BRADLEY
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3D Environmental Mapping and Imaging for AUVSI RoboBoat

David Bumpus, Daniel Kubik, Juan Vazquez

Dr. José Sánchez, Nick Schmidt

Electrical and Computer Engineering Department

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Executive Summary

Since 2013, Bradley University's Department of Electrical & Computer Engineering has competed annually in the International RoboBoat Competition. This competition requires teams to create an autonomous boat designed to complete challenges. These challenges involve tasks such as obstacle detection and avoidance of objects such as buoys and shoreline.

Historically, the Bradley RoboBoat team has struggled to determine objects' distance relative to their boat. To determine distances of objects, past Bradley projects have used a camera. This method has proved ineffective as camera images do not contain depth; distances must be approximated using geometric techniques.

Lidar is a viable method that can provide distance measurements to the RoboBoat. Lidar is a method in which a laser is emitted from a laser scanner. These beams of light are reflected off of surrounding objects, received by the scanner, and then interpreted to determine the distance to these objects. Lidar technology is already used in a variety of environmental mapping applications in the autonomous vehicle industry.

The Bradley RoboBoat project advisor desires a system that can be used to locate objects in front of the RoboBoat using accurate distance measurements. In addition to these raw distance measurements, images should be created that can clearly be interpreted by human users to determine depth in an image of the surrounding environment. Implementation of such a system requires three main components. First, a laser scanner will be used to measure the distance to surrounding objects by utilizing lidar. This lidar device will be used for the scanning and modeling of the surrounding environment in three dimensions. Second, a camera will be programmed to take still images. Lastly, an embedded device will communicate between the laser scanner and camera and process the incoming data. Furthermore, though not integral to the measurement system, a hard drive will be used for data storage. This storage will be helpful for post-run testing.

The projected cost of this project will be $8,275.97. More specifically, the laser scanner costs $8,094, the camera costs $14.43, the hard drive costs $60.99, and the embedded device costs $99.90.

To ensure that this system performs as desired, certain performance goals should be considered. First, registration of camera images and lidar data must be flawless to create accurate images with implied depth. Both the camera and the laser scanner will need to communicate with the embedded device. Similarly, the system must communicate with the existing electronic components typically used by the RoboBoat team. Finally, as the boat is participating in a competition, data processing must be performed in real time due to the time constraints imposed by the competition.

Abstract

Bradley University’s RoboBoat design team desires an accurate way to determine distances of objects relative to their boat. In competition, the boat needs to autonomously navigate around objects. For this reason, possessing distance measurements would provide the team a significant competitive advantage. Historically, obtaining these distance measurements has been a challenge; a solution is the use of lidar. By using a combination of a laser scanner (VLP-16 Puck™ (Velodyne LiDAR, Morgan Hill, CA)) and a camera, accurate distance measurements can be paired with photographic images to map the environment in front of the boat. Moreover, the use of registration can be used to create an image with overlaid color to represent depth. There are a few important issues that will need to be considered for the success of this project. First, all electronics must operate from the boat’s power supply. Likewise, communication between the laser scanner and camera with an embedded device (Odroid XU4, Odroid Hardkernel, ManAnRo, South Korea) is crucial for success. This document contains a discussion of this proposed solution and how it will be accomplished. Some topics discussed will include a detailed explanation of the problem, a system description, and a design approach.

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I. Introduction

A. *Problem Background*

Every spring, AUVSI (the Association for Unmanned Vehicle Systems International) has hosted an International RoboBoat competition in Virginia. Since 2013, Bradley University's Department of Electrical and Computer Engineering has sent a team to this competition. In this competition, teams are required to have designed a boat that is expected to navigate and perform challenges without human control; all actions must be autonomous. For this reason, the boat must be able to accurately measure and model the environment around it. Obstacles in the water must be detected and noted when making any navigational decisions. This detection has proven difficult for past Bradley teams. Historically, teams have chosen to use a camera to record the environment in front of the boat. While photographic images provide important information about the environment, these pictures do not provide distance information; it is difficult to determine how far an obstacle is relative to the boat. While geometric methods may be used to approximate this distance, these methods have proven to be ineffective. For this reason, the RoboBoat project advisor would like to improve sensing capability of the boat by adding sensors that provide depth information. Increasing the number of sensors on the boat will improve reliability of the boat's navigational system and will increase the chances for success in future RoboBoat competitions.

To provide distance measurements, a laser scanner can be used. These scanners use a method called lidar in which lasers are used to measure distance. Lidar is already commonly used in many autonomous vehicle applications, such as cars and planes.

B. *Problem Statement*

Dr. José Sánchez is advising the development of a three-dimensional (3D) environmental mapping system for use in the RoboBoat competition. Ultimately, the client desires to improve the sensing capabilities of the boat by adding a system that can measure depth. The system will use a laser scanner to complete a full lidar scan of the environment around the boat. This lidar information will include both distance and reflectivity measurements. These measurements are returned to the boat's central processing unit (CPU) and also stored in a hard drive for post-run diagnostics. In addition, the distance measurements will be registered with pictures from a camera to create an image with a color overlay to visually demonstrate depth. Finally, the system will return polar coordinates of the location of the object nearest the boat. The system should be lightweight and compact. The lidar system must operate on less than 12 V, draw less than 4 A, and consume less than 50 W. Additionally, the system must fit in a 10 inch (25.3 cm) cube. All of these specifications allow for the boat to function within competition constraints.

