Autonomous Underwater Robots

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Executive Summary

The main purpose of this project is to design and fabricate a swarm of underwater autonomous robots that generates a collage of images that represents the bottom of the underwater environment. The success of the swarm will be determined by six different metrics, and by creating an image of underwater terrain from smaller images taken from the individual robots. Research was focused on prior work and on low cost alternatives to the many different subsystems that a robotics swarm requires. The majority of the prior work that has been researched is similar to the team's project.

The motivation for this project originates from the large size of the oceans that cover the planet. Many areas of underwater terrain across the globe are unmapped. These unmapped regions of the planet may hold vital information for various scientific communities. Aquatic industries could potentially benefit from the images generated by this project as well. Obtaining the images that hold this vital information is where this project comes into play.

The physical design of the robots involves a prefabricated radio controlled (RC) submarine platform that will be modified to include the additional subsystems. The additional subsystems required for each submarine is listed as follows: the detection array, the power system, the motor control system, the directional navigation system, and the camera system. This prefabricated RC platform must offer a compact size, static diving capability, and low cost. Underwater submarines are not popular RC toys, which lead to difficulties in finding an RC submarine that met our criteria. A submarine that meets all of our criteria is the Motorworks Seawolf.

The individual swarm members will follow a minimalistic flocking algorithm in order to function as a group. The swarm members will follow cohesion, separation, and pseudo-alignment criteria in order to complete the swarming task successfully. Swarm members will use directional guidance acquired from multiple sensors to navigate the body of water desired to be mapped. Specialized detection methods and distance measuring will be generated by using blue light emitting diodes (LEDs) and blue filtered photodiodes. The team's contingency plan involves an array of alternative solutions that will solve any potential problems with our proposed design.

The team is proposing to make a swarm composed of four submarines. This number will allow the team to test the functionality of the swarming algorithm while minimizing the budget. The total projected cost is $838.16, which includes all materials to build and test the swarm. This total cost may be reduced if cheaper sensor alternatives, that the team is looking into, will work for this project. The performance abilities of the swarm will be tested in the Markin Center pool. The Markin Center pool offers a sufficiently sized body of water that will be appropriate for this project.

The engineering skills the team has acquired over the past few years and the research the team has conducted over the past few months has given us the technical expertise to accomplish all the goals of this project. The demand and usefulness of this project is apparent, and the only thing we still need to make it happen is your financial support.

Abstract

The goal of this project is to build a swarm of autonomous robots to map underwater terrain. Research was conducted by the Autonomous Underwater Robots team to determine the best means in which to approach this problem. Specialized detection methods and distance measuring will be generated by using blue LEDs and blue filtered photodiodes. The physical design of the robots involves an RC submarine platform that will be modified to include additional subsystems. The additional subsystems required for each submarine are the detection array, the power system, the motor control system, the directional navigation system, and the camera system. Individual swarm members will be designed to swarm using minimalistic swarming techniques. They will follow cohesion, alignment, and separation criteria in order to complete the task successfully. The swarm will be evaluated periodically to determine if using alternative solutions is necessary. Image stitching software will be used to compile an image from the smaller images taken by each of the swarm members. The swarm members will also be designed to meet specific cost criterion. Our proposed project can be accomplished with less than $1000. The autonomous submarines will also be designed with societal and environmental impacts taken into consideration.

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I. Introduction

Over the years, people have looked in awe at the large size of the oceans that cover our planet. Our planet's oceans cover more than 70% of the surface; however, only 5% of this has been seen by human eyes [1]. This portion of the planet holds vital information for various scientific communities. Biologists can gain information about the fauna and flora that survive in these conditions [2]. This information includes the patterns of animal migration through the oceans and even the health of the coral that occupy the reefs. Geologists can understand the tectonics of the planet, through the movement of the plates that make up the underwater terrain [2]. Obtaining images that hold this vital information is where this project comes into play.

This project can be summarized by developing a swarm of autonomous underwater vehicles (AUVs) to map underwater terrain. Since 1957, AUVs have been exploring bodies of water without human interaction. AUVs have since become a much more useful and feasible idea. AUVs operate for 8 to 10 times less cost and operate for longer periods when compared to ship-based surveys [3]. Many of the AUVs available commercially today have been designed for ocean use. The AUVs are typically equipped with powerful sonar sensors that allow them to detect objects at depths of 9000 meters [4]. The cost of these AUVs can vary greatly depending on the imaging ability and pressure rating. Purchasing commercial AUVs to complete this project is not possible due to the financial constraints. The team's only option is to design and build its own AUVs.

a. Project Description

The main purpose of this project is to make a swarm of autonomous underwater robots. Another goal is to design the swarm so that others can later build upon it. The team will be building a swarm of robots in the form of small submarines that will map a confined underwater area (i.e. the Markin Center pool). Each robot will navigate independently, taking images of the terrain. The swarm of robots will be versatile enough to operate in various controlled bodies of water, like a pool. The autonomous robots will navigate the environment, avoiding structures and life forms. Inter-robot detection will allow the robots to avoid collisions and minimize redundancies in the images taken. After the mapping is complete, a final image of the terrain will be generated.

b. Problem Definition

Through discussion with the project advisor, objectives, functions, and constraints were created. The goals of this project are summarized by six primary objectives and four primary functions. The objectives include cost minimization, autonomous motion, durability, underwater mobility, portability, and power efficiency. The functions include taking images of underwater terrain, restructure the swarm, detect others in the swarm, and generate a final image. Many of these objectives were set in accordance to guidelines set by Bohm and Jenson [5], which was used to understand the aspects for creating an underwater robot. The design of the overall system (the complete swarm of autonomous submarines) and the subsystems that are required for each submarine have constraints and functional requirements, as shown Table I. Specifications for the system/subsystems are shown in Table II.

