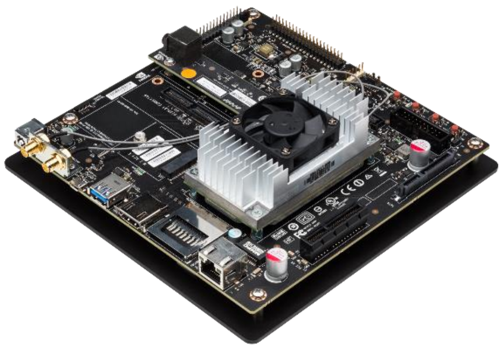

PRELIMINARY DESIGN REVIEW

SLAM IN AN UNKNOWN ENVIRONMENT

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1 Executive Summary

Simultaneous localization and mapping (SLAM) is a popular technique used by autonomous vehicles for creating maps of an environment while tracking the location of the vehicle within the environment (Maxwell, 2013). This technique began to be developed in the late 1980's and has been described as the "Holy Grail" of autonomous vehicle research because it eliminates the need for prior knowledge of an environment. Current systems use sonar, pressure sensors, and/or infrared sensors to preform SLAM and these systems can be inaccurate. Our client, Dr. Choi, has requested our team develop a system that can be attached to a Thumper rover and is capable of preforming SLAM in an unknown environment.

For this project, three different SLAM systems were analyzed one of which was suggested by our client. The system our client has suggested uses two new devices, the ZED Stereo Camera and Jetson TX1 Graphical Processing Unit (GPU) to create 3D maps of any environment in real time. The other systems we analyzed used combinations of microcontrollers, laser range finders, bump switches, and compass models to create 2D maps of environments.

Through a series of feasibility and merit criteria analysis, the system using the ZED Stereo Camera and Jetson TX1 was determined to be the optimal system to preform SLAM in an unknown environment. These feasibility and merit criteria were determined through our client's specifications. After the ZED Stereo Camera and Jetson TX1 system was selected, mounts to attach the ZED Stereo Camera were designed and analyzed. A mount constructed out of PVC with a flat, rotating platform for the ZED Stereo Camera was selected.

Power supply, mapping ability, processing power were all analyzed for the ZED Stereo Camera and Jetson TX1 System and force analysis was conducted on the mount design. Using the engineering backgrounds of the group, these in-depth analyses allow for more insight to the entire project.

By equipping the ZED Stereo Camera to a Thumper rover using a rotating attachment, the rover will be able to visually map its environment and respond to stimuli as it navigates the environment autonomously. The use of visual mapping should allow the robot to move more precisely around obstacles so it will no longer need the pressure, sonar, or infrared sensors. Since there is already an existing protocol to have a robot respond to environmental stimuli, this system will be adapted for the use of a camera.

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Glossary

3DR UBlox GPS + Compass Module – Global Positioning Device for use with the Pixhawk

Adafruti Motor Shield – Add-on to Arduino Uno for added control of motors

Arduino Uno– Microcontroller for use with GMapping System

CUDA – Compute Unified Device Architecture is a parallel computing platform and programming model implemented by GPUs

eDVS – Event-based Embedded Dynamic Vision Sensor

EKF SLAM – A class of algorithms which utilizes the extended Kalman filter (EKF) for simultaneous localization and mapping

FastSLAM – Algorithm that recursively estimates the full posterior distribution over robot pose and landmark locations, yet scales logarithmically with the number of landmarks in the map

FPS – Frames Per Second

GMapping – Highly efficient Rao-Blackwellized particle filer to learn grid maps from laser range data

GPU – Graphical Processing Unit

HMC5883L Compass – Sensor used to estimate pose of robot in GMapping system

Jetson TX1 – GPU designed to work with ZED

Laser Range Finder Sensor LRG/LIDAR – Laser range finder for use with GMapping system

Mouse Sensor PAW3504 – Sensor from optical mouse used in GMapping system to do odometry

Odometry – Use of data from motion sensors to estimate change in position over time

OS – Operating System

Pixhawk Autopilot – High-Performance Autopilot-on-Module

PVC – Polyvinyl Chloride Piping

RAM – Random Access Memory

Raspberry Pi 3-Model B – Microcontroller for use with GMapping System

ROS – Robot Operating System, a collection of software framework for robot software development

SDK – Software Development Kit

SLAM – Simultaneous Localization and Mapping

TeraFLOPS – A unit of computing speed equal to one million million (1012) floating-point operations per second

Thumper – All terrain chassis with 75:1 gear box

USB – Universal Serial Bus

ZED – 3D camera for depth sensing

List of Symbols and Units

A Amps

cm Centimeter

° Degrees

. Decimal

Ø Diameter

↓ Depth

$ Dollar

F Force

GB Gigabyte

Hz Hertz

“ Inch

kg Kilogram

MB Megabyte

MPix/s Megapixels per Second

mAH Milliamp Hours

mm Millimeter

* Multiply

Pa Pascals

% Percent

lbs Pounds

T Torque

V Volts

2 Introduction

2.1 Background

Simultaneous localization and mapping (SLAM) is a popular technique used by autonomous vehicles for creating maps of an environment while tracking the location of the vehicle within the environment (Maxwell, 2013). This technique was pioneered in 1986 by R.C. Smith and P. Cheeseman in their article "On the Representation and Estimation of Spatial Uncertainty" and has been further advanced by Hugh F. Durrant-Whyte. In one of his articles published in the IEEE, Whyte described SLAM as the "Holy Grail" of autonomous vehicle research because "it eliminates the need for artificial infrastructures or *a priori* topological knowledge of the environment" (Durrant-Whyte, H. F., 2001, June). There have been several theoretical techniques developed to do SLAM including EKF SLAM and FastSLAM, but there is not a technique or system that can successfully solve all facets of SLAM in a real-world environment (Milford, M. J., 2008).

2.2 Statement of Problem

Current SLAM systems use sonar, pressure sensors, and/or infrared sensors to preform SLAM. The pressure sensors help the robot adjust to barriers that the sonar and infrared sensors may have missed. Our client, Dr. Choi, has requested a physical robot, Thumper, be designed to perform SLAM in an unknown environment. Our client has also requested we use two new devices, the ZED Stereo Camera and Jetson TX1 Graphical Processing Unit (GPU) that have been developed to perform SLAM faster and more accurately than earlier systems. In order to confirm a SLAM system using these two devices would be optimal to preform SLAM, we will analyze the system along with two other systems against feasibility and merit criteria determined by our client and our team to either confirm or reject this claim.

3 Project Description

3.1 Project Goal

The goal of this senior design project is to provide Dr. Choi with an optimized SLAM system. The operational goal of the completed SLAM and Thumper system is to be able to map an unknown environment while simultaneously localizing its position within the given environment.

3.2 Mount Feasibility Criteria

To determine if the methods for manufacturing and assembly are feasible, feasibility criteria were determined. Three categories of feasibility criteria were determined: Technical, Payload, and Operational. Technical feasibility is closely related to the overall goal of the project. Simply put, it is if the product will function from an engineering perspective. Payload feasibility is if the product exceeds the allowed payload of the Thumper. Operational feasibility is related to how well the product will be received by the end-user.

3.2.1 Technical Feasibility

Using the developed manufacturing plans, the mount must be able to be produced by someone with an intermediate level of machining experience. The mount produced by the developed manufacturing plans must meet all criteria set forth by the client, Dr. Choi.

3.2.2 Payload Feasibility

In terms of payload feasibility, keeping the weight of the mount low is critical to the success of this project. To maximize the efficiency of the Thumper mechanics, the mount must be constructed with lightweight construction in mind. The maximum payload of the Thumper is 11 pounds. If the weight of the mount combined with the other components exceeds this amount, it will not be considered feasible.

