Road Surface Mapping

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Table of Contents

Table of Contents.... i
Figure List.... iv
Table List.... vi
1 Executive Summary.... 1
2 Project Description.... 3
2.1 Project Background.... 3
2.2 Goals and Objectives.... 4
2.2.1 Optical Goals.... 4
2.2.2 Electrical Goals.... 6
2.2.3 Programing Goals.... 7
2.3 List of Requirements and Specifications.... 8
2.4 House of Quality.... 9
2.5 Overall Project Schematic.... 12
3 Research and Part Selection.... 13
3.1 Existing Technologies.... 13
3.1.1 Scanning LiDAR.... 13
3.1.2 Flash LiDAR.... 14
3.1.3 Machine Vision.... 16
3.1.4 Technology Comparisons.... 17
3.2 Electrical Technologies.... 20
3.2.1 AC-DC Converter.... 20
3.2.2 DC-DC Converter.... 20
3.2.3 Voltage Regulator.... 22
3.2.4 Battery.... 22
3.2.5 Electronic Technology Comparison.... 23
3.3 Programming Technologies.... 24
3.3.1 WebGL.... 24
3.3.2 OpenGL.... 25
3.3.3 Threejs.... 25
3.3.4 Programming Technology Comparison.... 25
3.4 Part Selection.... 26
3.4.1 Illumination Source.... 26
3.4.2 Camera.... 29
3.4.3 Cylindrical Versus Powell Lens.... 33
3.4.4 Communication.... 36
3.4.5 Data transfer.... 38

3.4.6 GPS module........ 40
3.4.7 Microcontroller........ 42
3.4.8 Power Supply........ 44
3.4.9 Battery........ 48
3.4.10 Server........ 50
3.4.11 Database........ 53
3.4.12 Front-End Frameworks........ 55
3.4.13 Back-end........ 61
4 Standards and Constraints........ 64
4.1 Standards........ 64
4.1.1 Laser Safety Standards........ 64
4.1.2 Computer Standards........ 67
4.1.3 Electrical Safety Standards........ 71
4.2 Constraints........ 76
4.2.1 Safety Constraints........ 76
4.2.2 Economical and Time Constraints........ 77
4.2.3 Environmental Constraints........ 77
4.2.4 Manufacturability and Sustainability Constraints........ 78
4.2.5 Power Constraints........ 79
4.2.6 Electromagnetic Interface Constraint........ 80
4.2.7 Bandwidth Constraint........ 80
5 Project Hardware and Software Design........ 82
5.1 Initial Designs and Schematics........ 82
5.1.1 Scanning LiDAR........ 82
5.1.2 Optical System Schematic........ 84
5.1.3 Software Schematic........ 86
5.1.4 Electrical Schematic........ 87
5.2 Hardware Design........ 87
5.2.1 Emitting Optical System........ 87
5.2.2 Detecting Optical System........ 91
5.2.2.1 Initial Detection System Design........ 92
5.2.2.2 Redesigned Detection System........ 98
5.2.3 Optical System........ 101
5.2.4 Microcontroller........ 103
5.2.5 GPS........ 105
5.2.6 Data storage........ 106
5.2.7 Electrical System........ 108

5.2.7.1 Electrical Design Protection 110
5.2.7.2 Power Design 112
5.3 Housing Design 112
5.3.1 General Housing Design 113
5.3.2 Optical Housing Design 114
5.3.2.1 Emitting Optical System Housing Design 116
5.3.2.2 Detecting Optical System Housing 117
5.3.2.3 Summary of Optical System Housing 118
5.3.3 Electrical Component Housing 118
5.4 Software Design 121
5.4.1 Video Processing and Rendering 121
5.4.1.1 Video Processing 121
5.4.1.2 Online Point Cloud Rendering 123
5.4.2 Website Backend Design 124
5.4.3 User Interface Design 131
5.5 Summary Design 134
6 System Integration and Testing 135
6.1 Testing of the Optical System 135
6.1.1 Emitting System Testing 135
6.1.2 Detecting System Testing 136
6.1.3 Overall Optical System Testing 136
6.2 GPS Testing 137
6.3 Testing of GPS Data Loss 139
6.4 Microcontroller Testing 140
6.5 WebGL Render Testing 142
6.6 Road Scan Position Testing 144
6.7 Battery Testing 145
6.8 Machine Vision Implementation 146
6.9 PCB Design and Implementation 153
6.10 Summary of System Integration and Testing 155
7 Administration 157
7.1 Budget and Funding 157
7.2 Milestones 159
8 Conclusion 161
Appendix A - copyright permissions 163
References 164

Figure List

Figure 1: House of Quality 11

Figure 2: Overall Project Schematic 12
Figure 3: Scanning LiDAR System 14
Figure 4: Flash LiDAR System 16
Figure 5: Scanning Versus Flash LiDAR 19
Figure 6: AC-DC conversion Versus DC-DC conversion 21
Figure 7: Benefits of Batteries 23
Figure 8: BGGR (Blue, Green, Green, Red) Bayer Sensor Array 30
Figure 9: Plano-Convex Cylindrical Lens 33
Figure 10: Powell Lens Fan Angle Generation 34
Figure 11: Cylindrical Versus Powell Lens Line Generation 35
Figure 12: Front-End Framework Usage Statistics from 2016 to 2022 57
Figure 13: Front-End Framework Interest Statistics from 2016 to 2022 60
Figure 14: Front-End Back-End Database Flowchart 62
Figure 15: Bluetooth Power Classes 70
Figure 16: Packet Structure 71
Figure 17: Initial LiDAR Design 82
Figure 18: Servo Resolution 84
Figure 19: Side View of Optical System 85
Figure 20: Top Down View of Optical System 85
Figure 21: Software Schematic 86
Figure 22: Electrical Block Diagram 87
Figure 23: Placement of the Powell Lens 91
Figure 24: Zemax Design for Detection System 93
Figure 25: Spot Size 95
Figure 26: Zemax Field Curvature/Distortion 98
Figure 27: Graph of Sun Irradiance vs. Wavelength 99
Figure 28: Transmission Allowance at 330 nm to 930 nm 100
Figure 29: Transmission vs. AOI 101
Figure 30: Powell Lens and Camera Placement 102
Figure 31: Optical Component Schematic 103
Figure 32: Microcontroller Block Diagram 105
Figure 33: Initial Electrical Schematic - LM7805 109
Figure 34: Schematic - MOSFET 111
Figure 35: Ender 3v2 3D Printer 113
Figure 36: Side View of Housing 114
Figure 37: Truck Mounting 114
Figure 38: Main Optical Housing 115
Figure 39: Bottom View of the Main Optical Housing 116
Figure 40: Rail System 116
Figure 41: Emitting System Mounts 117
Figure 42: Detecting System Mounts 117
Figure 43: Aperture 118
Figure 44: Summary of Optical Housing Design 118
Figure 45: Electrical Housing Hinge Top 120
Figure 46: Electrical Housing Base 120

Figure 47: The Surface-Level Server-Client Relationship 124
Figure 48: Server Components Block Diagram 125
Figure 49: Website Hosting Flowchart 126
Figure 50: Port Forward Analogy 128
Figure 51: Client Components Block Diagram 129
Figure 52: Rest API Block Diagram 130
Figure 53: Website Use Case Diagram 131
Figure 54: Website Flow 132
Figure 55: User Interface Mockup 133
Figure 56: User Interface Final 133
Figure 57: Battery Testing 146
Figure 58: Sample Image From ELP-USBFHD08S-MFV 147
Figure 59: Sample Image as a 2D Pixel Array 148
Figure 60: Brightened and Lower Contrast 149
Figure 61: Color Curve GUI 149
Figure 62: Laser on Uniform Depth 150
Figure 63: Laser on Unequal Depth 151
Figure 64: High-level Machine Vision Algorithm 151
Figure 65: Area Calculations 152
Figure 66: Initial PCB Design 154
Figure 67: Initial Ground Pour PCB Design 155

