SeaSearcher
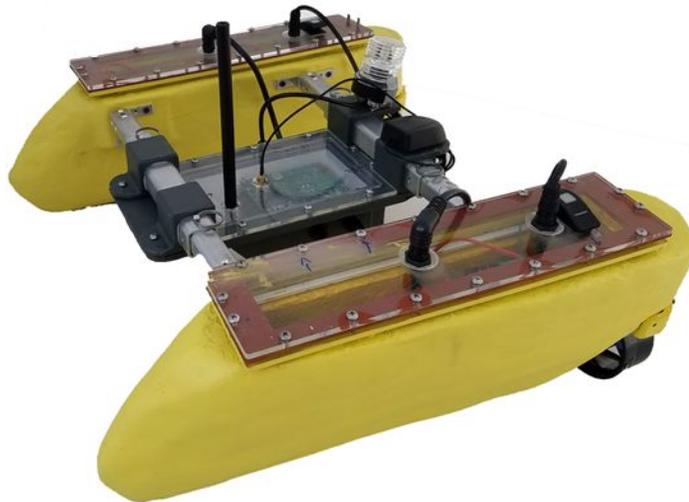
Better Data Collection for Coastal Environments

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Abstract

Coral reefs, worth up to $172 billion in tourism, climate regulation, waste treatment and other services, are being degraded.[1] Over 50% of the Great Barrier Reef's initial coral coverage was lost in the thirty years prior to 2009.[3] SeaSearcher aims to provide a portable, efficient, and cost-effective data collection tool to researchers studying coral reefs in coastal environments, so that they may in turn advise governments on the preservation of these valuable resources.

Professor John McManus of the University of Miami currently snorkels up to six hours a day to canvas coastal reefs and take images on his camera. This process is time-intensive, and alternatives such as diving equipment or tow-boards accrue additional expenses over time. SeaSearcher is an autonomous reverse-bow catamaran designed to slice through waves in a compact yet stable format, equipped with two GoPro cameras and a sensor package to collect data (depth, temperature, current) and capture images of coastal reefs.

SeaSearcher is powered by custom battery packs with lithium ion cells, allowing it to operate for upwards of seven hours once on site. SeaSearcher was designed with portability and air travel in mind: custom printed circuit boards, a telescoping bridge and optional disassembly make SeaSearcher weigh under 20lbs and fit within standard checked baggage on US airlines. The removable cells obey FAA regulations, allowing them to fly with the user.

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Executive Summary

The world's coral reefs are estimated to be worth as much as $172 billion per year supporting large groups of biodiverse organisms.[1] Reefs provide significant value in the tourism, medicine, and fishing industries and provide water surge protection for various coastal communities. Due to rising water levels, coral reefs are shrinking in size at an alarming rate, the most famous being the Great Barrier Reef, reduced to less than 50% of its original size during the past 30 years.[3]

Scientists and ecologists spend significant time monitoring and taking data from coral reefs across the world. This data helps researchers understand the changes in global weather patterns, represents changes to coastal environments, and yields information on how to better protect and save coral reefs. The goal of this project is to create a system that allows marine scientists to characterize these environments in a more efficient way.

Current monitoring techniques are very expensive and time consuming and not ideal for poorly funded research scientists who often go out on their own to conduct monitoring in small boats, via solo dives or swims. There is a need for a small scale autonomous craft to perform the various tasks that the scientists would normally do while surveying.

Seasearcher is an autonomous solution to help scientists map the coral reef environment. With an integrated sensor package that can collect image, video, depth, speed and temperature data, SeaSearcher allows scientists to shift their priorities from data collection to data analysis.

SeaSearcher uses a reverse bow catamaran hull shape to slice through the waves and conserve the most battery life while remaining stable in the environment. The hull was molded using a polyurethane foam that was lightweight and robust, and coated with fiberglass to provide robustness and finish.

Scientists require a portable system as they often travel alone, to remote locations and need a system that is easy to transport. SeaSearcher fits into a check-in suitcase and complies with all FAA regulations such that it is very easy to move across the globe. Using a telescoping bridge, SeaSearcher is able to be quickly compressed and expanded allowing for additional stability in water without compromising portability.

To aid in the a sleek and portable design, SeaSearcher uses a main custom circuit board to hold all of the electronic components and control the craft. This board is held in the custom electronics housing along with the sensors used to collect data. In addition, SeaSearcher uses custom battery circuit boards and cells to power the boat. These

battery packs allow for a higher energy density at the given size constraint, and help SeaSearcher run for 6 hours a day.

Validation is one of the most important aspects of a project, and testing allowed for us to test portability, stability, remote control, and waypoint guidance. We conducted various tests, in the pool, a local pond on campus, Lake Audrey in New Jersey, and at an actual fossilized coral reef in Miami.

SeaSearcher was able to easily travel to Miami and collect all of the required data while remaining stable in the operating environment. It is able to be remotely controlled using a phone application, and is also able to be waypoint guided, and in meeting with our stakeholders, proved to hit most of their requirements.

SeaSearcher won the Francis G Tatnall prize in Mechanical Engineering and Applied Mechanics for an outstanding senior design project.

Statement of Roles
Team Members

Nikhil Chari
Nikhil was the project manager of the team. He set deadlines, led meetings, reviewed all deliverables and made high level decisions about the team's strategy. In addition, he was in charge of the mechanical design of the hull and the design of the mold.

Eric Quesada
Eric worked on mechanical design and system modelling. He was in charge of the mechanical design of the electronics housing as well as that of the base station. In addition he created the dynamic model of the system and designed the controls system.

Jay Fleisher
Jay was in charge of the software and electronics of the system. Jay designed the custom circuit boards used to operate the system and the base station. In addition, he wrote the software that ran aboard SeaSearcher.

Alex Andalia
Alex was in charge of manufacturing for the project. He worked on manufacturing the system by constructing the mold, creating the polyurethane foam pontoon and coating it with fiberglass. In addition, he worked on system testing, design, waterproofing, and research.

Xavier Perraudin
Xavier was in charge of the integration of the camera systems into SeaSearcher. He designed the wifi enabled camera system such that it could take photos at the desired frequency. In addition, he machined the telescoping sub assembly that made SeaSearcher portable, worked on system design and manufacturing, and waterproofing.

Thomas Macchio
Thomas was in charge of Research for the system. He did the background research that allowed for the optimal solution. In addition he worked on the manufacturing of the polyurethane foam and the fiberglass exterior and helped with system design.

Primary Advisors

Dr. Mark Yim

Dr. Yim helped with the overall project path. He was a valuable resource that helped navigate through the various uncertainties associated with a robotics project. In addition he gave us general guidance on the design of the system.

Dr. Graham Wabiszewski

Dr. Wabiszewski helped with the high level system solution and general trajectory of the project. He was a valuable resource advising deliverables, and as a general consultant for this project. He was available to point us in the right direction when we were stuck and ensured that everything went smoothly.

Mr. Samuel Gaardsmoe

Mr. Gaardsmoe 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.

Technical Advisors

Dr. Paulo Arratia
Dr. Arratia helped us in the initial ideation stage. He was a resource to us when talking about the conditions in the coastal environment and how to model those conditions.

Dr. Bruce Kothmann
Dr. Kothmann was a valuable resource to our team when picking the project. He helped us decide on a project by providing strategic advising and insight. In addition, he gave us advice on the controls and autonomous navigation.

Prof. Peter Bressler
Professor Bressler was a valuable resource to our team in the system design. He helped us iterate and think more about our overall design and acted as a general consultant to us. He suggested to us the telescoping idea that we pursued. In addition, he helped us think through our graphics interface.

Prof. J.D. Albert
Professor Albert acted as a consultant to us in the system design phase.   He was able to talk us through the material choices and the various properties and tradeoffs. He also helped us through some of the design for manufacturability on the system.

Mr. Joe Valdez
Mr. Valdez worked with us on the manufacturing of the system. He helped us with the machining of the foam on the fall prototype and talked us through some of the steps of the final project manufacturing.

Mr. Peter Szczesniak
Mr. Szczesniak acted as a consultant for us on the manufacturing of the system. He gave us ideas on how to manufacture the final system and the various processes that we could pursue.

Background

The Importance of Coral Reefs

The world's coral reefs are estimated to be worth as much as $172 billion each year.[1] They rival the Amazon Rainforest in terms of biodiversity and support 25% of the planet's fish population, while only making up less than 1% of the ocean floor. This biodiversity provides benefits for tourism, advances in medicine, and supports close to 25% of small scale fishermen.[2] Reefs also provide wave and storm surge protection for oceanside communities around the globe although this is threatened by rising sea levels and the rapidly increasing rate of coral reef loss. A comparison of 2,258 surveys of 214 reefs over the years 1985–2012 show a loss of over 50% of the initial coral coverage of the Great Barrier Reef.[3]

Extreme weather events affect thousands of vulnerable coastal communities every year. In the United States, spending has reached close to $500 million to mitigate coastal hazards. Globally, insurance companies have spent more than $300 billion over the past ten years on disaster prevention. The United States currently spends a significant portion of it's money building man-made seawalls.[4] These seawalls have negative effects on the surrounding environment and have not yet proven to be the most effective method for wave surge protection. Although reefs are severely undervalued, they have been shown to dissipate incident wave energy during non-storm conditions by 97%. Reefs have been simulated using 3D models and have been shown to act like low-crested breakwaters. When combined with seagrass meadows, and other threatened coastal ecosystems, shear stresses on the ocean bed are reduced by 70%, to $0.05 \, N/m^2$, which is below the threshold for sediment motion.[4] Sediment motion induced by wave motion causes the gradual reduction in the width of beaches and eventually eats up residential lands, significantly damaging the various ecosystems that millions of organisms and people reside in.

An Overview of Monitoring

It is important to observe coastal environments, not only to monitor the effects of shifting global weather patterns, but also to learn more about how they help protect our shores. To do so, surveys focus on physical and biological parameters such as the following:[5]

       a) Physical
           i)   depth, currents, and temperature,
           ii)   water quality, visibility, and salinity
       b) Biological
           i)   coverage, size structure, genus/species, extent of bleaching or disease

Photos are also collected as visual indicators of the health of ecosystems. For coral reefs, total coral coverage is a common indicator of health and is tracked over time to show the effects of changing ocean conditions. Monitoring techniques are evaluated based on their monitoring level, scale, level of detail, precision, and potential to damage the coral reef.[5] Descriptions for each metric are listed below:

       a) Monitoring level - Type of initiative, from research to community
       b) Scale - Size of area that can be covered
       c) Level of Detail - Type of data, i.e. quantitative or qualitative
       d) Precision - Amount of detail obtainable
       e) Damage to Reef - This metric will assume a skilled worker

The best methods usually involve transects, or the tracing of a path along a reef. Doing this with video or photography is beneficial for speed but it is difficult to get congruent frames every time. Transects allow a medium scale effort with high quantitative detail and do not cause damage to reefs, but involve significant dive time. The video tow, which involves towing a camera behind a boat, is another potential technique but has repeatability issues.

A system that combines the repeatability of transects with the scale of a video tow to allow for more video and photo data to be collected over larger areas will be beneficial to the user. Such a system removes the diver from the process and allows the responsibilities of a scientists to shift from data collection to data analysis.

	Monitoring Level	Scale	Level of Detail	Precision	Damage to Reef
Manta Tow	Management	Broad	Semi-quantitative	Low	No
Video Tow	Management	Broad	Quantitative	Low	No
Human Observation	Community	Broad	Qualitative	Low	No
Timed Swims	Management	Broad - Medium	Semi-quantitative	Low	No
Line Intercept Transect	Management	Medium	Quantitative	High	No
Point Intercept Transect	Community - Management	Medium	Quantitative	High	No
Video Transect	Research	Medium	Quantitative	High	No
Visual Quadrat	Management - Research	Fine	Quantitative	Medium - High	Potentially
Permanent Photo Quadrat	Research	Fine	Quantitative	High	Potentially
Belt Transect	Management	Medium	Quantitative	High	No
Chain Transect	Management	Medium	Quantitative	High	Potentially

Figure 1 *A review of the characteristics of several surveying techniques currently used today*

Customer Profile

Dr. John McManus is a Professor of Marine Biology and Fisheries, and the Director of the National Center for Coral Reef Research (NCORE) at the Rosenstiel School of the University of Miami. He is known for his innovative approaches in science supporting coastal and watershed management, ranging from small community based initiatives to high technology projects. Recently, his work had involved reef geomorphology, human impact, and climate change, as well as developing a new coastal ecohydrology modelling approach to facilitate integrative research and management decision-making.

While being a world recognized figure in the field, John faces a common problem that plagues researchers around the world. Even at a large private university that sits on the environments in question, he deals with a lack of funding and support. Up until now, his data collection process has typically involved solo swims along coral reefs while carrying all of his own equipment. His process and wishes are very well summarized in his own words:

"I often work without a boat, and find that carrying lots of stuff on these quick swimming surveys has been bogging me down too much. However, I had been wishing that there was some way to automate the surveys, so that it would be easier to map the shallow areas. There has been a lot of progress with flying drones on this kind of work, but the depths obtained via 3D reconstruction generally require lots of field verification, and the places I go generally prohibit flying drones. Of course, portability is very important to me. Nobody likes a hitchhiker with too much gear!"

When working through possible solutions with John, he went on to say that "Lots of scientists would love to use (the solution). I need it to investigate if fringing coral reefs will retain their wave-protection as sea level rises, or leave millions of coastal dwellers to see their villages washed away in the future."

Another stakeholder, Dr. Curt Storlazzi of the US Geological Survey, noted that the idea of an automated surveying tool was an "interesting project and one that *(he's)* happy to support." Curt also helped us understand different operating conditions and gave insights based on his experience working for an entity which has been doing underwater video surveys for decades. Dr. Bernhard Riegl (Professor of Oceanography and the Associate Director of the National Coral Reef Institute), Dr. Sam Purkis (Professor and Chair Department of Marine Geosciences at the University of Miami), and Dr. Katie Barott (Professor of Biology at the University of Pennsylvania), also gave their input into the different system characteristics specifying the various functionality that their research requires and provided support of the concept.

Objectives

After gathering the information obtained through discussions with numerous potential stakeholders, we determined the following as essential characteristics of an optimal finished product:

Essential Characteristic	Description
Data Collection	Depth, temperature, velocity sensors, and HD images and video
Portability	Ability to easily travel with product
Control	Remote Control and Waypoint Guidance
Cost	Less than $3000
Endurance	Battery life of 6 hours

Figure 2 Breakdown of project goals

To be a useful tool to researchers, our finished product would need to be able to easily collect important data that gives insight to researchers about the state of coral reefs. We found that almost all researchers in the field made use of high definition imagery and video to track growth of these reefs. Based on feedback from researchers, we decided that both a frontward and downward facing camera were necessary. We also found that temperature, depth and current velocity data were used often by researchers studying these reefs, and therefore decided to include sensors to collect the respective data. We determined that the range of depth data we needed to be able to collect was from 0.5 to 10 meters from the surface of the water. This metric was driven by the environmental characteristics of fringing coral reefs.

Another major aspect of this product is the system portability. Most researchers in this field work alone, and therefore collect their own data, and carry their own equipment. Consequently, a product that is too large or heavy for a single person to operate would not be feasible. We set out to design a product that had an upper weight limit of 50 lbs to follow OSHA guidelines and set the sum of outer dimensions to be no more than 60

inches .[6] The size limit was chosen so that the device would be able to fit in a checked bag aboard any commercial airline, as researchers often have to travel to remote locations to collect environmental data. Additionally, we found that researchers often spend up to 6 hours on site collecting data. The reasons for this are the physical demands of collecting data using manual methods and the timeline of coastal tides, which would change the area of interest dramatically. This allowed us to set a target battery endurance time of 6 hours.

As is the case with much of academia, most of the researchers we were in contact with were not working with large budgets. Because they are underfunded, they are not able to spend hundreds of thousands of dollars on data collection. Most of their budget is spent on hiring the assistants to comb through data. Therefore, we aimed to create this system with a material cost under $3000 to maintain quality and respect the budgets of researchers.

Engineering Standards

Since SeaSearcher is a water based craft that with a deployment time of several hours, compliance with nautical regulations is necessary to allow for safe use. In addition, there are several standards related to both the logistics, and the customer needs of the project that the system needs to comply with.

Ingress Protection

Ingress Protection (IP Rating) is a standard that evaluates how water and dust resistant a product is.[7] In SeaSearcher's case, water resistance is of paramount importance as it can cause electronic failures as well as the sinking of the craft. There are two digits in the standard code IPXY where X stands for solid particle protection and Y stands for liquid ingress protection. Solid particle protection can range from 0 (no protection), and 1 (protection against anything larger than 50mm), to 6, which indicates that the device is dust tight. As the craft will be in an environment with sand and dirt, it needs to be sealed as tightly as possible and will require a solid particle protection value of 6.

The second digit corresponds to the liquid ingress protection and ranges from 0 (no water protection), to 9 (protection against high pressure water jets). Every external component on the SeaSearcher must have a rating of at least 7 or 8, depending on the location. A rating of 7 means the device can be submerged up to 1 meter for 30 minutes. A rating of 8 indicates that it can be submerged indefinitely at a certain depth specified by the manufacturer. IP67 is appropriate for any part of the boat that may get wet some of the time and IP68 is necessary for the underwater components.

OSHA

The Occupational Safety and Health Administration (OSHA) provides recommendations on how much an individual should be able to safely lift to avoid injury. OSHA says that an individual should not lift more than 50lbs to help prevent injury. The National Institute for Occupational Safety and Health (NIOSH) also publishes research on how lifting objects increases the chances of injury.[8] The following formula was created by NIOSH to determine the Recommended Weight Limit (RWL) for what a human can carry.

		METRIC
Load Constant	LC	23 kg
Horizontal Multiplier	HM	(25/H)
Vertical Multiplier	VM	$1-(.003\|V-75\|)$
Distance Multiplier	DM	.82 + (4.5/D)
Asymmetric Multiplier	AM	1-(.0032A)
Frequency Multiplier	FM	From Table 5
Coupling Multiplier	CM	From Table 7

RWL = LC X HM X VM X DM X AM X FM X CM

Figure 3 A review of the equation of Recommended Weight Limit as compiled by the NIOSH

Figure 3 shows a table describing what each of the variables is. The conservative estimation of each of these parameters yields a maximum weight of 14kg per person. SeaSearcher is intended to be used by a single scientist, thus needs to weigh less than 14kgs or 30 pounds.

COLREGS

The International Regulations for Preventing Collisions at Sea 1972 (COLREGS) is a set of regulations created by the International Maritime Organization.[9] The rules vary based on size, visibility, conditions, and age. Most of these regulations are only applicable to boats greater than 7m long, smaller crafts have fewer requirements. The most relevant regulations are Rules 22 and 23. As it relates to SeaSearcher, these regulations mandate that a boat going less than 7 knots and smaller than 7m have a single white light that can be seen from 2 miles away. Red and green lights mounted on both the port and starboard sides of the boat are optional. These lights can easily be purchased at an outdoor sports store.