TABLE I
CONSTRAINTS AND FUNCTIONAL REQUIREMENTS FOR THE OVERALL SYSTEM AND SUBSYSTEMS

System/Subsystems	Constraints		Functional Requirements		
Overall system	The submarines must be functional in up to 50 cm in depth		Software shall create an image that is collected from the individual submarine images.	The swarm shall reconfigure itself to the original formation if a robot is lost.	The swarm shall maneuver through a body of water.
Detection array	The submarines must detect other submarines	The custom circuit board shall be no larger than 58.06 square centimeters	Each submarine shall detect other submarines		
Power system	Battery capacity: 4.8V, 2500mAh		The submarines shall have a battery life of at least 15 minutes		
Motor control system	Atmel microcontroller family		Each submarine shall surface upon its battery level dropping below 5%		
Directional navigation system	Atmel microcontroller family		Each submarine shall be able to navigate independently		
Camera system	The submarines must capture images of underwater terrain		The swarm shall take images of underwater terrain		

TABLE II
SPECIFICATIONS FOR THE OVERALL SYSTEM AND SUBSYSTEMS

System/Subsystems	Specifications		
Overall system	The final image shall have at most 10% gaps in the mapped area	The submarines must be functional in up to 60 cm in depth	
Detection array	The submarines shall have a maximum detection range of at least 1.22 meters		
Power system	The submarines shall have a battery life of at least 25 minutes		
Motor control system	Each submarine shall surface upon its battery level dropping below 10%	The submarines shall remain at the same depth ± 10 cm	Each submarine shall be able to maintain a constant speed ± 5%
Directional navigation system	Each submarine shall navigate independently for a minimum of 1 minute upon separation		
Camera system	The swarm shall capture photographic images of the underwater terrain using a resolution no smaller than 640x480		

c. Research

The research shown below goes over various items that are needed to complete this project. The items that are needed for this project include detecting other submarines, AUV research, and some details on swarming techniques.

i. Blue Light Emitting Diodes

The team looked at various different methods for the robots to detect the other members of the swarm. The team started by looking at infrared (IR) light emitting diodes (LEDs), however, the team found that the distance that IR can travel in water is very low. Figure 1 shows the attenuation of light with various wavelengths in water. As seen in the figure, the attenuation coefficient of IR, 700 nm, is quite high in comparison to a blue color, which is near 450-500 nm. A blue color has a low attenuation coefficient, which means blue can penetrate the water best when compared to other colors. Thus, blue LEDs are a preferred option for transmitting information to other submarines in the swarm.

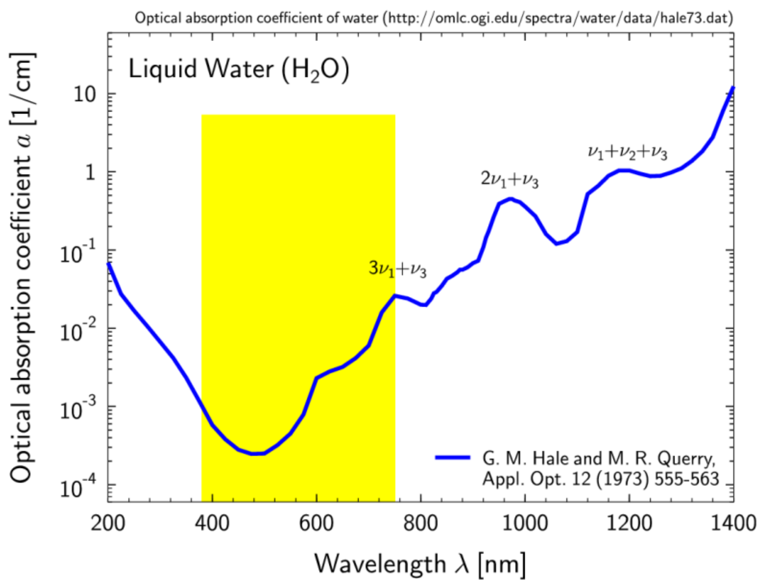

Fig. 1. The total optical absorption coefficient of water [6]. Visible spectrum is highlighted in yellow

The submarines will also need to be able to detect the transmitted pulses of light. The team found three different types of receiving devices: photoresistors, phototransistors, and photodiodes. From this list, the team found that photodiodes would be the most viable option because they have a unity gain and a linear output. The other choices had a small or large gains and many portions of nonlinearity [7]. The other choices are usable, however, linearity over a larger region will make detecting other swarm members easier.