3.2.3 Operational Feasibility

The mount must adhere to operational guidelines set forth by our client, Dr. Choi. The mount must be able to rotate to provide the system a full 360-degree view of the surrounding area in the case of the Thumper being in a tight area where it cannot alter the direction it is facing. The mount must also be at a low enough height to provide the system a view of the floor so that it can detect ledges and other dangerous obstacles. Adherence to these factors is critical for the success of this project.

3.3 Mount Merit Criteria

To determine the best design alternative, merit criteria were determined. Five merit criteria were developed and tested against: aesthetics, material density, arm length, ease of attachment, and cost of material.

3.3.1 Aesthetics

Aesthetics is important because it contributes to the overall satisfaction of the project. The way the mount looks reflects the quality of engineering performance but is not critical for the project’s success.

3.3.2 Material Density

Keeping the overall payload under 11 pounds is a strict requirement of the mount, but minimizing the weight is also key to retaining proper balance and functionality of the Thumper. Since weight varies with length, it is more appropriate to use density as a merit criteria. Choosing a material with an appropriate density will also relate to the strength of the material.

3.3.3 Arm Length

Arm length is important because the camera must be able to spin without hitting any of the other components mounted to the top deck of the Thumper chassis. With that in mind, if the arm is too long, it will cause shaking and vibrating when the robot is moving or coming to a sudden stop. Limiting length to only what is necessary will help to keep the weight of the attachment to a minimum.

3.3.4 Ease of Attachment
Another important factor is simple attachment. If the mount is too complicated to fit onto the Thumper or another rover of sorts, less will be able to be seen. The mount should be simple to attach and adjust with the tools on hand.

3.3.5 Cost of Material
The cost of the materials must be considered while designing the mount. The materials will be chosen keeping a $300 budget in mind.

3.4 System Feasibility Criteria
To determine whether or not the selected systems are feasible, feasibility criteria were determined. Three categories of feasibility criteria were determined: Technical, Financial, and Operational. Technical feasibility is closely related to the overall goal of the project. Simply put, it is whether or not the product will function from an engineering perspective. Technical feasibility is whether or not the product can be afforded by the client. Operational feasibility is related to how well the product will be received by the end-user.

3.4.1 Technical Feasibility
The system must be able to be configured and programmed by team members with extended knowledge of software languages and electrical hardware. The developed program must meet all criteria set forth by the client, Dr. Choi.

3.4.2 Financial Feasibility
In terms of financial feasibility, the systems researched as alternatives for this project are relatively expensive compared to other projects. The cost of the proposed alternative must be presented to the client and approved before moving forward with the purchase and implementation of the chosen system. If any design alternative is rejected by the client due to cost, it will not be considered feasible.

3.4.3 Operational Feasibility
In order to pass operational feasibility, the system must be able to pass the requirements set by the client, Dr. Choi. The system must be able to map its surroundings, localize its current position, navigate through the environment, and control the Thumper. If the system cannot pass these criterion, it will be deemed unfeasible.

3.5 System Merit Criteria
To determine the best design alternative, merit criteria were determined. Five merit criteria were developed and tested against: cost, data processing rate, weight and size, and memory.

3.5.1 Data Processing Rate
The data processing rate determines how quickly the system is able to process its surroundings and run the algorithms written in the software package. Faster is preferred.

3.5.2 Weight/Size

The weight and size of the system determines how well it fits onto the Thumper chassis and whether or not it impedes the balance and desired movements of the Thumper. Smaller and lighter is preferred.

3.5.3 Memory

Memory determines how much data the system can store while running the developed algorithms and camera system. Higher memory is preferred.

3.5.4 Cost

Cost is the deciding factor if all other merit criteria are balanced between the design alternates. Lower cost is preferred.

4 Design Alternatives

4.1 SLAM System Alternatives

Three SLAM Systems were analyzed to determine the optimal system to implement to successfully do SLAM in an unknown environment. Each system – ZED and Jetson TX1, GMapping, and eDVS – was analyzed according to its advantages and disadvantages. All the systems would be implemented on a Thumper chassis with a 75:1 gear box and a Pixhawk Autopilot with a 3DR UBlox GPS + Compass Module which can be seen in Appendix A.

4.1.1 System 1 – ZED and Jetson TX1

System 1 uses the ZED Stereo Camera by Stereo Labs and Jetson TX1 Developer Kit GPU by NVIDIA, shown in Figures 1 and 2 respectively, to solve the SLAM problem. The ZED Stereo Camera is the first device in the industry to offer real-time depth sensing, positional tracking, and 3D mapping capabilities. It will be controlled by the Jetson TX1 which is a powerful graphical processing unit (GPU) with 4GB of RAM, a quad-core ARM Cortex Processor, and Linux OS that can easily control the ZED, Pixhawk, and Thumper. These devices are compatible and work together by installing the ZED SDK on the Jetson TX1. This system will also utilize ROS which is a software framework used on embedded robotics platforms. The SLAM technology that has been designed and integrated into the ZED Stereo Camera is available for use through the ZED SDK and ROS nodes. A node is simply a process that involves computation.

Since this is a relatively new system, there is little documentation of these two devices being used together to perform SLAM and the cost is on the upper end of our budget at $1,098 for just these two devices. However, the ZED Stereo Camera is capable of producing 3D maps, can be used in all environments, and is very accurate.

Figure 1: ZED Stereo Camera by Stereo Labs

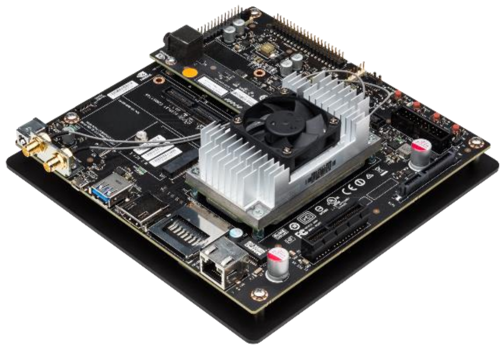


Figure 2: Jetson TX1 Developer Kit by Nvida

4.1.2 System 2 – GMapping

System 2 uses an Arduino Uno, Raspberry Pi 3-Model B, Adafruit Motor Shield, Laser Range Finder Sensor LRG/LIDAR, HMC5883L Compass, and Mouse Sensor PAW3504 to implement an ROS node called slam_gmapping. All of the components listed above can be found in Appendix B. The slam_gmapping node provides the packaging to do laser-based SLAM. The Raspberry Pi would be the main controller of the system and the component that processed the data from the other components to perform SLAM. The Adafruit Motor Shield would be attached to the Arduino Uno and together they would control the motors of the Thumper and pass all the data from the sensors to the Raspberry Pi. Using the components listed above along with the GMapping package, the system can create 2D occupancy grid maps of an area. An example map can be seen in Figure 3.

With so many components involved, there is a greater chance that issues will arise in trying to interface all of them. Also, the system would not always be reliable in outdoor environments because strong sunlight can cause the data from the laser rangefinder to become inaccurate.

Figure 3: Example Map Created by GMapping

4.1.3 System 3 – eDVS

System 3 uses an event-based embedded dynamic vision sensor and contact switches to autonomously explore and visually localize and map an unknown indoor environment in real time. An event would occur when there is a change in brightness at the individual pixel the sensor is reading. As the robot navigates an area, it would track the path it is taking and location estimates would be provided for events. However, information about obstacles cannot be derived from the visual input because the event-based vision sensor is pointed upwards as it uses features on the ceiling for self-localization. To detect obstacles, when the contact switches are triggered, the system would record the location of the collisions. By combining the self-localization provided by the event-based vision sensor and the data from the contact switches, a 2D map of the ceiling could be generated with indications of collision positions. A sample map generated by this system can be seen in Figure 4. The robot could then use this map to plan collision-free paths with that environment.

