	Field-filtered (0.45 um), Cool, < 6°C,	
	Nitrogen, Particulate	28 days	1 L HDPE	Filter onto glass fiber (0.7 um pore size), store at -20°C	
	Nitrogen, Total, Alkaline Persulfate	28 days	2 L HDPE	Cool, ≤ 6°C	
	Orthophosphorus, Soluble	48 hours	2 L HDPE	Cool, ≤ 6°C	
	Phosphorus, Dissolved, Alkaline Persulfate	28 days	2 L HDPE	Field-filtered (0.45 um), Cool, < 6°C	
	Phosphorus, Particulate	28 days	2 L HDPE	Filter onto glass fiber (0.7 um pore size), store at -20° ± 5° C	
	Phosphorus, Total, Alkaline Persulfate	28 days	2 L HDPE	Cool, ≤ 6°C	
	Residue, Filterable (TDS)	7 days	2 L HDPE	Cool, ≤ 6°C	
	Residue, Nonfilterable (TSS)	7 days	2 L HDPE	Cool, ≤ 6°C	
	Sulfate	28 days	250 mL HDPE	Cool, < 6°C	
	Turbidity (Nephelometric)	48 hours	2 L HDPE	Cool, < 6°C	

Bacterial	E. Coli	8 hours	1L PETG	Cool, < 6°C	(Temp. ≤ 6°C) without freezing
	Enterococcus				
	Coliform, Fecal (MTEC)				
Algal	Chlorophyll-a	28 days	250 mL HDPE	Filter onto glass fiber (0.7 um pore size), store at -20°C	
	Silica, Dissolved	7 days	250 mL HDPE	Field-filtered (0.45 um), Cool, < 6°C,	
Metals and Minerals	Chromium, Hexavalent - Dissolved	24 hours	250 mL HDPE	Field-filtered (0.45 um), Cool, ≤ 6°C	
	Mercury, Total	28 days	500 mL HDPE	HNO_3 to pH < 2	
	Copper, Dissolved	6 months	250 mL HDPE	Field-filtered (0.45 um), HNO_3 to pH < 2	
	Lead, Dissolved				
	Nickel, Dissolved				
	Zinc, Dissolved				
	Calcium, Total	6 months	250 mL HDPE	HNO_3 to pH < 2	
	Copper, Total				
	Lead, Total				
	Magnesium, Total				
	Nickel, Total				
	Potassium, Total				
	Sodium, Total				
	Zinc, Total				
Organics	Volatiles	14 days	40 mL Glass VOA vial	Cool, ≤ 6°C, HCl to pH < 2	
	Semivolatiles	Extraction 7 days, analysis 40 days	2.5 L Amber Glass	Cool, ≤ 6°C	

Tests for Weight & Size

Performance Measure	Design Target	Test	Result
Weight	100 pounds	The boat was weighed on a scale. What's more, the team members carried the boat during transportation to the river. Carrying the boat required 3 people.	138 pounds
Size	2m W x 2.4m L	The boat was fit within a standard pickup truck.	2.4m W x 1.4m L x 0.7m H

TASK FUNCTIONS

Performance Measure	Design Target	Test	Result
Depth reached	Up to 45 ft	In order to validate that, the sampling mechanism was tested in a dry environment	40ft
Time of Water Collection	19.3 minutes/column	The pump was lowered from the surface (3rd floor) to 40 feet (basement) and the water was	6 minutes per column

		pumped from a bucket up to the collection tray. For each sample, the team recorded the time to fill up 250mL HDPE bottles at each depth.	
Cross Sectional Map	100 Point Cross Sectional Map	Performance Measurements 1 and Performance Measurements 2 were tested and validated in the Schuylkill river. Multiple water samples were collected and a conductivity map was generated for the stakeholders.	Cross Sectional Map of Conductivity
Data Quality	within 2 mm resolution	A booster and filter circuit were implemented to ensure the depth sensor functionality within the 2mm resolution and to fit the vertical bounding box of 1m dictated by the stakeholders.	Within 2 mm resolution
Sampling Volume	41 sample metrics	From our design, the collection tray can hold 10 bottles of 250mL samples.	16 sample metrics

ACTUATION & CONTROL

Performance Measure	Design Target	Test	Result
Communication Range	2200m	Gradually increased the distance between 2 XBees while keeping monitoring if data communication was still functional.	2200m
Actuation against River Current	1.3m/s against 1.12m/s current	The boat was remotely controlled to drive against the current in a straight line with known distance and timed.	1.5m/s against 1.1m/s current

AUTONOMOUS NAVIGATION

Performance Measure	Design Target	Test	Result
Localization Output Range	<= 1m	The boat was driven in a straight line, and the trajectory was derived from a drone video. Then we plotted out the the filter outputs.	1m

Steady-State Control Boundary	2m radius	The boat was placed at 3 different locations in autonomy mode for 20 min. Then the trajectory was extracted from drone video	2m radius
Path Following and Stopping	Navigate along a path of 10 stop points and stop at each point	The boat was initialized with a set waypoints and started the mission.	Navigate along a path of 6 stop points and stop at each point

UX & DATA PROCESSING

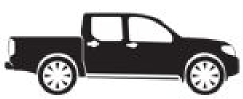
Performance Measure	**Design Target**	**Test**	**Result**
Functionalities Covered	Cover all functionalities needed throughout the operation	Simulating an actual sampling and measuring boat run as a user. During the test, we performed all the functionalities through a keyboard interface	All basic functionalities are covered
Ease of Use	Easy for 1 operator to understand and use outdoors	1. Ease of use: measure the number of clicks and typing needed to set up a mission. 2. Ease of understanding: Stakeholder feedbacks through email and phone call	1. 50 clicks and 10 typing actions for mission config. 3 clicks if using predefined config. 2. The user was able to understand the interface without a tutorial. Suggested replacing keyboard with joystick.