Table List

Table 1: Optical Goals 5
Table 2: Electrical Goals 6
Table 3: Basic Programming Goals 7
Table 4: Advanced Programming Goals 8
Table 5: Requirements and Specifications 9
Table 6: Specifications Based on Technologies 18
Table 7: Electronic Technology Comparison 24
Table 8: Comparison of Programming Technologies 26
Table 9.a: Laser Decision Matrix 28
Table 9.b: Criterion Definition for Table 8.a 28
Table 10: Resolution and Speed Specifications 31
Table 11: Features of ELP-USBFHD085-MFV and ELP-USBFHD03AF-A100 32
Table 12.a: Line Generator Lens Decision Matrix 36
Table 12.b: Criterion Definition for Table 12.a 36
Table 13.a: Communication Decision Matrix 38
Table 13.b: Criterion Definition for Table 13.a 38
Table 14.a: Data Transfer Decision Matrix 40
Table 14.b: Criterion Definition for Table 14.a 40
Table 15.a: GPS Module Decision Matrix 42
Table 15.b: Criterion Definition for Table 15.a 42
Table 16.a: Microcontroller Decision Matrix 44
Table 16.b: Criterion Definition for Table 16.a 44
Table 17.a: Power Supply Decision Matrix 47
Table 17.b: Criterion Definition for Table 17.a 47
Table 18: Battery Specification Comparison 50
Table 19: Server Decision Matrix 51
Table 20: Database Decision Matrix 54
Table 21: Front-End Framework Decision Matrix 56
Table 22: Standards 64
Table 23: Requirements by Laser Classification 65
Table 24: Classifying Lasers 66
Table 25: IEC Safety Standards 72
Table 26: Electrical ISO Safety Standards 74
Table 27: ANSI/UL Electrical Standards 75
Table 28: General Specifications of CPS635 88
Table 29: Optical Electrical Characteristics of CPS635 89
Table 30: LJ1765L1 Specifications 94
Table 31: Seidel Coefficient Variables 96
Table 32: General Specifications of FLH635-10 Bandpass Filter 100
Table 33: Storage Needs Calculations 107
Table 34: Power Specifications 110
Table 35: Power Design Specifications 112
Table 36: Summary of Hardware and Software Designs 134
Table 37: Angle VS. Laser Line Shift for 2 Inch Depth 137

Table 38: Testing of Rendering Pipeline 143
Table 39: Distance Accuracy 145
Table 40: Summary of System Integration and Testing 156
Table 41: Prototype Budget 158
Table 42: Project Milestones 160

1 Executive Summary

This project is a road mapping system that searches for damage such as potholes. The current system for road management to locate and identify road damage relies upon commuters to report the damage. The Department of Transportation would then have to send a team out to evaluate if the damage is significant enough to warrant a repair team. This system is slow and labor intensive and becomes even worse in remote areas. The goal of this project is to make detection and analysis of the road quicker, safer and easier for the road maintenance teams. By creating a device to map the surface of the road we enable maintenance teams to check the entire surface of the road without leaving their vehicle. The software used to analyze the damage can then compute the depth and size of the hole indicating whether the damage needs to be repaired and how much fill material would be required for the repair.

Initially this system was designed to be a form of scanning LiDAR where a point map would be created using a pulsing laser and time of flight calculations. The laser would be mounted on a rotating servo. The speed of the servo and the speed of the vehicle would be proportional. This is where the first difficulties with this design were detected. The speed required of the servo to handle even low vehicle speeds was more than the team was prepared to handle. The next issue to arise was with the detector. The detector would be required to have an extremely fast rise time to handle the pulse rate of the laser. The detectors capable of handling these speeds were outside of the group's budget constraints. In the end the team decided that a new design was needed to ensure a functional prototype be built within the time constraint.

The team briefly looked into using flash LiDAR technology. Flash LiDAR utilizes optics to spread the beam of a laser out to cover an entire area instead of a single point. The detector system uses an array of photodetectors to create a field of points simultaneously. This system would have reduced the servo speed but increased the cost of the detector. In the end this system would not meet the budget or time constraints.

The system design was then changed from LiDAR to machine vision. Machine vision entails using software to analyze video taken by a camera with a laser or other reference guides to gather data. In this project a laser line will be projected onto the road surface at an angle. The line will shift and deform as the road surface moves closer or farther from the laser emitter. The camera will be used to record these changes in the laser line's position. The software will then process the video to extract how much the line shifted at each pixel column. This data will be used to calculate the shift in the road's surface that would cause such a shift. Using a form of machine vision made creating the surface road mapping prototype a realistic venture as it fit within the time and budget constraints.

Goals, specifications, constraints, and objectives were considered and the design process began. While investigating parts and designing systems, it became apparent that the prototype would not be as effective as something that would be produced and sold to consumers. The goal became to prove the concept of the road surface mapper. Mainly due to budget constraints, the prototype will be built on a smaller scale with less resolution, more aberrations, lower run time and storage capacity than if a company was backing the project.

After finalizing the optical, electrical, and computer programming designs it was determined that this project is feasible given the time and budget.

2 Project Description

While driving, car owners are annoyed at the uneven road surfaces and unavoidable potholes. Their hope is their vehicles don't sustain any damage or need an alignment after a journey down a bumpy path. The department of transportation is usually informed of obstructions or irregularities in the road's surface by travelers; however many backroads or country roads are not reported as the number of people driving these roads are significantly smaller than city roads or highways. Our surface mapping device can be attached to any car and will indicate the location of obstructions and holes found on any road that the car drives down.

2.1 Project Background

Image processing is the act of modifying or analyzing a digital image to extract information or to alter the image in desired ways. Once in digital form operations can be applied and useful data can be extracted. Some of these operations include enhancement, restoration, compression, and pixel composition. Through analyzing the pixels of an image, it is possible to find changes in the location of a particular object in the image. Using this ability, it is possible to find shifts of a line due to depth changes of an object. In this project, our group explored the use of this subset of image processing to improve the effectiveness of road repair crews.

Our group is composed of two photonic engineers, two computer engineers, and one electrical engineer. The optical engineers will focus on the laser and camera setup, emitting a laser light and capturing images with a high speed camera, while the electrical engineer will focus on the power supply for the two designations in the project. Our device will have two components, one of which will consist of a laser diode and the second will include the web camera attachment to record the data in which the car is driving past, this is along the line provided by the diode. The role of the computer engineers is to make the data accessible. Accessibility will be implemented in two ways: organizing the data and presenting the data. Organizing involves establishing a database, synthesizing an algorithm that is capable of detecting road damage based on changes in laser line relative to the camera field of view, and refining data points into rasterization objects. Presenting involves designing a website to give the end user a visual of the damage to all scanned roads.

The goal of this project is to safely and efficiently map the surface of the road to locate road damage for repair. Therefore, the product needs to be securely mounted to a vehicle and protected from the elements, while operating at safe road speeds. The device will include a laser line system which will help indicate if there is a change in the depth of the road and a camera to capture these changes. The location of these changes or road damage will be tagged for repair using GPS. The data collected from the camera will be stored in a removable memory source such as a SD card or USB drives. The data will then be uploaded to a computer and run through a processing program to create a map of the road and identify damaged areas. A list of locations will also be generated that can be accessed through an application.

This project focuses on identifying road damage and where this damage is located. The Department of Transportation would benefit from this project as it presents a way of identifying and alert workers where they would need to go to repair the road. Companies like Google may also benefit as drivers could be altered to potential road damage on Google Maps. The government may be able to provide states with lower quality roads more funding through the federal-aid highway program. This project has the potential to provide many useful applications that would benefit companies, the government, and drivers.

2.2 Goals and Objectives

As stated above, the goal of this project is to safely and effectively map the road's surface and tag road work such as potholes with GPS tracking using a camera and laser system to detect changes in the surface of the road. After information is gathered from the optical system, this data will then be processed and users will be able to locate any road damage. Below are the core, advanced, and stretch goals for this project broken down by area and the objectives to reach these goals.

2.2.1 Optical Goals

The optical system goals of this project are pretty straightforward. Table 1 summarizes the optical goals of this project and the objectives needed to reach these goals. The table includes basic, advance, and stretch goals. The optical system must be built in a way that provides a mapping resolution of 4 in X 4 in while scanned at a minimum speed of 10 mph. Our goal is also to map approximately 2 feet. There are several objectives to meeting these goals. The camera frame rate will affect the resolution of our system along with the maximum speed the vehicle can travel. However, when choosing a camera the pixel size must be considered as it will affect resolution. The camera's field of view must be sufficiently wide enough to capture 2 feet. Also, the laser diode must have enough power to project a line of at least 2 feet and the powell lens that forms the line must have an angle of at least 90 degrees. Lastly, we want to be able to map damage that is at a minimum of 6 inches deep.