C. *Constraints*

The constraints for the project were agreed upon by Nick Schmidt and the design team. These constraints can be seen in Table I and are each applied to the system as a whole; all components must be included together under these constraints. Many of these constraints are due to limitations of the boat and rules of the RoboBoat competition. For example voltage, current, and power constraints exist as the system will obtain its power solely from the power supply provided on the boat. To prevent capsizing the boat or slowing the boat down, the weight of the system has also been constrained. The rules of the competition and size of the boat also limit how large the system can be, confining the lidar system to a 25.4 x 25.4 x 25.4 cm cube.

The remaining constraints are limited by the preferences of the boat team and how the lidar system will be used. First, the system must measure the environment directly in front of the boat. Assuming the extreme right side of the boat (starboard) is 0° in a traditional Cartesian plane, the lidar system must measure objects anywhere in the range of 0°-180° in front of the boat, from starboard to bow to port. Next, two constraints are given that require that the system must measure objects at a minimum distance from the boat. Using testimonials from previous RoboBoat competitions it was determined that objects of interest will be no farther than 9.1 m from the boat on the level of the water and will be no higher than 3 m above the level of the lake. Using (1), (2), and (3) found in Appendix A, it can be determined that the system must be able to measure at least 9.58 m from the boat. Furthermore, to ensure a competitive advantage, a full scan (360°) of the environment must be completed in under 5 s. Finally, the lidar system must operate for the full duration of a typical competition, 40 min.

TABLE I: LIST OF 3D LIDAR SYSTEM CONSTRAINTS

CONSTRAINTS
3D lidar system must operate on 12 volts or less
3D lidar system must draw less than 4 A
3D lidar system must consume less than 50 W
3D lidar system must weigh less than 3.6 kg
3D lidar system must fit in a 10 inch (25.4 cm) cube
3D lidar system must obtain 180° scan in front of boat
3D lidar system must measure a minimum distance of 9.1 m horizontally
3D lidar system must measure a minimum distance of 3 m vertically
3D lidar system must obtain full scan in no more than 5 s
3D lidar system must operate for 40 min.

D. Scope

Table II describes the items which have been determined as “in scope” or “out of scope” for the project. The items in scope will be completed for this current project. Out of scope items may be completed in future projects or can be delegated to future RoboBoat teams. Ultimately, the goal of this project is to provide lidar depth information and camera images to the boat’s CPU. Therefore, most of the processing of this information will be done by future teams, however processing will need to be undertaken in this project to a certain degree. For accurate registration, it will be necessary to detect objects in an image. This will be done through image processing. While these objects will be determined to be individual ‘elements’ of an image, the identity of these objects will not be explored in this project. Detecting objects moving faster than the boat is also considered out of scope as all of the objects during challenges are stationary. Detection of underwater objects is also out of scope as RoboBoat challenges are above the water.

Finally, it is assumed that the boat will be moving during the recording of camera and lidar information. While this movement poses some potential problems such as data misalignment, mitigation of the effects of the boat’s motion will be considered out of scope for this project. After creating a schedule to determine how long the project will take, it was determined that there is not enough time to mitigate these effects in the amount of time given.

TABLE II: 3D LIDAR SYSTEM SCOPE DESCRIPTION

CONSIDERATION	IN SCOPE	OUT OF SCOPE
Image acquisition	X	
Lidar data acquisition	X	
Object detection	X	
Classification of object identity		X
Mitigate the effect of the boat's motion		X
Register 3D distance data with 2D image	X	
Transmit data packets to central navigation computer	X	
Variable range selection	X	
Moving object detection		X
Detection of objects at surface of water	X	
Shoreline object detection	X	
Underwater object detection		X
Detection of nearest object location	X	

II. Statement of Work

The following section contains the statement of work of this project. This section is divided into six subsections for the reader's convenience: *System Description*, *Design Approach & Methods of Solution*, *Economic Analysis*, *Project Timeline*, *Division of Labor*, and *Societal & Economic Impact*.

A. System Description

1) System Block Diagram

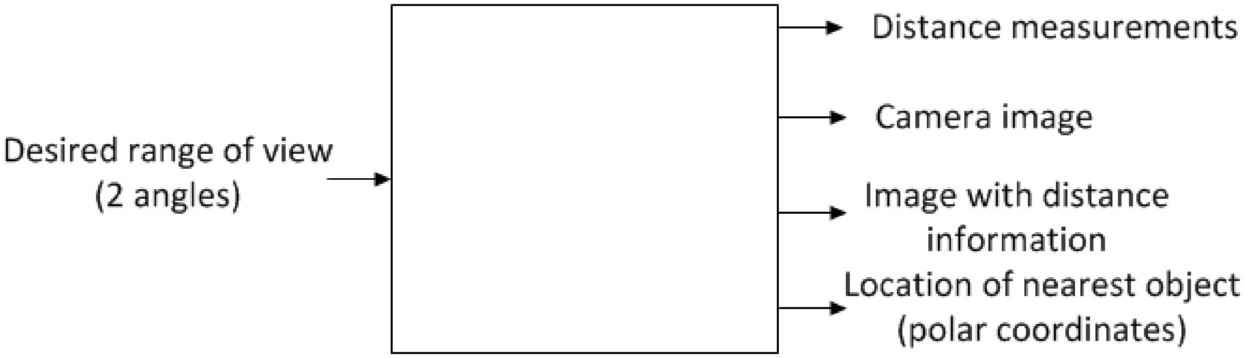


Fig. 1 Proposed solution black box diagram

As can be seen in Fig. 1, the inputs to the system will be two angles which represent a range of the boat's environment that is desired to be processed and mapped. The order of these angles matters as the range will be determined clockwise, from first angle to second angle. For example, if the two input angles were 180° and 0°, the desired range would be the front portion of the boat. Conversely, if the two input angles in order were 0° and 180°, the back portion of the boat would be returned, assuming nothing was blocking the view of the laser scanner. An image depicting the angles can be seen in Fig. 2. Notice that the front (bow) of the boat is considered 90°.