Electromagnetic Compatibility

Electronic devices must meet certain requirements that ensure they won't emit too much radiation that can interfere with other nearby devices.[10] They also must be able to function with a certain amount of radiation nearby. The United States has rule 15.23, which specifies that equipment doesn't need to meet any of the specific electromagnetic requirements if it is not marketed, constructed from a kit or made in quantities over five. This means that SeaSearcher requires following none of these regulations although all the specific components that are purchased off the shelf need to be EMC approved.

Battery Shipping

Last year, new shipping regulations were introduced that added restrictions on how battery cells can be shipped. They may not be put on passenger aircrafts and must have a state of charge under 30%.[11] There are also limits on how many can be shipped per package. Given the time constraints of the project, it is important that not too much time is lost in shipping. To mitigate these risks, suppliers that comply with this regulation and provide quick shipping to the university are prefered. LIION WholeSale Batteries provides the best option as they deal exclusively in batteries and are familiar with the new regulations. In addition, they are only located 40 minutes away from the university, which reduces lead time.

NMEA 2000

SeaSearcher needs a variety of sensors to take data. NMEA 2000 is protocol that standardized the way data is sent and received by marine sensors and other devices.[12] The protocol allows devices developed by many different manufacturers to communicate each other, including a variety of sensors and systems to view the data. It is an improvement over the previous NMEA 0183 protocol, because it supports 50x higher speeds and allows multiple devices to send data on the same bus. The physical layer of the protocol is the same as CAN (the Controller Area Network), which is a differential pair broadcast protocol typically used for sending data between devices in

cars. Conveniently, most microcontrollers have hardware support for CAN, which means these standards are easily integratable into the system.

Down Selection

Current Solutions

There are a number of autonomous vehicles made for collecting data in bodies of water. Liquid Robotics and Lockheed Martin are both manufacturing fleets for open ocean data collection. These are large, very expensive, and sell the information rather than the actual system at an astronomical cost. One such product, the Wave Glider, is designed to survey deep sea environments.[13] While it is likely stable enough to survey coastal environments, it lacks the necessary sensor package to deliver relevant information to our consumers. Another issue with the Wave Glider is its large draft. Draft is the height of the craft underneath the waterline, and the Wave Glider has a draft of about 8 meters. This would likely lead to collisions with the reefs.

Smaller scale solutions exist, such as Simple Scan, but these solutions are often made for inland waters or lakes that have little currents or swells. They are therefore not stable enough to survive the waves and other disturbances involved in coastal environments.[14] These smaller scale solutions are also sold for thousands of dollars.

The current solution used by the US Geological Survey is called the Jetyak, a gasoline powered autonomous kayak. While it can work well, it costs well over $5000 and is not conducive for a one person operation due to a restrictive size and weight.[15]

Ideation

One of the biggest design challenges in this project was choosing the optimal hull design such that the craft can travel in the most power efficient method and possess high stability in water. Figure 4 shows sketches of the various designs under consideration.
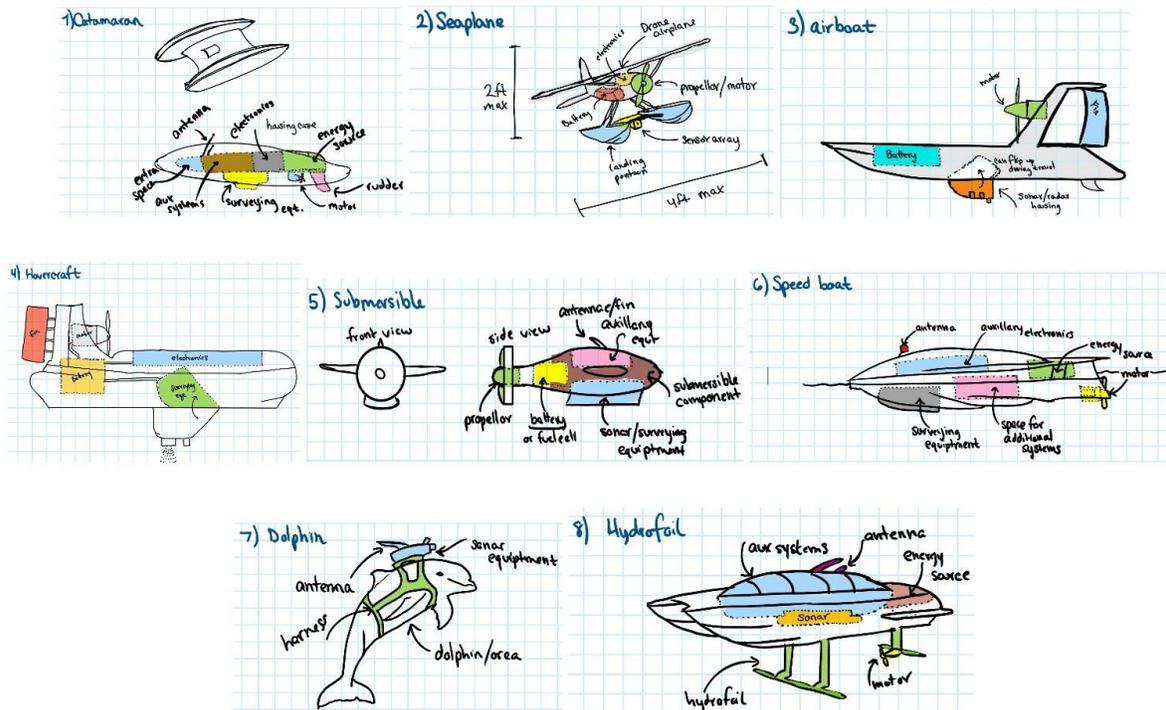
Figure 4 Sketches made during the brainstorming of solutions

The first design is a Catamaran, which is a double hulled watercraft with a wide beam and thinner hull sizes than a typical monohull boat. On a smaller scale, catamarans are great for increasing stability and decreasing keeling. Catamarans and trimarans are geometry-stabilized crafts which derive their stability from their wide beams, rather than a ballasted keel of a monohull craft, making them a better fit for a smaller craft.[16] A ballasted keel is a fin at the bottom of a monohull sailboat that uses water force to counteract wind forces felt by the sails to reduce roll. More specifically, since catamarans have buoyancy support at wider points of the craft, the vessel is subject to less roll along the length of the boat. Additionally, since the hull shape of catamarans is usually thinner and longer than monohull vessels this type of craft is lighter in the water and glides over waves. These stability benefits make the catamaran a very practical design for this project. Unfortunately this type of vessel does not displace as much water as a monohull of the same size. That means catamarans have a reduced carrying capacity in comparison to single hull vessels.

Another potential system level solution is an autonomous sea drone plane capable of flying to various reefs several miles away and landing on the water to survey the reef. The surveying equipment could be held between the two pontoons. Once on the water, the drone can idle and taxi to gather information while on the surface. This design would allow for more ground to be covered if multiple reefs were a few miles from each other. While this is a great solution for surveying multiple reefs in a day, the drone's stability on the surface and against waves is not ideal. There is significant concern with space and weight of the craft and adding all the sensors and power sources may make the craft too heavy to efficiently fly. Additionally, the complexity of this type of design adds an additional aerodynamics problem to the already complex design issues that may make this project a less than ideal solution under the scope of senior design. Finally, coral reefs are commonly found near military bases and there are typically restrictions on flight in these locations.

The third design is an airboat, which uses a single hull that is flat to reduce draft in the water. These types of crafts are primarily used in inland waters such as swamps and shallow waterways with lots of seaweed and vegetation in the water. The boat's source of propulsion is a large fan that sits outside of the water and on the back of the boat. This limits ecological impact of propellor blades on anything in the water. While this would be perfect to survey coral sitting very close to the surface of the water, the airboat would not be as stable over waves on the open ocean as it would be on calmer inland waters. These types of craft are not used for ocean travel and are popular for transportation in shallow areas where a submerged propellor would be impractical. Additionally large coastal wind forces may overpower the fan on a smaller craft such as the one in this project.

The fourth design is a hovercraft or ACV, which is a craft capable of travelling over land, water, and other surfaces. Hovercrafts operate by using a powerful fan to blow air underneath the craft into a nylon skirt, causing it to lift off of the ground. Depending upon the size of the hovercraft and the power of the engines, hovercrafts can lift from six inches to over seven feet into the air. Unfortunately this design is not an optimal design for the project due to the design of the hovercraft. It is important to have the sensors on the bottom of the craft such that they can dip down into the water to collect data. The fan on the bottom of the craft will not allow this to happen as there may be no space for the sensors, and the craft does not actually ride on top of the water. Not only does this limit design options but a hovercraft design as small as our craft would not be very stable over waves due to the size of the ocean waves and the size of our craft. Since the hovercraft rides over the water, a large wave breaking near a coastal reef may cause major stability problems. Additionally a constant battering to the craft's nylon skirt would require maintenance after continuous use since the constant friction and motion between the skirt and the water would wear out the material. These problems have been well documented in history even on larger crafts. In 1972, an accident occurred on the SRN-6 'The Ryde to Portsmouth' hovercraft overturned in a gale just 400 yards off Southsea beach.[17] Since the ACV rides on a cushion of air, the whole craft is subject to wind forces, especially on this size scale. This causes significant problems

if large winds were to lift this project's hovercraft.

A submersible craft could also survey the reefs while traveling out of the way of swimmers and other vessels. Choosing this design could allow our device to survey the reef and take photos from various angles. However, the time and effort it would take to design and build such a vessel that is autonomous and operates in three dimensions is likely beyond the scope of a senior design project. In addition, one of the design requirements of this project is a draft of less than 1 meter. A submersible craft will come very close to violating this requirement and may potentially damage the reefs under surveillance. A submersible would also be slower and much more difficult to control either by the user or an autonomous control system.

The monohull design is the most common commercially designed hull and it can hold the most weight due to the large displacement of water it provides. Large monohull commercial vessels have great stability on higher seas due to its sheer size and advanced design of the hull nose.[16] Smaller R/C monohulls are not as stable and have increased roll due to the small size and light weight of the RC craft. Monohull vessels do not have a wide beam and instead can increase their stability with a bottom fin that provides force to prevent keeling.[16] This ballasted keel is usually implemented on sailboats where a strong moment is applied to the mast and sails from the force of the wind. This keel is not ideal for our system because of the larger draft that it creates.

Another solution is the use of trained dolphins to travel to various areas and collect data. Undoubtedly this is very expensive and has a large time scale, but there is precedent. The United States NAVY currently employs multiple cetacean mammals that have been trained to search for underwater mines and report their GPS coordinates and depth by dropping transponders at the site of the mines.[18] These dolphins can be trained to traverse local coral areas and map out reefs. The drawback is that the time and money this would cost to train, feed, and employ these mammals is significant and a physical craft is a more financially viable investment.

The hydrofoil craft is another potential design that employs the use of a hydrofoil, a lifting surface or foil that operates in the water. A hydrofoil craft can reach faster speeds since the foils lift the boat's hull out of the water, reducing drag and significantly increasing the speeds that ships can reach. The hydrofoil takes the minimization of drag to the extreme by minimizing the wetted surface area that is used to support the weight of the vessel.[19] At high speeds the hydrofoil can lift the boat fully out of the water reducing the amount of hull area the water has to travel over. A major drawback of this design is that the hydrofoil will stick further into the water from the hull when the ship is not operating at the speed necessary for lift. This could cause problems with shallow reefs and coastal areas or sandbars. In addition, the efficient operating speeds would likely be fast for accurate surveying and the sensors that have to be underwater would add a lot of drag at these high speeds.

Further Down Selection

One of the most important design decisions is choosing the optimal hull shape to ensure flotation and stability of the system. After narrowing the selections down from the previous eight choices to three, analysis was done on the monohull, catamaran, and the trimaran. Each type of craft has varying characteristics. In the table below, the three hull choices are roughly weighed with regards to buoyancy, stability factor, speed in the water, and maximum draft. For more down selection figures, see Appendix A.

| Hull Design	Buoyancy *	Stability (1-10)	Speed in Water**	Max Draft
Monohull	2000 N	6	10 knots	12 in
Catamaran	1140 N	8	12.5 knots	8in
Trimaran	1020 N	8.5	15 knots	6in

* For a hull size with-- Mono: L=28in,W=12in,D=12in   Cat/Tri: L=28in,W=4-6in,D=6-8in

using the buoyancy equation Fb = (Density of water)(Volume)(gravity)

** max speed before stability loss over waves

Figure 5 Characteristics of different hull designs

A monohull boat can hold the most equipment and is the most commonly used hull for all different kinds of vessels. Currently, monohull vessels have great stability when used on very large ships that hold massive amounts of weight such as a container ship. Unfortunately these large vessels have had problems with parametric rolling when induced by the right types of waves.[20] When analyzing the stability of monohull boats on a smaller scale, such as hobby remote control boats, the angle at which the vessel encounters a wave from its port or starboard side is much larger than that of a multihull ship. As seen in the figure below, the angle of the roll of the monohull boat is larger than the angle of the catamaran. A ship has 6 degrees of freedom and catamarans/trimarans reduce rolling motion along its X axis. This is because of the length of the beam of the catamaran and other multihull vessels (beam is width of the ship). Thus, multihull vessels have more roll stability along the width of the ship. However, any pitch stability would remain the same among the hull design choices. Addressing roll stability is extremely important when trying to reduce keeling, occuring when a ship tilts on any of its sides and doesn't return back to an upright position. Keeling is unsafe for a craft and the various sensors aboard, and can be caused by waves, wind, and cargo placement. Furthermore, once flipped, our product will not have a self righting system to return to its state, however, a catamaran design reduces the possibility of flipping.

Roll Behavior & Pendulum Effect
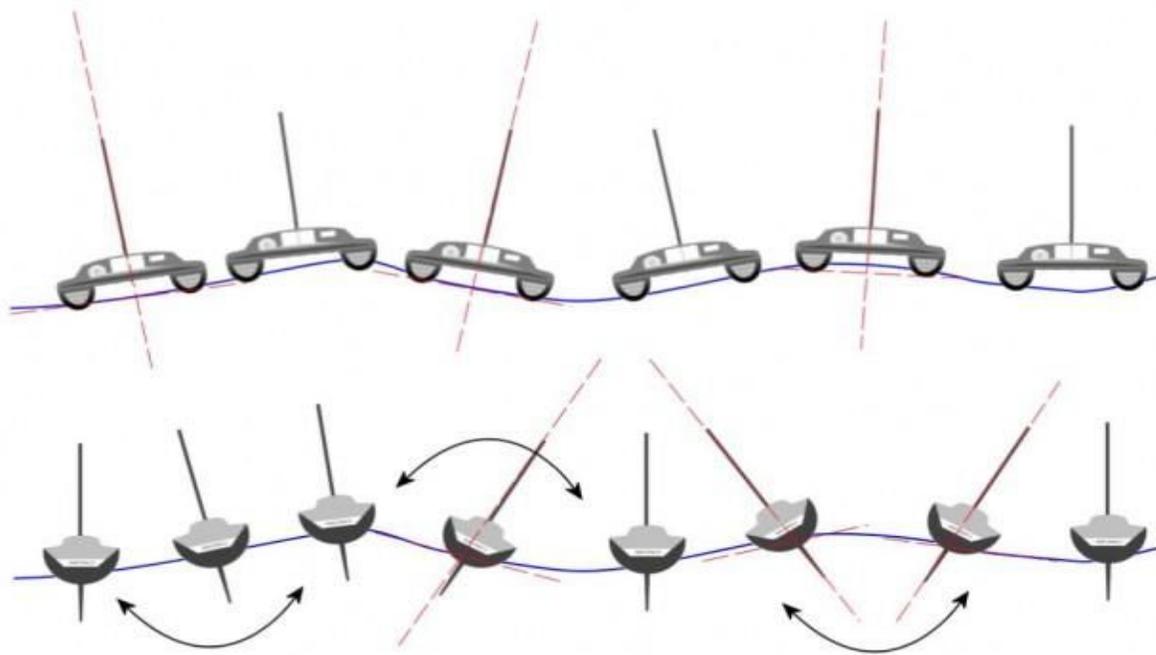
Figure 6 *Monohull vs Catamaran Stability*[18]

The multi hulled nature of both the catamaran and the trimaran leads to a smaller hydrodynamic resistance than comparable monohulls since the overall surface area is much smaller than that of a single hull.[16,21] This means that water has to travel over a smaller surface reducing the effect of drag and requiring less propulsive power from either sails or motors.

The main difference between the trimaran and catamaran is the cost of design and manufacturing. A trimaran significantly increases the cost of this product and is expensive for the current budget. A trimaran would require an additional mold for the central pontoon which has to be designed correctly as to not interfere with the flow of water over the two outer hulls. More specifically, if the center hull shape disturbs the tunnels of turbulent flow between the other pontoons, drag and speed flow over the hulls will be significantly increased and decreased respectively.

A two hull design only requires one mold since both hulls are symmetric. Furthermore, unlike catamarans, trimarans can feel the effect of parametric resonance or parametric roll (similar to monohull vessels). Although this situation does not occur very often, when induced, the stability required for our imaging and sensing will be impeded.
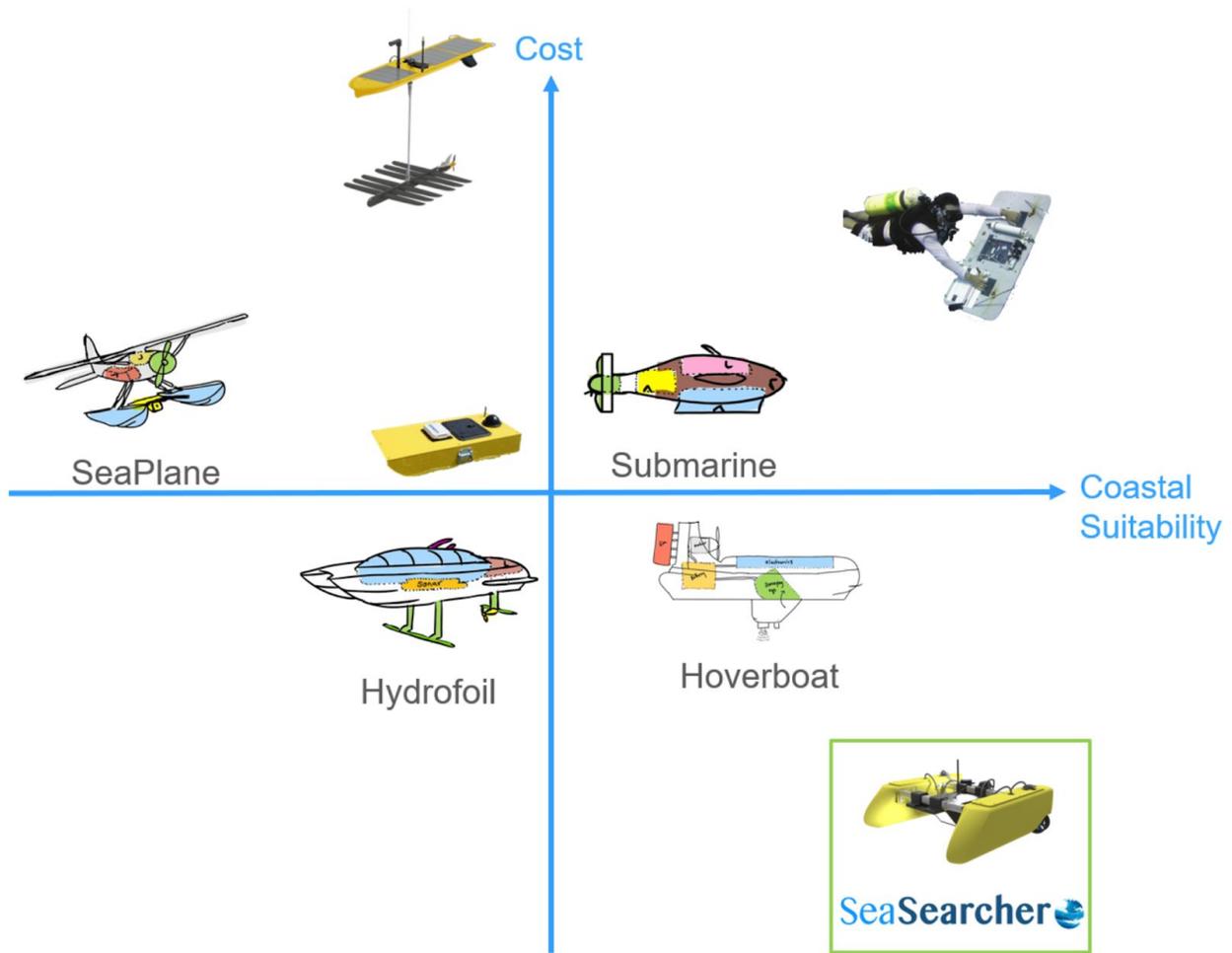
Figure 7 *Two dimensional comparison of both existing and ideated solutions*

This graph presents a qualitative summary of the different solutions considered in downselecting for Seasearcher, superimposed with current solutions including the Wave Glider top left, SimpleScan at the center and manta tow-board top right. The green box indicates the target area for our solution.