Table 1: Optical Goals

Type of Goal	Goals	Objective
Basic	Longitudinal resolution of 4 in X 4 in	Camera fps at a min of 40 Hz and vehicle speed of 10 mph.
	Vehicle speed of 10 mph	Camera frame rate needs to be a minimum of 40 Hz
	Map the road's surface	Camera field of view needs to image 2 feet wide Laser diode must have enough power to project a line of at least 6 ft. Powell Lens with an angle of at least 90 degrees
	Damage depth resolution of at least 6 in	Powell lens is set at an angle large enough to create a shift in the laser line when it encounters a pothole.
Advance	Longitudinal resolution of 2 in X 2 in	Camera fps at a min of 176 Hz and vehicle speed of 20 mph.
	Vehicle speed of 20 mph	Camera frame rate needs to be a minimum of 176 Hz
	Map the width of a car (6 feet)	Camera field of view needs to image 6 feet wide Laser diode must have enough power to project a line of at least 6 ft. Powell Lens with an angle of at least 90 degrees
	Damage depth resolution of at least 4 in	Powell lens is set at an angle large enough to create a shift in the laser line when it encounters a pothole.
Stretch	Longitudinal resolution of 1 in X 1 in	Camera fps at a min of 528 Hz and vehicle speed of 30 mph.
	Vehicle speed of 30 mph	Camera frame rate needs to be a minimum of 528 Hz
	Map 11 feet in width (tone lane)	Camera field of view needs to image 11 feet wide Laser diode must have enough power to project a line of at least 11 ft. Powell Lens with an angle of at least 90 degrees
	Damage depth resolution of at least 2 in	Powell lens is set at an angle large enough to create a shift in the laser line when it encounters a pothole.

After reaching the basic goals of our optical design, there are a few advanced and stretch goals that will be worked towards. The advanced goals include a scanning system resolution of 2 in X 2 in while moving 20 mph. We would also like to map the width of a car, 6 feet, and map any damage at least 4 inches deep. Finally, the stretch goals include a scanning system resolution of 1 in X 1 in at a speed of 30 mph or faster while scanning one lane or approximately 11 feet. Mapping damage that is at least 2 inches in depth would also fall under this goal.

2.2.2 Electrical Goals

This section describes the electrical goals for the surface road mapping system. These goals are tabulated in Table 2 and separated into basic, advanced, and stretch goals.

Table 2: Electrical Goals

Type of Goal	Goals	Objective
Basic	Power the laser diode	Provide enough power for the laser diode to function
	Power the web camera	Split power sources to provide the 5V current to the camera as well as what is needed for the diode
	Power the Raspberry Pi	Regulate the split voltage of 5 volts to the RaspPi and the other devices
	Minimum demo time	Complete a demo time of 5 minutes
Advanced	Extension of demo time	Complete an extended demo time of 10 minutes
	Provide visual battery charge level	Display the current battery charge so the user can approximate how much longer the device can run for
Stretch	Power any added components	Supply enough power for another device to be added or for a camera with higher capabilities

In the electrical perspective, there are several basic goals that would need to be met for the device to function properly. In the case of our device we have 2 main sections that need to be powered, including the laser diode and the web camera which will be capturing the recorded data to be sent to the server to be computed into where the road obstruction occurred and the measurements of it. With the objective/goals of these two parts being powered we also have to ensure that the device can turn on and maintain its function throughout the basic goal demo time of 5 minutes. During this demo time the device must start up efficiently and be able to transfer the data fully to the SD card to then convert into our database.

Once these basic electrical goals are met for this project, we can work on extending our basis to meet advanced and stretch goals to perform for the final demo. An advanced goal can include providing proof of an extended period of time that power is supplied for the road scanning around campus. Our current demo time for the scanner is 5 minutes of being able to scan and process data to our server, therefore an advanced goal that can be proved for the demo and still remain within the amount of storage capacity in the SD card, is to extend this time to 10 minutes. An example of a stretch goal would be to provide a port to the device, or allow for an extra use of the supplied power in the case that another feature would need to be added to assist with a further function of the device. If it is decided that our range of view needs to be lengthened or the capabilities of the software portion has to be increased then there should be variability in the supplied power to the device for such alterations.

2.2.3 Programing Goals

This section describes the programming goals for the surface road mapping prototype. Table 3 reviews the basic programming goals.

Table 3: Basic Programming Goals

Goals	Objective
Server	Ubuntu Server 20.04 LTS on a Raspberry Pi 4 Model B
Database	MongoDB Community Edition 4.4.18
Website Structure/Behavior	React
Website Look/Feel	Style the website’s components using CSS
Data Processing	Use Computer Vision principles to find differences in elevation

Some basic programming goals of this project will be having a server, a database and a web application all working together to store and transmit data to the user. The database should be configured to store all of the data we will be working with which includes GPS locational data to the data from road scans. The website should not distort the information pulled from the database. The web application should also be professional in the way it presents information.

The advanced programming goals for this project is to store only essential data in the database such an example would be to not include all GPS data just time and position as long as the signal is good. Categorization of road damage is also an advanced goal which will help the user see which areas are more damaged.

Providing user feedback upon startup of the device is an advanced goal because it is important to let the user know when the device is functioning properly and ready to record. Damage representation is important to allow users to see the exact damage in a particular area. Marking a map with road damage is important by giving the user a better understanding of where road damage actually is. A stretch goal for this project would be to include an interface where the user has a map of the scanned roads and the date they were scanned to keep track of which roads are due for scanning. This is a stretch goal because it is nice to have a feature where we can see what roadways were scanned most recently and it uses mostly the same method as marking a map with road damage. Table 4 reviews the advanced programming goals.

Table 4: Advanced Programming Goals

Goal category	Objective
Database	Store only essential data
Website	Provide road damage categorization
Device	Provide user feedback on startup
Website	Display damaged road and location
Website	Mark map with road damage
Website	Map to display all scanned roads

2.3 List of Requirements and Specifications

When designing a prototype, engineers must take into account specifications that must be incorporated. Table 5 describes the requirements for the road surface mapping device. Numerical specifications and a description are included along with the level of priority. The three highlighted requirements are specifications that must be met for our prototype to be successful.

Table 5: Requirements and Specifications

Requirement	Specification	Priority
Due to the difference in ambient light, during the day, a spatial filter aperture and bandpass filter is used which reduces the length of the line. At night, the aperture and bandpass filter is not needed allowing the line to be longer.	Day: 2 ft. Night: 6 ft.	High
The DOT classification for a pothole is 2 in depth or 8 in diameter. The margin of error must be acceptable between the calculated and actual values.	Less than 50% difference	High
Longitudinal resolution to detect a pothole is determined by the camera's frame rate and vehicle speed. The car will travel at a minimum speed to be safe to use on most roads. A minimum frame rate of 40 and a speed of 10mph must be used. As the frame rate increases, the faster the vehicle may go.	Maximum longitudinal resolution of 4 inches.	High
GPS tag locations of scans so the road damage can be located. Location is based on the center of the saved scan.	Less than 5 meters	High
Laser emits in the visible spectrum as the camera can only process visible light.	400 nm to 700 nm	High
The design of the PCB allows for adequate power consumption to maintain operation off all components	Less than 6 volts	High
Google Lighthouse Metrics: Performance, Accessibility, Best Practices, SEO	> 80/100 all metrics	Low

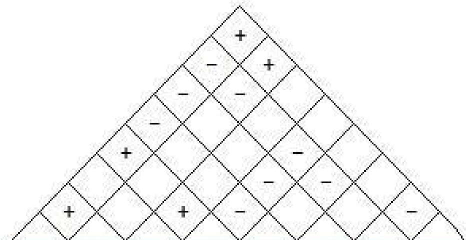
2.4 House of Quality

The house of quality is a diagram that shows the relationship between marketing requirements and engineering requirements. It helps determine a product's ability to satisfy customer needs by examining the product's characteristics and features. The marketing requirements are standards that are important for the customer and include user experience, safety, affordability (low cost), portability, performance, efficiency, reliability, and durability. Since this project is not sponsored by a company, our group members are considered the customers in this scenario. We chose specifications that would be important to a consumer interested in purchasing a road mapping device. Engineering requirements describe the design goals of the product that the group as the engineers on the project should adhere to. These requirements include image quality, output power, dimensions of damage, frame rate of the camera. storage, car speed, cost, and laser wavelength

Figure 1 shows the house of quality diagram with marketing requirements on the left and engineering requirements along the top. Target values for the engineering requirements are located at the bottom of the diagram. Each engineering and marketing requirement was then noted as having a strong, moderate, or weak correlation. To form the “roof” of the diagram a negative or positive correlation between engineering requirements was considered. One factor that stood out was the effect on cost. To improve any aspect of the product aside from wavelength, there will be a negative impact on cost.