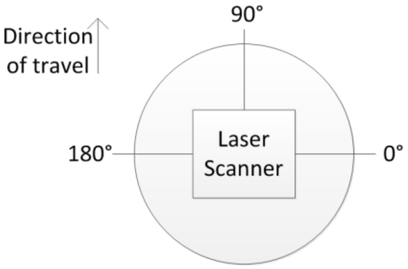


Fig. 2 Input/output angles

The system also has four outputs. First, the system returns distance measurements of the selected range of the 3D environment around the boat. These distances will be sent in the form of spherical coordinates (*r, θ, φ*), where *r* is distance, *θ* is the azimuthal angle, and *φ* is the altitudinal angle measured from the vertical relative to the scanner. This can be seen in Fig. 3 below.

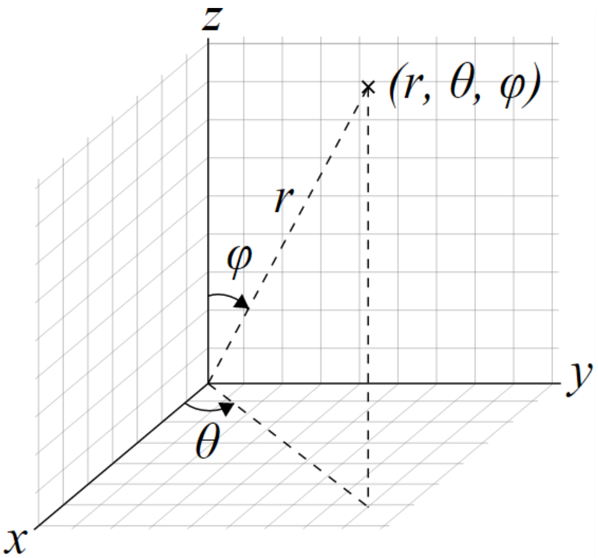


Fig. 3 Spherical coordinate system for returning distance measurements

The system will also return the location of the nearest object. This location will be returned using polar coordinates (*r*, *θ*), where *r* is the distance the object is from the boat, and *θ* is the azimuthal angle found in Fig. 2. The "nearest object" is determined to be the closest non-water object to the boat. This object will most likely be a buoy, the shoreline, or other hazards in the water. The third output will be a camera image. Finally, the fourth output will be an image registered with distance information. This image is, in essence, a combination of the distance measurements and the camera image. To represent distances in the image, a color overlay will be used. This image will be most helpful for diagnostic testing between competitions.

2) *Subsystem Block Diagram*

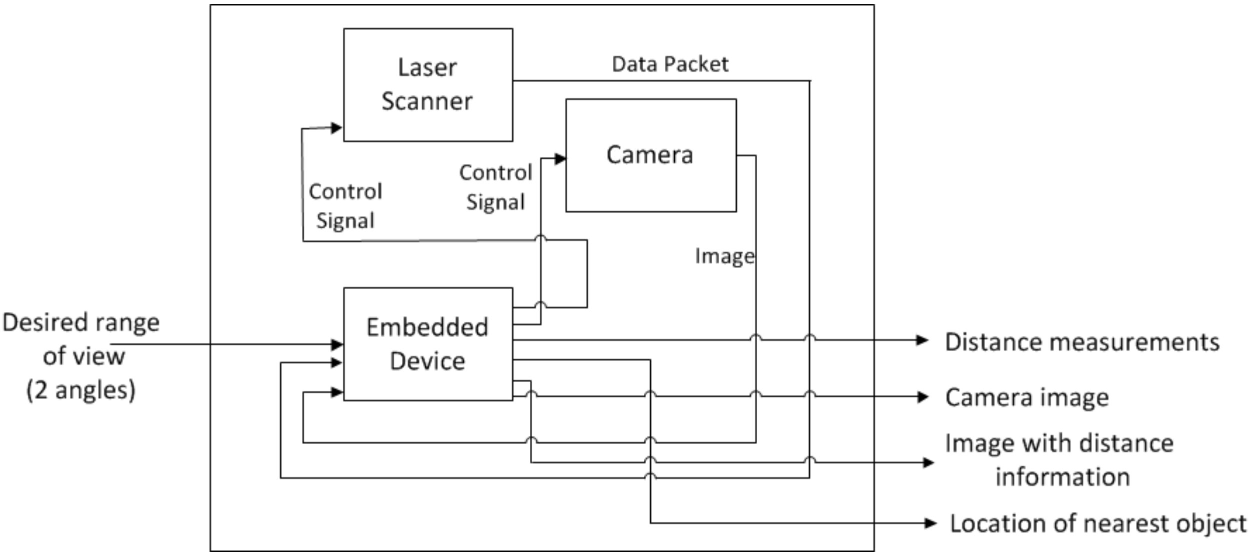


Fig. 4 Proposed system glass box diagram

Figure 4 depicts a high level of the internal components of the system and how they interact. As can be seen, there are three main components: a laser scanner, a camera, and an embedded device. The embedded device receives the two angles for the desired field of view. Once the distances have been measured by the scanner and the camera images been taken, the embedded device will process this data as necessary. The laser scanner measures using spherical coordinates, so the embedded device will need to convert this data into rectangular coordinates for use in registration. Registration of the image and the distance measurements will also be completed using the embedded device. Using this information, the location of the nearest object can be determined.