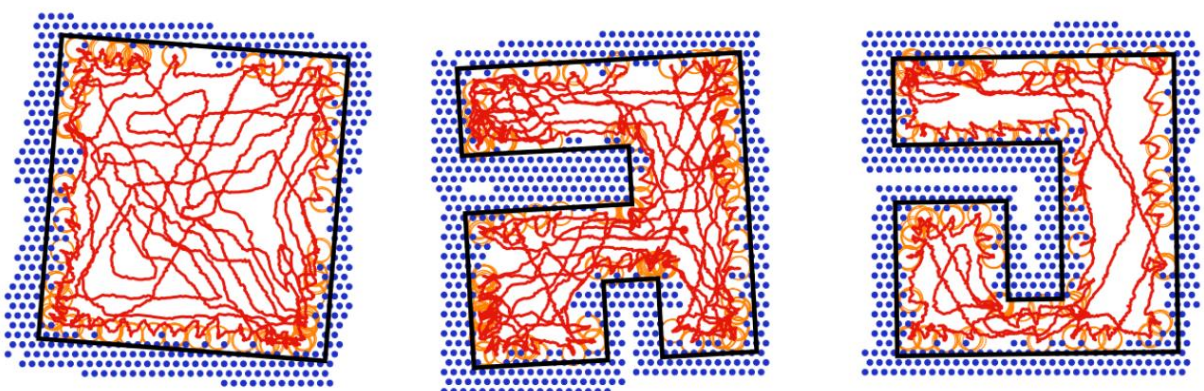


Figure 4: Sample Maps Generated by eDVS

4.2 Mount Design Alternatives

Three different camera mount designs were analyzed to determine the appropriate way to attach the ZED Stereo Camera to the Thumper. The first is a direct mount, attaching the ZED Stereo Camera to the Thumper using a simple strap. Design 2, shown in Figure 5, is a mount set on top of a five-inch length of tubing with a separate motor to drive its rotation independently from the Thumper. This design will use a nylon strap to secure the ZED to the platform. Design 3, shown in Figure 6, is similar to Design 2; the tubing is 11 inches long and utilizes a cage to hold the camera in place.

In addition to the three different designs, the merit criteria were used to evaluate materials for the arm as well. Aluminum, PVC, Steel, and Carbon composite were all assigned merit scores for cost and density.

Figure 5: Mount Design 2

Figure 6: Mount Design 3

5 Evaluation of Design Alternatives

5.1 Feasibility of Mount Designs

To compare the three designed mount alternatives against the feasibility criteria set forth in the section above, a matrix was created. The project team considered all options and assigned each method of manufacturing a rating of pass or fail with respect to the project scope.

Table 1: Feasibility Analysis for Three Mount Designs

	Mount Feasibility Criteria		
	Technical	**Payload**	**Operational**
Design 1	Pass	Pass	Fail
Design 2	Pass	Pass	Pass
Design 3	Pass	Pass	Pass

Based on the technical, financial, and operational criteria set forth by our client, Design 1 failed for its inability to rotate separately from the rest of the robot. The remaining two designs were compared using merit criteria.

5.2 Merit Evaluation of Mount Designs

All mount merit criteria were scored on a scale of 1 to 10. Each merit criteria was deemed important, and thus were equally weighted for the calculation of total merit values.

5.2.1 Aesthetics

The two designs were evaluated based on looks. The top deck of the chassis sits nine and a half inches from the ground, and has a four-inch antenna, bringing the total height of the robot to 13.5”. Attaching design 2 to the top deck will bring the total height of the robot to 14.5”, allowing the camera to clear the antenna, and maintaining a compact look to the Thumper. Design 2 was awarded a score of 8.

Attaching Design 3 to the top deck off the chassis brought the total height of the robot to 20.5”. This is about knee height for an average person. This height is not unreasonable, but it is noticeably higher than Design 2. An arm sitting this high off the deck begins to appear unstable and may prevent to robot from navigating narrow environments. For this reason, Design 3 was awarded a score of 4.

5.2.2 Material Density

Steel, carbon fiber, PVC and aluminum were all considered for the mount material. 4140 Steel has a density of 0.284 lb/cubic inch, carbon fiber-0.06, PVC-0.05, and 6061-0.1. Plotting these values of Figure 7, the merit scores for each material can be determined.

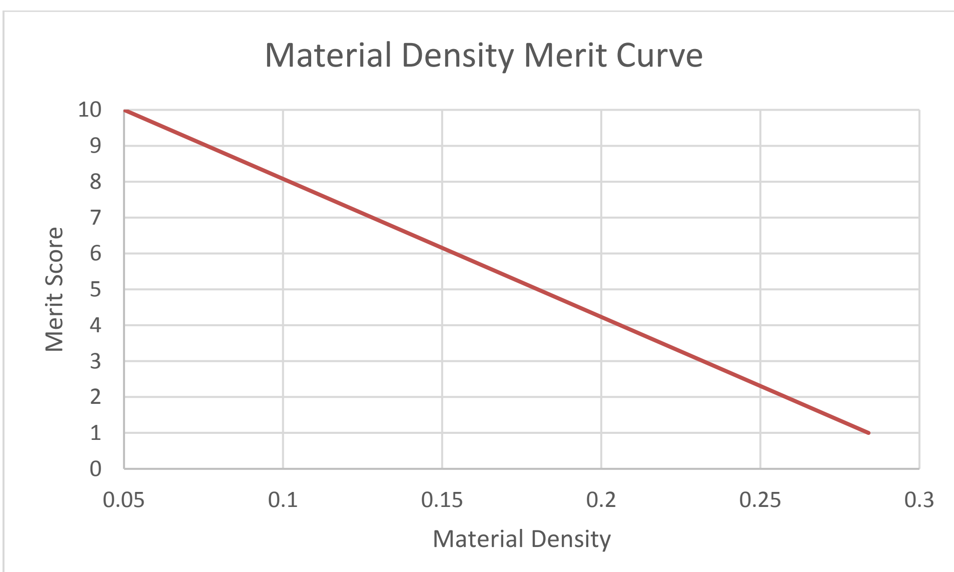


Figure 7: Material Density vs. Merit Score. The value merit score is inversely related to the density because of the weight limit for the Thumper

From the graph, the PVC scores a merit value of 10, Carbon fiber scores a merit value of 9, steel scores a merit value of 1, and aluminum scores a merit value of 8. It can be concluded that PVC is the preferred material with which to build the arm. For the rest of the merit analysis, the designs will be assumed to be constructed from PVC and both designs will be given a merit score of 10 for material density.

5.2.3 Arm Length

Arm length is important for several reasons. First, it effects the Thumper's ability to fit into confined spaces. Second, the increased lever arm also increases the moment within the cross section of the arm at the base. The arm length for Design 2 is five inches and the arm length for Design 3 is 11 inches. Figure 8 shows the merit score for arm length is inversely related to arm length because of the weight limitation of the thumper chassis and the fact that arm length is related directly to the moment cause be the force applied at the top of the arm. The arm length starts at four inches because the camera platform would be unable to rotate fully because of the antenna.