ii. AUVs

Swarming is defined by the collective behavior of individuals that allows them to move as a group. Some research on AUV swarming [8] discussed using a swarm to map an underwater minefield. The ideal swarm size to map an underwater minefield as well as a simulation is discussed. This research and many others like it focuses on swarm simulations rather than swarm implementation. There is a large amount of research about an AUV swarming project in Europe called Cocoro, which stands for collective cognitive robots [9]. The Cocoro project encompasses five universities and has substantial funding. The project has successfully implemented an organized swarm of AUVs. The goal of Cocoro is to use the swarm for

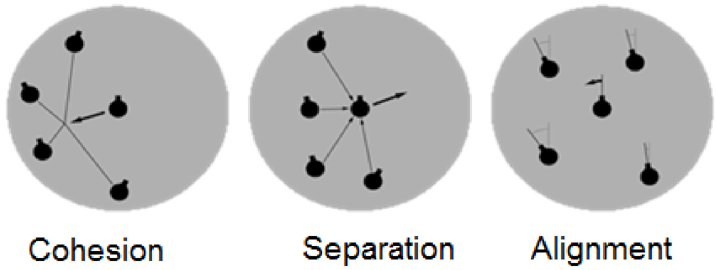

Fig. 2. The criteria used for Boids [10]. The three criteria that the Boids flocking algorithm requires are depicted.

"ecological monitoring, searching, maintaining, exploring, and harvesting resources in underwater habitats" [9]. Cocoro is similar to the team's proposed project in that they both use small, inexpensive submarines with minimal inter-robot communication. Cocoro uses the same blue LED detection method that the team's project is proposing. From the videos, it appears that the Cocoro team uses the blue LEDs and photodiodes to create a dense swarm in comparison to our proposed swarm. We are planning to use blue LEDs to detect others in our swarm at a further distance. The success of and the interest in Cocoro project proves the feasibility and worth of our proposed project.

iii. Swarming Techniques

Flocking is the cohesive and aligned motion of a group of individuals along a common direction [11]. Boids is the most common flocking algorithm and it simulates the flocking of birds in nature [12]. Boids functions by having all the robots in the swarm behave the same and follow three criteria: cohesion, separation, and alignment [12]. Cohesion is steering toward the average position of local flock members [12]. Separation is steering to avoid crowding local flock members [12]. Alignment is steering towards the average heading of local flock members [12]. A visual depiction of these behaviors is shown in Fig. 2. The interaction between the simple behaviors of the individuals produces complex and organized group behavior; because the component behaviors are nonlinear, implementing the behaviors all at once produces a lifelike behavior [12].

Another swarming technique the team researched is a minimalistic swarming technique based upon Boids. This method requires cohesion, separation, and pseudo-alignment. Pseudo-alignment means the flock members will only require approximate alignment knowledge. The minimalistic swarming technique removes the need for a steady communication channel between the submarines. A pair of receivers on each side of the submarines could gather the pseudo-alignment information. Figure 3 depicts the different zones around a single submarine. A paper on minimalistic swarming techniques inspired the creation of this zone layout [13]. The blue zone at the front of the submarine is a strictly active sensing region. The photodiode circuit at the front will only acquire a reading when the blue LED located at the front is emitting. This circuit will allow the robots to detect obstacles in its current path. The green regions surrounding the submarine will be strictly for passive sensing. The ideal location for an adjacent submarine would be in the aligned region, but all of the green regions are acceptable. If an adjacent submarine were to enter the red zone, the submarine depicted in Fig. 3 would follow the separation behavior in order to prevent crowding. If an adjacent submarine entered the yellow zone, the submarine would follow the cohesion behavior to stick together. The pseudo-alignment behavior would occur continuously to allow the submarines to maintain the same general heading.

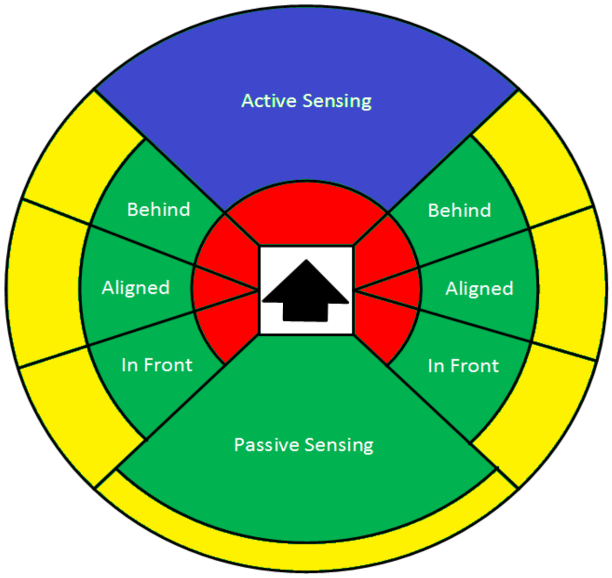

Fig. 3. The minimalistic flocking zone layout. The spatial organization around each submarine in the flock is depicted by the colored zones.

II. Design Approach

The main design idea is to use a standalone swarm. With the standalone swarm, there is no leader for the swarm and each submarine has the same characteristics: the same code, the same sensors, and the same physical structure. The only difference between each submarine would be the individual subsystem tuning (e.g. motor control system, and photodiode system).

The main algorithm that is planned to be used is the minimalist swarm technique. Flocking is the swarming technique that will be implemented. The team needs to use the minimalistic approach to get the results that we want, while keeping a smaller budget. Due to the budget constraints that we have, the team cannot use expensive sensors that would help in making high precision and accurate maps. The budget limitations determine the sensors and software that will be used.