Relationships	
Strong	●
Moderate	○
Weak	▽

Correlations	
Positive	+
Negative	−
No Correlation	



Column #	1	2	3	4	5	6	7	8
Engineering Requirements / Customer Requirements (Explicit and Implicit)	IMAGE QUALITY	OUTPUT POWER	DIMENSIONS OF DAMAGE	FRAME RATE OF CAMERA	STORAGE	CAR SPEED	COST	LASER WAVELENGTH
USER EXPERIENCE	●	▽	●	●	○	○	▽	▽
SAFETY	▽	●	▽	▽	▽	○	▽	●
AFFORDABILITY	●	○	▽	●	●	●	●	○
PORTABILITY	▽	▽	▽	▽	▽	▽	○	▽
PERFORMANCE	●	●	●	●	○	○	○	●
EFFICIENCY	▽	●	●	●	▽	○	○	●
RELIABILITY	●	○	○	○	▽	●	▽	▽
DURABILITY	▽	▽	▽	▽	▽	▽	○	▽
Target	4in X 4in resolution	TBD	2 IN DEPTH OR 8 IN DIAMETER	≥ 40 FPS	TBD	10 MPH	≤ $600	400 - 700 nm

Figure 1: House of Quality Diagram

2.5 Overall Project Schematic

Figure 18 shows a basic overview of the surface mapping project. Each block is color coded to show which engineer is responsible. Currently each stage of progression of the project is in the design stage. Color assignments can be found to the left of the figure.

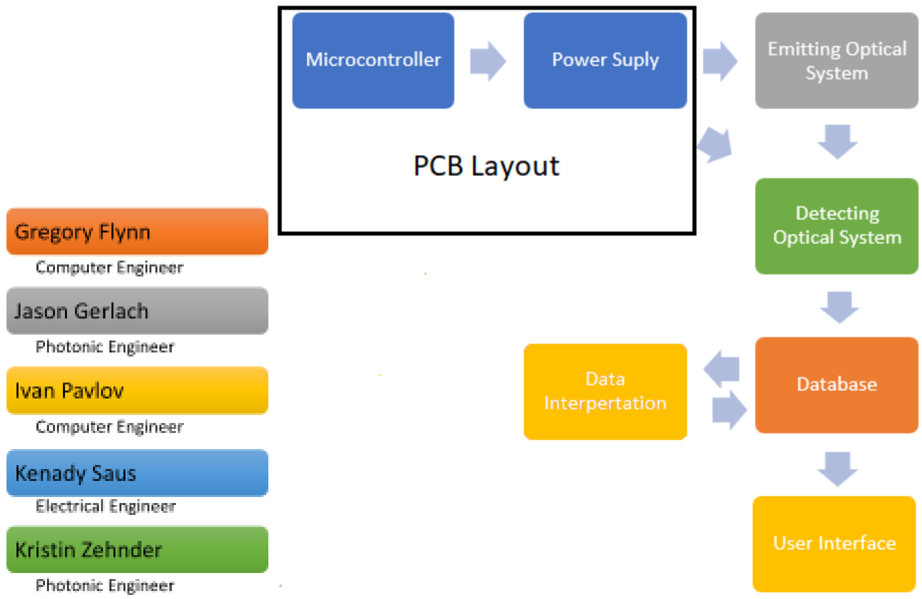


Figure 2: Overall Project Schematic

3 Research and Part Selection

This section reviews the existing technologies in which the prototype is based and also provides information on the parts that were selected.

3.1 Existing Technologies

While investigating ways that we could produce a product that would map the roads surface, different technologies were investigated. LiDAR (Light Detection and Ranging) is an emerging technology that can be used for many applications. The most commonly known is for navigation of autonomous vehicles in which LiDAR is used to gather information about the surrounding environment and obstacles. Light is emitted from a source and reflected back to a detector. The time-of-flight is recorded by the detector allowing the system to calculate the distance to the objects in the environment. In the next sections scanning and flash LiDAR are discussed in more detail with a third technology, camera vision.

3.1.1 Scanning LiDAR

Scanning LiDAR uses a laser and photodetector to generate a point map of distances from the emitter. The laser and photodetector are usually placed on a rotation servo that allows the LiDAR device to scan the entire environment it is placed in. The laser emitted a beam that creates a point on a wall or object and the scattered light is then detected by the photodetector. The time between the laser emission and the scattered light detection, called ‘time of flight’, is used to calculate the distance to the object.

The emitting system consists of a laser and lens system. For safety reasons, the laser is usually in the infrared range, 780 - 2500 nm, and normally 905 nm. The laser is required to have enough power to generate an appropriate amount of scattered light from the object being scanned. This power level needs to be balanced with keeping the laser in an eye safe range of power. The laser needs to be pulsed to create a unique emission event. The time of the pulse needs to be recorded for use in the time of flight calculations. The lens system is used to focus the laser to a small spot and then collimated to maintain intensity of the laser for the length of the beam. The laser pulse rate is determined by the detector's rise time. The shorter the detector rise time, the faster the laser is able to be pulsed.

The detection system consists of a lens system, filter, and detector. Once the collimated light leaves the emitting system, it will collide with an object for scanning. Scattered light reflects off the object and is collected by a lens system that will focus onto a detector. The lens system must be optimized to collect as much light as possible as scattered light has a low intensity reading. The detector needs to have a fast enough rise time to capture the incoming light and must have a signal to noise ratio that will enable the detector to overcome background noise from the environment. To help with the noise level, as light is focused onto a detector it will pass through a bandpass filter that will filter all light except for the wavelength of interest.

The emitter and detector systems are mounted onto a rotating servo to allow the system to scan the entire environment. In a typical scanning LiDAR system the emitter and detector would tilt to scan the environment in an up-down direction while the rotation would allow a 360 degree scan of the environment. The combination of tilt and rotation enable the system to cover most possible directions, resulting in a complete point map of the surrounding environment. To convert the recorded data into the point map requires the system to know the angle of tilt and the angle of rotation of the servo at the time of emission. The tilt of the system is controlled and recorded by a microprocessor. To find the angle of rotation, time must be recorded as the servo spins and speed of rotation must be known. With this information a map can be generated. Figure 2 shows a general scanning LiDAR system. This system includes a light source passing through an optical system. The reference light hits the object, or car in this case, and is reflected to another optical system onto a photosensor.

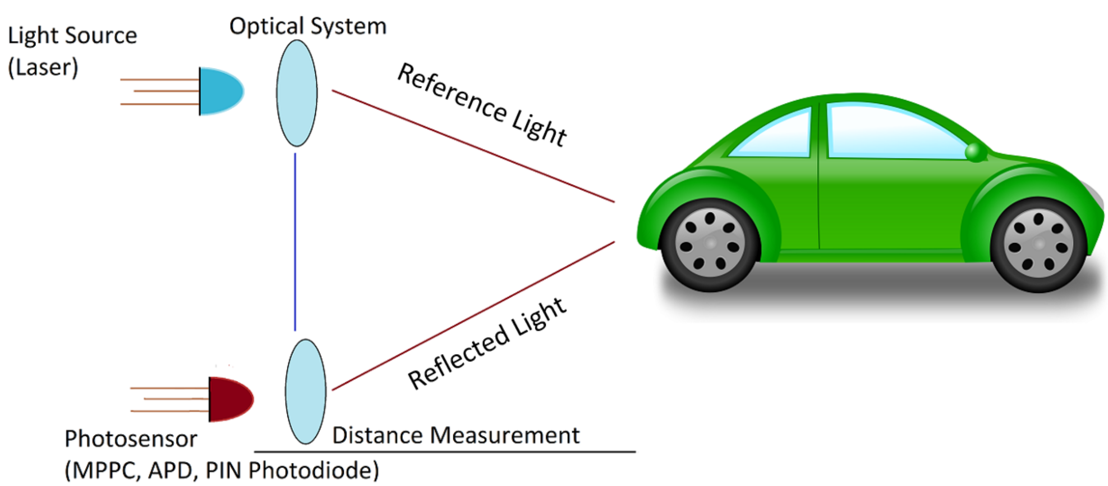


Figure 3: Scanning LiDAR System.

3.1.2 Flash LiDAR

Flash LiDAR is similar in concept to scanning LiDAR. However, with flash LiDAR the entire field of view is illuminated by a single pulse of a laser and an image sensor is used to detect and analyze the received photons. Depending on the application, the optical system may be on a rotation device such as a servo or may be stationary.

The emitting system of flash LiDAR uses a laser and a lens system. The laser is in the infrared range, 780 - 2500 nm, to remain eye safe for use around people. The nominal wavelength is typically 905 nm or 940 nm as a result of dips in the background radiation due to the fact that these wavelengths are easily absorbed by water in the atmosphere. Figure 3 shows the spectral photon flux or irradiance at different wavelengths. A clear dip at 905 nm and 940 nm can be seen. The lens system will be used to create a large spot in the object field. This spot will illuminate a large area that is then imaged through an array of photodetectors. This allows flash LiDAR to generate many points for the point map at once.The laser is pulsed at a rate depending on the detector's rise time and time of flight is still used to determine the distance of an object. The emitting system also uses beam shaping optics to create the area of illumination. Collimating lenses are used to guide light through a diffractive element, such as a cylindrical lens.