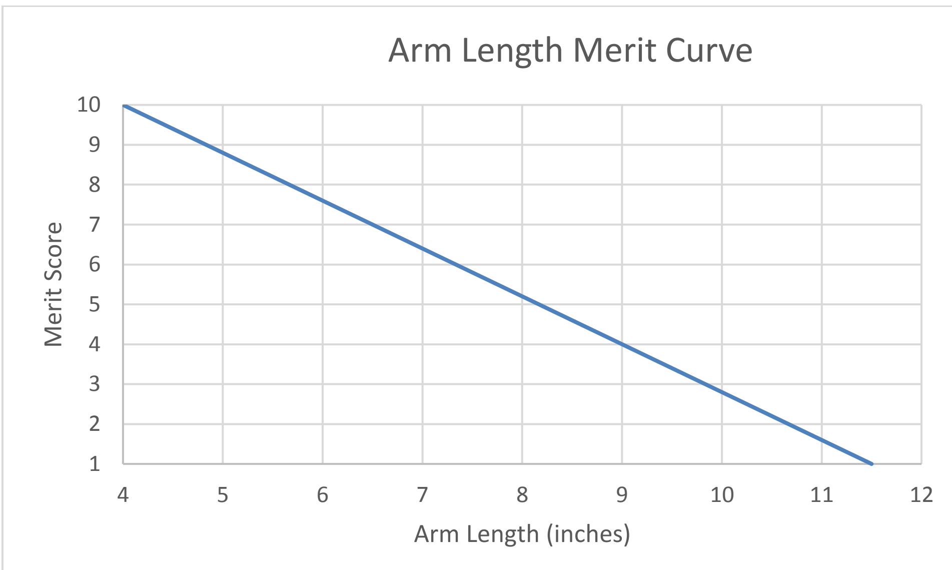


Figure 8: Merit Curve for Arm Length

Plotting the respective arm lengths on the curve, Design 2 receives a merit score of 9 and Design 3 receives a merit score of 2.

5.2.4 Ease of Attachment

Both designs have similar assembly. For this reason, their merit scores for ease of attachment will be similar. Design 3 has one extra step when it comes to attaching the camera. The cage designed to hold the camera in place requires slightly more work than the nylon strap from the other design. This causes the merit score for Design 3 to fall. Design 2 scored a merit value of 7. Design 3 scored a merit value of 6.

5.2.5 Cost

Assuming the mount arm will be constructed using PVC, the total cost of each design was calculated to determine the merit score for cost. Ideally, the mount would be constructed for free, so a perfect merit score is obtained when the cost of materials is \$0. The maximum budget provided is \$300, so if materials cost \$300, a merit score of 1 is obtained. The cheaper design is desirable, so the merit score is inversely related to cost.

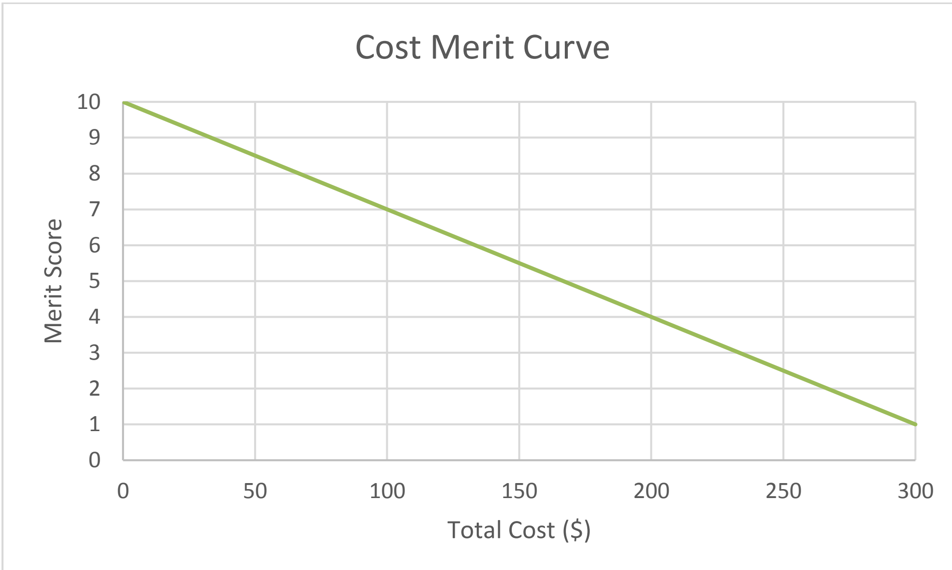


Figure 9: Cost Merit Curve

Only the cost of raw materials was assessed for this merit score. The total cost of materials for Design 2 is \$115. The total cost for Design 3 is \$125. Design 2 was awarded a score of 7, and Design 3 was awarded a score of 6.

5.2.6 Conclusion

Table 2: Merit Analysis for Three Mount Designs

	Mount Merit Criteria					
	Aesthetics (5%)	**Material density (35%)**	**Arm Length (30%)**	**Ease of Attachment (20%)**	**Cost (10%)**	**Total**
Design 2	8 (0.4)	10 (3.5)	9 (2.7)	7 (1.4)	7 (0.7)	8.7
Design 3	4 (0.2)	10 (3.5)	2 (0.6)	6 (1.2)	6 (0.6)	6.1

**** Merit value (Weighted value)***

Design 2 is the preferred design based on merit analysis. The length of the arm plays an important role in keeping the weight at a minimum. The increasing length of the arm also causes the aesthetics score to decrease. The material chosen for the attachment arm is PVC pipe, which will keep the weight down and provide the necessary strength to support the ZED Stereo Camera and motor during any acceleration of the Thumper.

5.3 Feasibility of Systems

To compare the three SLAM systems against the feasibility criteria set forth in the section above, a matrix was created. The project team considered all options and assigned each SLAM system a rating of pass or fail with respect to the project scope.

Table 3: Feasibility Analysis for Three SLAM Systems

	System Feasibility Criteria		
	Technical	**Financial**	**Operational**
ZED and Jetson TX1	Pass	Pass	Pass
GMapping	Pass	Pass	Pass
eDVS	Pass	Pass	Fail

Based on the technical, financial, and operational criteria set forth by our client, eDVS was eliminated as a possible design alternate. The remaining two systems were compared using the determined merit criteria.

5.4 Merit Evaluation of Systems

Table 4: Merit Analysis for Three SLAM Systems

All merit criteria were scored on a scale of 1 to 5. The data processing rate, weight and size, and memory criteria were weighted at 30%. Cost was only weighted at 10% because the client placed emphasis on performance of the system and had little concern for the overall cost. For simplicity, the ZED Stereo Camera and Jetson TX1 is referred to as System 1 and GMapping is referred to as System 2.

5.4.1 Data Processing Rate

System 1 contains a quad-core ARM Cortex-A57 MPCore Processor that is able to run at 2.3 GHz or higher, as required by the ZED camera. System 2 includes a raspberry pi which contains a 1.2 GHz 64-bit quad-core ARM Cortex-A53 processor. The maximum merit value of 5 was awarded to System 1, and a score of 3 was awarded to System 2.

5.4.2 Weight and Size

System 1 includes the ZED Stereo Camera weighing 0.35 pounds and measuring 7 x 7 x 1 inches and the Jetson TX1 weighing 1.5 pounds and measuring 6.6 x 6.6 x 3 inches. System 2 includes the raspberry pi 3 weighing 0.1 pounds and measuring 3.4 x 2.2 x 0.8 inches and an Arduino weighing 0.1 pounds and measuring 2.7 x 2.1 x 0.1 inches. System 2 was awarded a score of 5 while System 1 was awarded a score of 3.