Design and Realization

SeaSearcher is a multidisciplinary project combining numerous mechanical, electrical, and software systems. To ensure adequate progress through the academic year, a prototype platform was created to enable the continuous testing of software improvements and electronics changes. The platform also gave the design team insight into usability and other design considerations. Future changes to the initial platform were made to accommodate a change in microcontroller, custom circuit boards, and telescoping ability for increased portability. The final version was manufactured using low volume techniques like 3D printing, laser cutting, and non-reusable molds.

Initial Prototype

The initial SeaSearcher prototype was created using materials at hand or cheaply available, such that it could be manufactured quickly. Our goal was to get a platform in the water as soon as possible and begin iterating the software while continuing to improve the hardware design.
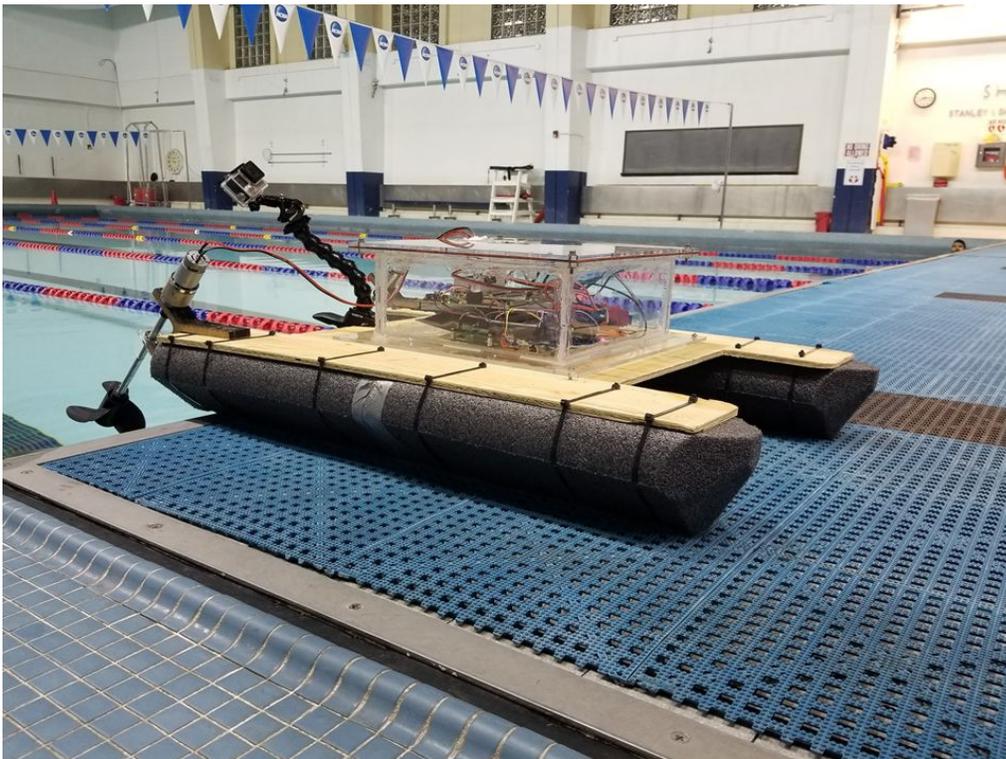
Figure 8 *SeaSearcher's initial prototype during testing at the Pottruck Fitness Center*

The pontoons were made from polyethylene foam rollers, that were cut into simple hydrodynamic shape. Each pontoon was made of two 24'' long foam roller attached to form a single 48'' long pontoon. The pontoons were connected by a single piece of ¼'' thick plywood that was cut where support was not needed to reduce weight. The motor brackets and electronics enclosure were mechanically fastened to the plywood bridge. The motor brackets were made of layered laser cut pieces, angled at 45 degrees in order to keep our recycled DC motors out of the water while extending the shaft and propellor below the surface.

The prototype included a waterproof electronics enclosure. Its footprint was determined by the planned use of the Jetson TX2 as SeaSearcher's microcontroller. Additionally, its height was chosen to allow enough room for hassle free manipulation of hardware and wiring. The enclosure was constructed using clear laser cut acrylic panels that were assembled using acrylic adhesive. The enclosure used donated epdm (ethylene propylene diene monomer) rubber gasket material and fasteners to waterproof the interface between the lid and body. This gasket material is commonly used for outdoor applications because of its high UV and temperature resistance. Additionally, silicone sealant was used to waterproof every edge of the enclosure.

Testing of this initial prototype revealed a set of potential improvements to focus on during the design process. Transporting the platform proved to be cumbersome and tiring. This was a result of its weight and dimensions. Some of the solutions brought up for this problem was a reduction in size and adding wheels or handles for transport. Another problem was the large mess of wires and components in the electronics enclosure. Lastly, the enclosure used 28 bolts to apply ample pressure on the gasket material and tightening the lid became a lengthy process.

Hull Design

The spring prototype had significant hull design changes compared to our initial platform, because it needed to meet several more requirements such as both stability and portability standards. Seasearcher's goal was to fit into a checked suitcase such that it would allow for easy transportation aboard cars and commercial airlines.

The potential reduction in size lead to a losses in stability as larger waves effect the boat more. There was a balance between size/shape of the pontoons and its effective stability. Stability can be influenced by multiple factors including but not limited to: the type of sea vessel, hull shape, size, surface finish, and weight balancing.

At the beginning of the process, a catamaran was chosen due to its increased stability and suitability for the SeaSearcher mission. A great way to increase stability and reduce pitching motion is to use a reverse bow hull shape. This curved down bow allows the vessel to cut through waves instead of being pushed over them and helps reduce the vertical movement provoked by waves. Furthermore it limits slamming impact on bows and the concentrated pressure on the front section of the bow when slamming onto a wave. This results in more stability for the cameras and sensor package contained in the central enclosure. One notable downside of this design is that it generates more spray as it cuts through waves and water will flow over the top of the pontoon. This meant that every compartment both in the middle and in the pontoons must be fully waterproof and submersible.

The hull shape was then modelled in SolidWorks using 3 cross sections connected via a loft feature. This allowed us to easily change certain geometry parameters as we ran fluid flow simulations to achieve the best overall configuration. SolidWorks was used to obtain an accurate prediction of SeaSearcher's waterline. First, all internal cavities were treated as solid spaces. Then, volume was iteratively calculated from the bottom of the system until the volume of displaced water created the buoyancy necessary. It was determined, after preliminary drag studies, that the most significant way to reduce drag would be to insure the waterline did not reach the frame. By modifying key hull dimensions, the waterline was successfully reduced to keep the frame out of the water while maintaining adequate submersion of the camera windows. The drag studies mentioned were also performed in SolidWorks. To accurately compare different designs for hull shapes, drag coefficients were obtained using flow simulations, which output a drag force. By using the drag force and an approximated area from the model, a coefficient can be backed out using the drag equation. This also allowed us to use the coefficient in a MATLAB model to accurately represented the system.

Bridge Design

SeaSearcher's bridge was composed of a telescoping aluminum frame and an attached 3D printed electronics enclosure. The aluminum frame gave the system the necessary rigidity and the telescoping ability needed to meet our portability goal. The aluminum was purchased from Alcobra Metals, as they sold sizes of 6005A-T6 rectangular tubing made specifically for telescoping applications. Due to the geometry of the system, the longest tube section was 8''. This short length and a wall thickness of ⅛'' created a bridge with high bending resistance. Additionally, aluminum is highly resistant to corrosion in seawater, unless in contact with other metals. In order to lock the bridge in different configurations, aluminum quick release pins were inserted into pre drilled holes. Acrylic was chosen for the camera windows because of its ease of manufacturing and low cost. While more brittle than polycarbonate, initial impact tests done using a hammer proved its strength when used with small sizes

SeaSearcher's new electronics enclosure was designed to be hydrodynamic and fit all necessary electronics as efficiently as possible. The first two pieces of hardware considered were the front and downward facing GoPro cameras. They were placed as close together as possible while still allowing access and the width was set to allow the GoPros and the USB cable that would be extending from their sides. Two lasers were added in line with the downward camera. The last piece of hardware that determined the size of the box was the custom circuit board. The dimensions of the board were adjusted such that is could be mounted on the pins of the waterproof connectors that would extend out of the enclosure body.
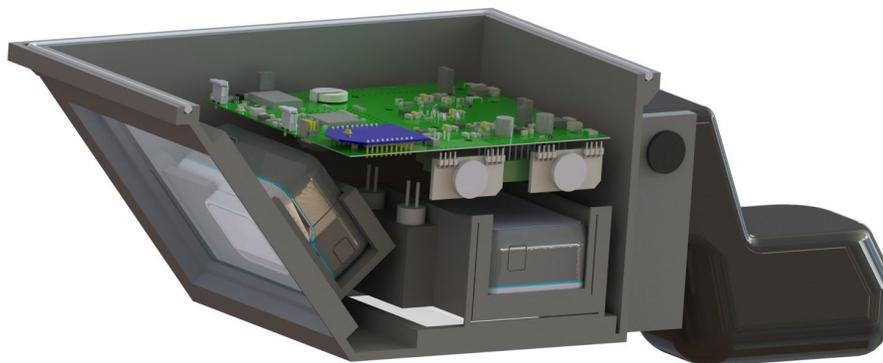
Figure 9 *CAD model of the middle electronics enclosure*

Features such as a lip for the O-ring, lips for insertable acrylic windows, and an outer feature for attachment of the P39 triducer were added once the size of the enclosure was determined. The final SeaSearcher was designed to utilize epdm O-rings instead of

gaskets. However, the design did not use an industry standard length so made-to-order lengths were required. One of the other goals of the design was a reduction in part count and interfaces that needed to be waterproofed. The initial design of the final compartment combined the space for electronics, brackets for attaching it to the bridge, and a flange plate connecting them all together. The intent was to print it all as one piece.

Besides geometry, high level changes were made based on lessons learned from SeaSearcher's initial prototype. The decision to 3D print the enclosure cut down weight by reducing material density and the necessary wall thickness. To reduce the amount of effort needed to assemble and assure a watertight interface, the final SeaSearcher prototype was designed to utilize semi-permanent plastic rivets to replace all fasteners. Rotating knobs pressing down on lids would replace bolts at watertight interfaces.

Initially, the smaller aluminum tubing of the bridge, with a flange attached, was to be inserted into the mold as the polyurethane expanded to form a secure fit around the tube. Due to shipping logistics, L-brackets had to be used to attach the frame after the pontoons were molded. These L-brackets were machined out of aluminum stock and aluminum hardware was used to attach them to the tubes in order to prevent corrosion. To attach the brackets to the pontoons, aluminum wood screws were used.

To test the integrity of our design, finite element analysis was used to show the system could withstand normal conditions. This included reasonable torsion and bending of the bridge, as well as abnormal loading at all mechanically fastened interfaces. Due to the complexity of modelling foam and fiberglass, the interface where the bracket attach the bridge to the pontoon was tested using a model made from the same materials as the system. Once constructed and fastened, two team members attempted to pull the bridge off the pontoon and were unsuccessful.

Due to the extreme costs of 3D printing our initial design, SeaSearcher's final enclosure was redesigned to be an assembly of laser cut parts and smaller 3D printed parts. Reducing the size of 3D printed parts reduced costs and the amount of support material needed. Parts would be assembled with a permanent adhesive after printing. The additional steps in manufacturing were necessary to maintain the utility of the initial one-part design. Changes included separating the brackets from the body, separating and splitting the flange plate for laser cutting, and making internal features of the enclosure separate parts that would be inserted later.

3D printed parts were sanded to prepare the surface for fiberglassing. Fiberglass was used to add durability to the assembly as well as provide extra waterproofing of the interfaces. Once assembled, the body of the compartment proved to be watertight and durable. However, the interface between the lid and body was not watertight. The rivets and knobs used had too much play in them to apply the pressure needed on the O-ring used in the design. To assure a watertight interface and not push the project schedule further back, rivets and knobs were replaced with bolts. The original lid also had to change to accommodate the new bolts.

Pontoon Fabrication

Each pontoon was created with a non reusable mold and expanding urethane foam, then sanded into shape, and fiberglassed over to strengthen the component. SeaSearcher was designed with a foam filled hull to provide intrinsic flotation in the case of a punctured pontoon. The density of the foam was chosen to provide structural support while still being lighter than water. Fiberglass was chosen to provide additional strength because of its strength, common use on other vessels and low weight.
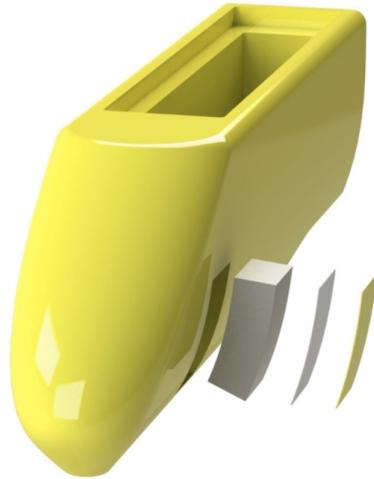
Figure 10 *CAD model of the pontoon showing the foam, fiberglass, and gelcoat layers*

Mold design was extremely important to the manufacturing of the pontoon. Many processes were discussed before the order of operation, mold type, and pontoon materials were finalized. Traditionally, RC boats and other fiberglass forms are made using a positive mold. Due to SeaSearcher's internal urethane material, it was created by first forming the internal shape of foam using a negative mold and plug. This mold was created using spaced layers of MDF, each separated and each cut with a specific cross section of the hull shape. The mold was created by directly referencing the 3D model of the pontoon. To connect the layers, a few different options were attempted. First, pink insulation foam was sandwiched in between the MDF layers and sanded into shape. Not only did this process take a long time, but the outcome was highly variable. A full stack up of MDF was considered, but this was skipped because of the amount of resources necessary. In the end, layers were connected using duct tape, which expanded slightly during the molding process to give extra material that could be sanded away during post processing. The duct tape non stick side was easily peeled off the finished foam and gave a smooth starting surface. The plug was also made of MDF, but designed to match the shape of the needed cavity. This plug was also covered in duct tape, and the entire mold was sprayed with mold release. Additionally, the plug

was integrated into the lid of the mold, which contained overflow holes for the urethane to expand into.
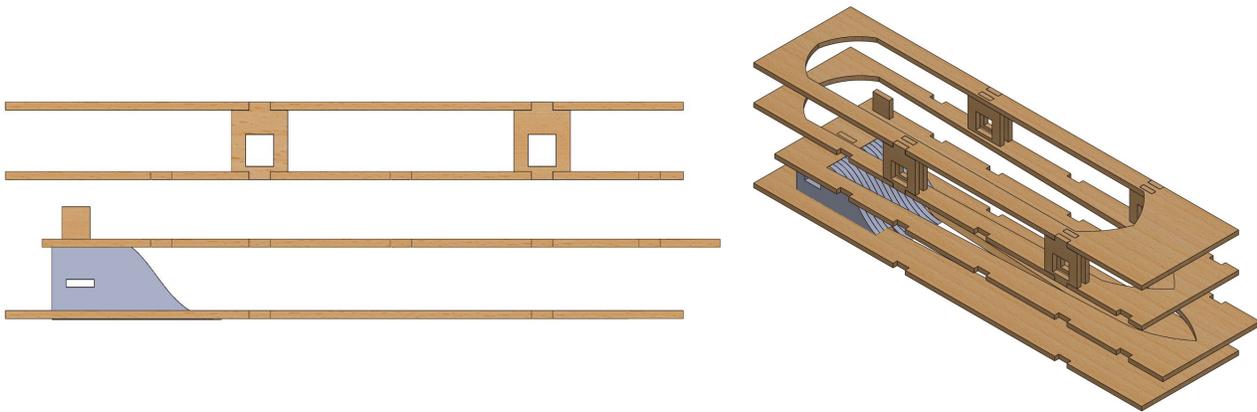
Figure 11 *CAD model of the mold created for SeaSearcher's pontoons*

To begin the actual manufacturing process, the first step was to pour the foam mixture into the mold. To start, 400 grams of each component of the urethane was mixed. Once mixing began, the curing process began and the mixture had to be poured into the mold quickly. The plug was then placed and clamped to the rest of the mold. After 15 minutes, the urethane mix had expanded out of the overflow holes and hardened. Once hardened, the lack of draft on the plug made it hard to remove, so the resulting foam body had to be cut in half. Once cut, the plug was removed and the two halves were reattached using permanent adhesive.

After the pontoons were sanded into shape, the hulls had to be finished by laying fiberglass over the positive shape of the foam. The foam would provide a buoyant inner structure for the fiberglass to harden onto and around. The fiberglass material was cut into certain shapes dependant on the side or face of the pontoon it is being applied to in order to avoid wrinkling. After pre applying the resin mix to the pontoon surface, the cut fiberglass material was then applied to surface and more epoxy resin was applied over the fabric. This was done until the first layer was applied over the entirety of the pontoon. A second layer was then applied for added strength. Between each layer, the hull was sanded to remove divots or bumps and inspected for holes or cracks. If there were any, more resin was applied.