In addition, the swarm will use directional guidance in order to gather the necessary information in the minimalistic swarm technique, due to the requirement that each submarine needs to know a relative direction. The exact size of the green, yellow, and red zones in Fig. 3 will be determined during the testing and tuning stage of this project. The zone sizes will be selected while considering the required image overlap, the submarines' maneuverability, and the transmission distance of the blue LEDs.

There are many disciplines that will be covered within this project. From electrical engineering, topics include controls, software development, circuit design, power systems, and electromagnetics. In addition, mechanical engineering topics include pressure containment, buoyancy control, and possibly fluid dynamics. The team will be able to handle the electrical engineering topics by using existing knowledge. However, the tasks that cover the mechanical engineering topics will require more testing and learning in order to complete these tasks to the fullest.

The plan for testing this swarm is to start in the robotics lab in the electrical engineering department at Bradley. In the lab, the team will use a polyvinyl chloride (PVC) pipe bench top setup to test the various positions and movements that the swarm will have to deal with. Due to the lack of water in the labs, an off-site location will be used to do initial tests. The final test location will be the pool at the Markin Center.

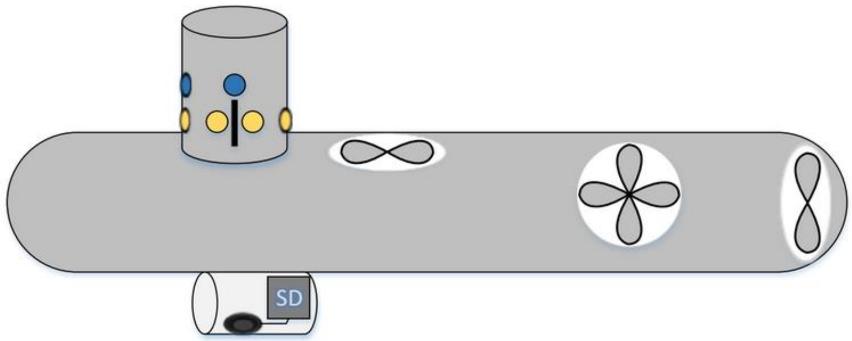

Fig. 4. The rendering of the proposed submarine for the project. The necessary modifications to a Motorworks Seawolf are shown.

a. Individual Submarines

The platform choice for the individual submarine is the Motorworks Seawolf. This specific submarine is a static diving submarine, which satisfies our mobile underwater criterion, shown in Table III. This submarine also has literature that the team has found, during research, that suggests that the submarine can be made autonomous.

For the detection array the team will design and build photodiode transimpedance amplification circuits that will convert the current generated by the photodiode to an amplified 0 to 5 volts output.

The submarine power system will be redesigned for our application. The power system in the submarine is 0 to 6 volts. The photodiode circuits and pressure sensor that we have chosen require more voltage than the submarine currently provides. Specifically, the pressure sensor, which requires 12 volts for operation. The submarines power system is attached to a radio controller. The radio controller takes up more space in the submarine than we have allocated, meaning that the radio controller has to be removed. This newly allocated space will be used to house a microcontroller.

This submarine design has a camera system attached to the bottom of the submarine to capture photographic images of the terrain. The submarines are required to take pictures of the bottom of a body of water. The camera system will be a separate system. This system will be designed to be completely self-contained, this will help keep microcontroller costs lower by minimizing resources required. The self-contained unit will also help with individual submarine testing as well as stitching software testing. We would use various objects to determine if the image stitching worked in conditions where it is difficult to determine terrain changes. In addition, there will be a ring of LEDs around the camera to increase the quality of the images taken [14], adding LEDs will increase the lighting in the pictures, this will increase the lighting similarly to a flash on a camera.

In Fig. 4, the sail of the submarine houses the detection array. The blue dots signify blue LEDs that are used to transmit position information. The yellow dots are photodiodes; the photodiodes are used to detect the blue light emitted by the LEDs attached to each submarine. For the front of the submarine, the team will create an active sensing region. The blue LED located in the front of the sail of the submarine will pulse and a photodiode, located on the same submarine, will be used to receive the light. Using that principle, the team will be making a basic obstacle avoidance region. The right and left side of the submarine will have two photodiodes separated by a baffle that protrude beyond the front of the photodiodes to an appropriate distance that will be decided through experimentation . This set of photodiodes will be used to determine which quadrant of Fig. 3 contains other submarines. The rear of the submarine has a photodiode that is used to determine if there are any followers.