5.4.3 Memory

System 1 has 4 GB of RAM, significantly higher than the 496 MB of RAM in System 2. System 1 was awarded a merit value of 5 while System 2 was awarded a value of 1.

5.4.4 Cost

The components in System 1 and their prices include the following: Jetson TX1, $599; ZED Stereo Camera, $449. The combined cost of System 1 is approximately $1,040. The components in System 2 and their respective prices include the following: Raspberry Pi 3 Model B, $40; Arduino UNO, $20; laser rangefinder, $220; motor shield, $20; compass, $20; mouse sensor, $10. The combined cost of System 2 is approximately $220. System 1 was given a merit value of 1 and System 2 was given a merit value of 5.

5.4.5 Conclusion

	System Merit Criteria				
	Data Processing Rate (30%)	**Weight/Size (30%)**	**Memory (30%)**	**Cost (10%)**	**Total**
ZED and Jetson TX1	5 (1.5)	3 (0.9)	5 (1.5)	1 (0.1)	4.0
GMapping	3 (0.9)	5 (1.5)	1 (0.3)	5 (0.5)	3.2

**** Merit value (Weighted value)***

After scoring each system according to the merit criteria, it was determined that System 1 was the preferred alternative.

6 Work Accomplished

6.1 Designing the mount

While designing the mount, there were several things to take into consideration. First, the camera must sit on an arm, allowing it to rotate freely from the robot. The arm would have to be more than four inches long because there is an antenna that reaches four inches higher than the top of the Thumper chassis. Second, it was known that the ZED Stereo Camera is light, and it would be virtually impossible to design a mount that would break under any loads applied by the camera. Third, the total weight of the mount and camera would not be able to exceed 11 pounds. Based on these criterion, it was concluded that the mount should be kept as short as possible to minimize weight and vibration. It was also concluded that a step motor would be easier to control and program, so a step motor will drive the platform that rotate the camera. PVC pipe will be used to build the mount due to its low cost and weight.

6.2 Mount Design Analysis

The mount must be able to support the ZED Stereo Camera during acceleration and deceleration of the Thumper. To determine the stresses within the mount arm, the maximum acceleration of the Thumper must be calculated. The Thumper has six motors which can muster a max torque (T) of 49 N-cm, a wheel diameter (D) of 120 mm, and a mass of 2.7 kg.

$$\boldsymbol{T = F * d} \qquad \textbf{Equation 1}$$

$$\boldsymbol{F = M * A} \qquad \textbf{Equation 2}$$

Applying Equation 1 with *d* defined as the distance from the force to the axis about which the torque is applied, it can be shown that the max force (*F*) the Thumper can apply to the ground is 8.2 N per motor. The maximum acceleration the Thumper can achieve is 18.3 m/s^2, by applying Equation 2. Knowing the mass of the camera is 159 g, Equation 2 can be reapplied to determine the max horizontal force applied at the top of the mount arm is 2.91 N.

$$\boldsymbol{\sigma = -\frac{My}{I}} \qquad \textbf{Equation 3}$$

Knowing the maximum force applied and the length of the lever arm, we can use Equation 3 to calculate the maximum stresses in the mount arm. At full acceleration, the maximum moment (M) on the arm is 369.57 N-mm. The distance from the centroid of the cross section of the arm (y) is ±44.45 mm. This yields the maximum stresses in the arm at ± 11.64 kPa. The maximum tensile stress of PVC plastic is on the order of 60 MPa, therefore, the maximum stress predicted is well beneath the failure capacity of the material being used.

6.3 Battery Supply Analysis

Two Turnigy hard case pack LiPO batteries will be used to power the entire system, including the Thumper, Jetson TX1, ZED Stereo Camera, and Pixhawk. Each battery is a 5000mAh 2 cell 7.4 volt battery. The recommended motor voltage for the Thumper is 2-7.5 volts. The Jetson TX1 uses a 5V/3V converter. The ZED USB is rated for 5V and 380mA. The Pixhawk USB is rated for 4.8-5.4 volts. The total maximum input voltage for these components is approximately 23 volts; however, that much voltage is not required for operation. Prior testing has confirmed that the two provided batteries are capable of running the entire system together.

6.4 ZED Mapping and Localization Capability

Our main feasibility criteria for this project was the system had to be able to map an area and localize itself within that area. The ZED Stereo Camera meets and exceeds this requirement because it has been designed to add depth perception, positional tracking, and 3D mapping to any application. It can generate a 3D map of an area by using its binocular vison, also known as stereo vision. Similar to how humans can view the world around us in 3D by combining images from each of our eyes to create a 3D image, the ZED Stereo Camera combines images from its two side-by-side cameras to create a 3D stereo picture. The ZED is able to do this process in real-time at a frame-rate up to 100Hz in WVGA mode and can sense how far away objects are from 70cm to 20m. The ZED Stereo Camera is also able to localize itself within the area it is mapping because it has built in 6-axis positional tracking that is accurate within +/- 1mm and 0.1°. Figure 5 shows an example of a 3D map generated by the ZED Stereo Camera. On the right side of Figure 5 the red line shows the camera’s ability to track its location within the map it generates. On the left side of Figure 5 the top picture shows a real-time view whereas the bottom picture shows what the ZED Stereo Camera is seeing.

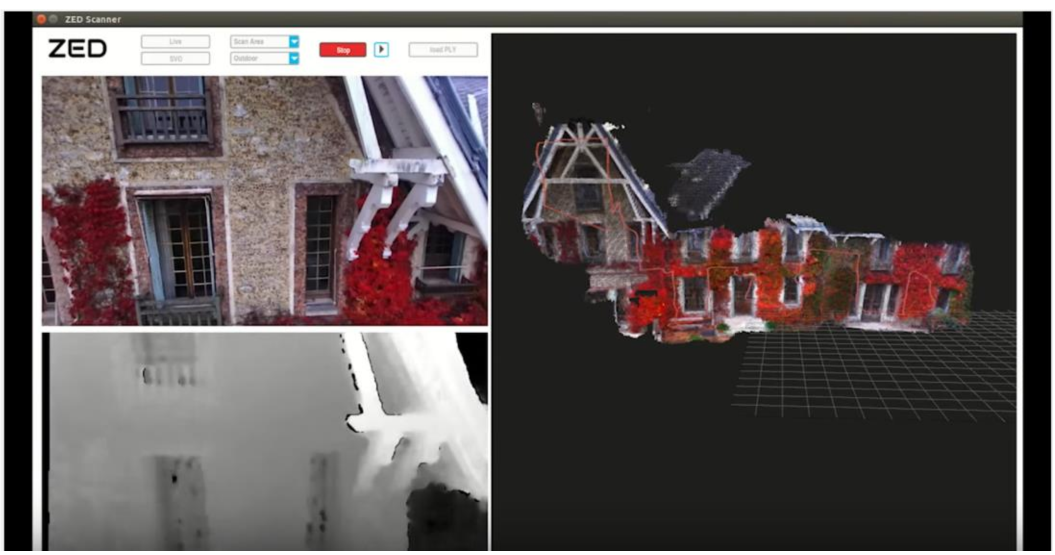


Figure 10: Example 3D Map Generated by ZED Stereo Camera

6.5 Jetson Ability to Process Data

The Jetson TX1 contains a quad-core ARM Cortex-A57, which extends the reach of ARM architecture into premium 64-bit mobile and infrastructure applications. The Cortex-A57 features cache coherent interoperability with ARM Mali^{TM} family graphics processing units (GPUs) for GPU compute applications. The Jetson TX1 also contains an NVIDIA Maxwell GPU with 256 CUDA-cores delivering over 1 TeraFLOPs of performance and has 4GB of LPDDR4 memory. The included camera interface is capable of 1400 MPix/s. These technical specifications make the Jetson TX1 a highly desired and competitive piece of technology for processing SLAM algorithms and will contribute greatly towards the success of this project.