POWER

Performance Measure	**Design Target**	**Test**	**Result**
Runtime	>= 4 hours	Had the generator running for a consecutive 4-hours with its tank filled and all of our major electrical components plugged in and running on the river	Runtime >=4hr.
Refueling Time	5min	Timed the refueling process of the generator	5min

APPENDIX: CONSTRUCTION, ASSEMBLY AND OTHER MECHANICAL ENGINEERING

ASSEMBLY FOR A USER



Arrive on site

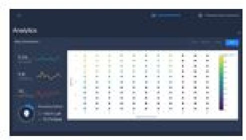
Unload SS MAPR

Turn on the generator

Pump up the pontoons

Input desired waypoints

Off it goes!



Follow SS MAPR's progress

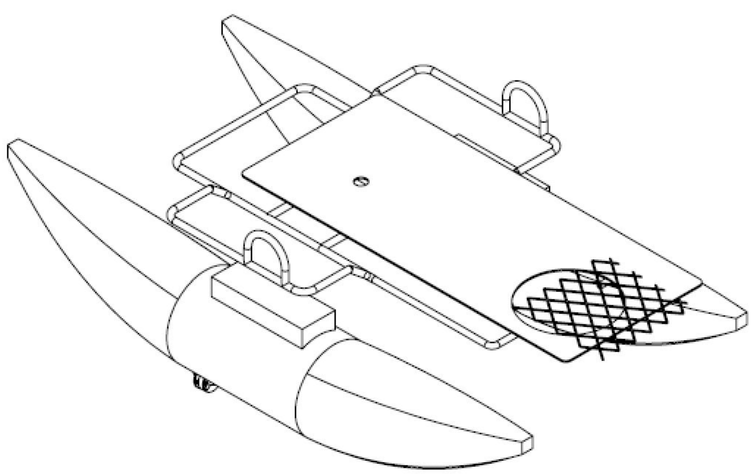
> 25 minutes to setup

> 4 hours for data & samples

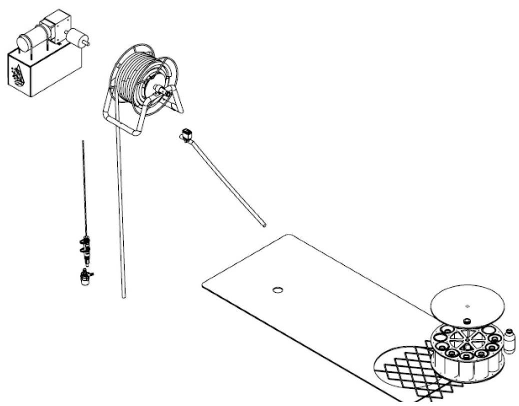
CONSTRUCTION FOR AN ENGINEER

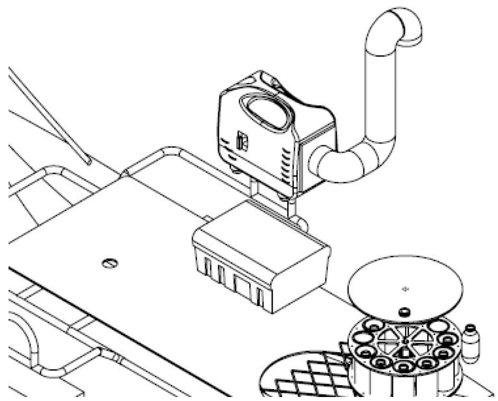
The assembly procedure is outlined below.

1. Strap inflatable pontoons to metal frame
2. Attach propellers to the bottom of the pontoons
3. Attach plywood to metal frame, and the perforated steel sheet onto the plywood