The submarine will be using an inertial measurement unit (IMU); the IMU will be used as a backup for collision detection if the collision avoidance sensors do not see an object. Along with the IMU, the sub will be using a compass for directional guidance. The directional guidance will be used to form a general path for each member of the swarm. The submarines will maintain a constant depth by using a proportional-integral-derivative (PID) control loop, a pressure sensor, and a vertical motor. With these components, the team can theoretically maintain a constant depth. By keeping all of the submarines at the same depth, the team can simplify the three-dimensional swarming problem to a two-dimensional swarming problem.

b. Alternative Solutions

A boat could be added to guide the swarm if the directional guidance method is not accurate enough. The boat could travel to global positioning system (GPS) waypoints while emitting a light at a constant frequency. The submarines would seek this frequency of light in order to follow the boat. If surfacing the submarines with the vertical motor alone is not good enough (i.e. does not remain surfaced long enough to retrieve), we could add a drop weight system to each of the submarines. The system would release a weight upon the submarines battery dropping below a certain level. In the event that the swarm is tested in a body of water with shallow spots, a bottom detection system could be added to each of the submarines to allow them to detect shallow areas and avoid beaching themselves. The bottom detection system could be done with an additional LED and photodiode of the same wavelength. As shown in Fig. 4, the team plans to house the photodiode and LED array in a single watertight container on top of the submarines. If having the photodiodes this close together presents a problem, then the team could add smaller watertight containers around the sides of the submarines to spread out the array. In the event that the Motorworks Seawolf submarine does not end up working for this project (i.e. not maneuverable enough), the team can make custom-built submarines. Part of the research the team has conducted was on building these custom-built submarines and the team found multiple resources that explain how to build them. The structure of these would be mostly PVC and it would allow for more internal space and customization of the placement of the motors. Custom building submarines is not ideal as it adds significant labor time to the project.

c. Testing and Metrics

For the design process, a metric is a measure of an objective. The metrics in Table III will be used to determine the degree at which the primary objectives are met. The objectives will be ranked on a scale of 0-10, with 10 being the best possible score. These scores will provide an idea on which design will be best to use in this project.

The objectives listed in Table I are defined further with the use of metrics. The first metric listed is minimize cost. This metric has scoring based on an ideal unit cost of $300 and for every increase in the cost of the individual subs the scoring decreases. The third objective listed is durable. The metric for this objective is determined by number of failure points on the structure of the vehicle. This allows for nine or less failure points before the structure is deemed incompatible for the project. The power efficient objective will be measured based on how much area each robot can map per unit of power. The ideal value for this governing equation, K, is unknown as the Autonomous Underwater Robots team does not currently have sufficient information to calculate the value. The value of K will be calculated as the project progresses. Other metrics involve subjective evaluation, which will be determined at a later date.

III. Schedule

For this project, we have split the main task into multiple subtasks. First is designing the software structure, where we are researching and testing the appropriate sensors for this project. Next is designing a

TABLE III
OBJECTIVES AND METRICS FOR TESTING

Objective	Metric
Minimize Cost	Determined by the production cost of one member of the swarm. Scoring: Total Points = 10 - (cost - $300)/100
Autonomous	The amount of human interaction needed for the swarm to function. Scoring: Total Points = 0-10 by Subjective Evaluation
Durable	The amount of places that fail per swarm member. Scoring: Total Points = 10 - # of failure points
Mobile Underwater	The turn radius of each swarm member. Scoring: Total Points = 0 - 10 by Subjective Evaluation
Portability	The perceived size and weight of each swarm member. Scoring: Total Points = 0 - 10 by Subjective Evaluation
Power Efficient	The amount of power required for each swarm member. Scoring: Total Points = 10 - (Watts/Sq.foot - K*)/5 *This value is to be determined.

single submarine, which is the designing of the placement, organization, and design of the sensors, circuits, and pressure containers. After the software structure has been designed, the sensor algorithms will be created and integrated during the directional guidance phase. At this point, all of the parts will be ordered and the group will have done some testing with them. This goes along with the building and testing of the single submarine. In this stage, we will be testing a single submarine and its sensors with our algorithms.

The largest portion of work is in the building and testing of the swarm. The team is predicting that the design of the swarm will take up the entirety of the second semester, due to significant design work and testing that is required for the swarm to be operational. The design of the swarm is also scheduled in the second semester, due to the prerequisite parts needed for the swarm. Some of the parts have a couple week lead time to be received from China, so ordering these parts before the break will give us plenty of time to work with them. The last subtask is the various project deliverables that are needed for the senior project. For more details of the schedule, please see Appendix A. The critical path can been seen in red along with the project deadlines.

IV. Distribution of Tasks

For this project, the team has distributed the tasks into nine categories, with each of the members responsible for a different portion of the project. Cameron will be primarily responsible for the circuitry and the submarine construction. This includes the detection array, the camera circuit, construction of submarine, and printed circuit board (PCB) design. Nicholas is responsible for the program structure. Ryan is responsible for the controls aspect of the project. Due to the amount of sensors and algorithms that are in this project, this portion will be split between Ryan and Nicholas. Lastly, the most complex portion of this project, the swarm algorithm, will be split between all three team members. For more information about the detailed distribution of tasks, please refer to Appendix B.

V. Budget

There are various expenses that need to be covered for this project. For each submarine in the swarm, the team is estimating the expense to be $190.00. This includes the various sensors and parts needed for a single submarine to navigate the water and detect other members of the swarm. For the entire swarm, the team is estimating that four submarines will be effective enough to show the swarm's capabilities. Giving the total cost of the swarm to be $760.00. Moreover, there is equipment that has been purchased to test the methods of swarming and pressure containment. The team will need a microcontroller that can be placed in a breadboard for testing purposes, which adds more cost. For testing material, the team plans on spending $78.16, giving a grand total of $838.16. This grand total could be minimized by finding cheaper photodiodes. At this time, the photodiode circuit costs around $10.00 and there are 24 of these circuits in the four submarines. Currently, the team is looking into different photodiodes to reduce the cost and increase the amount of submarines that we could afford to have in the swarm. For more details about the budget, please refer to the Appendix C.