6.6 Size of Area Able to Map

Since the ZED Stereo Camera is a new device, we were unable to find information about the size of the files created when the ZED Stereo Camera maps an area. This information will be gathered through future testing and our information will be updated accordingly. Since the Jetson TX1 will be where the files are saved and it has 4GB of RAM with the ability to increase this capacity through the SD card slot, we predict the system should be able to map any area our client desires.

7 Final Design Specifications

The final design specifications are divided into two categories, system requirements and mount design.

7.1 System Requirements

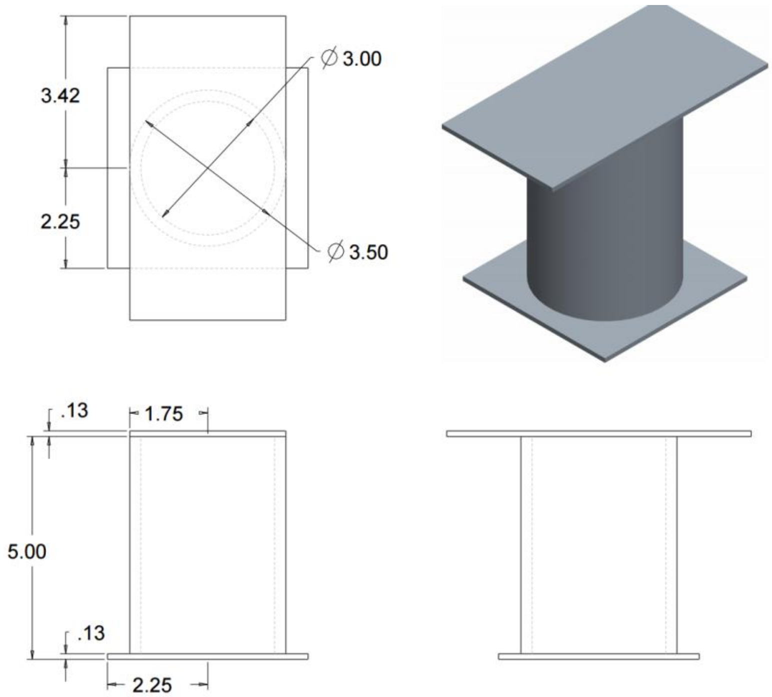
For the ZED and Jetson TX1 system to function properly, all the following hardware and software requirements must be met.

Requirements for ZED Stereo Camera and ZED SDK:

- Dual-core 2.3GHz processor or faster
- 4 GB of RAM
- NVIDIA GPU with Compute Capabilities > 2.0
- CUDA 8.0
- USB 3.0 port with latest drivers
- Windows 7, Windows 8, Windows 8.1 (64bits), Ubuntu 14.04

7.2 Mount

The chosen mount design, Design 2 which can be seen in Figure 11, will be constructed from PVC with an arm length of 5” and a platform width of 7”. The ZED Stereo Camera will be secured to the platform by using a nylon strap. Constructing the mount out of PVC will keep the cost low, $115, while still meeting all feasibility criteria.



our client

Figure 11: Final Mount Design

8 Budget and Costs

This project requires many components in order to be successful. The client has provided us with Thumper, Pixhawk Autopilot, and 3DR UBlox GPS + Compass Module so they will not be included in our budget analysis. The resources required have been divided into two categories: Financial and Guidance. Without either resource, this project would not be able to be completed.

8.1 Financial

Table 5 shows the cost of the parts for the ZED and Jetson TX1 system, as well as the total cost of the system. Table 6 shows the cost of the materials needed to build the mount and the total cost of the mount.

Table 5: ZED and Jetson TX1 System Budget

Item	Supplier	Price
ZED Stereo Camera	Stereo Labs	$449.00
Jetson TX1 GPU	NVIDIA	$599.00
Total Cost		**$1,048.00**

Table 6: Mount Budget

Item	Dimensions	Supplier	Amount	Price
PVC pipe	3.5” outer diameter 3” inner diameter	Home Depot	2 ft.	$5.44
Motor	2.25”x2.17’	Automation Direct	1	$35.50
Aluminum Plate	1ft x 4ft	Materials Depot	1	$75.60
3”x4” PVC reducing coupling	3”x4”	Home Depot	1	$6.57
PVC pipe	4.5” outer diameter 4” inner diameter	Home Depot	2 ft	$6.56
4” PVC Hubcap	4”	Home Depot	1	$7.94
PVC Cement	N/A	Home Depot	1	$4.94
Total Cost:				**$142.55**

8.2 Guidance

Each team member chose one to two advisors as a guide for their respective area of the project. The chosen technical advisors provided great insight and guidance in terms of their specialization. Their contributions are invaluable to this project.

9 Proposed Test

The following tests have been deemed appropriate to gauge the project's progress and steer the team towards timely completion.

9.1 Mount Operation

Test the mount to ensure it is operational and can properly rotate to accommodate the needs of the ZED Stereo Camera and the corresponding algorithms.

9.2 Mount Strength and Endurance

Attach the ZED Stereo Camera to the mount and the mount to the Thumper. Have the Thumper navigate a safe environment and observe the stability of the mount. Take notes and make changes as required.

9.3 Safe Thumper Navigation

Fully assemble the system, and test the movements of the Thumper to ensure it can safely navigate through any environment without running into obstacles or rolling off a ledge. Localization and mapping is not required to pass this test.

9.4 SLAM by ZED

Test the mapping capabilities of the ZED Stereo Camera to ensure a desired result is achievable. Use of the Thumper is not required to pass this test.

9.5 SLAM in Different Environments

Test the entire system: Thumper, ZED Stereo Camera, and Jetson TX1. Have the system perform SLAM in various environments, both indoors and outdoors. Make observations and update the system as necessary. Repeat until the outcome is satisfactory and meets the project requirements. This is the final test and will determine the success of the project.

10 Team Talents

This team is made up of three students from the Mercer University School of Engineering. Each student has completed three years of schooling for their respective degrees and each has been cleared to work on this project by finishing the prerequisite coursework. Appendix C contains the resumes for each team member detailing qualifications and related experience.

Matthew Deremer is a senior pursuing a Bachelor’s of Science in Electrical Engineering, a minor specialization in Computer Science, and a Master’s of Science in Computer Engineering. He has gained extensive experience in research and development, drafting, building cables, and constructing a database using the Microsoft Access IDE through his internship at Georgia Tech Research Institute (GTRI). The experience that Matthew Deremer holds will allow him to be successful in the electrical workmanship of the project as well as make effective contributions towards the work of other disciplines.

Luke Pace is a senior pursuing a Bachelor’s of Science in Computer Engineering and a Master’s of Science in Computer Engineering. He has gained extensive programming experience in Java, C++, Angular, and CSS through his internship at ScienceTRAX where he works as a junior developer. The experience that Luke Pace has will allow him to be successful in the programming of the SLAM system.

Christopher Woiwode is a Senior studying for both his Masters and Bachelors of Science in Mechanical Engineering, has been trained in drafting, manufacturing and machining throughout his courses at Mercer. He has also held leadership positions and jobs putting him in charge of handling money and negotiating with clients. Christopher’s experience will help the team achieve success on this project.

11 Project Management

The management of this project has been divided into three areas, scheduling, internal, and external. Each area has contributed greatly to the success of this project.