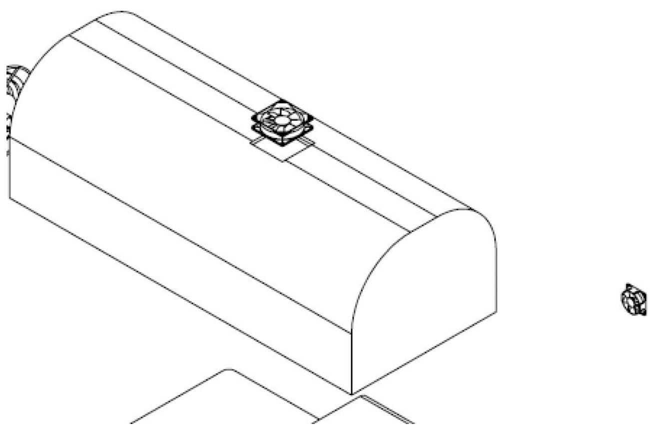


4. Screw pulley motor box, pulley, collection tray, electronics box, and generator to plywood

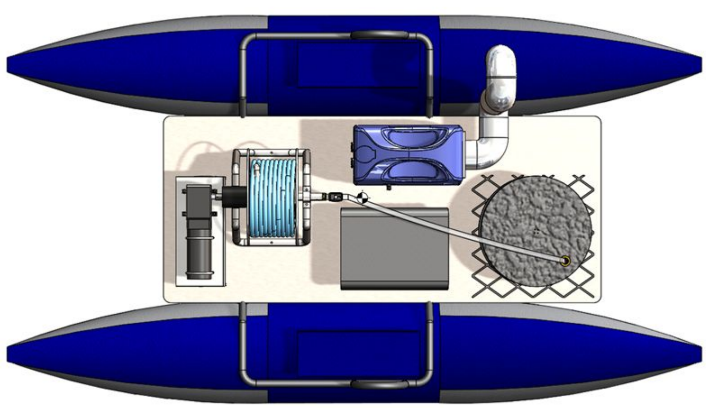




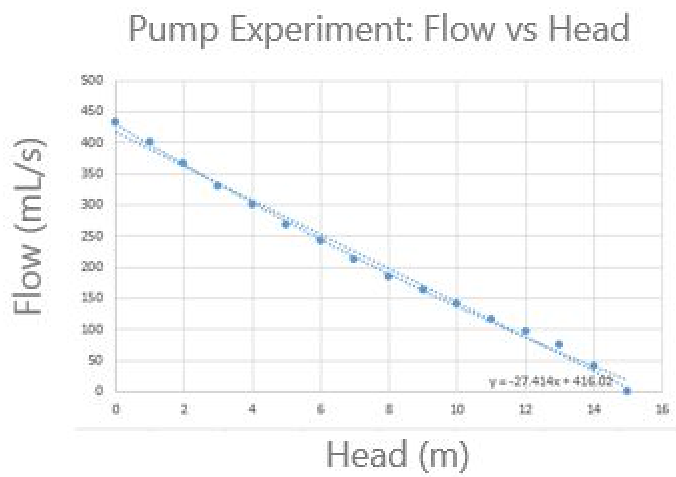
5. Cover all components on the plywood with foam carbon fiber lid and close latches



CENTER OF GRAVITY



PUMP TRENDLINE



This graph presents the estimated flow rate for each depth based on pump performance trend line (at 90% duty cycle, 90% efficiency, 5% loss due to friction)

COLLECTION MATERIAL DOWN-SELECTION

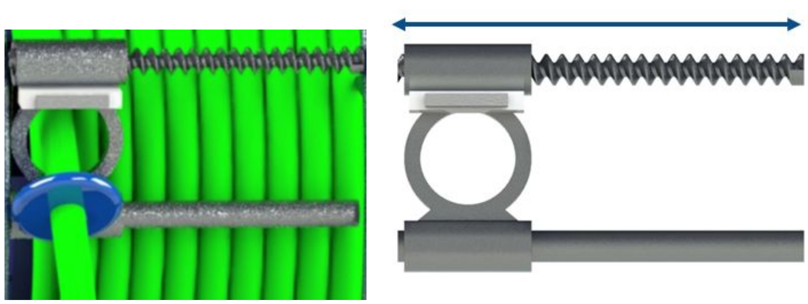
Metric	Acrylic	MDF	ABS	PVC
Density	1.18 g/cm^3	0.78 g/cm^3	1.06 g/cm^3	1.39 g/cm^3
Cost (per in^2)	$0.04	$0.07	$0.05	$0.04
Water resistance*	1	0	1	1