The team found several AUV projects that were custom made for the oceans. The cost of these usually ranged from tens of thousands to hundreds of thousands of dollars. An example of this is the OceanServe AUVs, which advertise that AUVs are affordable as these AUVs cost less than $50,000 [15]. The team found a remotely operated vehicle (ROV) called OpenRov. This ROV uses a Beagle Bone Black that the group has used before, but the still cost around $850 [16]. This costs more than what is currently planned, but still shows that it is viable to make a highly custom shell and equip it with sensors for less than $1000. Our project differs in that the team will be modifying an existing submarine and not going to the depths that these products advertise, giving the idea that this project is feasible with the given constraints.

VI. Societal and Environmental Impact

This project's societal impact will be positive. The intended use of the project is ethical. Misuse of this project may cause environmental problems (e.g. pollution). The images the swarm will be taking could be used for many types of aquatic research, including monitoring underwater ecosystems where endangered species live. Being able to generate new maps of underwater terrain efficiently will make environmental research easier. Many aquatic industries could be benefit from a project like this. The Motorworks Seawolf submarine has been marketed and sold in this country as a toy RC submarine. Because of this, the submarine has passed the required safety regulations for RC vehicles. Even though the team will modify the submarines, the submarines will remain safe to others. The submarines will operate at slower speeds than advertised which means that any collision with a person would cause no bodily harm. In the event that testing the swarm is in a natural body of water, a motorboat colliding with the swarm is the only legitimate concern. The submarines are constructed of plastic, which means that the submarines would likely be damaged if they were in a collision with a motorboat. The only damage the motorboat could sustain from a collision with the AUV is scratches. The obvious solution to this scenario is to test the swarm when motorboats are not present.

The project will require few natural resources. The team will be purchasing a toy RC submarine that is manufactured in high quantity, which means the manufacturer has minimized the cost per submarine by minimizing product used. The submarines are made of a non-toxic acrylonitrile butadiene styrene (ABS) plastic that will not pollute the water if the submarines were lost underwater. The batteries, on the other hand, will leak battery acid into the water if the submarines were left underwater. The team will only be testing in easily accessible locations to make retrieval of any stranded submarines simpler. The submarines have the potential to hurt plant life with their propellers. To avoid this as much as possible, the submarines will be tested in locations with minimal plant life. Large obstacles will be detected and avoided using the active sensing region on the submarine. Large obstacles include large fish or other animals that may be in the water with the submarines.

VII. Conclusion

The main objective of this project is to map underwater terrain using multiple autonomous robots. Each robot will navigate independently, taking images of the terrain. The swarm of robots will be versatile enough to operate in various controlled bodies of water. The autonomous robots will navigate the environment, avoiding structures and life forms. Inter-robot detection will allow the robots to avoid collisions and minimize redundancies in the images taken. After the mapping is complete, a final image of the terrain will be provided to the client.

The problem definition of this project presents a unique task. The success of the Cocoro project and the interest in the Cocoro project proves our proposed project is feasible and worth doing. Funding this project will allow us to provide a sensible solution to our client's request of mapping underwater terrain with robots. Valuable aquatic industries could potentially benefit from this project as well. The demand and usefulness of this project is apparent, and the only thing we still need to make it happen is your financial support.

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Appendix A – Detailed Gantt Charts

Task Name	Start	Finish
Research - Sensors - Sub Detection	**Thu 8/28/14**	**Thu 10/9/14**
Research - Surfacing Techniques	**Thu 8/28/14**	**Sun 8/31/14**
Research and Test - Sealing/Pressure	**Thu 8/28/14**	**Thu 9/4/14**
Research - Power System	**Thu 8/28/14**	**Thu 9/4/14**
Research - Sensors and Algorithms - Accelerometer	**Sat 8/30/14**	**Sun 8/31/14**
Research - Sensors and Algorithms - Compass	**Sat 8/30/14**	**Sun 9/7/14**
Design - Mock Drawings	Tue 9/2/14	Thu 9/4/14
Research - PCB Construction Method	Sat 9/6/14	Sat 9/6/14
Research - Sensors and Algorithms - Bottom Detection	**Tue 9/9/14**	**Thu 9/18/14**
Research - Submarines	**Thu 9/11/14**	**Sat 10/18/14**
Proposal Presentation	Thu 10/2/14	Thu 10/2/14
Design - Amplifier Circuit	**Sat 10/11/14**	**Tue 10/14/14**
Research - Sensors and Algorithms - Pressure	**Sat 10/11/14**	**Sat 10/18/14**
Research - Sensor Algorithms – LED Detection	Thu 10/16/14	Sat 10/18/14
Proposal Paper	Thu 10/16/14	Thu 10/16/14
Design - Motor Control	**Sat 10/18/14**	**Sun 10/19/14**
Research - Microcontroller	Sun 10/19/14	Thu 10/23/14
Design - Software Structure	Thu 10/23/14	Sat 10/25/14
Research - Image Capturing	**Sun 10/26/14**	**Tue 11/4/14**
Design - Algorithms - Detection Array	**Sun 10/26/14**	**Thu 10/30/14**
Design – Algorithms - Compass	**Sun 10/26/14**	**Thu 11/6/14**
Design - Algorithms - Motor Control	**Sun 10/26/14**	**Sat 11/8/14**
Testing/Tuning - Bench Top - Detection Array	**Thu 10/30/14**	**Sun 11/9/14**
Webpage Release	Thu 10/30/14	Thu 10/30/14
Design – Algorithms - Pressure	**Thu 10/30/14**	**Thu 11/6/14**