The laser is pulsed at a rate depending on the detector's rise time and time of flight is still used to determine the distance of an object. The emitting system also uses beam shaping optics to create the area of illumination. Collimating lenses are used to guide light through a diffractive element, such as a cylindrical lens.

The detector system in flash LiDAR is an array of photodetectors, similar to the way a camera works. Each photodetector in the array will be used to record the distance to one point in the large spot illuminated by the emitter system. The detector system uses a lens system to both collect the scattered light from the object and to limit light coming from outside the target area. The collection lens works much like an aperture focusing only the light from the target area onto the photodetector array. This aperture behavior is what allows the system to know that the light hitting the array in the upper left photodetector is coming from the upper left of the target area. The photodetector array's rise time must be proportional to the speed of the laser pulses, and signal to noise ratio must be taken into account. However, like scanning LiDAR, a bandpass filter is used to reduce the noise from the light gathered from the target area. The bandpass filter allows the system to remove light not in the same wavelength as that of the emitting system. This is crucial since the photodetectors in the array are sensitive to all wavelengths of light. Figure 3 shows a general flash LiDAR system. This system includes a light source passing through beam shaping optics and illuminating an area. Scattered light from the area is captured by the receiving optics and projected onto a photodetector where the signal is processed.

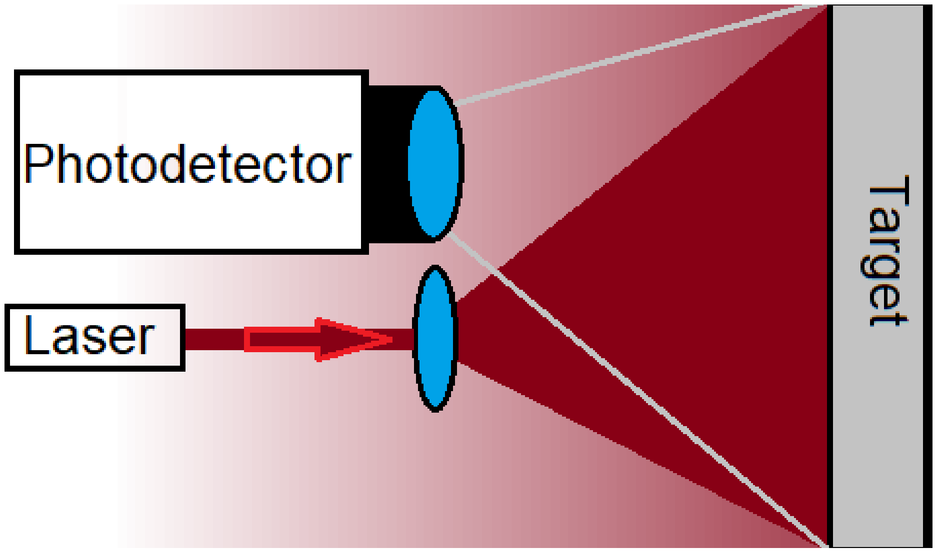


Figure 4: Flash LiDAR System

3.1.3 Machine Vision

Machine vision, or camera vision, uses the images collected by one or many cameras to extract information about a targeted area. This can be a multiple of properties such as the location, orientation, condition, or identity of an object. After an object is illuminated, an image is sent to a camera's sensor where the analog data is converted to digital data. Signal processing is used to send the resulting data to a receiver such as a computer. The computer uses automated processes to extract the information from the images.

The illumination system lights the objects of interest to ensure the camera can capture a usable image. The lighting system used can have many different sources such as an LED, halogen light, or fluorescent light. Depending on the conditions, light may emitted from an angle, from behind the object, or straight on. Qualities such as brightness, distance from the light source, and color of the light must be taken into account to optimize the system.

After an object is illuminated a lens will capture the image. The lens chosen for the system will be determined depending on characteristics such as the field of view, aperture, depth of field, and depth of focus. For example, if the field of view of the camera does not capture the entire object, a wide angle lens may be used to lengthen this constraint. After the lens has captured the image it will send it to a camera's sensor. The sensor will capture the light, and convert the analog data into digital data. The camera is usually in the form of a charged coupled device (CCD) or a complementary metal oxide semiconductor (CMOS). It is chosen based on many qualities, but an important aspect is whether the camera is area scanning or line scanning. An area scanning camera captures a two dimensional image made up of a rectangular area of pixels that includes the area of interest.

A line scanning camera captures a one dimensional image made of a line of pixels very quickly as the camera is moved over an object. These one dimensional images are then stitched together to form a two dimensional area. Other features that should be considered when selecting a camera for machine vision are resolution, the number of pixels that make up an image, and sensor size, the physical area exposed to light. Frame rate, number of frames per second, and exposure time, the length of time it takes the camera to capture the light from the object of interest, should also be considered.

The use of 3D imaging is a growing sector of machine vision with the most common being scanning based triangulation. Scanning based triangulation utilizes motion of the target object or of the imaging system during the imaging process. This process uses a laser projected onto the surface of the target object at an angle different from the angle that the camera is viewing the object at. The camera records the changes in the laser line profile as the object passes through the laser. Changes in the surface of the object cause deviation in the laser line profile which the computer can process into changes in the elevation of the surface to create a depth map of the object's surface. This allows the computer to create a 3D image of the object, which can be further processed by the computer to gather the data desired by the system. An example of machine vision would be during the production line. For example, an object on a conveyor belt can be illuminated and a camera and lens system can capture an image of the object. From the camera, a digital signal can be sent and processed, and information about the object can be extracted. This is a useful process as it can help identify defects in an object as a product is assembled before inspection by a quality inspector.

3.1.4 Technology Comparisons

This section will compare the previous three technologies, scanning LiDAR, flash LiDAR, and machine vision. Pro’s and con’s on each are weighed and a decision on a technology to pursue for the project. Table 6 tabulates specifications that apply to the surface mapping system prototype and gives a synopsis on how that specification would be met.

Table 6: Specifications Based on Technologies

Specification	Scanning LiDAR	Flash LiDAR	Machine Vision
Resolution (4in X 4in)	Based on rotation devices and car speed Detector must have a fast rise time	Based on rotation devices and car speed Requires detector array with fast rise time	Based on camera fps and speed of car
Vehicle Speed (10 mph)	High rpm and laser pulse frequency	High rpm and laser pulse frequency	Resolution decreases as speed increases
Laser (Wavelength)	Near infrared Light	Near infrared Light	Visible Spectrum
Cost	High	High	Medium
Horizontal Field of View (6 feet)	Determine when to record the data based on angle of rotation	Determine when to record the data based on angle of rotation	Wide angle lens on camera

While researching these technologies, there were many similarities found between scanning and flash LiDAR, as previously stated. The emitting systems both use near infrared light around 905 nm or 940 nm. The LiDAR systems are mounted on a spinning platform and many qualities of the system, such as resolution and vehicle speed are based on this rotation. To achieve an usable level of resolution would require the servo to spin very fast. Because the rotation will be very fast, a detector with a fast rise time must be used which is very expensive. As the speed of the car increases, the pulse frequency of the laser must also increase to capture enough time of flight information and again the detector's rise time must be even faster. It was also found that capturing the entire horizontal field of view would require a lot of calculations, specifically the angle of rotation of each pulse as the system spins on the servo.

Although there are many similarities in scanning and flash LiDAR there are also many differences. For example, since flash LiDAR illuminates an area the pulse frequency would not be as fast as scanning LiDAR. This is because flash LiDAR collects multiple points with each pulse whereas scanning LiDAR records only one point with each pulse. To obtain the same level of resolution scanning LiDAR must make multiple passes over the area that flash LiDAR can image in one pulse. This is demonstrated in figure 4.