WATERPROOFING

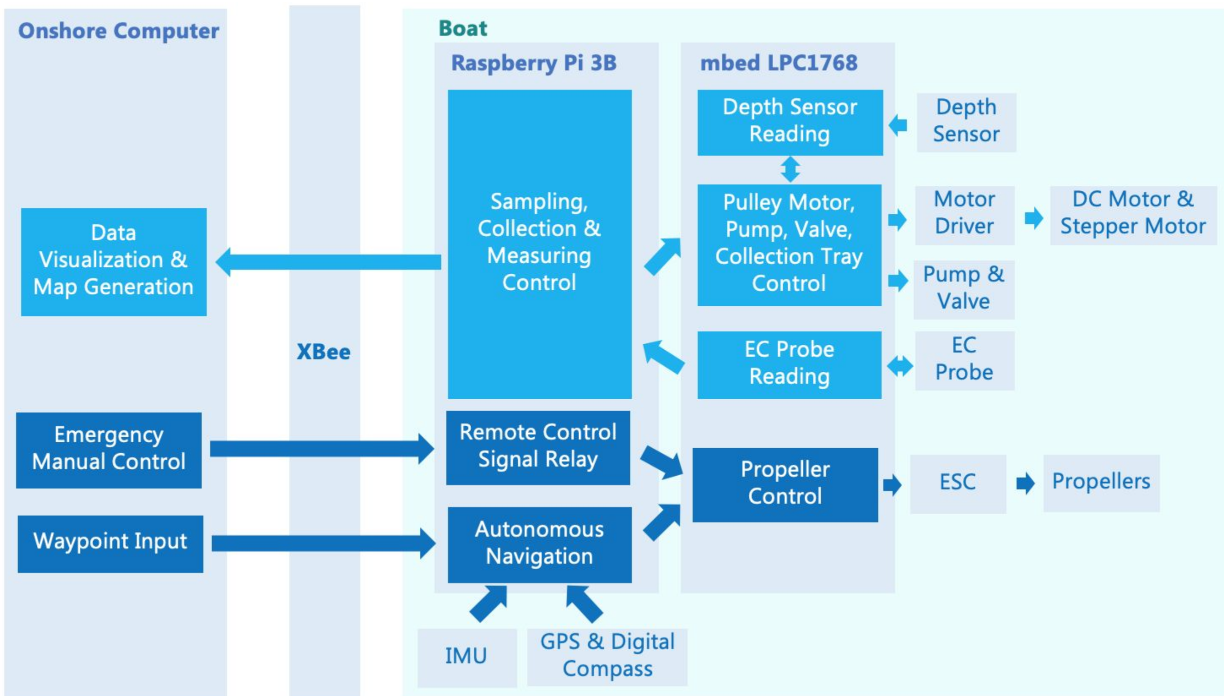
DANGLING NEXT STEP

The mechanical subteam hopes to make design improvements with regards to the dangling and winding of the pump and probe:

- Limit switch as feedback to stop the motor
- Guide for tube winding and unwinding
- Elevated mount for pump and sensor