The pontoons needed another layer after the fiberglass to provide a better surface finish. Typically, this is done using a special resin called gelcoat. The outer surface of a fiberglass boat or hull is usually done with a special resin called gelcoat. The gelcoat provides no added structural integrity but instead is used for color, a glossy finish, and UV resistance. The gelcoat is usually sprayed onto the hull and polished to provide a mirror like surface. However, there were some problems and challenges that occurred during the application process. Firstly, the gelcoat was brushed onto the pontoon instead of sprayed because no spray gun was available. Although gelcoats can be

brushed on, the one used did not have a self leveling quality which leaves a smoother finish. Many hours were spent sanding in the attempt to get a good surface finish. In the end, after encountering the trouble with gelcoat, another method of providing a surface finish to both the pontoons and the rest of the boat was needed. Spray paint was chosen because of its fast dry time, range of colors, and due to some paints having UV resistance. The quick dry time and bright colors allowed a quick turn around and nice finish.

Stability

We performed a variety of analysis techniques to ensure that SeaSearcher remained stable in the operating environment. The first of these methods was finding the metacentric height. The metacentric height is a measurement of the initial static stability of a floating body. It is calculated as the distance between the centre of gravity of a ship and its metacentre. A ship's metacentre is the point about which a body starts oscillating for small displacements. A larger metacentric height implies greater initial stability against overturning. The metacentric height also influences the natural period of rolling of a hull, with very large metacentric heights being associated with shorter periods of roll which would in turn mean greater roll velocities. This could cause motion blur in our cameras. So a sufficiently high, but not excessive, metacentric height is desirable. SeaSearcher's metacentric height was 17.44'', which was close to the maximum value it could be given our size constraints.
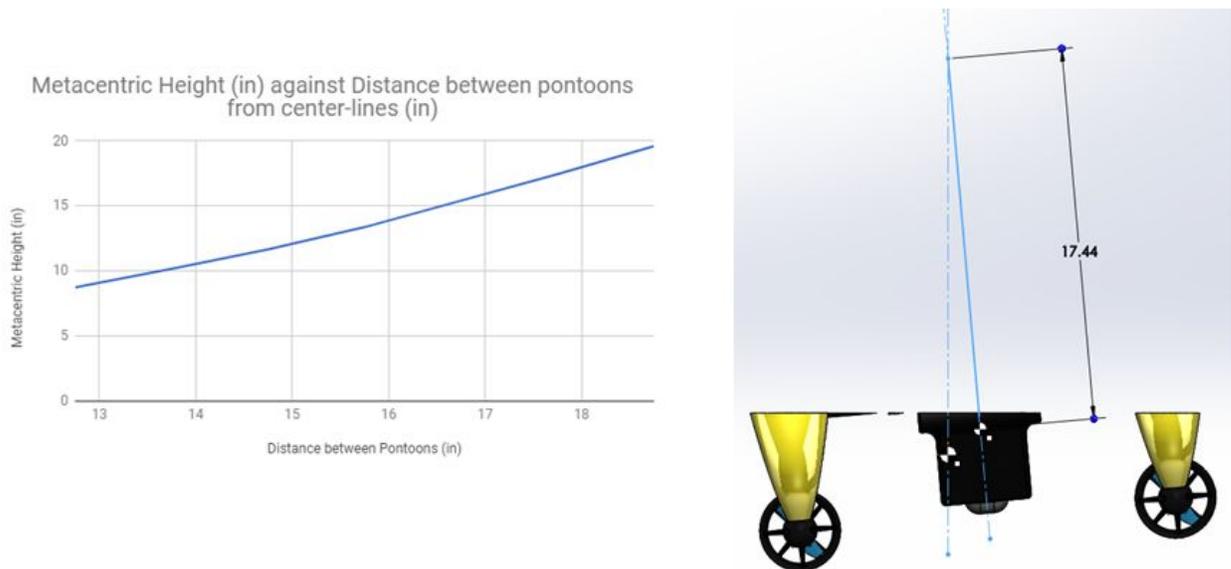

Figure 12 *Measurement of metacentric height and the effect of beam width*

The second method of analyzing stability was to track the objects righting arm for increasing angles. The righting arm is the horizontal distance between the objects center of mass and center of buoyancy. For a stable object, the righting arm becomes increasingly large initially, then falls to zero. Below zero, the object will not right itself and would flip over. Below is the graph of SeaSearcher's righting arm, showing a tipping angle of 89.6 degrees.
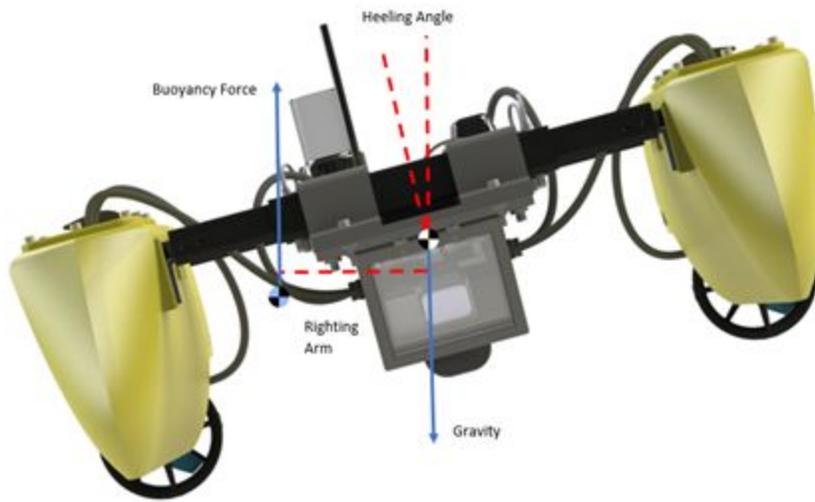
Figure 13 *Diagram illustrating heel angle and righting arm*
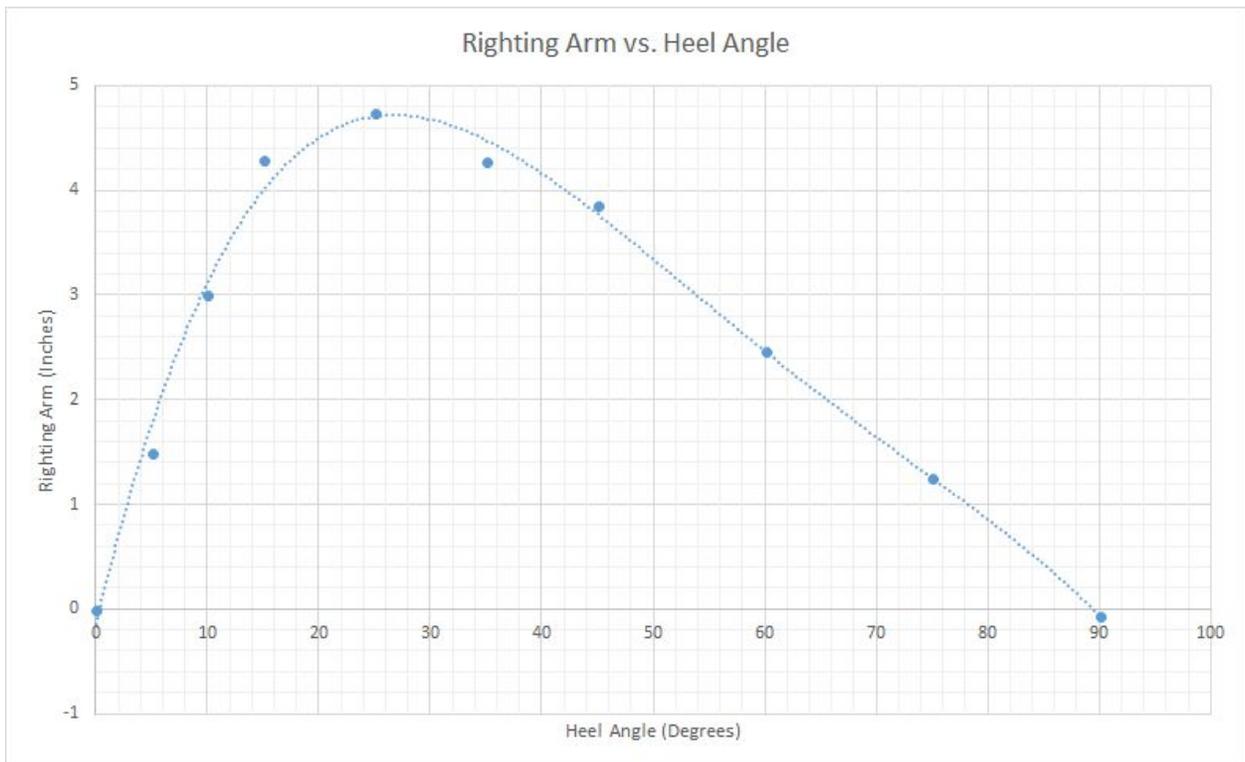
Figure 14 *SeaSearcher's righting arm vs. heel angle curve*

Power Source Selection

Choosing a power source was an important decision, because it affects many parts of the design. The two feasible options are electricity and gas and within electricity, either batteries or solar panels. Solar panels will also require batteries to store energy to run at night, when it's cloudy or for burst power. Gas requires either batteries or an alternator to run the electronics. The following table includes a more detailed comparison of the different options.

Power Source	Clean	Noise	Usable Energy Density	Motor Control	Cost	Testing
Batteries	No Emissions	Quiet	0.8MJ/kg	Easy	Medium	Ideal
Solar Panels	No Emissions	Quiet	0.15 MJ/kg/day	Easy	High	Not useful
Gas	Pollutes	Loud	4MJ/kg	Hard	Low	Limited places

Figure 15 *Review of the various characteristics of applicable power sources*

The Usable Energy Density column accounts for the estimated motor efficiency, which is important, because gas motors (especially small ones) are far less efficient than electric motors. Nevertheless, gas has far more energy than the same weight in batteries, however, in almost every other category gas is worse than batteries. It pollutes and is loud, which may be a concern in sensitive coral reef environments. It is also much more difficult to precisely control a gas engine than an electric motor and likely comes with the loss of backdrive. Gas engines would be heavier than an equivalent power electric motor and a gas tank also adds weight and complexity. One customer also noted the difficulty in finding gas in remote locations as well as transporting it to the same locations. Gas would also make testing challenging, because it eliminates any indoor testing locations. All of these disadvantages outweigh the higher energy density and therefore gas isn't the optimal solution.

Solar panels make it possible to get a theoretically infinite range, but they produce so little energy that they are impractical. To get enough energy to be useful so many panels would be required, that they would take up most of the weight of the boat. It would take more than five sunny days for solar panels to produce as much energy as the same weight in batteries. Additionally, the costs are prohibitively expensive and the researchers don't need long deployment times. Batteries can provide sufficient range for this application, don't cost nearly as much as solar panels and don't have all of the disadvantages of gas and are the best choice

Battery Design

Two of the key design considerations for the implementation of the battery packs on SeaSearcher were endurance and form factor. We determined that the pontoons were the ideal location for the battery packs, because they would otherwise be filled with foam. In addition, enlarging the center enough to fit them would increase drag a significant amount and possibly make the boat too big to fit into a suitcase however, this location's long and narrow form factor made finding a suitable battery impossible.

Several smaller batteries could have been combined in parallel or series, but this would have created a mess of wires and would have required using batteries with a significantly lower energy density. Instead, we made the decision to design a custom battery pack out of smaller rechargeable cells connected to each other through a custom printed circuit board (PCB). We decided on the configuration of three cells in series and 8 in parallel, because several components needed to run at 12V and that was as many cells in parallel as could fit in the pontoons.

Many different cells were considered and Panasonic NCR18650B Lithium-Ion cells were chosen, because they had the highest energy density we could find, with over 260Wh/kg of capacity. This is almost twice the energy density of typical off the shelf lithium polymer battery packs, which themselves are much more energy dense than any other type. The high capacity of the cells comes at the expense of the maximum continuous current rating, which is only of 6.8A however, that isn't a problem in this application, because even at the top speed, the peak current per cell is under 2A. The PCB and battery holders did add weight, but they also reduced the amount of wiring required and were only ~15% of the total battery pack weight.

There are several FAA regulations on taking lithium ion batteries on airplanes. Batteries must be packed in carry on bags and the terminals must be properly insulated. Each SeaSearcher battery pack has around 294Wh of capacity, which is greater than the FAA maximum of 160Wh. To work around this restriction, the cells can be removed from the holders, and there is no quantity restriction, because the cells are so small.

Lithium ion batteries can be dangerous and therefore it is important to have sufficient protection circuitry to prevent anything from happening to them. Each of the 24 cells on each battery PCB has its own 3A PTC resettable fuse to protect against overcurrent. This is mainly important in the case where cells with different amounts of charge are put in parallel when assembling the pack. These fuses will blow if the difference in voltage is too great and stop the cells from shorting through each other. Since they are resettable fuses, they will let a small amount of current through in this state and eventually reset once the cells are balanced.
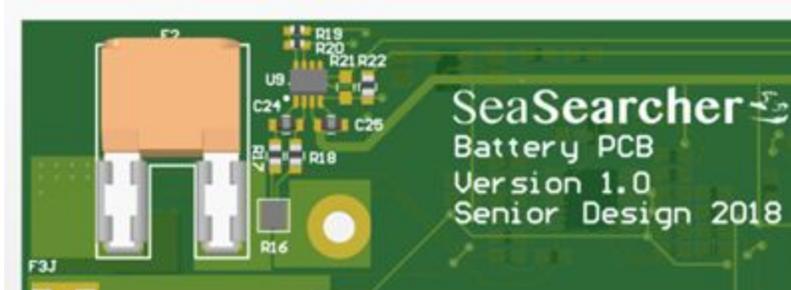
Figure 16 *Render of the fuses on the battery circuit board*
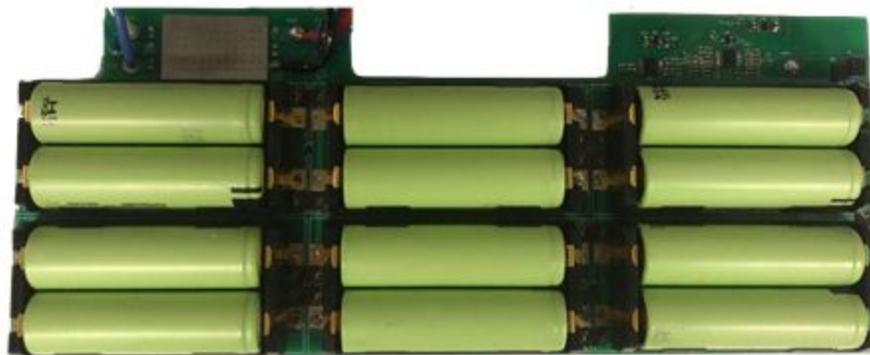
Figure 17 *Photograph of the soldered battery pack with cells*

Over time, the different series segments of the pack will shift out of balance and will have different voltages due to slight variations in the cells. The PCB doesn't have integrated balance circuitry to deal with this however, whenever the cells are rearranged for travel, they will balance each other as they are placed in random locations. There is no risk of damaging the cells because they have proper fusing and have their voltage individually monitored. A standard 20A mini ATC fuse is also included to protect the entire pack from short circuits and will blow much more quickly than the PTC (Positive Temperature Coefficient) resettable fuses. It is placed at the top of the pack so it can easily be checked and replaced. A battery protection chip (U1: S-8254AAWFT) also protects the cells from going under or over voltage by turning off a couple of MOSFETs (Q1,2: BSC030P03NS3G) in series with the output of the pack. It will also disconnect the cells if the pack goes over temperature, which is detected by comparing a constant threshold voltage with the output of four temperature sensors (U3-7: LMT87QDCKTQ1) that are distributed around the cells. These components were selected to minimize power consumption, because they are never turned off, even after the pack cuts off below 3V per cell. In total they use only a few microamps, meaning it would take years for them to drain the little remaining energy before the cells went below the datasheet minimum of 2.5V. A current sensor (U9: INA219AIDCNTG4) measures the voltage across a sense resistor to determine the amount of current being drawn from the pack

and can also measure the pack voltage. The central microcontroller can read this data over I2C when the packs are connected.

Charging

The battery packs have significantly more energy than most off the shelf packs and this means standard chargers aren't designed to output as much power as the pack can handle. These chargers are also expensive because they need to be able to support many types of cells. The search for alternatives eventually led us to using industrial lighting drivers to charge the packs. These are typically used for high power LED lights, but are perfect for this application because they supply a constant current until they reach the maximum voltage.

**Figure 18** *LNE-12V185WAAA charger used with SeaSearcher*

The LNE-12V185WAAA was selected because it outputs up to 12V and has a high maximum output current of 13A, which is exactly the maximum charge current of the cells and also exactly the same as the current rating of the connector. This allows the cells to charge in under 3 hours. It also will run off the AC wall voltage in any country and is IP65 water resistant rated. A plug was connected to the input and a waterproof connector was added to the other side so that the pack could be charged in place without being removed from the SeaSearcher. This is safe because the battery protection circuitry is always active and can disconnect the charger if the cells start overheating. The cells could go up to 12.6V and therefore some capacity is lost, but it is only 3% of the total and the navigation light and on/off switches aren't rated to go over 12V.
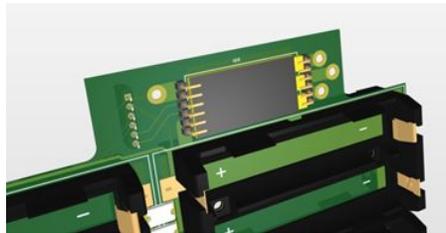
Figure 19 *Render of the Electronic Speed Controller (ESC) on the battery circuit board*

Motor Control

A Blue Robotics ESC (U10) controls each T100 thruster, and are mounted directly to the PCB to reduce wiring. This was done by removing the built-in wires and soldering right angle headers to the pads where the wires used to connect however, most of the components of the ESC are located on the bottom and there were concerns that it might overheat when placed on a PCB, because it would block natural convection. To ensure there would still be sufficient cooling, a copper plane was placed underneath the metal ESC case on both sides of the board and these were connected with over 50 copper vias to ensure a low thermal conductivity. Before the ESCs were soldered in place, thermal paste was also placed in between the ESC and PCB to reduce the thermal resistance and better cool them.
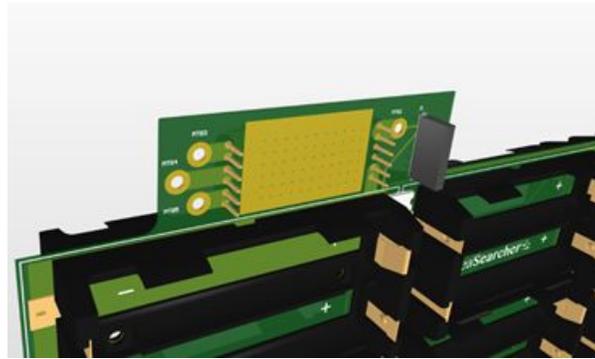
Figure 20 *Render of copper plating on underside of the ESC for cooling*

Battery Wiring

There were several benefits to keeping the battery packs independent. It significantly reduced the amount of current that needed to leave each side and go to the center, allowing smaller connectors to be used. It also provides redundancy, because the central PCB and a computer can connect when either battery pack is on. This was very useful in one lake test where a fuse blew. Control of one thruster was sufficient to get the boat safely back to the dock. To ensure both sides stay at the same voltage, the center compartment draws current from whichever pack is lower. Each battery pack has an IP68 waterproof rocker switch (V1D2GHNB-AAC00-000) to turn it on and off. The switches are rated to 12V and 20A, meeting the pack requirements. The switch also has a green light and an amber light to make it easy for the user to see the current pack state. The different possible light configurations are shown in Figure 19.