11.1 Scheduling

The Preliminary Design Review phase of this project has been outlined in detail using a Gantt chart, as seen in Appendix C. The Gantt chart was used to optimize the order of operations necessary to complete and manage the scheduling of the PDR phase. The Gantt Chart also shows a proposed outline of task to be completed in the Critical Design Review phase.

11.2 Internal Management

At the commencement of this project, the decision was made to segment the project into two divisions, SLAM system and mount . Each division was managed by the individual with the most experience in that particular area. Luke Pace managed the SLAM system aspect of the project and also functioned as the team leader. Matthew Deremer assisted with the SLAM system, focusing on the hardware aspect. Chris Woiwode managed the mount portion of the project.

11.3 External Management

External management was primarily provided by our team, Dr. Wright, along with our client, Dr. Choi. Both Dr. Sumner and Dr. Vo provided weekly feedback to the project team to determine project, progress, workload distribution, direction, and team cohesiveness. Their continuous feedback was invaluable to the PDR phase of this project and will be necessary once more during the Comprehensive Design Review during Fall 2015

12 Conclusion

After conducting the merit analysis, the Jetson TX1 and ZED Stereo Camera combined system is confirmed to be the preferred system alternative, based on the established design criteria. The merit analysis conducted for the mount alternatives confirmed mount Design 2 as the preferred alternative. The detailed engineering analyses shows that the preferred alternatives are feasible solutions and that by completion of the project will be able to pass the performance requirements set by the client, Dr. Choi. The team recommends using the chosen alternative for implementation of the project in the coming semester.

13 References

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Appendix A. Components for Use with all SLAM Alternatives

Figure 12: Thumper Chassis

Figure 13: Pixhawk Autopilot

Figure 14: 3DR UBlox GPS + Compass Module

Appendix B. GMapping Components

Figure 15: Arduino Uno

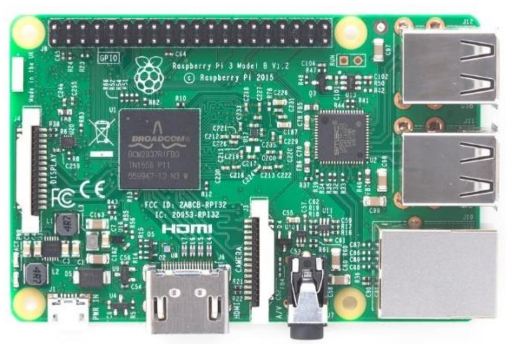

Figure 16: Raspberry Pi 3-Model B

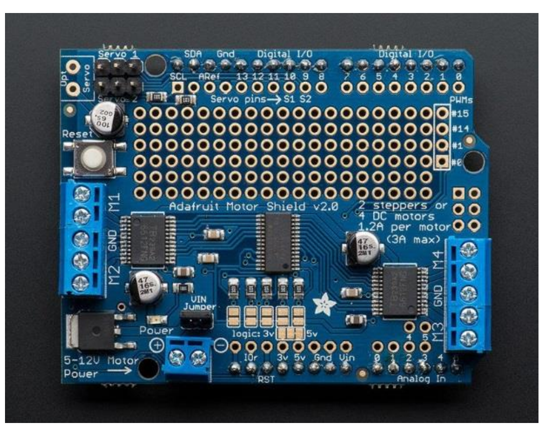

Figure 17: Adafruit Motor Shield

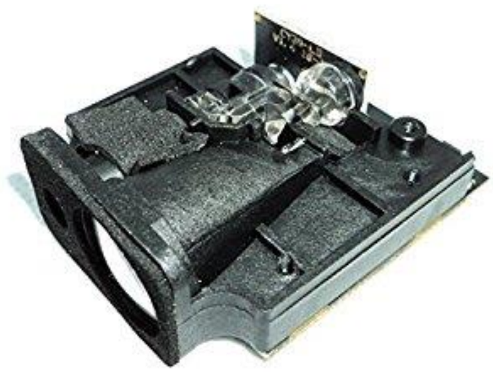

Figure 18: Laser Range Finder Sensor LRG/LIDAR

Figure 19: HMC5883L Compass

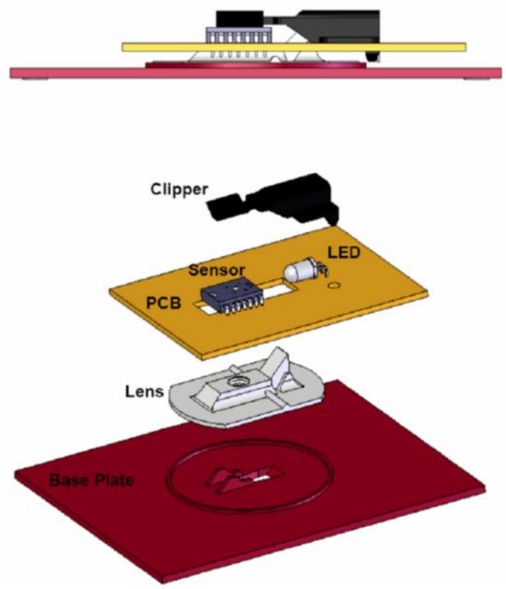

Figure 20: Mouse Sensor PAW3504

Appendix C. Gantt Chart

	Task Name	Start	Finish
1	Gather Information	Tue 8/23/16	Tue 9/13/16
2	Write Proposal	Tue 8/23/16	Tue 9/6/16
3	Determine Design Alternatives	Tue 9/13/16	Tue 10/4/16
4	Determine Merit/Feasibility Criteria	Tue 9/13/16	Tue 10/4/16
5	Conduct Engineering Analysis	Tue 10/4/16	Tue 10/18/16
6	Conduct Materials Analysis	Tue 10/4/16	Tue 10/18/16
7	PDR Documentation	Tue 10/11/16	Tue 11/15/16
8	Design Electrical Configuration	Tue 10/18/16	Tue 11/1/16
9	Design Mount Assembly	Tue 10/25/16	Tue 11/8/16
10	Deliver PDR	Wed 11/16/16	Wed 11/16/16
11	Collect Information from Dr. Choi	Tue 11/15/16	Tue 12/13
12	Plan Programming Design for ZED	Thu 9/29/16	Tue 10/18/16
13	Write Code Foundation	Tue 10/18/16	Tue 11/8/16
14	Conduct Mount Assembly	Tue 10/25/16	Tue 11/8/16
15	Assembly Electrical Hardware	Tue 10/25/16	Tue 11/8/16
16	Continue Coding ZED	Tue 11/8/16	Tue 11/15/16
17	Test Progress of Design	Tue 11/8/16	Tue 11/15/16
18	Make Proper Changes to Physical Design	Tue 1/10/17	Tue 2/21/17
19	Make Proper Changes to code	Tue 1/24/17	Tue 3/21/17
20	Test Plan	Tue 3/7/17	Tue 4/4/17
21	Complete Documentation	Tue 3/21/17	Tue 4/18/17
22	Deliver CDR	TBD	TBD