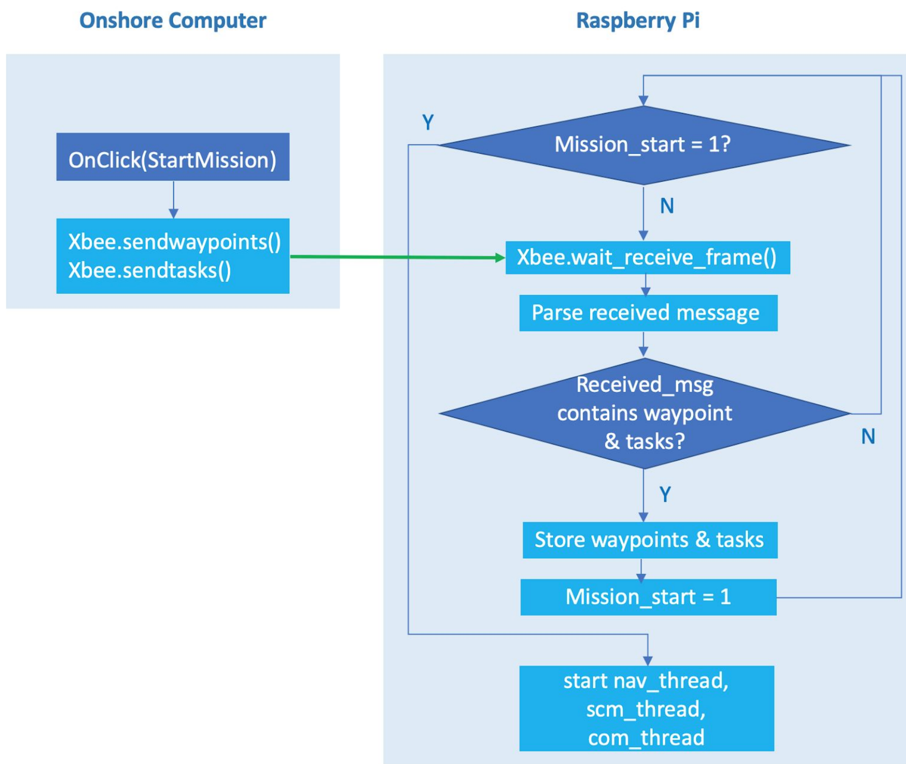


SOFTWARE BLOCK DIAGRAM

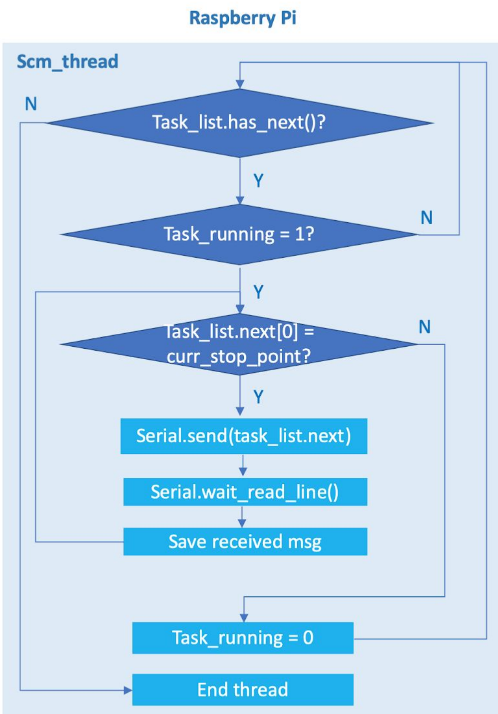


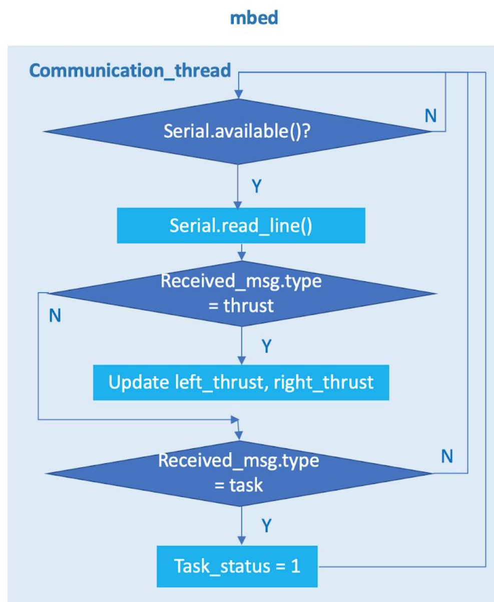
SOFTWARE FLOWCHARTS

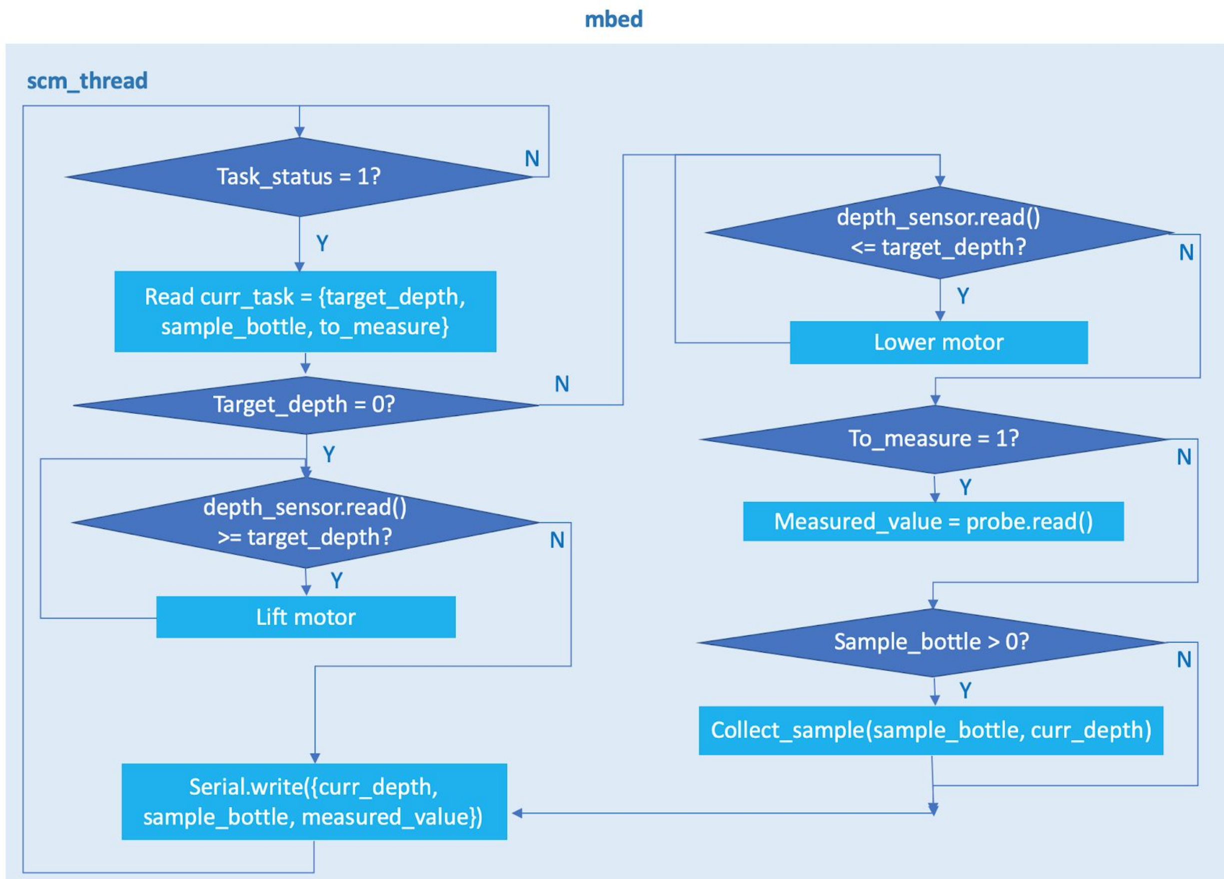
INITIALIZATION

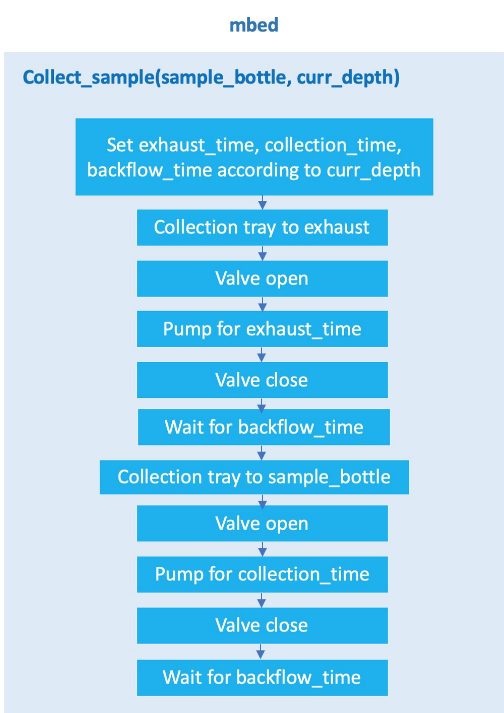


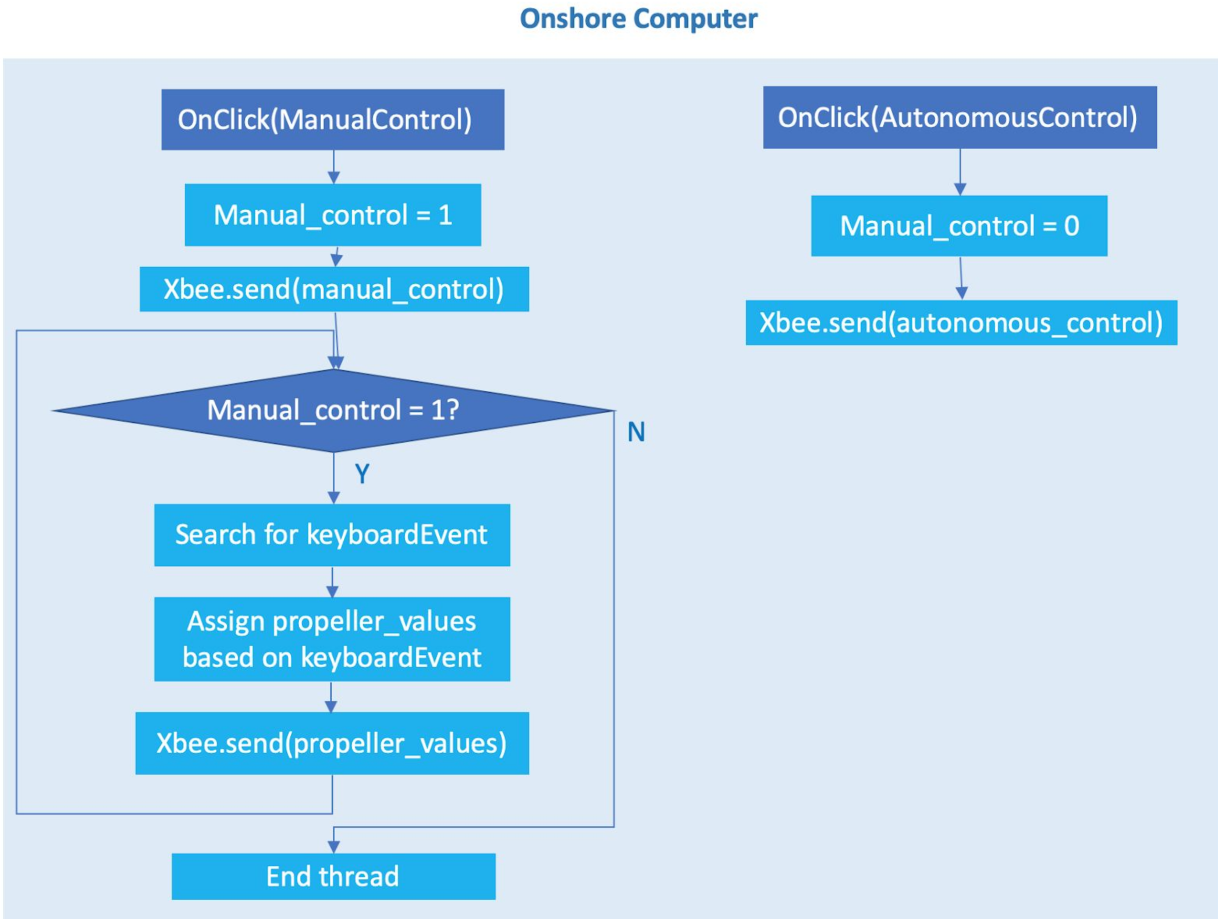
TASK FUNCTIONS

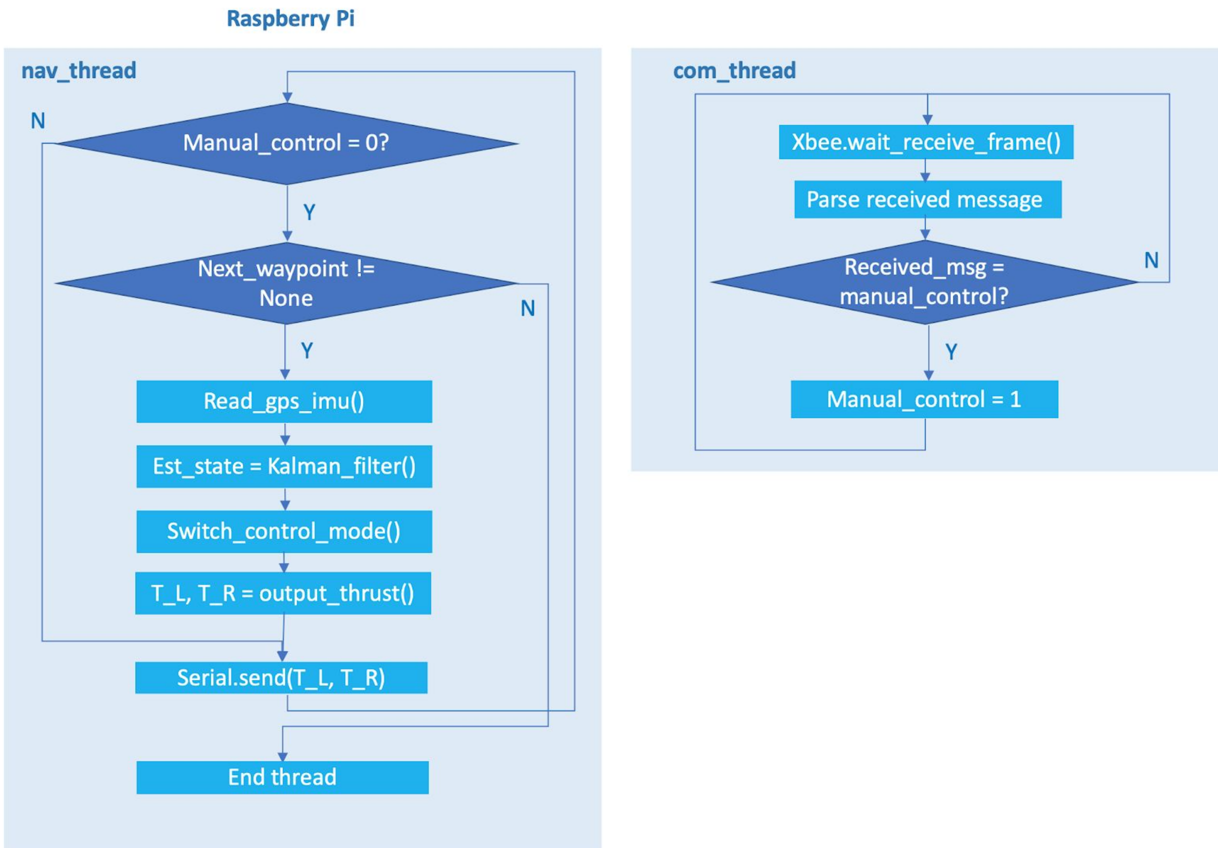





mbed
scm_thread
Task_status = 1?
N
Y
Read curr_task = {target_depth, sample_bottle, to_measure}
Target_depth = 0?
N
Y
depth_sensor.read() >= target_depth?
N
Y
Lift motor
depth_sensor.read() <= target_depth?
N
Y
Lower motor
To_measure = 1?
N
Y
Measured_value = probe.read()
Sample_bottle > 0?
N
Y
Collect_sample(sample_bottle, curr_depth)
Serial.write({curr_depth, sample_bottle, measured_value})


mbed
Collect_sample(sample_bottle, curr_depth)
Set exhaust_time, collection_time, backflow_time according to curr_depth
Collection tray to exhaust
Valve open
Pump for exhaust_time
Valve close
Wait for backflow_time
Collection tray to sample_bottle
Valve open
Pump for collection_time
Valve close
Wait for backflow_time


Onshore Computer
OnClick(ManualControl)
Manual_control = 1
Xbee.send(manual_control)
Manual_control = 1?
N
Y
Search for keyboardEvent
Assign propeller_values based on keyboardEvent
Xbee.send(propeller_values)
End thread
OnClick(AutonomousControl)
Manual_control = 0
Xbee.send(autonomous_control)