A variety of waterproof switches were considered. However, many were only IP67 rated, had too low a current rating or didn't have enough configuration options. The Switchcraft EN3 series was determined to be the best option, because it has a wide variety of IP68 connectors, ranging from 2 pins to 18. They also come in many variants, including panel mount, PCB mount and cable versions, and are rated to 250V with current ratings ranging from 3A to 13A.

Switch Light	Description
	The battery fuse has blown, the pack has died, or the cells were reinserted, and the pack hasn't been charged yet.
	The pack is off
	The charger is connected, and the switch is still off
	The pack is on

Figure 21 *Mapping of Battery LED indicators*

The T100 thrusters connect to the battery packs through a 6 pin connector. Two pins are used for each phase for a maximum rating of 15A for each one, which is a little over the 11.5A maximum thruster current. The other battery connector has 8 pins and connects to the center of the boat. It has two pins each for power and ground to a achieve the 13A rating necessary for charging. Two other pins are used for the SDA and SCL signals for I2C communications with the current monitor chip. The remaining two are the thruster PWM signal and an extra ground wire that acts as a return path for this signal to reduce the chances of encountering noise issues.

Circuit Board Design

The central PCB fits on top of four EN3 series connectors that connect both battery packs, the depth sensor and the navigation light. Beneath it are both GoPros and two red lasers. When the battery packs are turned on, current flows through Scottkey diodes (D2,4: B340A) before going to two buck converters. One of these supplies power to the GoPros through individually controllable load switches. The other supplies 5V to the rest of the board, including a linear regulator that powers a 3.3V rail.
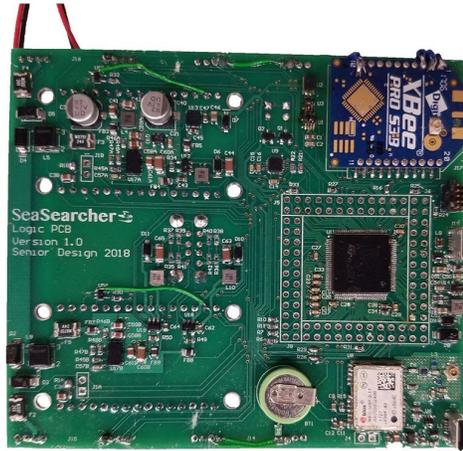
Figure 22 Photo of our custom circuit board

The PCB can also be powered off a USB port on the other side of the board. The 5V from the USB port goes through another diode (D8: B340A) to connect with the main 5V rail. It doesn't power the GoPros, because a single USB port can't supply enough power. The USB port also has a USB to UART interface (U15: FT234XD-R) to allow a computer to connect directly to the board for debugging purposes. Two ESP8266 microcontrollers are mounted to the bottom of the PCB. These are used to control the GoPros by connecting over WiFi and sending them HTTP commands. TVS diodes were added to the data lines to prevent damage from ESDs when the modules are plugged in and jumpers make it possible to disconnect 5V so that a USB cable can be safely connected for testing and debugging. A CAN transceiver (U1: TCAN337GDCNT) connects the microcontroller to the CAN bus for the depth sensor. The 120 termination bus resistor was forgotten and added to the PCB later.

Processor Selection

Selecting the processor for the system is also important because has implications on sensor selection. There are many possible options and figure 8 below shows a comparison between a few of the more feasible ones that were considered.

| Processor	Performance (FLOPS)	Logging	Camera Support	OS	Cost	Power
ATMega32U4	$\sim 10^4$	Difficult	No	None	$4	0.1W
Arduino	$\sim 10^5$	Easy	No	None	$40	0.5W
STM32F7	$\sim 10^7$	Doable	Difficult	RTOS	$15	1W
Raspberry Pi 3	$\sim 10^8$	Easy	Yes	Linux	$35	5W
Jetson TX2	$\sim 10^{12}$	Easy	Yes + Vision	Linux	$300	7.5W

Figure 23 *Review of different processor characteristics considered*

This table covers everything from the small 8 bit AVR microcontroller used in the Penn MEAM 510 Mechatronics course to the Nvidia Jetson TX2, which is almost a billion times as fast. The microcontrollers (ATMega32U4, Arduino and STM32F7) have the advantage of being significantly lower power, which will increase the maximum range and eliminate overheating concerns. However, the ATMega32U4 can't handle logging data and doesn't support CAN, which is required to use the depth sensor.

There are many other similar microcontrollers that could be chosen, but the STM32F7s are a better option than any of these. This is because we have a significant amount of experience working with them in the past and some high performance low level libraries that take advantage of direct memory access to achieve better performance.

Before the decision to use GoPros had been made, the team considered logging camera data with the rest of the log files and only the Raspberry Pi 3 and Jetson TX2 would have supported this. The Jetson TX2 would even be able to run computer vision algorithms on the images, which could be useful for several additional features, such as deciding when to take a picture or using them for more precise localization. Initially, the Jetson TX2 was chosen, but challenges working with it and the desire to make a smaller boat led us to switch to the STM32F7. Another reason for the change was that preliminary attempts at computer vision showed that lighting variations were detected as edges and features as much as the things on the ocean floor.

Microcontroller Layout
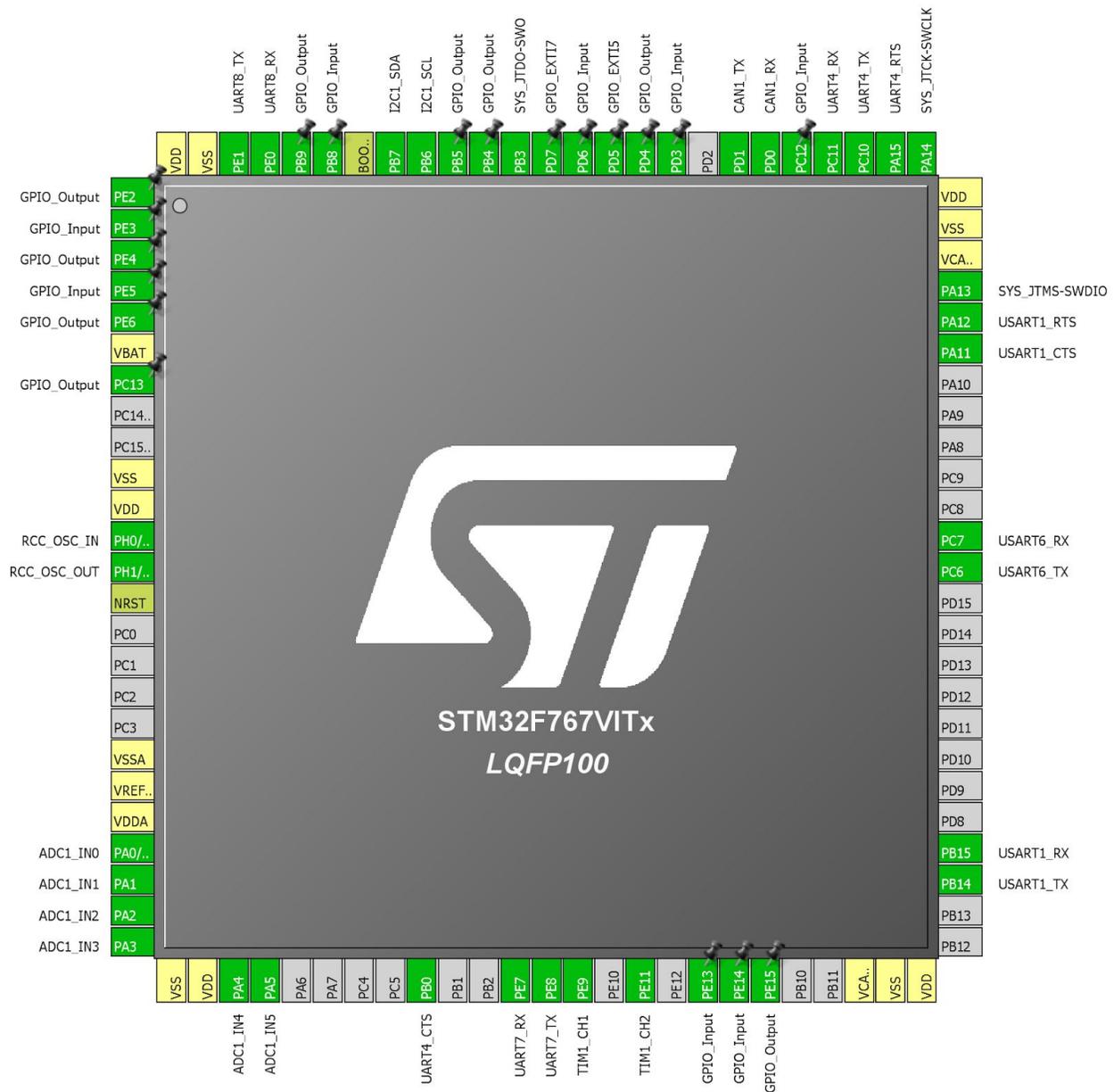
Figure 24 *SeaSearcher's microcontroller pinout*

A pinout for the microcontroller had to be carefully determined, because it was important to ensure pins were chosen that were close to the corresponding components on the board, there simply isn't space for many tracks to go all the way around. While this was decided, the orientation of the microcontroller had to be selected to simplify routing. At the same time, only certain pins can have certain functions and choosing valid pins was complicated by the fact that so many peripherals were required. Finding valid

configurations of these ports while also finding open direct memory access streams for each of them proved impossible however, by not using the serial port connected to the USB port, we found a way to make everything work. The decision was made to surround the microcontroller with pads so that it would be easy to make changes if a mistake was found or something needed to be added. Code is uploaded to the microcontroller through a single wire debug (SWD) header that connects to an external J-Link debugger.

Each laser is enabled through an N-channel MOSFET, giving the microcontroller easy control without having all the current needing to go through the microcontroller itself. The T100 thrusters were controlled through two timer channels to ensure there was no error in the outputs. In addition to the main communication interfaces, a variety of other inputs go the microcontroller. This includes analog inputs to measure the battery voltages, gopro supply and 5V supply through voltage dividers. There are fault inputs from the power supplies for the GoPros and enable outputs to control them.

Wireless Communication

There are many different options for integrating wireless communication into the system and these were divided into three main categories. These include point to point modules that send data between two transceivers, such as xbees, modules that send data through the cell tower network and satellite communication modules. The following table shows some of the most important criteria for comparing these different options.

Wireless Module	Range	Power	Data (bit/s)	Cost	Latency
Xbee SX 20mW	Horizon	150mW	10^5	2x$35	milliseconds
3G/4G Module	20mi from tower	2W	10^6 (peak)	$50+??/MB	seconds
Rockblock	Anywhere	500mW	40	$300+$1/KB	minutes

Figure 25 *Review of wireless communication options*

Satellite based communication is appealing, because it will allow the researcher to control it from anywhere, no matter where the boat is located. It's the only way to transfer data from far out at sea, however since the SeaSearcher will be used in coastal areas rather than the open ocean, this is not necessary.

Cell tower modules are a viable solution but latency is not ideal and the pricing might be such that high performance is out of our budget, although there is very little information available. The biggest problem with this approach is that there might not be a signal in a remote testing site. Coverage at sea is better than one might expect, but this restriction is still a potentially significant issue.

The final option of using point to point modules seems ideal, because the researcher will have to be on sight at all times regardless. There are no data limits with this method and the range should be sufficient for almost any expected use case. It's worth noting that more than one these options can be combined to get the benefits of each, but point to point modules seem sufficient for the scope of this project and adding something else may increase the cost and software complexity.

Many different radio modules could have been used to communicate with the SeaSearcher, but most types are too low range to be feasible. WiFi will only go a few hundred feet for example. A 900MHz xbee pro radio was chosen for its long range of 4 miles thanks to its 250mW output power. It can transmit 200kbps of data, which is sufficient for this application and can easily be connected over serial. An IP67 waterproof UMC to RP-SMA antenna adapter was used to connect to the IP67 antenna outside the box. This antenna was chosen because it's frequency range coincided with

that of the xbee and could fold down to easily fit in the suitcase. It is a dipole antenna, because these have a higher gain in every horizontal direction, which is perfect for a boat that will be at a similar height to the user. It also had a slightly higher gain than some of the other antenna options.

IMU

The MPU9250 Inertial Measurement Unit (IMU) was included on the PCB for use in navigation, because it is small, accurate and inexpensive. It has an integrated 3-axis gyroscope to measure angular velocity, 3-axis accelerometer to measure acceleration and 3-axis magnetometer to measure magnetic fields.

GPS

Arguably the most important sensor on the SeaSearcher is the GPS, because without it, there's no way to know where any of the other data is collected. After challenges with GPS on past projects, a significant amount of research was done to ensure that they worked. GPS is particularly difficult to work with on a PCB, because it is such a high frequency signal and because the amplitude of the signal is more than an order of magnitude lower than the ambient noise at that frequency. The team decided to use Real Time Kinematics (RTK) to achieve the best possible accuracy.

Most GPS error is attributable to atmospheric effects that don't vary over relatively short distances. RTK works by setting up a second GPS receiver at a known position that can measure this error and then send it to the rover which then uses this information to correct its own position estimate. Once this decision was made, the only feasible option was to use the u-blox NEO-M8P RTK GPS module, because every other module is prohibitively expensive.

Many different antennas can be used for GPS, including onboard chip antennas, passive antennas and active antennas. The Taoglas AA.161.301111 active antenna was chosen, because it is an active antenna, which means it has a built in Low Noise Amplifier (LNA) to amplify the signal. It was also smaller and cheaper than most other options and one of the antennas specifically recommended by the manufacturer.

The datasheet also warned of noise concerns when the module would be operating near radio signals. With two WiFi modules and an xbee in close proximity, it was important to add an additional Surface Accoustic Wave (SAW) filter to attenuate this noise. This filter is specifically designed for GPS and is the smallest component on the PCB. It has 5 small pads on the bottom, but only measures .055"x.043", making it one of the most challenging parts to solder correctly. The GPS antenna is IP67 rated and enters the central enclosure through a similar adapter to the one the xbee uses. The GPS signal enters the board through a UMC connector and goes through a high pass filter. Power is supplied to the built in antenna amplifier back through the radio input.

Inductors block the GPS signal from going through the power and ground connections. With such high frequency signals, it was important to carefully layout this area of the board. All the other unrelated tracks were kept as far away as feasible to keep away noise. The components were placed very close together to reduce the distance that the GPS signal would have to travel. Ground planes cover the top and bottom of the board in this area to protect the GPS signal. All the tracks in the path of this signal are carefully sized to have the required impedance of exactly 50 ohms, taking into account the distance to the ground plane on the bottom of the board and the one beside the signal. The GPS module is also connected to a backup coin cell that always provides power, so the module can store the satellite positions and reacquire a signal much more quickly when the board is turned on. This cell also provides power to the Real Time Clock (RTC) on the microcontroller so it can keep track of the current time.
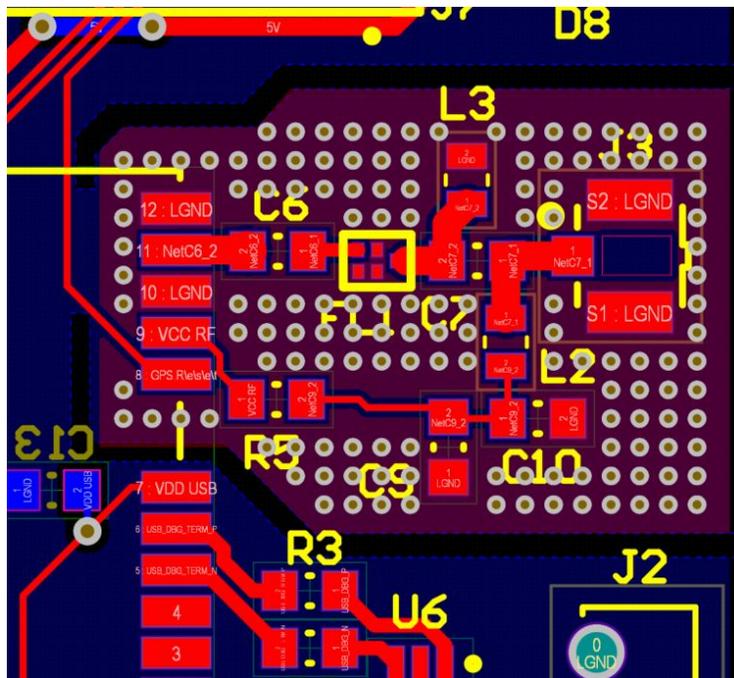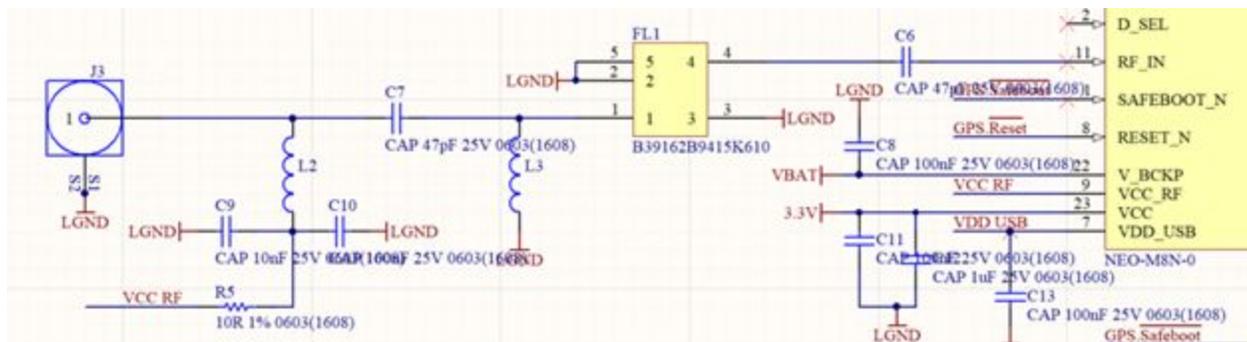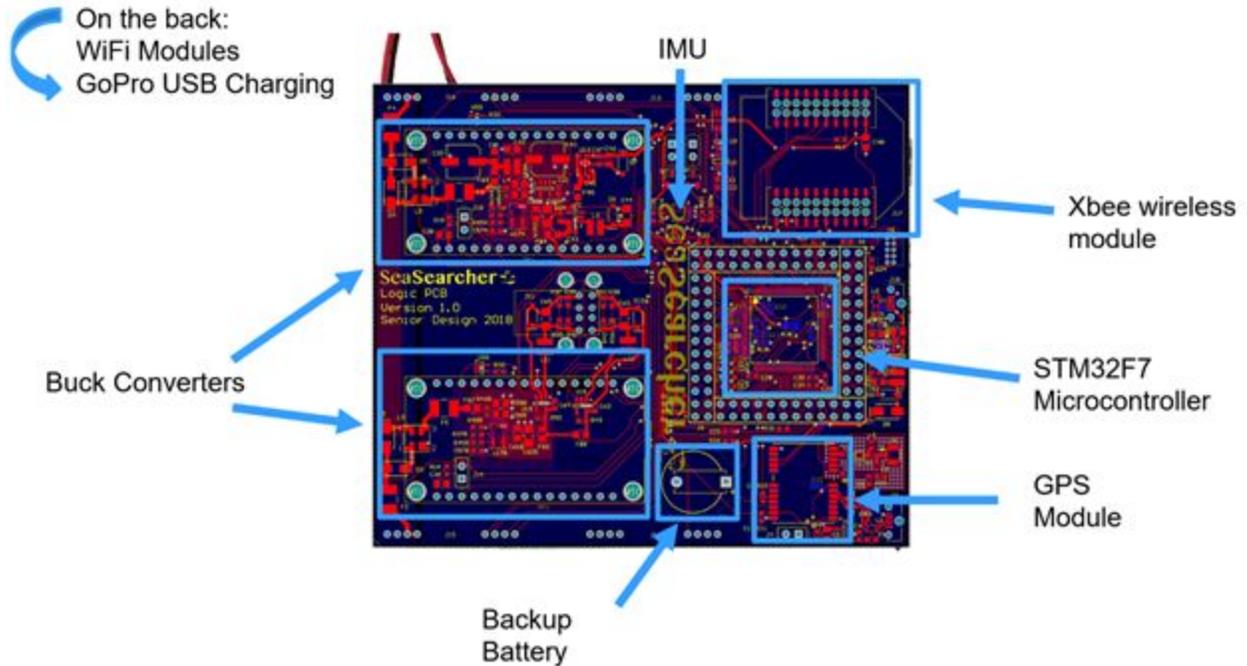