3) *System State Diagram*

A flowchart depicting the high level design of the preferred solution's software can be seen in Fig. 5 below. First, inputs are provided that signify the desired range to be further processed. Next, lidar data and camera images are acquired. A full 360° scan will be taken by the laser scanner. The camera will record video, from which still images from the individual frames are obtained. All of this data will be sent directly to an external hard drive. Next, "cropping" occurs. For the recorded 360° view of data, the data that falls within the range specified by the input angles can be selected and returned as outputs. All other data in the 360° is unneeded for further processing except the 180° range of data of the front of the boat as seen in Fig. 2. This data will be used for registration. To register 3D distance information with a camera image, it will be necessary to convert the distance measurements from spherical coordinates to Cartesian (rectangular) coordinates. This conversion can be made using (4), (5), and (6) as seen in Appendix A. Once converted, a registration technique will be used to detect edges and objects in the distance and image data. An adaptation of the patented [2] SIFT (scale invariant feature transform) algorithm will be used, composed of feature detection, feature matching, a Transform Mode I estimation, image resampling, and transformation [3]. This technique will be used to determine the nearest object and produce a registered image with color overlay. Once calculated, the nearest object and registered image will be returned as outputs.

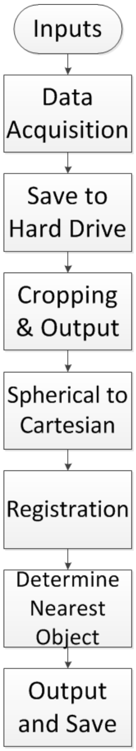


Fig. 5 High level flowchart of lidar system software

4) *Nonfunctional Requirements*

TABLE III: LIST OF 3D LIDAR SYSTEM NONFUNCTIONAL REQUIREMENTS

OBJECTIVES
3D lidar system should be weatherproof
3D lidar system should be configurable
3D lidar system should be mechanically stable
3D lidar system should be lightweight
3D lidar system should be executing in a timely manner

Included in Table III is a list of nonfunctional requirements developed for the 3D lidar system. Table IV in Appendix B covers the metrics that will be used to measure how effectively each nonfunctional requirement is met. These metrics are rated on a scale from 1 to 5, with 1 representing the least amount of effectiveness for the nonfunctional requirement and 5 represented the greatest.

“Weatherproof” refers to the ability of the system to survive against the elements such as water, wind, and sun. As the boat will be in a lake outside, it would be beneficial for the system to have safeguards against getting wet. “Configurability” refers to the ability for the system to return the most useful and pertinent information. Useful information is information that can be read easily by the boat, both because the communication interface matches with one or more interfaces of the boat and because the information is presented in an efficient way. “Mechanically stable” means how the motion of the system (if any) affects the motion of the boat. Less motion is desired so the boat will not be affected. “Lightweight” refers to the preferable lower weight of the system. The boat is less likely to sink with a lighter load. “Executing in a timely manner” refers to the fact that the system will be used in competition. Faster data acquisition and communication is desired to produce faster results.

5) *Functional Requirements*

TABLE IV: LIST OF 3D LIDAR SYSTEM FUNCTIONAL REQUIREMENTS

OVERALL FUNCTIONS	SPECIFICATIONS
3D lidar system should pass information to a hard drive	180° of unprocessed scan data, image data, angle and distance to nearest object, and registered image are passed to hard drive.
3D lidar system should pass information to the boat's onboard electronics	Angle and distance to nearest object are passed along with 180° of unprocessed scan data, image data, and registered image.
3D lidar system should accept input angles to define range	Azimuthal range of data can be adjusted without interfering with registration. The dataset returned is reduced accordingly.

Included in Table IV is the list of the functional requirements of the overall system and their specifications. These specifications determine whether or not the overall function is met. The first function listed involves the storage of all data in an external hard drive so that it is accessible for troubleshooting during system testing or after competitions. The specification for this function lists 4 sets of data to be stored in the hard drive. For the second function to be met, the azimuthal angle and distance to the nearest object must be returned. Likewise, unprocessed image, distance, and reflectivity information will also be returned to the boat's CPU. Finally, the last function listed is the reduction of the dataset for improved processing speed. This reduction occurs according to a range determined by the angles defined by the boat's CPU and should not interfere with any subsystem functions. Registration of the front half of the boat's surroundings should occur regardless of the angle range selected.

TABLE V: LIST OF 3D LASER SCANNER SUBSYSTEM FUNCTIONAL REQUIREMENTS

SUBSYSTEM FUNCTIONAL REQUIREMENTS	SPECIFICATIONS
Laser scanner must pass complete scan to embedded device	The entire 360° by 30° dataset of environment must be accessible via the embedded device.
Laser scanner must system must return distance measurements	Distances must range from at least 0 m to 9.58 m, obtained with 95% accuracy.
Laser scanner must return azimuthal angles	Azimuthal angles must range from 0° to 359.99°
Laser scanner must return reflectivity measurements	Reflectivity measurements must range from 0 to 255

Table V lists the functions and specifications for the laser scanner component of the system. These functions exist without any additional subsystem functionality. The first function describes what data is required for initial storage. An entire field of a 360° view measured from all 16 laser channels (30° vertically) is to be stored in the random access memory (RAM) of the embedded device. The second through fourth functions describe what type of information must be returned by the laser scanner to the embedded device. The accuracy of the second function is dictated by the accuracy of the scanner and is given as a percentage of the measured distance. Next, the reflectivity data must be stored in the embedded device RAM. These values should fall within the 0 to 255 range as described in [1].