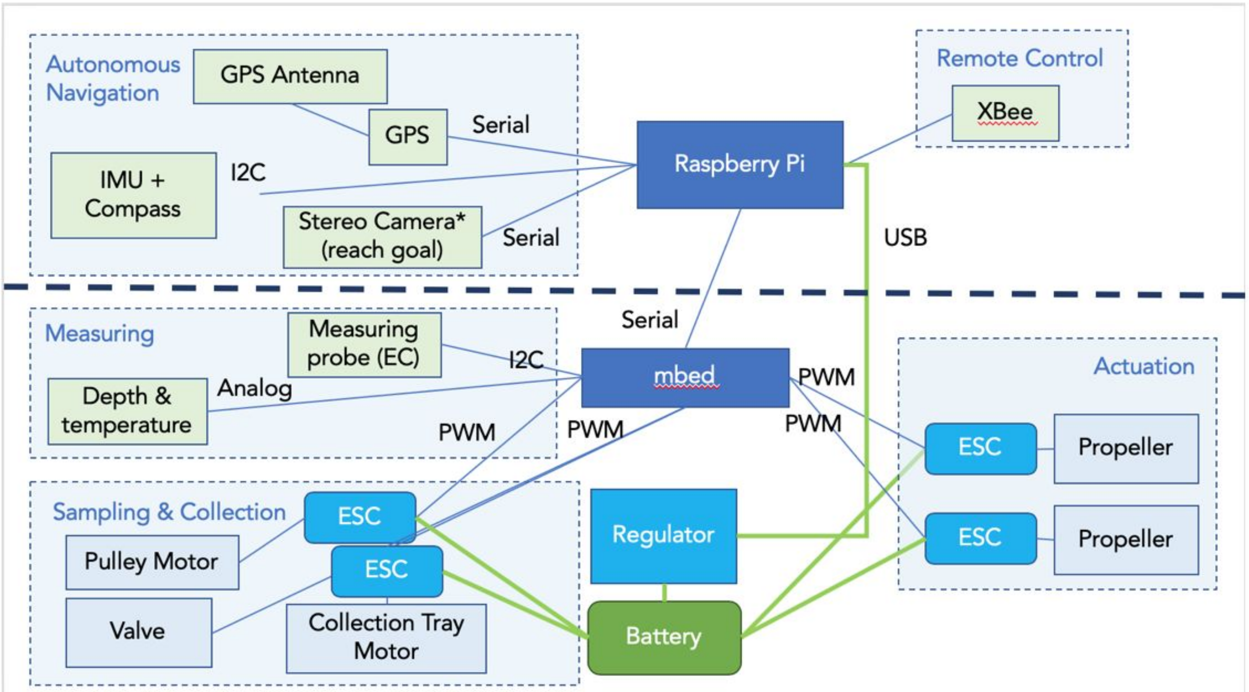


CODE

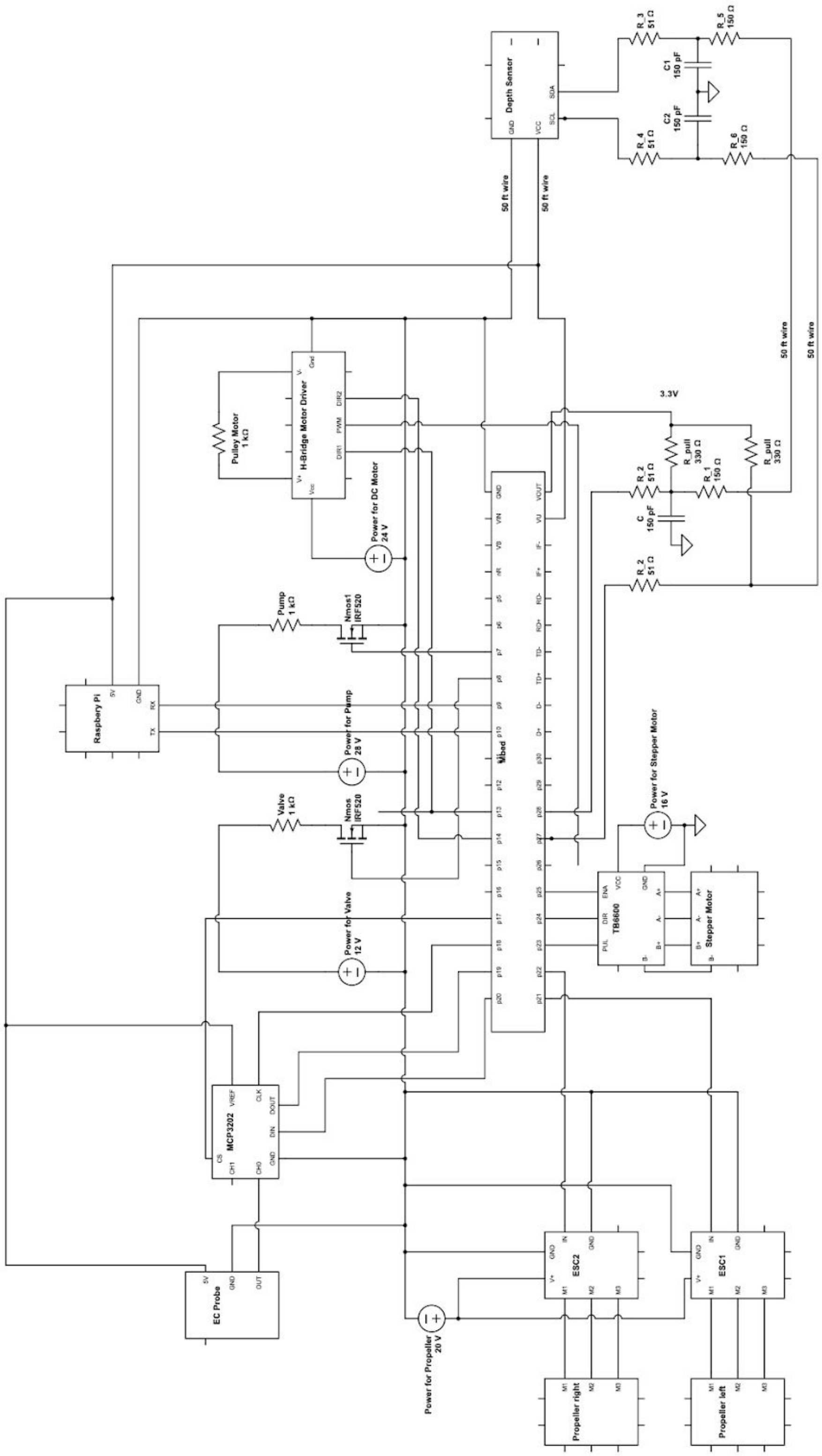
Due to the large amount of code, we present flowcharts in the report and attach the code in the package submitted with the report.

APPENDIX: OTHER

ELECTRONICS BLOCK DIAGRAM



CIRCUIT DIAGRAM



ENGINEERING STANDARDS AND REGULATIONS

Boat design

- Weight limit: NIOSH Lifting Recommendations
- Ingress protection: international standard IEC 60529
- Boat size & operating area: Pennsylvania Waters With Special Boating Regulations
- Boat design: Electronic Code of Federal Regulations

Telecommunications

- Industrial, scientific and medical (ISM) radio bands

USGS MEASURING MAPPING