Figure 26 *Close up of the RTK GPS Circuit Schematic and PCB Layout*

Circuit Board Layout

On the back:
WiFi Modules
GoPro USB Charging

IMU

Xbee wireless module

Buck Converters

STM32F7 Microcontroller

GPS Module

Backup Battery

Figure 27 *SeaSearcher's central PCB with major areas highlighted*

Most of the rest of the PCB layout was straightforward, because the components are spread out and it is mostly composed of digital circuitry. The design started with determining the mechanical integration considerations, including the board size, connector positions and ensuring there was sufficient space for everything to fit. The sections of the board were then arranged one by one to figure out approximately where everything would go. Finally, the tracks were placed, and final adjustments were made. We considered using a four layer board but found there was enough space to fit the tracks on two layers and this decreased the board costs. The tracks were kept on the top layer where possible and the bottom layer was mostly reserved for a ground plane, so all the signals would have a nearby return path, reducing noise.

Base Station

Figure 28 *Photo of SeaSearcher's base station*

RTK GPS requires a base station and the computer needed a way to communicate with the SeaSearcher, so another circuit board needed to be designed. Since many of the same components were required for this design, including xbees, a microcontroller, USB circuit and GPS, the schematics for the main PCB were reused. Only a few minor modifications were necessary, such as adding a power input so the base station could be powered by an external battery if a computer wasn't connected. To further save time, the main PCB was designed from the beginning to have everything necessary for the base station on the right side. This meant the PCB design could also be copied. Everything extra on the left was removed and a couple tracks were moved to make the board a bit more compact. The xbee was also replaced with a slightly different version with an SMA connector so an antenna could be directly connected, instead of having to go through an adapter. A 3D printed enclosure was designed to protect the base station and it includes a clear window on top, so the circuitry within is still visible.

Assembly
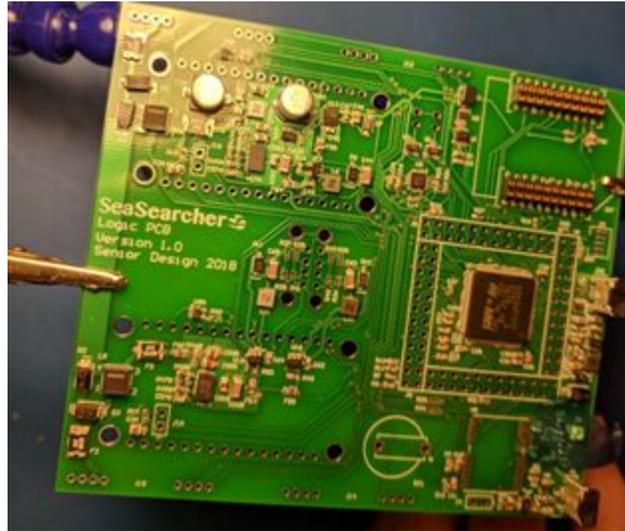
Figure 29 *Photo of SeaSearcher's central PCB during soldering operations*

The PCBs were hand assembled by first putting solder paste on all the pads and then placing all the surface mount components with tweezers. A heat gun was used to melt all the solder into place. The components on the back were done the same way afterwards. After this, the through hole components were soldered. Once soldering mistakes had been fixed, board changes had been made and everything had been verified to work, the PCBs were all conformal coated to protect the components from Electrostatic Discharges (ESDs) and from moisture.

Camera Selection

Cameras are readily available, but few have a way to control them remotely. Initially, we considered cameras that were compatible with the Jetson TX2, which included mainly USB webcams, along with some more specialized cameras that use the Camera Serial Interface (CSI). Unfortunately, most of these options were lower resolution and once computer vision seemed infeasible, we decided to find something better. There are few ways to control a camera with a microcontroller and most of them are hacky and don't allow for configuration. GoPros are a rare exception to this. They have a WiFi interface that allows them to be controlled by proprietary remotes.

In addition, the Go Pros are lightweight, very compact and have up to 4k photographic quality with a high megapixel count, as well as wide angle lenses critical for covering the large areas of shallow coral reefs. GoPros are also tuned to avoid motion blur, due to their design for extreme sports, and critically they are also wifi-controllable allowing potential integration into the SeaSearcher system. Our stakeholders requested that SeaSearcher have two cameras, one front facing to capture panoramic shots of reefs and one down facing to collect images for later analysis. The GoPro Hero 5 Black specifically was chosen because it supports taking RAW images, something our stakeholders requested. Price was also a consideration in selecting the GoPro cameras, because rival specialist cameras often cost thousands of dollars, whereas each GoPro costs under $300.

Figure 30 *GoPro Hero 5*

Two red lasers are located next to the downward facing GoPro camera and can be used for determining the image scale. They were selected, for their high power output of 5mW.

In its current state, each of Seasearcher's cameras is configured to take 1080p wide-angle 12MP video. Camera configuration is done manually through the GoPro user interface. The cameras are switched on to record and then sealed in the bridge. Adjusting recording settings during a test run is not an option at this time. Instead, the cameras are kept on and recording throughout a test run and the desired footage can

be extracted from these videos. Each of the cameras uses a high speed (10MB/s) 128GB SD card for memory storage, allowing storage of upwards of 36 000 JPG images (at 3.5Mb each) or upwards of 10 hours of video (12.6GB/hour).

The GoPro cameras also have integrated batteries, however the battery life (under two hours) is insufficient for our six hour target runtime, Seasearcher's cameras are plugged into the main circuit board via USB A to USB C cables to supply power to the cameras directly from the custom battery packs and thus extend their lifetime.

Progress was made to further integrate the cameras, so that they could be controlled by SeaSeacher automatically. Two wifi-enabled ESP8266 microcontrollers were configured to send http command lines to each of the cameras using the ESP8266HTTPClient. The GoPros were configured to create their own wifi networks. Each ESP8266 connected to one camera's wifi network and sent HTTP get requests to control of the cameras. The ESP8266s were configured to send instructions to the GoPros upon receiving serial commands, however this functionality was not fully integrated into the Seasearcher prototype, because conformal coating got into the mounting headers and there wasn't time to replace them. This remains a place for improvement in further design iterations.

Depth Sensing

Initially we hoped to find a 3D scanning sonar module that would allow us to easily generate a 3D model of the reefs however, these sensors are difficult to use and prohibitively expensive. Therefore, we focused on searching for the best 1D depth sensor. Standard ultrasonic sensors can be made water proof and aren't very expensive but have several drawbacks that make them impractical including being short range and having a wide beam. Many sensor options exist, but those that measure depth, temperature and water speed seem to be the best choice, because they make it possible to measure everything with one sensor.

Sensors used on actual boats seem ideal, because they have the required accuracy and range and are mass produced and therefore cheap. Most options are analog transducers that use proprietary interfaces and reverse engineering would be prohibitively difficult however, some use NMEA 2000, which is a standard protocol built on the Controller Area Network (CAN) protocol supported by our microcontroller. Initially we looked at the DST800, which measures depth, speed and temperature however, these are intended to be mounted through the hull of a boat, which would make integration difficult. The P39 is similar but weighs half as much and can measure depths up to 150m, 50% deeper than the DST800. It is designed to mount with a bracket, making it the ideal sensor.

Figure 31 *P39 Triducer*

Navigation Light

The International Regulations for Preventing Collisions at Sea (COLREGs) require all boats smaller than 12m to have a white navigation light visible from all sides. A 12V LED light designed for boats was selected to ensure it could be easily powered and would be sufficiently bright. It is IP65 rated, but the rest of SeaSearcher is submersion proof and this led us to modify the light to make it more waterproof. The bottom holes were filled, and the two wires were replaced with a single waterproof cable. The interface between the clear plastic and the base was left as is to allow the bulb to be changed and because it is farther above the water and seals well.

Figure 32 *Navigation light for COLREGS*

Firmware

All of them embedded firmware for both the base station and main PCB was written in C++. An embedded operating system called FreeRTOS was used to improve reliability by ensuring that even if there was a bug in one part of the code, the other threads could continue running. It also made it easier to have different operations run at different speeds. A total of four threads were used, one for reading sensors, one for controlling the GoPros, one for the motor outputs and control algorithm and one for communicating with the computer.

The control code is the most important part, because if something goes wrong, there is the potential to lose control of the boat. This could lead to the boat going off into a large body of water with no way to stop it. To prevent this, we kept this code simple and tried to follow NASA's "*The Power of 10 Rules for Developing Safety-Critical Code*". For example, there are no loops in this section other than the main loop, to prevent infinite loops. All the motor commands are sanity checked and there is a timeout that stops everything if no messages are received from the base station in the past second. The control thread also has the highest priority to ensure it takes over even if another thread has issues. This feature saved the boat once when it went out of range of the base station while in autonomous mode headed for a point too far away. The boat stopped until we got the antenna into a better position and were then able to remote control it back.

Autonomous control was implemented as a separate mode within this loop to ensure it would always be possible to switch back to remote control if necessary. First the heading and distance to the target were calculated from the latitude and longitude using the haversine formula. The heading was then compared to the boat heading estimated by the GPS module and this error was input into a PID controller. To allow this algorithm to run at 200Hz, which is much faster than the GPS update frequency of 10Hz, the gyroscope data was integrated and used to update the angle estimate in between datapoints. The output of this controller determines the difference in the command for both of the motors, which makes the boat turn towards the target while always continuing forward. A variation of this was also attempted that would make the boat turn more sharply by slowing down more at sharp turns, but this algorithm had some issues that were never resolved.

The sensor thread is responsible for reading all the sensors, including analog inputs, the onboard temperature sensor, the depth sensor, the IMU and the GPS. It monitors the GoPro supply voltage and both battery voltages by measuring two voltage dividers. The TMP05A temperature sensor is read by measuring the ratio between the high and low parts of a PWM signal. The xbee also outputs the Relative Signal Strength Indicator (RSSI), which is another PWM signal that indicates the quality of the wireless connection. The depth sensor sends data over CAN with the NMEA2000 protocol. To make this work, the CAN library had to be modified to support the correct baud rate,

which is 250kbps. We also created a NMEA2000 helper class to make it easier to integrate other NMEA2000 sensors in the future, but no others ended up being added. A total of 6 Parameter Group Numbers (PGNs), which correspond to 6 different possible NMEA2000 messages. Each one contains several different parameters, but most of them don't provide useful information, because they aren't supported by the P39. The data from each PGN is parsed into a struct to make it easy to retrieve the data. One of the most difficult parts was figuring out the format of the data, because good documentation is so hard to find. The IMU contains an accelerometer, gyroscope and magnetometer, but the magnetometer is actually a different chip embedded within the same package. The MPU9250 is essentially an MPU6250 with a connected Ak8964. The MPU9250 was configured to connect the Ak8964 directly to the I2C bus to simplify communications. The sensor ranges were set to the most precise settings, to increase accuracy at the expense of a narrower range. This was fine because the boat doesn't experience large accelerations or angular velocities. The data is then read at 200Hz along with the other sensor inputs.

Data Management

Data was sent between the computer and boat over using custom binary protocol and code generation system. An xml file was written with a list of around 75 variables and code generation turned this into C++ headers and source files. This system also provided a basic user interface that made it possible to type in values for each variable. In addition, it allows for live graphing of the data for quick debugging and for the data to be saved and analyzed later however, this system didn't directly support integrating the base station in the middle.
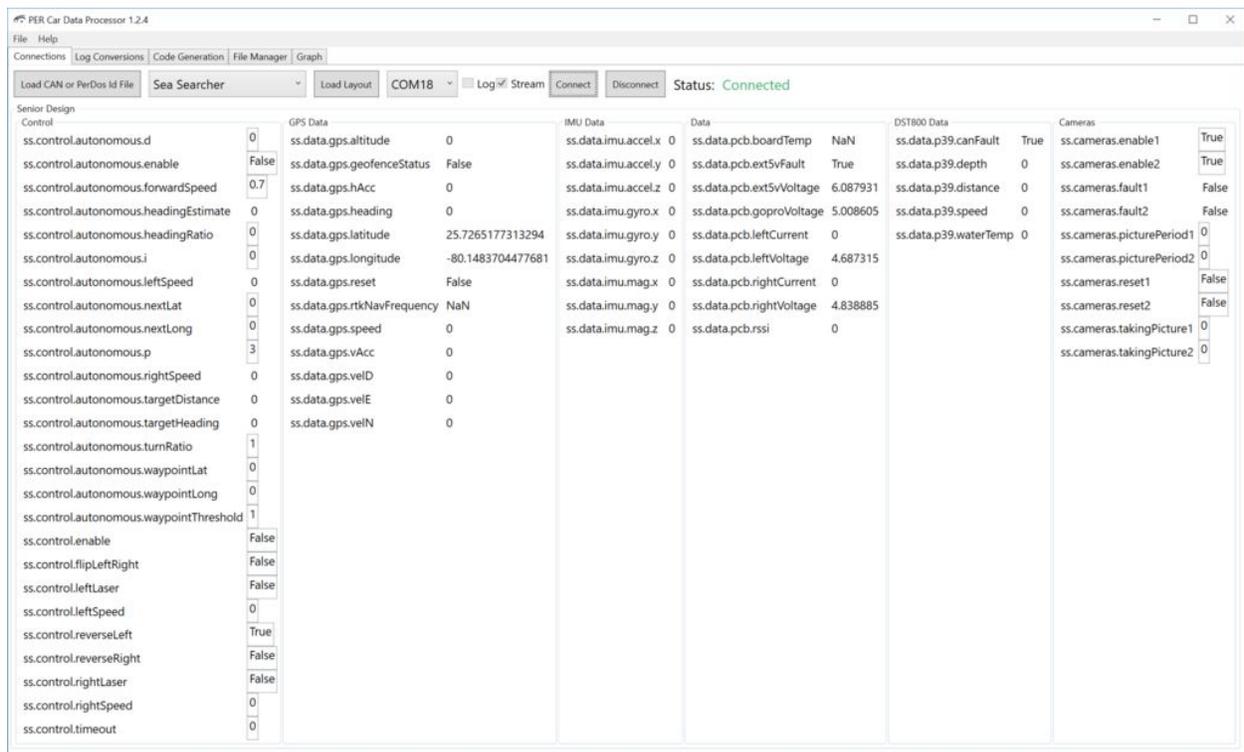

Figure 33 *SeaSearcher's initial user interface used for testing*

RTK GPS

The base station is an important part of the system, because it provides the RTCM messages needed for the SeaSearcher GPS to use RTK to achieve centimeter level accuracy. The NEO-M8P module on the base station was configured to send these messages at 10Hz. The position is configured to a fixed latitude and longitude so it can determine the correct offsets to send. The module on the boat is configured to receive these messages and to also output information about the GPS signal. The ublox binary protocol was used, instead of the more standard NMEA GPS sentences, because this data was easier to parse. Again, the module was configured to send the data at 10Hz, the fastest speed supported. To simplify the parsing of both the ublox format and RTCM messages in a stream of binary data, a BinaryDataParser class was created. It was written in a general way to support almost any binary packet format. The parser waits until enough data has been received for there to be a full message and properly handles edge cases without risking skipping valid data if a checksum failure occurs.
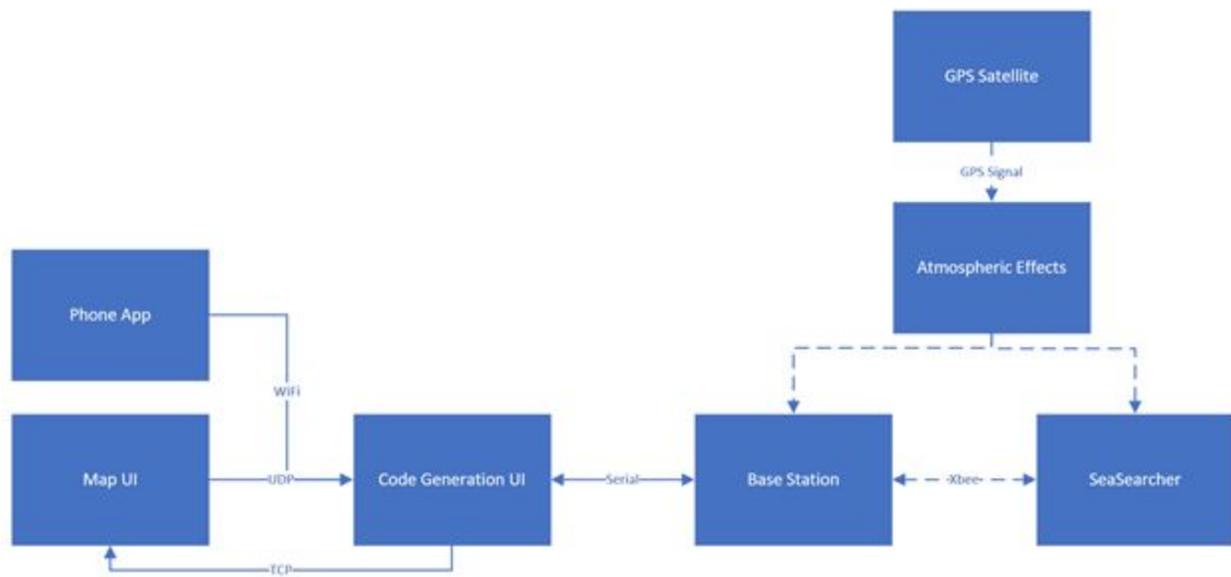
**Figure 34** *Block diagram of SeaSearcher's communications and signals*

The base station had the parsed RTCM messages and the streams of binary data going to and from the boat, but still needed a way to integrate with the code generation system to send the data to the boat. This was done by parsing the stream of packets in this binary protocol, using the same BinaryDataParser class. Extra packets with the RTCM data were then sent between messages that were coming from the computer and these new packets were formatted so they would automatically get parsed into arrays of data when they arrived. This made it appear to the boat as if they were just more messages being sent from the user interface, even though they were actually coming from the base station. Unfortunately, sending the RTCM messages seemed to

work, but we never successfully got an RTK fix and are still unsure of exactly what the problem was.