TABLE VI: LIST OF CAMERA SUBSYSTEM FUNCTIONAL REQUIREMENTS

SUBSYSTEM FUNCTIONAL REQUIREMENTS	SPECIFICATIONS
Camera must communicate with embedded device	Images must be taken and returned on command
Camera must capture boat environment	Image must be in color and contain at least environment in front of boat from 0° to 30° above water level.

Table VI shown above lists the functions and specifications for the camera component of the system. These functions exist without any additional subsystem functionality. The camera must capture images when commanded by the embedded device. These images must be colored to capture a true representation of the environment. Moreover, the field of view of the camera images must contain at least the frontal environment of the boat with altitudinal angles ranging from 0° to 30° above the level of the water.

TABLE VII: LIST OF EMBEDDED DEVICE SUBSYSTEM FUNCTIONAL REQUIREMENTS

SUBSYSTEM FUNCTIONAL REQUIREMENTS	SPECIFICATIONS
Embedded device must register lidar data with image data	Image overlaid with depth information should have RGB colors ranging from 0 to 255
Embedded device must determine nearest object location and distance	Within 9.58m, distance to object must be accurate to within ±0.3 m and angle within ±5°
Embedded device must reduce dataset to desired angle of view	Dataset returned must contain all points within desired range as defined by the two input angles
Embedded device must store information in hard drive	Hard drive must store unprocessed image, unprocessed lidar data, and processed data (distance to nearest object, image overlay with depth information) for one 40 min. boat run.

Table VII lists the functions and specifications for the embedded device. These functions are dependent on the functionality of the camera and laser scanner subsystems. First, registration between the lidar data and a camera image must occur. The color scale used to represent distance must be consistent from image to image and should include a full color spectrum from RGB (red, green, blue) values ranging from 0 to 255. Next, within the constrained region of 9.58 m (minimum), the distance and location of the nearest object must be determined and returned. Finally, the embedded device must store all of the data listed in Table VII in a hard drive. This hard drive must have enough storage space to store all of this data for a full run of the boat on the water; this may last up to 40 minutes.

B. Design Approach and Method of Solution

A solution has been proposed to fulfill the functions, objectives, constraints, and requirements discussed. The following paragraphs will describe this desired solution and the approach the team plans to take to obtain this solution. In the case that this solution proves inadequate, an alternate solution has been proposed; this alternative solution is further described in Appendix C.

First, the laser scanner selected for the solution is the Velodyne VLP-16 Puck™. The Puck™ is a 3D (three-dimensional) laser scanner that is relatively inexpensive compared to other competitors' similar products; even with this lower price, the Puck provides many options that are ideal for this application. First, the Puck™ is able to operate in the range of 9 V to 32 V. This fits within the constraint of 12 volts or less provided by the boat's power supply. Second, the Puck™ consumes only 8 W of power. This value is far below the constraint of 50 W. This will allow additional room in the system for components that may require additional power. In addition, the dimensions of the Puck™ fit within a 25.4 cm cube. The scanner measures distances up to 100 m; this capability is much further than the required 9.58 m, and will greatly improve accuracy at close range. The Puck™ is able to scan an environment with an azimuthal range of 360° and an altitudinal range of ±15°. The 360° range is sufficient to meet the 180° requirement for the front portion of the boat, and the extra range enables greater flexibility among selectable ranges. To determine the minimum required altitudinal angle, the inverse tangent of the horizontal and vertical measurement requirements as seen Table I can be obtained as 18.24°. While the Puck™ has a maximum altitudinal range of +15°, the scanner can be mounted and tilted so that this 18.24° altitude can be reached. The 3.24° below the horizon will not have a significant impact of the measuring of the environment around the boat as this environment will mostly consist of water. According to [1], the Puck can measure a full 360° field of view in 200 ms, easily meeting the 5 s constraint. To communicate, the Puck™ uses an Ethernet port; therefore, the embedded device selected must also have an Ethernet port.

For the camera, a 1.3 MP Logitech C500 webcam was selected for the design. This camera uses a Universal Serial Bus (USB) for power. The USB uses, at most, 5 V which is below the 12 V constraint. The current and power draws are also less than the constraints for this project. The camera is small and lightweight, meeting these requirements as well. As this camera uses a USB to communicate, the selected embedded device must also have USB capability.

An Odroid XU4 was selected as the embedded device for this solution. As mentioned above, it was necessary for the embedded device to have Ethernet and USB capabilities in order to communicate with the laser scanner and camera. The Odroid provides these capabilities as well as two additional USB ports. To ensure the Odroid will have enough memory space, an embedded MultiMediaCard (eMMC) is also included in the design. In order to meet the storage necessary to hold an entire 40 min. run of the boat, a 1 terabyte (TB) hard drive has been selected for the solution.

To verify that these components are functioning as desired tests can be performed. These tests can be used to compare the functions of these components to the specifications listed for each system and subsystem. A more complete description of these tests can be found in Appendix D.