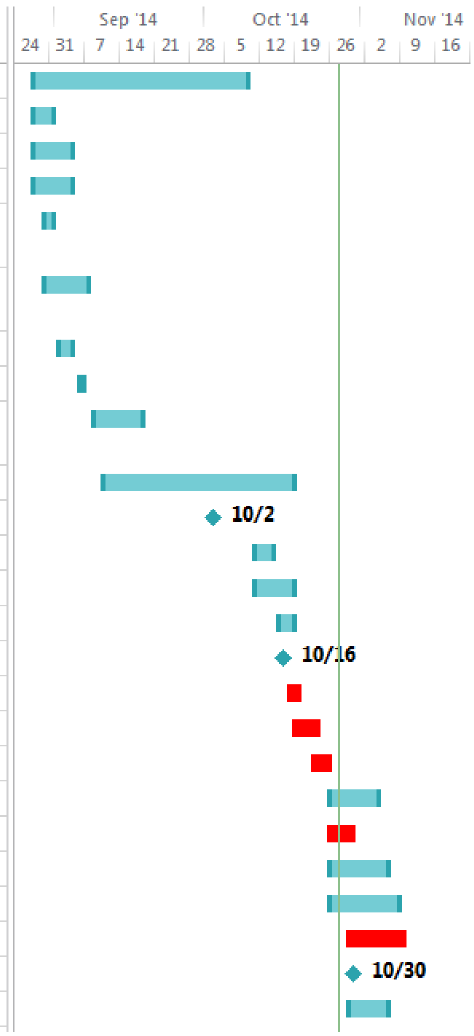

Fig. 5. The detailed Gantt chart for the first half of the schedule

Task Name	Start	Finish
Design - Algorithms - Accelerometer	**Sat 11/1/14**	**Thu 11/6/14**
Design – Algorithms – Bottom Detection	**Sun 11/2/14**	**Thu 11/6/14**
Design – Power System	Tue 11/4/14	Thu 11/6/14
Design - PCB Circuit Layout	Thu 11/6/14	Thu 11/6/14
Design - Submarine Layout	Thu 11/6/14	Thu 11/13/14
Design – Position Guidance Algorithm	Sun 11/9/14	Sat 11/29/14
Assemble - Single Submarine	**Sat 11/15/14**	**Sun 11/16/14**
Testing/Tuning - Single Submarine	**Sun 11/16/14**	**Thu 12/18/14**
Fall Progress Presentation	Thu 11/20/14	Thu 11/20/14
Research and Test - Photo Stitching Software	**Sat 11/29/14**	**Sat 11/29/14**
Testing/Tuning - Bench Top - Directional Guidance	**Sun 11/30/14**	**Tue 12/9/14**
Performance Review	Thu 12/4/14	Thu 12/4/14
Research - Swarming Techniques	Thu 1/22/15	Sat 1/24/15
Assembly - Swarm	**Thu 1/22/15**	**Sat 2/21/15**
Simulate - Swarm Algorithm	Sat 1/24/15	Thu 2/5/15
Design - Swarm Algorithm	**Thu 2/5/15**	**Tue 2/17/15**
Testing/Tuning - Bench Top - Swarm	**Tue 2/17/15**	**Tue 3/3/15**
Spring Progress Presentation	Thu 2/19/15	Thu 2/19/15
Testing/Tuning - Swarm	**Sat 2/21/15**	**Thu 3/26/15**
Project Demonstration	Thu 3/26/15	Thu 3/26/15
Final Presentation	Thu 4/9/15	Thu 4/9/15
Report Draft	Thu 4/16/15	Thu 4/16/15
Student Expo	Thu 4/16/15	Thu 4/16/15
ECE Advisory Board Poster Presentation	Sat 4/25/15	Sat 4/25/15
Final Report	Thu 4/30/15	Thu 4/30/15