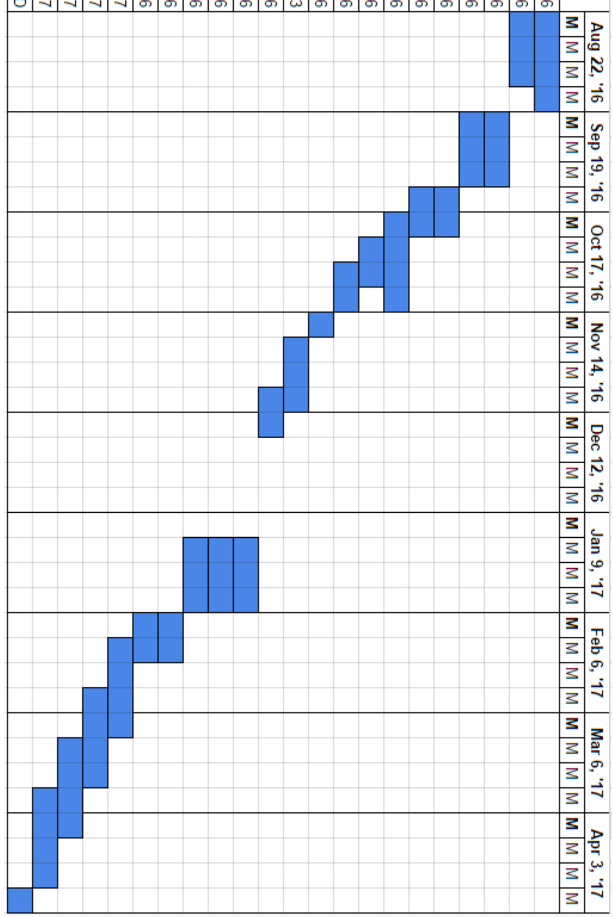

Figure 21: Gantt Chart for Project Schedule

Appendix D. Team Resumes

Matthew R. Deremer
157 Stonewall Place, Macon, GA 31204
mattderm95@gmail.com
(706) 983-1983

WORK EXPERIENCE

Intern: Georgia Tech Research Institute, Warner Robins Field Office – Oct 2014-Dec 2015, May 2016-current

- Gained AutoCAD experience with real-world projects
- Helped develop a database in Microsoft Access using the Access IDE

Intern: 4C Talent – Summer 2014

- 5-week internship program developing a database for a startup company

Head Lifeguard: Jefferson Parks and Recreation Department – 2011-2014

- Responsible for safety of patrons and pool facilities as well as managing other lifeguards

EDUCATION

Mercer University, Macon, GA – Aug 2013-Present

- Pursuing Bachelor's degree in Electrical Engineering, Minor in Computer Science, Master's degree in Computer Engineering
- Undergraduate academic GPA: 3.835 out of 4.0
- Current undergraduate classes: Communication systems I, Engineering Senior Design Project, Programming II (Java), Theory of Data Communications
- Graduate academic GPA: 4.0 out of 4.0
- Current graduate classes: Introduction to Computer Architecture
- Expected graduation date: May, 2018

HONORS & AWARDS

Dean's Council – Fall 2015

- One of four students from the engineering school selected to participate in a council that provided feedback to Mercer's administration on how to improve academic opportunities for students

President's List, Mercer University – Fall 2015
Dean's List, Mercer University – Fall 2013, Spring 2014, Fall 2014, Spring 2015, Spring 2016
Boy Scouts of America Eagle Scout – 2011

- Highest honor awarded in Scouting – Based on leadership and requirements (exceeded requirements)

ACTIVITIES & AFFILIATIONS

Mercer University:

Tau Beta Pi – Sep 2015-Present

- Engineering Honor Society
- Offered to top fifth of Junior class

Sigma Xi Honors Research Society – 2014-Present
Phi Eta Sigma Honors Society – 2014-Present
Honors Engineering Program – Aug 2013-Present
Alpha Tau Omega Fraternity – Sep 2013-Present

- Chaplain (2016), responsible for interfraternity relations and planning chapter retreats
- Secretary (2015), responsible for attendance and chapter meeting minutes

Luke J. Pace

Current Address
1400 Coleman Avenue
MU Box 72962
Macon, GA 31207-0002
(864) 723-5455

Luke.Joseph.Pace@live.mercer.edu

Permanent Address
208 Creekwood Lane
West Union, SC 29696
(864) 638-8424

Objective

Seeking to design a SLAM system using the ZED camera system and Jetson TX1.

Education

Bachelor of Science in Computer Engineering, Mercer University, Macon, Georgia
Currently a Senior GPA: 3.556
Masters of Science in Computer Engineering, Mercer University, Macon, Georgia
Currently Enrolled GPA: In progress

Work Experience

Science Trax, Macon, Georgia January 2015-Present
Support Analyst and Junior Developer
· Design test in our database for electronic data capture using Javascript and HTML.
· Send emails and participate in conference calls with coworkers and clients to communicate progress of test development.
· Assist in the training of new employees.
· Write detailed proposals of projects to present to clients.
· Collaborate with coworkers to develop the most efficient design of test.

Mercer University, University Center, Macon, Georgia Summer 2014-Present
Bear Force Leader
· Work with a team of supervisors to manage the University Center, Mercer Basketball games, and Mercer Football games.
· Supervise events within the University Center ensuring all necessary accommodations are met.
· Take part in weekly meetings to discuss scheduling, goals, and address necessary situations.
· Develop and implement plans to motivate workers so they reach their maximum potential and consistently generate a customer service environment.
· Constantly engage workers to ensure goals set by supervisors are achieved.
· Assist in the interviewing, hiring, and training of new employees.

Advanced Electronics, Seneca, South Carolina Summer 2013 and 2014
Computer Technician
· Communicated with customers to pinpoint their problem and provide a diagnostic including approximate time to resolve problem and cost of repair.
· Individually repaired computers and printers which had either software problems or hardware problems.

· Solely managed retail store front by answering customer questions over the phone and in person, operating the cash register, and walking customers through any issues they had with their devices.
· Created spreadsheets for store inventory.
· Assisted in the installation of surveillance systems for professional and residential use.

Computer Skills

C++, Java, Javascript, Angularjs, CSS, HTML, Microsoft Office

Honors and Professional Organizations

National Society of Leadership & Success

Dean's List 2013, 2014

Phi Eta Sigma National Honor Society

Christopher Woiwode
1248 Shamrock Street, 31201, Macon, GA
(Cell) 912-856-7676
cwoiwode@gmail.com

Education: **Mercer University School of Engineering, Macon GA, August 2013 - present**
Master of Science Degree - Mechanical Engineering
Bachelor of Science Degree - Mechanical Engineering

Completed Coursework

- Manufacturing practices
- Visualization, Graphics and Solid Modeling
- Experimental Methods
- Machine Design
- Electrical Fundamentals 1 & 2

Other Skills

- Operating Systems:
    - IOS
    - Windows
    - Linux
- PTCreo
- AutoCAD
- MatLab
- Microsoft Office
- C++ Programming

Projects:

- Manufacturing Practices Fixture
    - Worked in a team of three to build a fixture designed to produce a bottle opener using an end mill
    - Presented the working fixture to the instructor and colleagues
- Tug-of-War K'nex Car
    - Worked in a team of three to build and compete with a car built out of K'nex pieces in a tug-of-war competition
    - Prepared and presented a proposal, PDR and CDR to the instructor and colleagues
- Freshman Design Toothpick Bridge
    - Worked as a team to build a model bridge to withstand tension and compression loads
    - Prepared and presented a proposal, PDR and CDR to the instructor and colleagues

Experience:

- Real Estate Broker July 2016 - Present
    - Qualifying broker
    - Represent client in real estate transactions
    - Experience working with clients to achieve a specific goal in a set amount of time
- Real Estate Salesperson June 2013 - Present
    - Represented a broker who represented a client
    - Experience working with clients to achieve a specific goal in a set amount of time

Involvement:

- Order of Omega, Honor Fraternity August 2015 - Present
- Interfraternity Council January 2015 - Present
- Sigma Alpha Pi, Leadership Fraternity August 2014 - Present
- Sigma Nu Fraternity September 2013 - Present