C. *Economic Analysis*

The total cost for the proposed project is $8,275.97. Table VIII lists each component of the system, the manufacturer of the component, and the price. As can be seen, a majority of the total system cost comes from the price of the Velodyne VLP-16 Puck 3D scanner. While this may seem expensive, the initial costs of the project were actually projected to be higher; most commercial laser scanners are much larger and designed for larger vehicles such as cars. The Puck is reasonably priced for the features that it can provide and a good size for the RoboBoat application.

TABLE VIII: 3D LIDAR SYSTEM BUDGET

Brand	**Part**	**Price**
Velodyne LiDAR	Puck™ (VLP-16)	$8,094.00
Hardkernel	Odroid XU4	$75.95
Hardkernel	8GB eMMC 5.0 Module	$23.95
Logitech	Webcam C500	$14.43
WD Elements	1TB External Hard Drive	$54.99
Ameridroid	Shipping Estimate	$12.65
Total		$8275.97

D. *Project Timeline*

The appointed milestones for the project are designated in Table IX below. These milestones are associated with both the overall system and each subsystem’s development. Each team member plays a role in the completion of all of these milestones; each milestone will be attained once all three team members have finished their portion of this milestone. Included alongside each milestone is an estimation of the total hours required for completion of each task. An in depth breakdown of the project timeline is formatted in the form of a Gantt chart in Appendix E. The projected finish date for the project is February 16th, 2016.

TABLE IX: PROJECT TIMELINE MILESTONES

ID	Activity	Hours
1	Simulation	45
2	Implementation	90
3	Mount System	30
4	Testing	30
5	ECE 498 Deliverables	N/A

E. *Division of Labor*

The labor has been divided so that each team member has been designated as a captain of one major project development category of tasks. As captain, each team member will lead the development of those tasks, though other team members will mostly likely help them throughout the project.

TABLE VIII: 3D LIDAR DIVISION OF LABOR

Captain	Task Category
David Bumpus	Image registration and processing image data
Daniel Kubik	Scan data acquisition and processing
Juan Vazquez	Camera and scanner interface and communication with embedded device

F. *Societal and Environmental Impacts*

As with any project, there will be concerns for the hazards to society of the environment. While this project contains minimal concern, there are a few points that should be mentioned. First, the Velodyne Puck is a class 1 laser product. Class 1 lasers are not hazardous, and thus pose little to no health risk to observers. If planning to recycle any of the components of this project it can be noted that the Odroid XU4 is not a RoHS certified device. While this implies that the Odroid may contain hazardous substances, given that only one unit will be produced, this design will expose marginal risk to the environment.

III. Summary and Conclusions

The purpose of this project is to develop a system which returns an accurate three dimensional representation of the environment around the autonomous boat used in the RoboBoat competition. A camera, laser scanner, embedded device, and external hard drive have been selected to meet these needs. As these devices will all need to communicate with the embedded device after acquiring data, the next step in the design of this system is the individual testing and setup of communication interface for the lidar, camera, and embedded device. After this, processing and further registration can occur.

IV. References

[1] “VLP-16 User Manual and Programming Guide 63-9243 Rev A.” Velodyne, Aug-2015.

[2] Method and apparatus for identifying scale invariant features in an image and use of same for locating an object in an image by David G. Lowe, US Patent 6,711,293 (March 23, 2004). Provisional application filed March 8, 1999. Asignee: The University of British Columbia.

[3] Lowe, D.G., 1999. “Object recognition from local scale-invariant features.” International Conference on Computer Vision, Corfu, Greece, pp. 1150 -1157.

V. APPENDIX A: CALCULATIONS

Initially, two requirements were given describing the distance measured by the laser scanner. These requirements requested that at a minimum, the laser scanner must be able to measure at least a horizontal distance of 9.1 m and at least a vertical distance of 3 m from the laser scanner. Because it is possible that an object can be both 9.1 m away and 3 m above the scanner, it is desired to know this maximum distance from the scanner that is necessary to meet the requirements.

Equation (1) below can be used to determine this distance. As can be seen, the Pythagorean Theorem is used to determine the maximum. It has been determined that the scanner must be able to measure at least 9.58 m away.

$$MaximumRequiredDistance = \sqrt{HorizontalMin^2 + VerticalMin^2} \tag{1}$$

$$MaximumRequiredDistance = \sqrt{(9.1\,m)^2 + (3\,m)^2} \tag{2}$$

$$MaximumRequiredDistance = 9.58\,m \tag{3}$$

Equations (4), (5), and (6) describe the conversion from spherical coordinates to rectangular (Cartesian) coordinates. R represents distance, ω represents the altitudinal angle and α represents the azimuthal angle.

$$X = R * \cos(\omega) * \sin(\alpha) \tag{4}$$

$$Y = R * \cos(\omega) * \cos(\alpha) \tag{5}$$

$$Z = R * \sin(\omega) \tag{6}$$

Equation (7) is used to estimate how many hours will need to be allocated per task in the Gantt chart seen in Appendix E. The variables in the numerator correspond to an optimistic, pessimistic, and most likely estimation of time that a task will take to accomplish.