Phone Application

It is important for the user to have easy control over the boat and therefore some type of remote control was necessary. To avoid additional costs, we decided to design a phone app. The app connects to the boat through the basic computer user interface. The computer connects to a WiFi hotspot created by the phone and this allows the phone to send the data. User Datagram Protocol (UDP) was used, because the packet structure made it easier to format and parse the data. The existing UI had to be modified to support this new source of commands. The accelerometer on the phone was used to determine the amount the phone was angled, which was turned to determine the thrust commands. This made it easy to control the boat by simply tilting it forward to make the boat go forward, back to go back or to the side to make the boat turn. A deadzone was added around the center to ensure the boat would completely stop. The app only works on Android, but was written in C# using Xamarin, so can easily port to iOS without rewriting much of the code.

Mapping User Interface
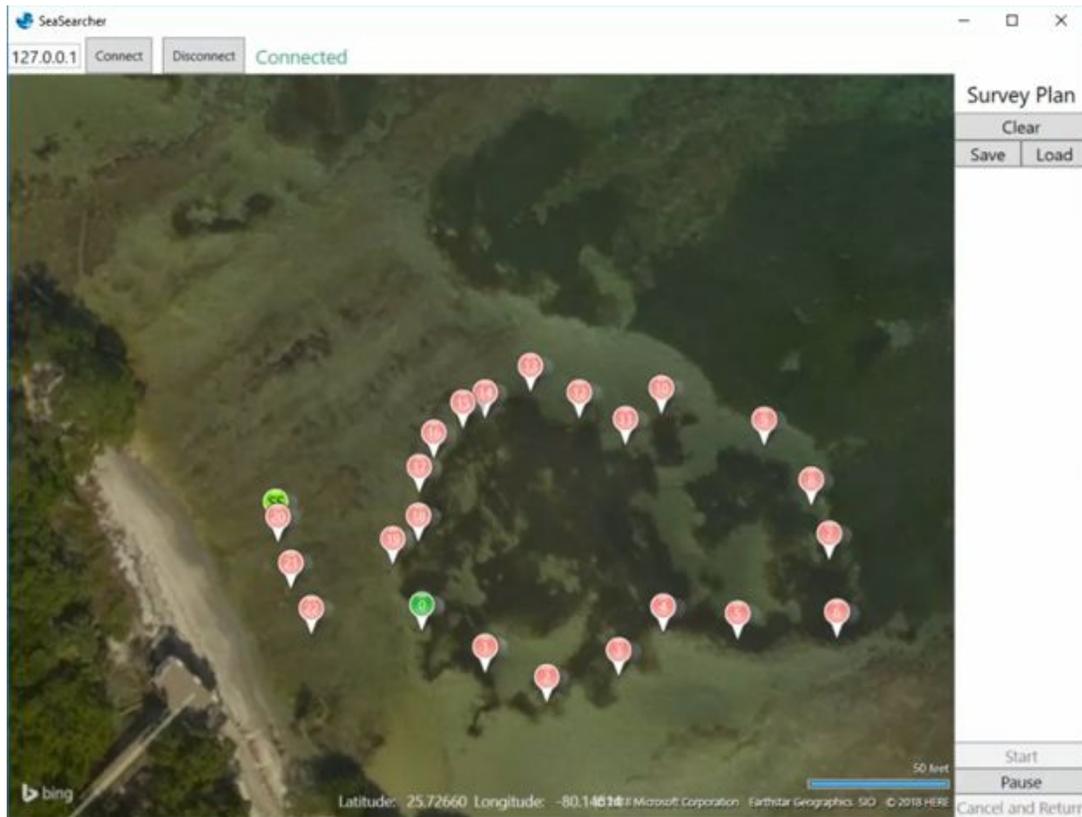
Figure 35 *SeaSearcher's user interface for mission planning*

The Android app made it easy to control the boat, but there was still no easy way to input waypoints for autonomous movement. This functionality could have been added to the mobile app, but it seemed like it would be easier to do this from the computer. This led us to create a mapping program. The Bing Maps WPF Control is used to provide the easy to use map controls. Most of the boat commands are sent through keyboard shortcuts and these make it simple to copy the latitude and longitude of a point to the clipboard, manually set the boat's next waypoint or plan future waypoints. These waypoints are numbered can then be saved to files and loaded later to make it easy to plan a survey in advance. It can send waypoint commands to the boat over the same UDP interface that the Android app uses. All the data from the boat is received through a separate Transmission Control Protocol (TCP) connection and this is data used to plot SeaSearcher's position. When the user is ready to start a survey, they can click the start button and the first two waypoints are sent to the boat and it starts following the path. Waypoints turn green once the boat starts moving towards them to make it easy for the user to determine where in the path the boat is. At any time, the user can stop the boat by clicking the pause button.

Dynamics and Control

In order to understand the system and test autonomous controllers, a mathematical model was needed. To do this, an equation of motion was derived for each of the 3 degrees of freedom of the system. The following figure shows a free body diagram for the forward, side, and yaw degrees of freedom, followed by the equations for each.
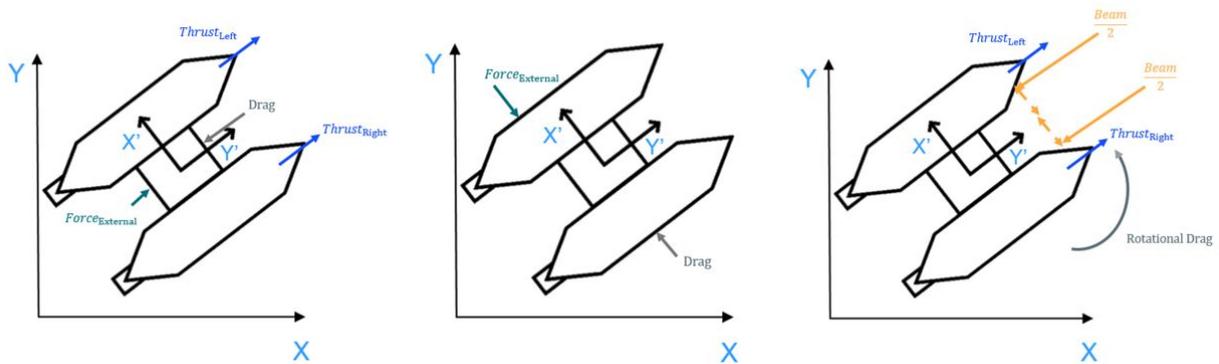

$$Sum_{Y\prime} = Thrust_{Left} + Thrust_{Right} + Drag + Force_{External}$$

$$Sum_{X\prime} = Drag + Force_{External}$$

$$Sum_{Yaw} = Thrust_{Left} * \frac{Beam}{2} + Thrust_{Right} * \frac{Beam}{2} + Rotational\ Drag$$

Figure 36 *Free body diagrams of SeaSearcher's forward, side, and yaw degrees of freedom respectively as well as their respective equations, shown in the same order*

A virtual testing environment was created utilizing MATLAB. The equations were used with a time step dynamic model to plot the system's position over time as a function of its past state and thruster values. The model also utilized both local and global coordinate system to make calculations easier. Before autonomous controllers were added, the model was given thruster curves and the resulting motion was tested against intuition. Once the model dynamics were confirmed, a simple four step controller was implemented. The first step was to determine the desired heading using the systems current position and the next waypoint. Next, a PID controller was used to find the needed turning rate and motor differential. With that critical number determined, the differential is applied to the motors and both speeds are brought down using another tunable parameter.
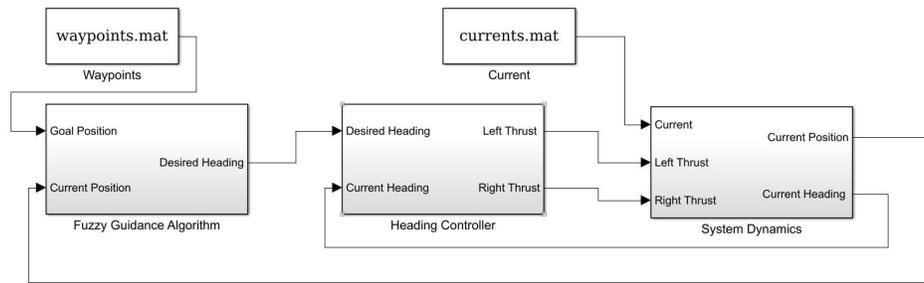
Figure 37 *Flow diagrams of SeaSearcher's control loops*

Tests on this and other controllers were done to tune the model, in hopes that due diligence here would lessen the amount of trial and error in field testing. Although the model worked well, there were certain aspects of the system were neglected. The first of these was the simplification of the system to be a 3 degree of freedom one. Pitch, roll, and the z axis were all considered fixed. Time delay was also not included the the MATLAB controller. The largest of these delays was a 200 millisecond update time from the GPS module. Although time delay is a significant factor in control systems, because of our system size scale and speed, SeaSearcher was able to perform similarly to the model without it.
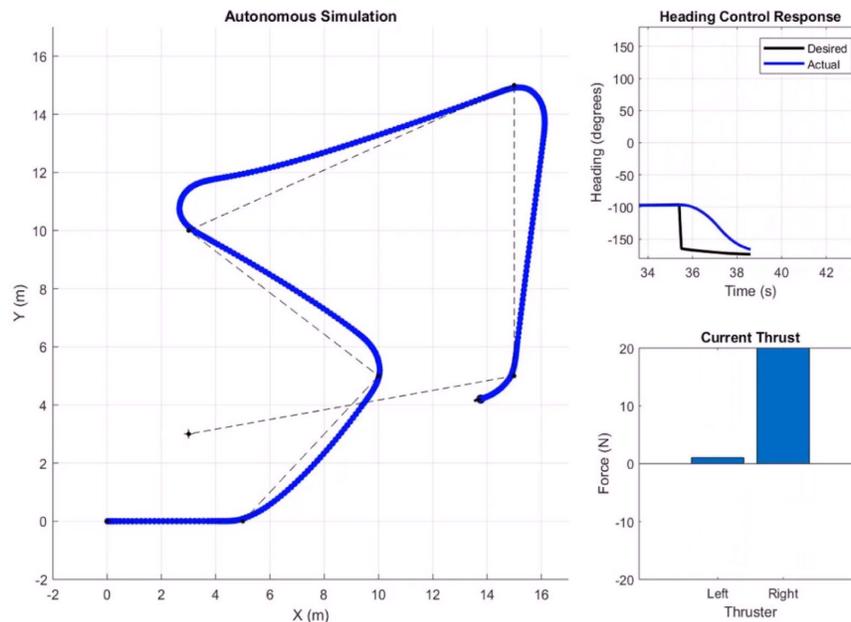
Figure 38 *MATLAB figure showing a simulated system following waypoints, the controller time response, and thruster values*

Validation and Testing

Electronics Testing

The electronics draw a maximum of around 20W in the worst case while charging both GoPros and the batteries have so much energy that everything could run for nearly 30 hours. The motors draw significantly more, but their power consumption varies a lot depending on the torque command, which makes it difficult to estimate the battery life. At maximum thrust, the batteries would die in around 2 hours, but the thrusters aren't rated to run at this power for any significant amount of time. At a more realistic 50% thrust, the batteries will last for nearly 7.5 hours. All the testing that was conducted focused on validating the various subsystems, but this meant there wasn't time to perform long runs and see how much energy would be used in a survey scenario. Unfortunately, there was a problem communicating with the current monitor chips, which made it impossible to measure the actual power consumption.

The P39 triducer measures depth, speed and temperature and with some work, we were able to log each of these values. The water temperature is measured precisely, but it does take a significant amount of time for the sensor to reach ambient temperature, with a time constant of approximately 3.5 minutes. We hoped the water speed measurement would be useful in measuring the amount of current in the water, by comparing it to the known speed from GPS however, the sensor was intended for much faster boats and the sensor was unable to measure any speed, even when the SeaSearcher was going at its fastest.

The depth sensor is the most important for this project, because it makes it possible to create bathymetric maps. It worked initially, but the data had a large offset on the order of over 16 million and was stored in a 32 bit floating point number. This data type lacked the precision to record the least significant digits of the number, but this was what contained all of the useful information. The result of this was that only 2 different values were recorded, because the water wasn't deep enough for the increase in depth to be enough to change digits that were actually recorded. This mistake was later corrected and the raw 32 bit data was recorded, instead of using a floating point datatype however, the sensor stopped sending any data in further tests for unknown reasons. This was bad enough, but it got even worse when the depth sensor started shorting the power supply. The boat had fuses on almost every part of the system, from the cells, to the navigation light and every regulator and buck converter. However, the one thing that didn't was the depth sensor and when it shorted, the PCB track acted as a fuse and heated up so much that it started burning the board within seconds.

Water Temperatures over Time
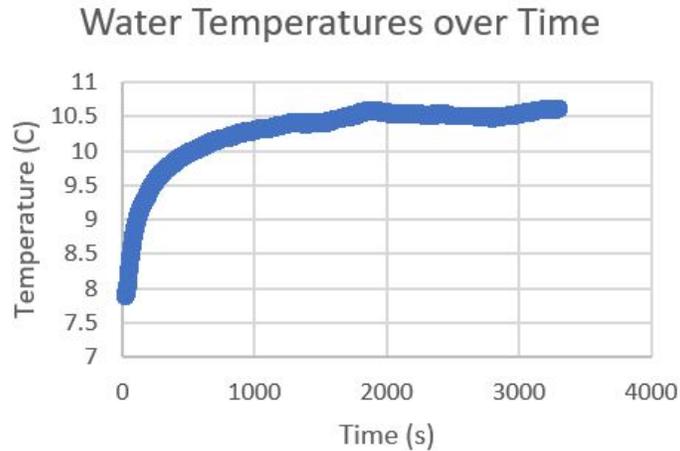
Figure 39 *Plot showing the time to ambient of the water temperature sensor*

In addition to measuring the water temperature, the SeaSearcher had a temperature sensor on the PCB. It was placed right next to one of the power supplies, which was expected to be one of the hottest points on the board. The temperature starts at the ambient temperature, but quickly rises to around 35C as everything else in the central compartment heats up. However, everything heats up significantly more with the boat outside of the water. A maximum temperature of nearly 60C was recorded, which is significantly higher than expected. Still, everything on the PCB is rated to either 85C or 125C, so this isn't that concerning.

PCB Temperatures over Time
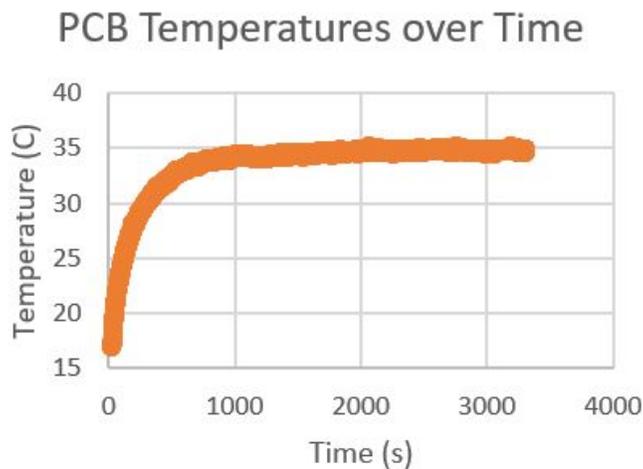
Figure 40 *Plot showing time to ambient for the temperature sensor on the center PCB*

Xbees are advertised as being easy to use and we didn't run into any problems with them on the fall prototype. However, we started encountering several issues for the final design. The connected serial pins on the microcontroller had a tendency to stop working, possibly due to Electrostatic Discharges (ESDs). This meant the microcontrollers had to be replaced multiple times and by the end of the project we had

soldered a total of 7 microcontrollers onto the main PCB. Additional TVS diodes were eventually soldered onto these pins and others to dissipate the energy if any further ESDs occurred. The boards were also conformal coated to make this less likely and this also made them more water resistant. The xbees also struggled to connect when they were too close together and broke entirely a couple times, possibly because the received signals had too much energy and this damaged the internal RF circuitry. On the final day of testing, the wrong polarity connector was used to connect the base station antenna, which led to connection issues until the module eventually failed. Unfortunately, this was already a backup after another had failed and this was the end of validation in Miami. The modules claim an outdoor range of 4 miles with no obstructions and dipole antennas, but we found the range to be significantly lower. The longest range achieved with the boat operating in the water was 180 feet before connection was lost, but this was with the transmit power below the maximum. Had it been at the maximum, we still estimate a range of approximately 570 feet, which is far less than the datasheet states. This could be because of the water affecting the radio signals, because we were able to regain connection by raising the antenna by a few feet, but we didn't test the range further to avoid risking losing the boat.

The navigation light is supposed to be visible up to 2 miles away, as required by maritime regulations, but this distance was never actually verified. However, nighttime testing was conducted and the light was bright enough to not only make the boat visible, but also light up the entire surrounding area. It was so bright that it even had the unintended effect of lighting up the bottom of a lake when the boat was in relatively shallow water.

Figure 41 *Night photos of the system with the navigation light and lake bed illuminated by the navigation light*

The IMU was useful for navigation and didn't need to be that accurate, because the data only needed to be integrated for 100ms before a new GPS data point would arrive. Nevertheless, it proved to be surprisingly accurate. After this three-minute period, the error is around 60 degrees and this could probably be reduced with further calibration. There is a significant amount of disagreement in the middle, but this is actually because

the GPS loses track of heading when the boat stops. The GPS thinks the boat is facing in the wrong direction and when it figures it out again, it thinks the boat turned around the other way. Ideally both sources of heading would be combined, but this didn't fit into the time constraints of the project.