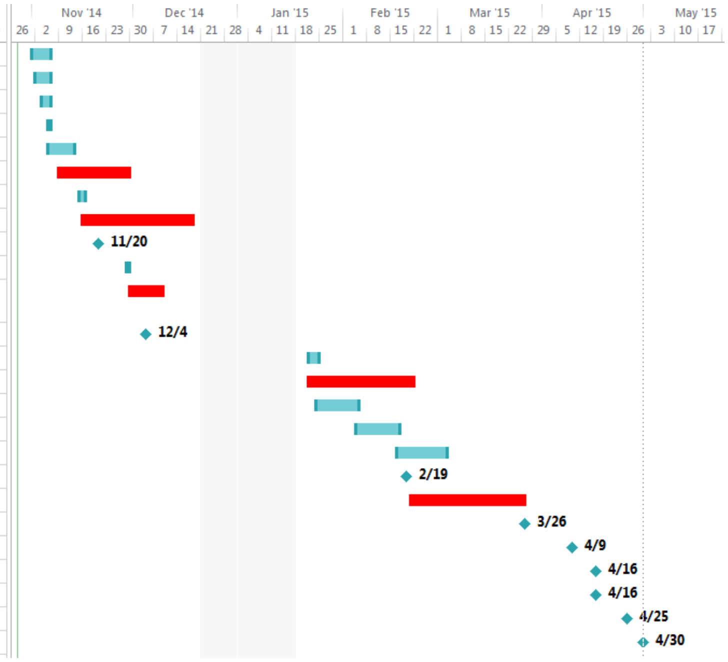

Fig. 6. The detailed Gantt chart for the second half of the schedule

Appendix B – Detailed Distribution of Tasks

TABLE IV
Detailed Distribution of Tasks

Task Name	Resource Names
Research - Sensors - Sub Detection	Cameron Putz, Nicholas Sikkema, Ryan Lipski
Research - Surfacing Techniques	Cameron Putz, Ryan Lipski
Research and Test - Sealing/Pressure	Cameron Putz, Nicholas Sikkema, Ryan Lipski
Research - Power System	Cameron Putz, Ryan Lipski
Research - Sensors and Algorithms - Accelerometer	Nicholas Sikkema
Research - Sensors and Algorithms - Compass	Nicholas Sikkema
Design - Mock Drawings	Ryan Lipski
Research - PCB Construction Method	Cameron Putz
Research - Sensors and Algorithms - Bottom Detection	Nicholas Sikkema, Ryan Lipski
Research - Submarines	Cameron Putz, Nicholas Sikkema, Ryan Lipski
Proposal Presentation	
Design - Amplifier Circuit	Cameron Putz
Research - Sensors and Algorithms - Pressure	Nicholas Sikkema
Research - Sensor Algorithms – LED Detection	Cameron Putz
Proposal Paper	
Design - Motor Control	Ryan Lipski
Research - Microcontroller	Nicholas Sikkema, Cameron Putz, Ryan Lipski
Design - Software Structure	Nicholas Sikkema
Research - Image Capturing	Nicholas Sikkema
Design - Algorithms - Detection Array	Cameron Putz
Design – Algorithms - Compass	Nicholas Sikkema
Design - Algorithms - Motor Control	Ryan Lipski
Testing/Tuning - Bench Top - Detection Array	Cameron Putz
Webpage Release	
Design – Algorithms - Pressure	Nicholas Sikkema, Ryan Lipski
Design - Algorithms - Accelerometer	Nicholas Sikkema, Ryan Lipski
Design – Algorithms – Bottom Detection	Nicholas Sikkema, Ryan Lipski
Design – Power System	Cameron Putz, Ryan Lipski
Design - PCB Circuit Layout	Cameron Putz
Design - Submarine Layout	Cameron Putz, Nicholas Sikkema, Ryan Lipski
Design – Position Guidance Algorithm	Nicholas Sikkema, Ryan Lipski
Assemble - Single Submarine	Cameron Putz
Testing/Tuning - Single Submarine	Cameron Putz, Nicholas Sikkema, Ryan Lipski
Fall Progress Presentation	
Research and Test - Photo Stitching Software	Nicholas Sikkema
Testing/Tuning - Bench Top - Directional Guidance	Nicholas Sikkema, Ryan Lipski
Performance Review	

Research - Swarming Techniques	Nicholas Sikkema, Ryan Lipski, Cameron Putz
Assembly - Swarm	Ryan Lipski, Cameron Putz
Simulate - Swarm Algorithm	Nicholas Sikkema, Ryan Lipski, Cameron Putz
Design - Swarm Algorithm	Cameron Putz, Nicholas Sikkema, Ryan Lipski
Testing/Tuning - Bench Top - Swarm	Cameron Putz, Nicholas Sikkema, Ryan Lipski
Spring Progress Presentation	
Testing/Tuning - Swarm	Cameron Putz, Nicholas Sikkema, Ryan Lipski
Project Demonstration	
Final Presentation	
Report Draft	
Student Expo	
ECE Advisory Board Poster Presentation	
Final Report	

Appendix C – Detailed Budget

TABLE V

Detailed Budget Submarine

Quantity	Cost Per	Total Cost	Description
4	$10.00	$40.00	Pressure Sensor
4	$50.00	$200.00	Submarine
4	$5.00	$20.00	Surface mount processor
12	$3.00	$36.00	3 Watt blue LEDS
24	$10.00	$240.00	Blue Filtered Photodiodes
4	$10.00	$40.00	Compass and IMU
4	$10.00	$40.00	Camera Circuit
4	$20.00	$80.00	Surface mount Components
4	$15.00	$60.00	PVC material
4	$10.00	$40.00	H-Bridge Chips
	Total	$756.00	
	Per Submarine	$189.00	

TABLE VI

Detailed Budget Testing

Quantity	Cost Per	Total Cost	Description
3	$5.00	$15.00	Microcontroller
1	$17.05	$17.05	PVC Test Stands
1	$46.11	$46.11	PVC Test Container
	Total	$78.16	

TABLE VII

Detailed Budget Total Cost

Description	Cost
Swarm cost	$756.00
Testing	$78.16
Total cost	$834.16