$$t_E = \frac{t_O + 4t_M + t_P}{6} \tag{7}$$

VI. APPENDIX B: METRICS FOR NONFUNCTIONAL REQUIREMENTS

TABLE IX: METRICS FOR 3D LIDAR SYSTEM FUNCTIONAL REQUIREMENTS

Objective: 3D lidar system should be weatherproof	
5	Can operate in rain, fog, wind, waves, and varying light intensities
4	Can operate in fog, wind, waves, and varying light intensities
3	Can operate in wind, waves, and varying light intensities
2	Can operate in wind
1	Only works indoors
Objective: 3D lidar system should be configurable	
5	System is highly configurable
4	System is configurable
3	System is somewhat configurable
2	System is not very configurable
1	System is not configurable
Objective: 3D lidar system should be mechanically stable	
5	Motion in system is contained
4	Motion in system is mostly contained
3	Motion in system is somewhat contained
2	Motion in system will impair other boat functions
1	Motion in system will disable boat
Objective: 3D lidar system should be lightweight	
5	Weight less than 2 kg
4	Weight less than 2.86 kg
3	Weight less than 3.72 kg
2	Weight less than 4.58 kg
1	Weight less than 5.44 kg
Objective: 3D lidar system should execute in a timely manner	
5	Scan time and processing less than 5 s
4	Scan time and processing less than 5.5 s
3	Scan time and processing less than 6 s
2	Scan time and processing less than 6.5 s
1	Scan time and processing less than 7 s

VII. APPENDIX C: DESCRIPTION OF ALTERNATIVE SOLUTION

Some concerns have been voiced about the Odroid XU4 that may interfere with the completion of this project. For example, the Odroid may take longer than expected to arrive. Also, the Odroid is a newer technology than some more conventional embedded devices, so there may be less online support. In the case that the Odroid takes longer than two months to arrive, or that a hurdle is reached involving the Odroid that cannot be addressed, an alternate solution is available as a contingency plan. This alternative solution includes a micro ITX with an Intel Core 3 as a processor. This embedded device is currently owned by the Bradley University Department of Electrical and Computer Engineering and is available for use at no additional cost. This processor has fewer cores than the Odroid XU4, but more resources are available both online and in the department to help solve any issues that may arise.

VIII. APPENDIX D: SYSTEM TESTING

To verify that the system is performing the required functions, a series of tests should be issued. First, the subsystems must be tested individually.

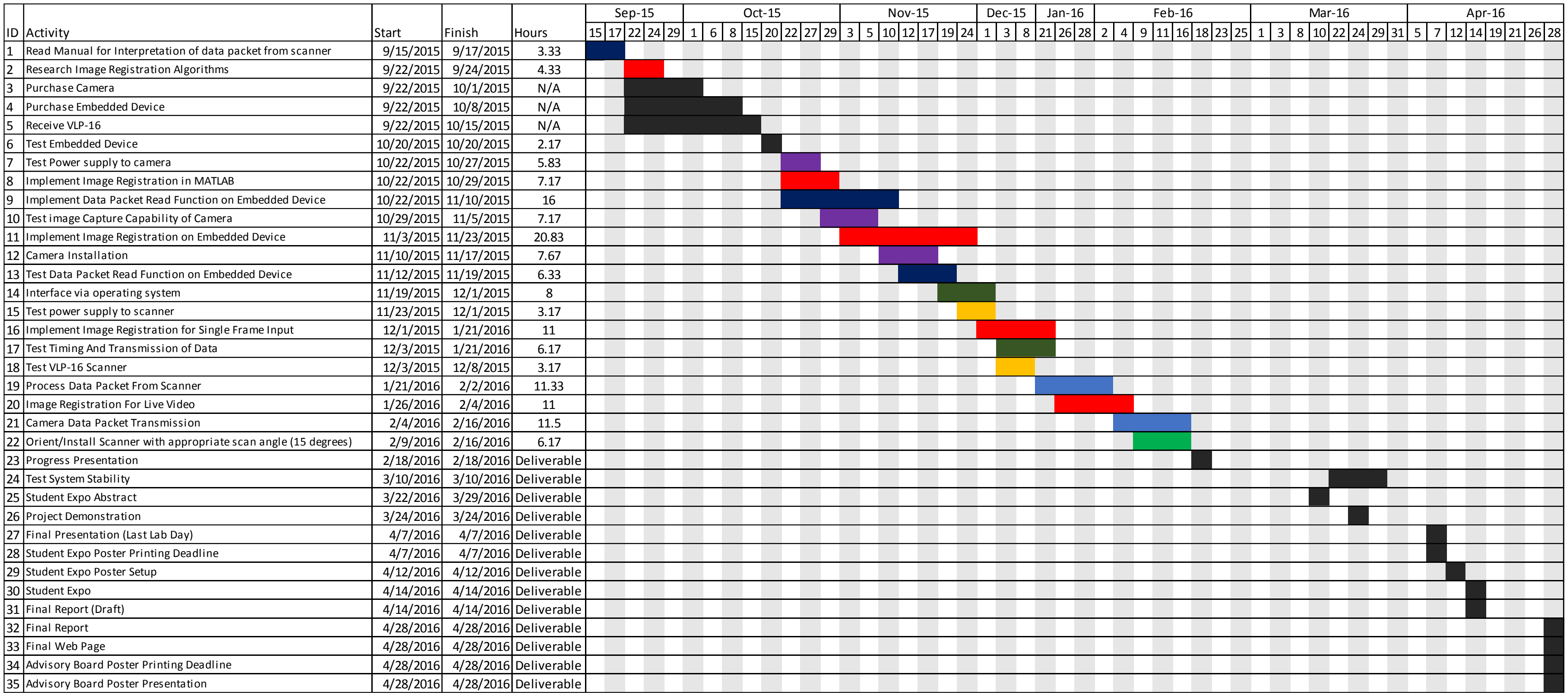
For the laser scanner, first it must be identified that a full 360° by 30° field of view is being recorded and passed to the embedded device. This can be checked using the Veloview software. By running the scanner using the Ethernet connection, Veloview will visually represent the data being received. Additionally, the scanner must return distances at least 9.58 m away with 95% accuracy and reflectivity measurements from 0 to 255. These values can be obtained using Veloview, and the 95% can be determined by comparing the measurements seen in Veloview with measurements taken in the classroom. For example, the scanner can be placed in a box. This box is clearly identifiable and can be easily measured.