While we never were able to finish getting RTK working, the normal GPS accuracy was quite good, based on both the horizontal accuracy it reports and by comparing the position to known coordinates from Google Maps. Even with the backup battery, it still takes the boat a few minutes to get a very accurate fix. Once it does, the accuracy is consistently under 1m, especially when the boat is in the water with few near obstructions to block the signal.
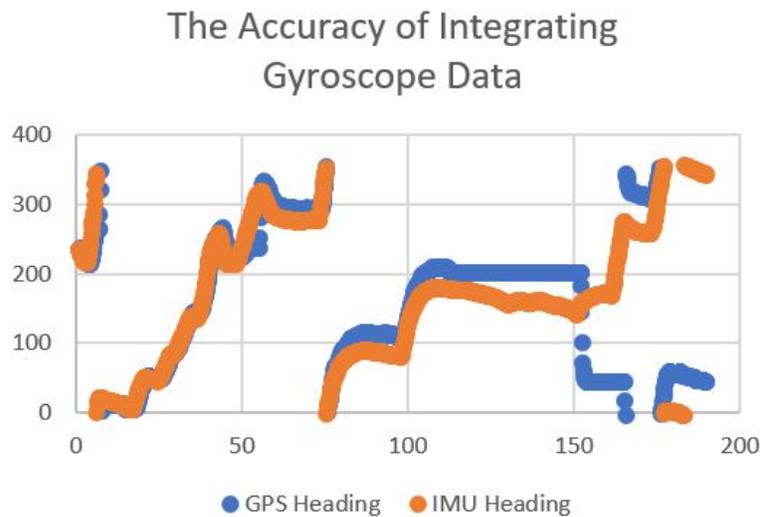
Figure 42 *Plot of GPS heading vs integrated IMU heading*
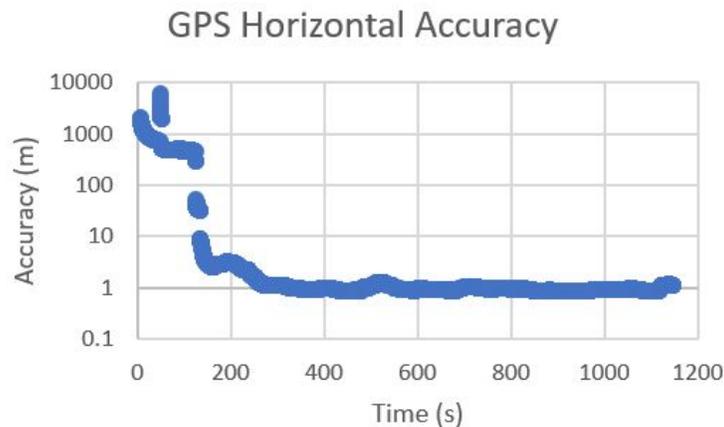
Figure 43 *Plot of GPS accuracy as measured by the level of noise in measurements*

Pool Test

Throughout the prototyping and validation process, systems were tested in the University of Pennsylvania swimming pool. Each time, the transportation process was a way of testing how portable and easily deployable the system was. Additionally, pool tests allowed field test of communications, remote control, and the functionality of certain sensors. In preparation for further field and autonomous tests, pool testing also gave insight into dynamics for tuning the MATLAB simulation and verify waterproofness.

Milestones reached during pool tests include waterproofing, remote control, speed vs motor input verification, camera quality tests, temperature measurement, and depth measurement.
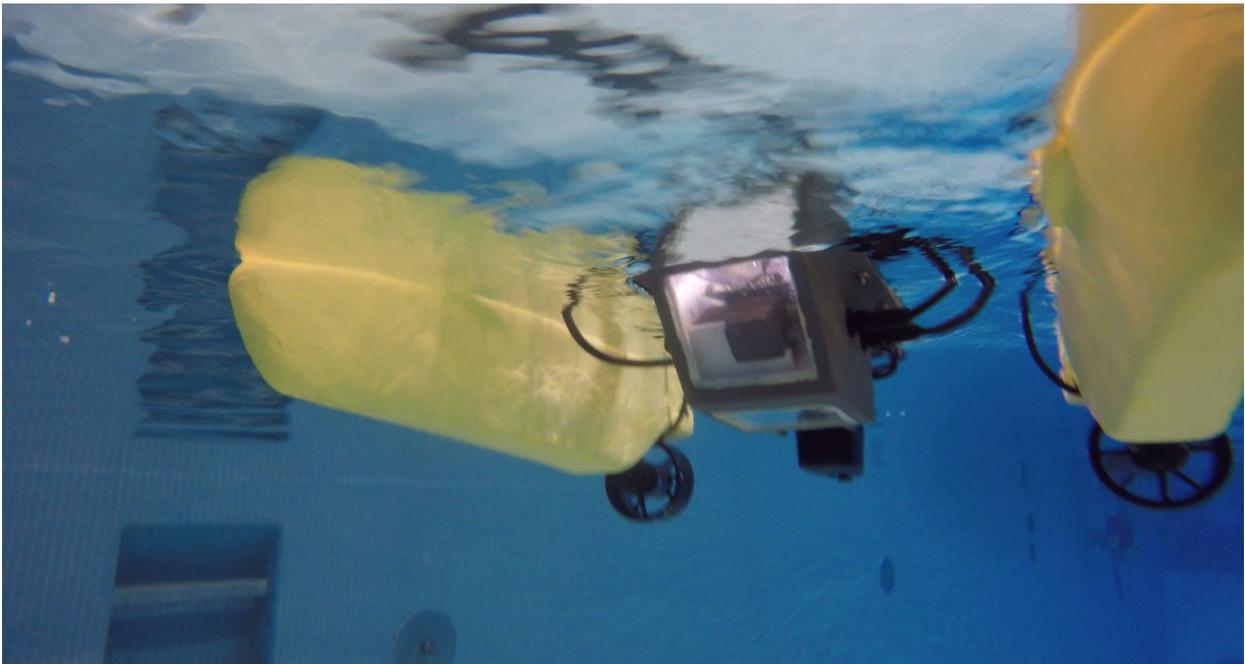
Figure 44 shows SeaSearcher in the pool during one of the tests

BioPond Test

Tests in the University of Pennsylvania BioPond were also performed due to its close proximity. These tests had similar goals to the pool tests, but with the added benefit of testing image quality in brackish water, outdoor communication strength, and small scale GPS tests.

It was at the BioPond where SeaSearcher gathered its first GPS data where a discernible path was plotted. Additionally, SeaSearcher was able to capture its first set of interesting photos and videos in brackish water.

Figure 45 *shows the testing of portability before a pond test*

Lake Audrey Test

After the biopond test, the SeaSeacher team wanted to test in a larger body of water to capture autonomous data, GPS data, stability, and further RC control. The team drove out to Lake Audrey, New Jersey for an all day field test. During the test, SeaSearcher successfully completed an autonomous field test in which it maneuvered to and around three waypoints.
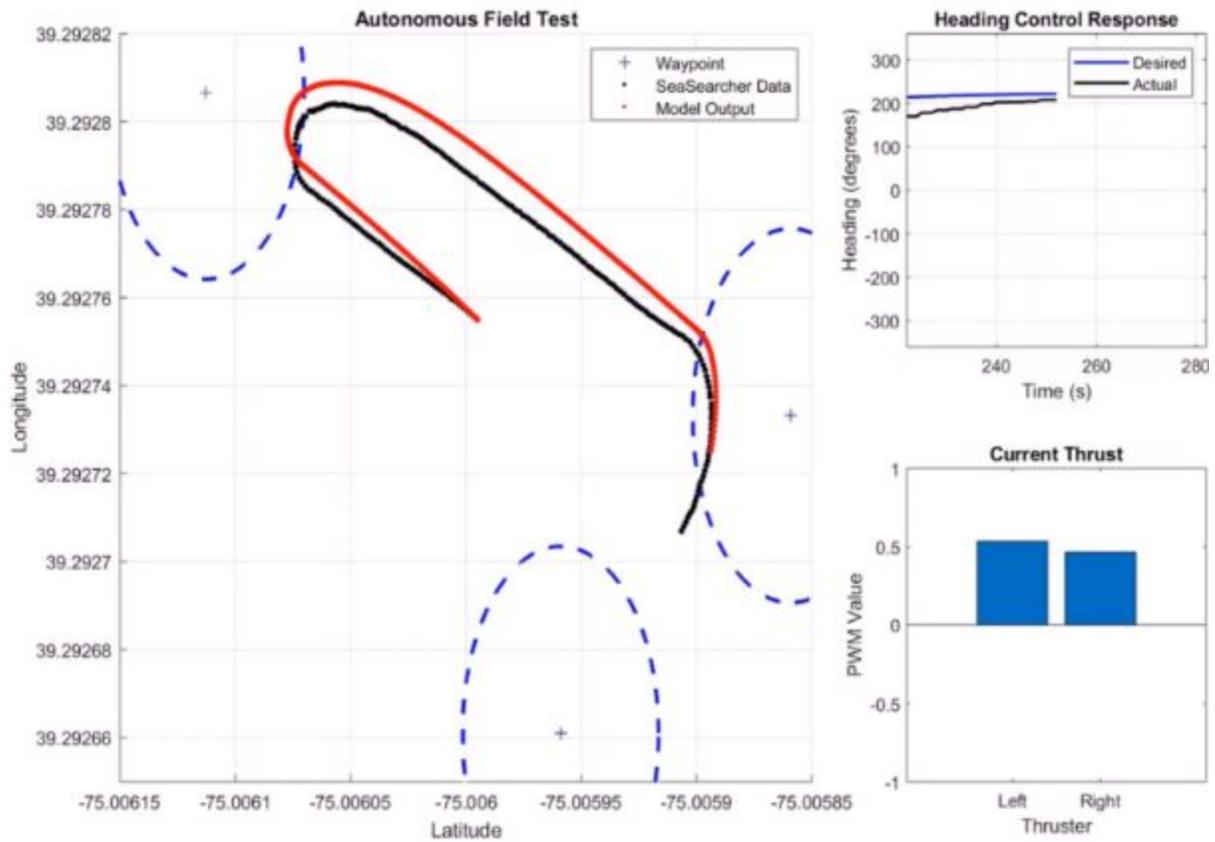
Figure 46 *Plot of one of SeaSearcher's autonomous tests. The black data is logged GPS data, the red data is the system model running alongside the real data. The time response and thruster values represent the real system*

Miami Test

SeaSearcher's trip to Miami was in efforts to validate portability, performance in the target environment, and to get feedback from our main stakeholder. The system was packed in a standard checked bag with foam to protect the system during handling. The battery cells had been removed from the battery circuit board and backed into a carry on bag. Once at the airport, the bag containing the system was successfully checked and loaded onto the plane. The carry on bag made it through TSA, after being checked by gate agents. Upon arriving in Miami, the system was unpacked and checked for damage and none was found. This proved the ability to travel via commercial airlines.

Next was deployment to our target environment. Although transportable with the rolling baggage, moving long distances on a sandy beach proved tiresome. This could be solved with a custom carrying bag that has more application specific wheels. Once in the water, the ship performed well. Its small size made the system oscillate in the waves, unlike large vessels that can "average" over the waves with their longer hulls. However, these oscillations did not affect camera quality very much. Something else that was noted was the appearance of a natural frequency during point turns, where the boat oscillated with increased frequency and amplitude. The environment was also full of seaweed, which would occasionally get sucked into our propellers.

Even in our first deployment of the system in our target environment, our main stakeholder was very pleased with the project. He noted the size of the boat didn't allow it to "average" over the wave, but understood the advantages of the size for portability. He also noted the usefulness of both remote control and waypoints while expressing his interest in using the system as a platform for future work.

Figure 47 *Picture from Miami with Dr. John Mcmanus*

Discussion and Recommendations

SeaSearcher reached a majority of its specified goals by the end of the project. The following figure reiterates the project goals and the results that will be discussed below.

Essential Characteristic	Description	Result
Data Collection	Depth, temperature, and velocity sensors, and HD images and video	Temperature, velocity, 4K video, 12 MP photos
Portability	Ability to easily travel with product	Successful trip on a commercial airline
Control	Remote Control and Waypoint Guidance	Remote Control and Waypoint Guidance
Cost	Less than $3000	$2200
Endurance	Battery life of 6 hours	Estimated Life of 7 hours

Figure 48 *Breakdown of project goals and achieved metrics*

At different points in the validation process, every sensor was able to collect data. This was an important step in the process but unfortunately all sensors were never able to operate in tandem. This was not due to any system limitation, but rather hardware failures throughout the process.

Depth data was to be gathered via two mechanisms. In shallow water, the two on board laser would be used to determine depth. In deeper water, where lasers could no longer be seen, the P39 triducer would measure depth. While the laser systems worked, the P39 suffered a hardware failure before a sufficiently deep field test was conducted. For this reason, depth is not listed as a success and is an area for improvement. Temperature and water speed were successfully collected by the P39 sensor. Additionally, system velocity data given by the GPS proved useful and steady. The GoPros selected worked remarkably well, producing high quality video footage and photos of the same quality as the current camera used by our stakeholder. Wireless control of the camera's shutter and setting was also successful.

SeaSearcher's portability was validated by a successful trip to Florida for testing. The team was able to travel with SeaSearcher's batteries in carry on bags and were able to check the bag containing the SeaSearcher. Upon arrival the system was unharmed and

tested successfully. For mission flexibility and reliability, both remote control and autonomous waypoint following were tested and validated. Throughout validation, battery life was never an issue and by extrapolating battery drainage, an estimated endurance of 7 hours was calculated. Our estimated cost of materials also came in at $2200, below our goal. Most of that cost is in electronics and sensors, with $1400 of the total. The remaining $800 was spent on materials like fiberglass, urethane foam, and aluminum tubing, and also account for estimated labor and 3D printing. These numbers assume manufacturing 100 of the systems and does not include development costs nor margins.

Many improvements have been considered for future iterations of this product. More work on electronics and sensors would bring SeaSearcher to its intended operational capacities. Once all the sensors are operational and integrated, SeaSearcher could theoretically meet all the needs of our stakeholders.

There is some future mechanical design that can go into the craft. The pontoon lid design can be redesigned to incorporate changes made during the manufacturing process to make it IP67 rated. This would also decrease the current height and weight the pontoons. The connection between the aluminum bridge and pontoons can also be redone to increase its reliability. Permanently fixing them into the molded foam would not only make the connection stronger, but also give a better method of ensuring the proper fit for the telescoping assembly. The central enclosure could also be change dramatically to improve ease of use. With the current design, the PCB must be removed to access the cameras and lasers. The insertion of the PCB is also not a user friendly process. In a future iteration, the enclosure could contain a removable rack, which could hold each component of the enclosure in a more accessible way. Camera gimbals could also be added to further stabilize video data.

A more dramatic redesign would change the platform completely, based on ideas received from one of our technical advisors. The new design would feature a central assembly containing the entire system. This assembly would be completely submersible and be connected to two buoys via actuated arms. The actuation would allow the assembly to be lowered, which would increase stability, but also raised in the case of possibly collisions. Furthermore, a deployable camera unit was considered to photograph deeper areas.

An additional change that could be made would be to omit sensors from the product package and move processing into one of the pontoons. This change would leave the entire bridge free for researchers to attach their own data collection devices. This would also reduce costs greatly and could benefit researchers who already have data collection methods but no way of automating the collection.

Budget, Donations and Resources

The SeaSearcher team began this project with a budget of $2400 dollars and received additional infusions of $300 and $900 to continue work. The project was also awarded an additional $750 form the Berkman Fund. Below is a breakdown of expenses.

Component Type	Cost
Motors	$302
Depth Sensor	$283
GPS	$425.25
Polyurethane Foam	$89.50
Batteries	246.21
Aluminum	$51.61
Fiberglass + Epoxy + Gelcoat	$283.58
Waterproofing Components and Fasteners	$55.73
Misc Electronics	$1863

Figure 49 *Breakdown of expenses by category*

The money from the Berkman fund was spent on testing reimbursement, and other miscellaneous electronics that were necessary.

FINANCIAL ANALYSIS
MEAM Design Team 7 - SD7

"Eric Quesada, Jay Fleischer, Xavier Perraudin, Nikhil Chari, Alex Andalia, Thomas Macchio"

July 1, 2017 - June 30, 2018
130-1306-1-000000-5228-6510-7248

Revenues:

	Depatment fund		2,400.00
18-Dec	Transfer from team 13 per Graham		300.00
2-Mar	Transfer from team 13 per Graham		900.00

Total Funds Available for FY2017: 3,600.00

		Log #		
Expenditures - 07/01/2017 - 04/04/2018:				
27-Nov	Blue Robotics	205941	302.00	
27-Nov	gemeco	206046	12.95	
27-Nov	Digikey	205921	138.52	
19-Jan	Gemeco	207680	283.00	
26-Jan	eBay	208105	559.90	
29-Jan	Ublox - canceled	208101	0.00	
10-Feb	Ublox	209026	425.25	
21-Feb	Jamestownesidt	209628	248.42	
21-Feb	USComposites	209720	89.50	
21-Feb	Digikey	209600	470.57	
21-Feb	Mouser	209602	34.31	
26-Feb	PC - Shoer	211163	41.98	
6-Mar	Digikey	210194	485.61	
8-Mar	Liion Wholesale	210222	246.21	
8-Mar	alcobra	210246	51.16	
8-Mar	AMAZON	210442	14.88	
8-Mar	Mouser	210691	25.36	
14-Mar	Jamestownesidt	210526	35.17	
15-Mar	McMaster	210601	55.73	
26-Feb	PC - Shoer - Transfer to team 5	211163	-41.98	

3,478.54

Total Expenditures

Commitments:

18-Jan	Digikey	207705	0.00	???? Canceled b
28-Mar	DIGI KEY	211307	218.17	
4-Apr	DIGI KEY transfer to Berkman	211307	-218.17	

Total Commitments 0.00

Total Expended and Committed 3,478.54

Uncommitted Balance: 121.46

MR

Figure 50 *Total Purchasing*

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Appendix

Appendix A: Down Selection Tables

A-1 Price Comparisons of different solutions

All Solutions	Cost of Operation	Range	Portability	Labor for Researcher
Hiring Divers (not including boat and equipment)	23/hr/diver	1 mile	n/a	Low
Chartering Boating expedition (DIY)	200/hr	100+ miles	n/a	Medium
Renting/Training Dolphin	High...	20 miles	n/a	Low
Castable Scanner: Deeper Smart Portable Fish Finder	Negligible	130 ft	High	Low
Buy a kayak	$200 + wages	10 miles	Medium	High
Best Autonomous Solution	Negligible	100miles on 1 charge	High	Low

A-2 Comparison of different Hull models

Autonomous Solutions	Cost($)	Efficiency (10 kg m/kJ)	Stability (ability to survive waves)	Power Type Compatibility: Assign values from 0 (not at all compatible) to 5 (very compatible)		
Notes:	Powertrain Cost Estimate for a 10kg craft		Qualitative Ranking from 5 (High) to 0 (Low), High being desirable	Gasoline	Solar	Battery
Sea Plane	450	25	1	3	1	5
AirBoat	250		1	5	3	5
Powered Catamaran	350	55	5	5	3	5
Powered mono-hull	200	55	4	5	3	5
Sail Powered Hull	100	330	4	0	3	5
HoverCraft	250		1	1	2	5
Powered HydroFoil	450	25.2	3	5	3	5

A-3 Basic Power Source Comparison for the autonomous solution

	Estimated Weight	Energy	Efficiency	
Batteries	2kg	400WHr	0.8	320WHr
Gas	1kg	13kWHr	0.1	1300WHr
Solar Panels	2kg	400WHr/day	0.8	320WHr/day