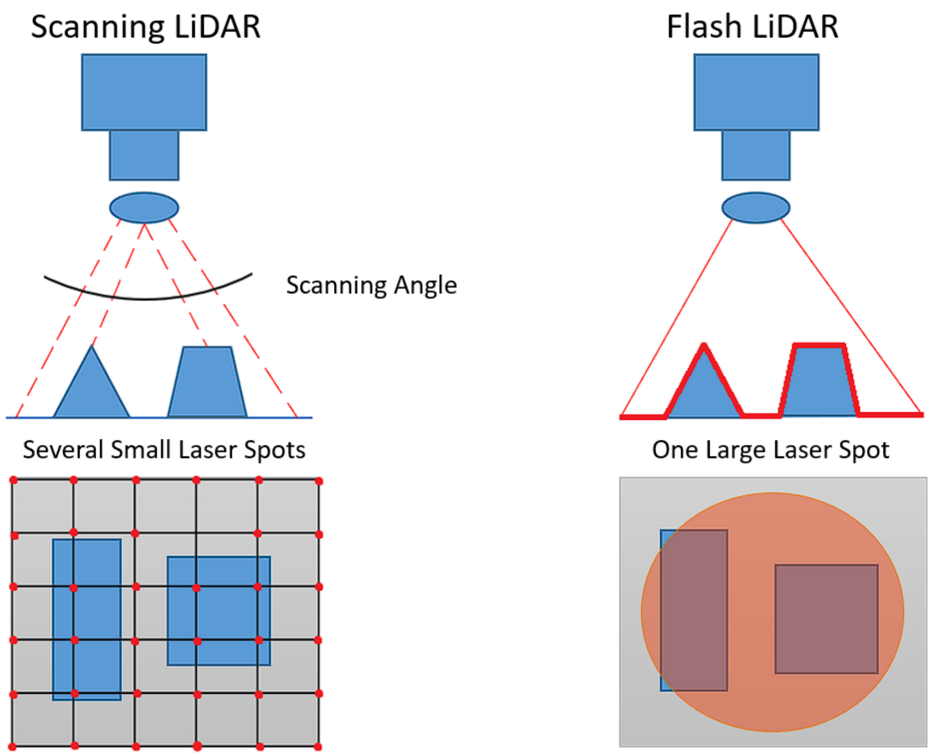


Figure 5: Scanning Versus Flash LiDAR

Figure 5 shows the differences in scanning techniques between scanning and flash LiDAR. Multiple spots will need to be scanned in scanning LiDAR to cover the same area as flash LiDAR.

Another difference is the detector type. Scanning LiDAR only requires the use of a photodetector with one sensor, while flash LiDAR requires an array detector which is a lot more costly. Flash LiDAR uses a lens system to spread the laser beam out to create a large spot in the object field. This dispersion of energy means that flash LiDAR requires a more powerful laser than scanning LiDAR and can be the reason for a short effective length on the imaging system. Flash also requires a lens system on the detector side that is used to gather the scattered light. This lens system must gather as much scatter light as possible while also ensuring that the light gathered is restricted to the target area. Scanning LiDAR uses a lens system to focus the laser to a fine point which is then collimated to maintain the spot size. This allows the beam to maintain most of its intensity till it hits the target. Lastly, if imaging an area, resolution would be based on the amount of points within the area scanned if pursuing scanning LiDAR as opposed to flash LiDAR where the resolution would be based on the detector array.

3.2 Electrical Technologies

In the sense of the electrical aspect of what option we have available to power our device, there are several options. These options include the decision between a DC-DC converter opposed to an AC-DC converter. Our next options are a voltage converter or using a battery as our form of supplied power. Each has very common uses in everyday technical applications, such as the medical, automotive industry or the phones that we carry with us everyday. The sections below will explore how each form of power supply performs in further detail. These options are also seen as a technology selection as well as the basis of part selection.

3.2.1 AC-DC Converter

The AC-DC Converter is a power supply option and is also known as a rectifier. This option is an electrical circuit that converts the alternating current into direct current. This process is completed by rectifying the AC waveform to produce a directional flow of current. This form of conversion is commonly used in electronic devices that require DC power such as computers, televisions and mobile devices.

The step by step process of the converter involves a circuit that uses one or more diodes to allow current to flow in only a single direction. The inputted message signal (AC) will have its voltage reduced to be suitable for the rest of the circuit to process. The diodes then in place of the circuit will rectify the AC waveform to allow the current to move in only one direction. This can be done by using a full-wave or half-wave rectifier. This will produce a DC waveform, however, this still needs to be filtered to ensure there are no fluctuations in the current. A capacitor can be a component used to filter the remaining DC current. Finally, if needed the voltage will have to be regulated to ensure it remains constant if the input voltage or load changes. Most applications that use an AC-DC converter option are devices that are supplied their current through an outlet. Such as a computer or a television, the device is plugged into the wall so the available current is much higher than what is needed from the device to operate. The converter is needed to ensure that the voltage is transformed or stepped down to only supply what is needed to the device as well as filtration.

3.2.2 DC-DC Converter

The DC-DC converter, also known as a voltage converter, is an electronic circuit that converts a DC input voltage into a different DC output voltage. This output is constructed by either increasing or decreasing the voltage level. This type of converter is used in applications that need stable and regulated power provided to different components. Examples of where this converter can be used are, solar power systems, automotive applications and electronic devices.

This process conducted by the DC-DC Converter is the input voltage supplied which can come from any other power source. The circuit then uses components such as diodes, capacitors, transistor or inductors to regulate the input voltage and provide a stable output voltage. Depending on what the end goal is of the converter, it can either step up or step down the voltage. The output voltage is then monitored to ensure that it remains stable and within a desired range for performance. Once regulated this can then be used to power the component or system. Benefits of this system is it provided features such as overcurrent, overvoltage and thermal protection. DC-DC converters can be used to provide different voltage levels to components in your phone such as the camera and the display. This converter is also used to disperse various voltage levels to systems in automotive applications such as the audio system, navigation and lighting. Figure 5 shows the difference of direction between an AC-DC Conversion and a DC-DC Conversion. Our device would benefit from the use of a direct current versus an alternating current because of researched advantages with battery space reduction and the high probability of less damage. In the next section, we will discuss other applications that could be used instead of the converter.

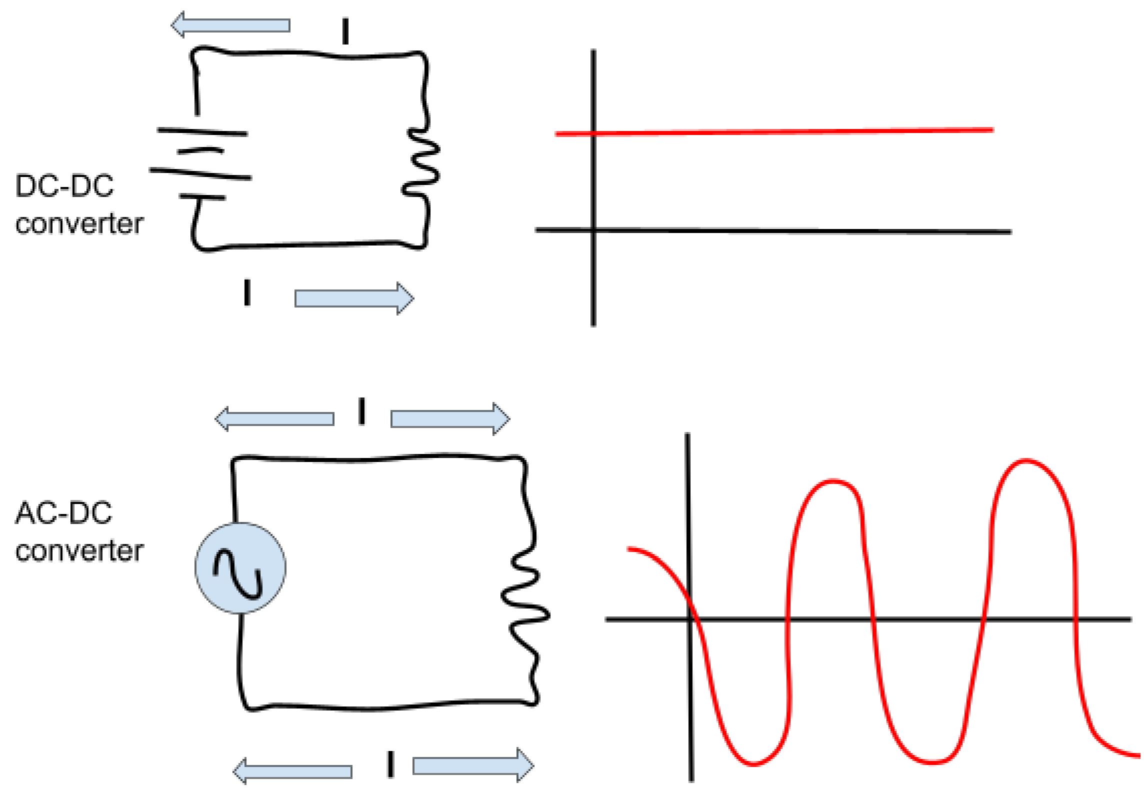


Figure 6: AC-DC Conversion Versus DC-DC Conversion

3.2.3 Voltage Regulator

A voltage regulator is an electronic device used to maintain a constant output voltage level regardless of input variations. This system can adjust the input voltage or output current to maintain a steady voltage level. These are commonly used in electronic devices and power supplies to ensure a stable consistent voltage to different components is provided. This is important to prevent damage from voltage fluctuations.