The embedded device must determine nearest object location and distance. This can be determined by setting up a mock environment where there are a select amount of objects in a room. For example, it has been mentioned that the atrium in the Renaissance Coliseum may be used. In this atrium, objects can be systematically placed and measured as to their whereabouts. Placing the system up high, looking down into the lobby can represent an open area like a lake. If the system can return the angle and distance to their nearest object, it can be determined that the test was a success. To determine if the embedded device is reducing the desired angle of view correctly and performing the registration properly, the outputs from the system sent to the external hard drive can be obtained and examined.

To test the capabilities of the camera, the camera can be connected with the embedded device and commanded to take pictures. By examining these images, it can be determined if the images contain objects further than 9.58 m away with distinguishable edges. In addition, the range of these images can be tested by comparing the size of the frame of the image and how wide the field of view is.

After all of the subsystems have been tested, full system testing can commence. Oscilloscopes, voltage meters, and current meters can be used to determine voltage, current, and power usage. Once calculated, these values can be used to calculate if the system can continuously run for 40 min. The weight requirement can be tested using a scale. The system can be measured using a meter stick to determine if the system will fit within a 25.4 cm cube. Timing of scans are provided by the laser scanner and be used to determine how long it takes to make a full 360° scan.

IX. APPENDIX E: GANTT CHART



ID	Activity	Start	Finish	Hours
1	Read Manual for Interpretation of data packet from scanner	9/15/2015	9/17/2015	3.33
2	Research Image Registration Algorithms	9/22/2015	9/24/2015	4.33
3	Purchase Camera	9/22/2015	10/1/2015	N/A
4	Purchase Embedded Device	9/22/2015	10/8/2015	N/A
5	Receive VLP-16	9/22/2015	10/15/2015	N/A
6	Test Embedded Device	10/20/2015	10/20/2015	2.17
7	Test Power supply to camera	10/22/2015	10/27/2015	5.83
8	Implement Image Registration in MATLAB	10/22/2015	10/29/2015	7.17
9	Implement Data Packet Read Function on Embedded Device	10/22/2015	11/10/2015	16
10	Test image Capture Capability of Camera	10/29/2015	11/5/2015	7.17
11	Implement Image Registration on Embedded Device	11/3/2015	11/23/2015	20.83
12	Camera Installation	11/10/2015	11/17/2015	7.67
13	Test Data Packet Read Function on Embedded Device	11/12/2015	11/19/2015	6.33
14	Interface via operating system	11/19/2015	12/1/2015	8
15	Test power supply to scanner	11/23/2015	12/1/2015	3.17
16	Implement Image Registration for Single Frame Input	12/1/2015	1/21/2016	11
17	Test Timing And Transmission of Data	12/3/2015	1/21/2016	6.17
18	Test VLP-16 Scanner	12/3/2015	12/8/2015	3.17
19	Process Data Packet From Scanner	1/21/2016	2/2/2016	11.33
20	Image Registration For Live Video	1/26/2016	2/4/2016	11
21	Camera Data Packet Transmission	2/4/2016	2/16/2016	11.5
22	Orient/Install Scanner with appropriate scan angle (15 degrees)	2/9/2016	2/16/2016	6.17
23	Progress Presentation	2/18/2016	2/18/2016	Deliverable
24	Test System Stability	3/10/2016	3/10/2016	Deliverable
25	Student Expo Abstract	3/22/2016	3/29/2016	Deliverable
26	Project Demonstration	3/24/2016	3/24/2016	Deliverable
27	Final Presentation (Last Lab Day)	4/7/2016	4/7/2016	Deliverable
28	Student Expo Poster Printing Deadline	4/7/2016	4/7/2016	Deliverable
29	Student Expo Poster Setup	4/12/2016	4/12/2016	Deliverable
30	Student Expo	4/14/2016	4/14/2016	Deliverable
31	Final Report (Draft)	4/14/2016	4/14/2016	Deliverable
32	Final Report	4/28/2016	4/28/2016	Deliverable
33	Final Web Page	4/28/2016	4/28/2016	Deliverable
34	Advisory Board Poster Printing Deadline	4/28/2016	4/28/2016	Deliverable
35	Advisory Board Poster Presentation	4/28/2016	4/28/2016	Deliverable

Fig. 6 Project Timeline Gantt Chart

Appendix E contains a Gantt chart representing the proposed schedule for the completion of this project. The project timeline was created using the equation (7) as seen in Appendix A. This formula averages three variables associated with each task; each variable corresponds to an optimistic, pessimistic, and most likely estimation. The timeline is formatted around two lab days a week in which all team members work together for three hours. Furthermore, the chart is color coded to demonstrate task dependence. For example, for an item in red to begin, the previous item in red must be finished first.

The critical path for the design of this system depends on the arrival time of the components. While some initial work can be done without the laser scanner, camera, or embedded device, possession of these components is crucial to the success of this project.