Several options of voltage regulators are line, switching and programmable regulators. Line regulators are the simplest version as they work by using a series pass transistor to drop the excess voltage from the input to the output. This allows the constant output voltage to be provided, but it is not always efficient because this system generates heat. Switching regulators are a much more efficient option. They use switching transistors to quickly turn the input voltage on and off. This allows the transistors to regulate the output voltage without wasting excess energy or heat. Lastly, programmable regulators allow the user to adjust the output voltage using an external feedback resistor. More flexibility is created allowing this to be used as a single regulator in multiple applications. Some voltage regulators can also provide the benefits of overvoltage, overheating and overcurrent protection.

This electronic technology option can be used in a wide variety of devices, such as mobile devices using the same concept as a DC-DC converter with the current being dispersed properly to multiple components including the display and camera. The regulator can also be used on industrial equipment to ensure that the different components receive the correct voltage at a stable and consistent rate.

3.2.4 Battery

A battery is a chemically storing device that converts the chemical energy into electrical energy. The electromechanical cells are connected and produce a desired voltage and capacity. This cell is made up of a cathode and an anode, and an electrolyte that separates the two electrodes. When a battery is charged, a chemical reaction occurs in the ions to then be transferred between the electrodes and electrolyte. This process stored the energy in a battery. When the battery is used the reverse reaction takes place. The stored energy is converted into electrical energy to be used as power. The amount of energy available is determined by its capacity, and this is labeled by its voltage and ampere-hours. Batteries are beneficial for many applications, especially portable devices such as phones, and backup power supplies. Another benefit is that many batteries have the capability of being rechargeable. This means they can be charged and discharged multiple times using a different form of chemical reaction.

With a battery's portability and convenience they are used in many common applications. Devices such as phones, laptops or portable speakers require a small and lightweight powersource that can be easily recharged. Batteries are an ideal solution in this case. This ideal solution is also used in vehicles because they can be designed to withstand the high currents required to start the engine, or they can be used to supply power to the lights in your vehicle. Another very popular use is the inclusion of batteries in toys and games, such as video game controllers and electronic toys. The ideal-ness of a lightweight power source that can be replaced easily is very desirable. Figure 6 highlights the benefits of using a battery in a visual manner as our main power source for the device.

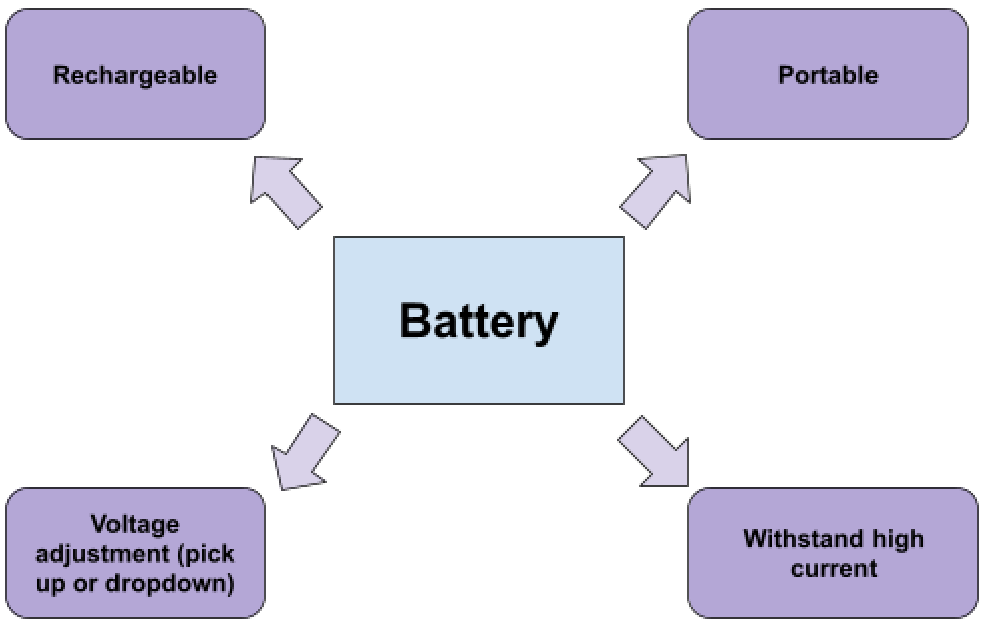


Figure 7: Benefits of Batteries

3.2.5 Electronic Technology Comparison

The electrical applications to technology as described above have many different benefits when used in specific circumstances. Using conditions specified to the needs of our project we can conclude that the battery option would have a better outcome for us. This conclusion will then be explored again in the part selection portion to compare the efficiency, cost, performance and noise. The application of these forms of power are considered both technical options as well as part selection options. Table 7 compares different electronic technologies and their features. Due to design constraints and specifications a battery was chosen for the prototype.

Table 7: Electronic Technology Comparison

Specification	AC-DC Converter	DC-DC Converter	Voltage Regulator	Battery
Features:	-Single flow of directions for current -Uses wall outlet at current provider	-Stable regulated power -Thermal protection -Disperse various voltage levels	-Benefits for overcurrent and overheating -Ensure correct voltage at stable, consistent rate	-Portability -Rechargable -Easily replaceable -Withstand high currents

3.3 Programming Technologies

There are many programming technologies available for us to use for this project. These programming technologies range from programming languages to libraries we will use to simplify the work. Such technologies that will be discussed in more detail include WebGL, OpenGL and Threejs. These technologies all focus on include built in functions that will help with the rendering of 2D and 3D graphics. As there is a time constraint on this project utilizing such technologies is beneficial in both reducing time necessary to create our own 3D graphical pipeline as well as reducing the number of lines of code we will need in the final product. It is assumed that we will be able to decompose the image data gathered from the camera sensor into a simple 3D object model which will then be displayed on our website when the user wants to observe the road damage virtually. In the next sections these three application programming interfaces will be discussed in more detail.

3.3.1 WebGL

WebGL or Web Graphics Library is a javascript API used for rendering and interacting with high-performance 2D or 3D graphics in compatible web browsers. WebGL provides certain functions such as rendering contexts, multiple types of buffers, textures and much more all of which will simplify programming and reduce the necessary code size. WebGL is based on OpenGL ES 2.0 being a subset of OpenGL means it may not include all the features that OpenGL has, such features include tesselation shaders and compute shaders. WebGL is designed to be used on a website, and includes support for hardware graphics acceleration from the user's device. WebGL does not require native driver support. One benefit of WebGL is that it is easy to learn in comparison to OpenGL.

3.3.2 OpenGL

OpenGL or Open Graphics Library was released in 1992 by Silicon Graphics Inc and is an application programming language that is cross platform and cross language. This means that multiple languages can run this library such as python, java and javascript. Supporting multiple different languages is useful by allowing the developer to choose which language they want to use for their 2D and 3D graphical needs. OpenGL is desktop-centric, typically used to interact with the graphics processing unit. OpenGL has less overhead when compared to the overhead from WebGL. Some features OpenGL includes are accumulation buffers, tessellation shaders and compute shaders. Accumulation buffers are useful for creating effects such as anti-aliasing, and motion blur, both of which are features you would expect in a game. Tessellation shaders are useful for creating smoother surfaces than the original mesh allows, in other words tessellation allows the addition and subtraction of detail to a 3D mesh. The compute shader allows for high-speed computing utilizing the parallel capabilities of the GPU.

3.3.3 Threejs

One such software is a library called Three.js, which is a programming interface designed to create and display 3D graphics and animations in a web browser using WebGL. Threejs was first released in 2010 using the javascript language. Threejs offers support for scenes, data loaders and animations. Scenes offer support for adding and removing objects at runtime such as fog. Data loaders are important for loading 3D objects for rendering, including this means there is no need to import an individual library for loading objects. Animation support allows us to move 3D objects the way we want, such as making a player character jump correctly.

3.3.4 Programming Technology Comparison

The three different technologies above each provide their own benefits. In terms of this project some features included by the technologies are more valuable than others. Features that are not quite valuable to this project are tessellation shaders and compute shaders. These two shaders are provided by the OpenGL library but are excessive for our needs. Useful features to this project include object loaders as well as basic 3D rendering features offered by all technologies like scaling and rotation. Another criteria of these 3D modeling technologies is experience, which one of our group members took a computer graphics course which focused on utilizing the WebGL platform. WebGL being a subset of OpenGL and therefore being the software which we have the most experience in was the main driving force in choosing WebGL over Threejs or OpenGL. Table 8 compares the programming technologies WebGL, OpenGL, and Threejs and breaks it down by experience and features. Table 8 shows a comparison of the features of the different rendering technologies. We ended up using Threejs for its easy implementation utilizing its object loaders and pre-built rendering pipeline.

Table 8: Comparison of Programming Technologies

Category	WebGL	OpenGL	Threejs
Experience	One semester	Zero experience	Zero experience
Features	• Simple • Vertex shader • Fragment shader	• Vertex shader • Fragment shader • Tessellation shader • Compute shader • Accumulation buffer • multi-language support	• Vertex shader • Fragment shader • Object loader

3.4 Part Selection

This section will discuss the hardware and software we are considering for this project, explaining what they do and deciding which parts will be chosen. Hardware and software categories include illumination, camera, data transfer, GPS, microcontroller, power supply, battery, server, database, frontend and backend frameworks.

3.4.1 Illumination Source

There are two illumination sources that were considered for the road surface mapping prototype. These sources include Light Emitting Diodes (LEDs), and a LASER. These two sources work by converting electrical energy into light energy. They differ in irradiance, emission spectrum and beam profile. Each light source has its pros and cons in regards to their appropriateness to this project.

LED or Light Emitting Diodes, are made from semiconducting materials such as gallium arsenide and gallium phosphide. The use of these materials allows LEDs to emit light in the form of a photon. The three layers of an LED include a n-type semiconductor containing negatively charged electrons, a p-type semiconductor containing positively charged holes and a depletion region which acts as a barrier between the two types of semiconductors. When a forward bias is applied, a positive voltage terminal is connected to the cathode and current flows through the p type semiconductor to the n-type out through the anode to the negative voltage terminal. The depletion region narrows while holes and electrons move towards each other. Eventually the free electrons are able to combine with the holes and energy is released in the form of a photon.

An LED produces a wide spectrum light with an omnidirectional emission. The light is not focused and has a wide spectral width. LEDs are a low cost, low energy solution to illumination. They produce little heat with most of the energy used in their operation going to light emission. Multiple LEDs can be used in tandem to create a single high power light source. This prototype requires a single coherent light source for illumination; therefore, the optical engineers determined that LEDs would not work well as an illumination source.

Laser is an acronym for "Light Amplification by Stimulated Emission of Radiation." A laser is composed of a laser cavity where the medium is composed of a solid, like a crystal, liquid, or gas and 2 mirrors, one with 100% reflectivity and the other between 30% to almost 100% reflectivity. Atoms are then excited by either optical or electrical energy. Once population inversion occurs, where more atoms are two or three levels above ground state than are at ground state, the excited atoms will release energy in the form of photons. As one atom is excited and produces a photon through spontaneous emission, it will initiate a second atom to release a second photon as they interact with each other, and so on. These photons have the same properties such as wavelength, polarization, and phase. The goal is to create optical gain within the system which will increase optical power of the system. To create this gain, photons will travel through the laser cavity, bouncing back and forth from mirror to mirror through the lasing medium. As the light gains intensity or is amplified, some of the light escapes from the cavity through the output coupler and the laser will emit a beam of light that is monochromatic, directional, and coherent.

There are properties of a laser that are beneficial to this project including monochromatic, coherence, and collimation. Light that is monochromatic is made up of only one wavelength. In reality, the light is composed of a small bandwidth of light. The light emitted is also coherent, meaning all the waves of light are in the same phase spatially and temporally. Coherence allows the light to be focused to a very fine spot which is needed when using a powell lens in the illumination system. Lastly, light emitted from the laser will be collimated which will ensure the waves will travel parallel to each other and will not diverge even over long distances.

The surface road mapping prototype will require an optical system that generates a line across the road using lasers and a powell lens system. This section will investigate the type of laser needed. The camera chosen dictated that the light must be in the visible spectrum so the camera can see it. The most readily available laser colors are red, green, and blue and the colors are dictated by their wavelength. Table 9.a shows the Decision Matrix used to help determine which color (wavelength range) the laser should be for this project, while Table 9.b defines the criteria used.

Table 9.a: Laser Decision Matrix

Decision Factors		Red Light (630 - 670 nm)	GreenLight (520 -532 nm)	Blue Light (360-480 nm)
Criteria	Weight			
Cost	2.0	4.25	3.5	0.5
Safety	2.0	3.0	1.0	2.0
Wavelength	1.0	1.0	2.0	1.0
Weighted Total		15.5	11	6

Table 9.b: Criteria Definition for Table 9.a

Criteria	Definition
Cost	The price of a single laser diode of less than 5mW
Safety	safety elements that pertain to blue, green and red laser light
Wavelength	Wavelength that the laser will emit

Supported by the decision matrix, a laser with a wavelength in the red spectrum, 630 - 670 nm is best for this project's prototype. Below is an explanation behind the thought process of choosing red and why different criteria are weighted differently.

Cost was a criteria that was taken under consideration when choosing a laser for our product. Blue lasers are the most expensive, around 7 times more than green, while green is around 20% - 25% more expensive than red. Some of this is due to blue lasers using the newest technology of the three. Beam generation also adds to the cost for blue lasers. Green and blue lasers have similar beam generation processes. A pump laser diode emits a light at 808 nm wavelength. This beam enters a neodymium doped crystal which emits light in the 1064 nm range. The 1064 nm light passes through another crystal that doubles the frequency of the light causing the beam to become a 532 nm laser. This process of generating 1064 nm light then using another crystal to double the frequency to 532 nm light for green is much more efficient that generating 946 nm light then using another crystal to double the frequency to 473nm light for blue. A blue laser's frequency doubling crystals are more rare and the laser itself requires a larger pump diode which also increases cost.

Safety was also explored which incorporated which wavelength to use. There are four main classifications for lasers that describe hazard levels. For example, a class 1 laser is considered eye safe but may be hazardous if viewed with an optical component. The output power has a maximum of 0.4uW and is usually found in an enclosure such as a CD or DVD player. A class 2 laser has a max output power of 1mW and emits only visible light. They are considered to be safe for any unintentional eye exposure due to the aversion response. The aversion response is the time it takes of someone to blink or turn their head away from unintentional exposure which is 0.25 seconds. Class 3R lasers have an output power between 1 and 5 mW and are considered safe from unintentional eye exposure. However Class 3B are hazardous to the eyes as they can burn the retinas. It is suggested or recommended to wear protective eyewear when operating these lasers. Class 3B lasers are not considered burn hazards, but they will heat up the skin and other materials. Output powers between 5mW to 500mW fall into this category. Lastly, class 4 lasers have an output power over 500mW. They are hazardous when exposed to the eyes and can be burn hazards to the skin and other materials. Protective eyewear is always recommended when operating a class 4 laser.

Aside from taking into account the class of a laser for safety reasons, there are also aspects of the visible light spectrum that should be considered. For example, researchers from the National Institute of Standards and Technology have found that green lasers may emit levels of infrared radiation that can be harmful to the human eye. This is due to the way that the green light is generated in the green lasers. Inexpensive green lasers may lack the infrared filter that keeps this energy confined. The human eye is also sensitive to green light which may actually be a deterrent. The brightness of the laser has been known to leave an “after-image” on the retina. Researchers are also studying the negative photobiological effects of blue light and the resistance of the aversion response. Since the eye is less sensitive to wavelengths in the blue and violet range, the blinking or head turning response may be slower and could cause injury to the eye.

3.4.2 Camera

As light travels to an object, some rays are absorbed while others are reflected. The human eye perceives color by using cone cells to gather the reflected light and sends a signal through optic nerves to the brain telling it what wavelength and in turn what color is seen. The human eye is most sensitive to green which is why it appears the sharpest. However, in this project we are not looking at light with the visible eye, but instead we are using a camera to capture the required laser color.

A camera sensor can not see color and filters must be used to tell the amount of a certain color of light. There have been many versions of filters on a camera, one being a three-CCD camera. A three-CCD camera uses 3 separate sensors each with a different color filter of either blue, red, or green. The information from each sensor is combined through processing methods and a color image can be produced. This method of color imaging is inefficient and costly. Currently, the most popular method of imaging in color is the use of a Bayer filter which is an array filter. A simple pattern of blue, red, and green filters cover different pixels.

Each pixel can only report one color depending on the filter. The Bayer filter consists of 25% blue filters, 25% red filters, and 50% green filters. Figure 10 shows a typical Bayer array filter pattern. There are more green filters because the human eye is more sensitive to green light and it helps mimic the human eye. Since each pixel is filtered by only one of the three colors, each pixel can not specify what color it is on its own. An algorithm is applied which will essentially guess what color should be present based on the neighboring pixels. This process results in a camera with more pixels dedicated to green light rather than blue or red. Figure 7 shows a BGGR Bayer Sensor Array and how it is broken down into 3 components: blue, red, and green channels. Notice there are twice as many green pixels as red or blue.

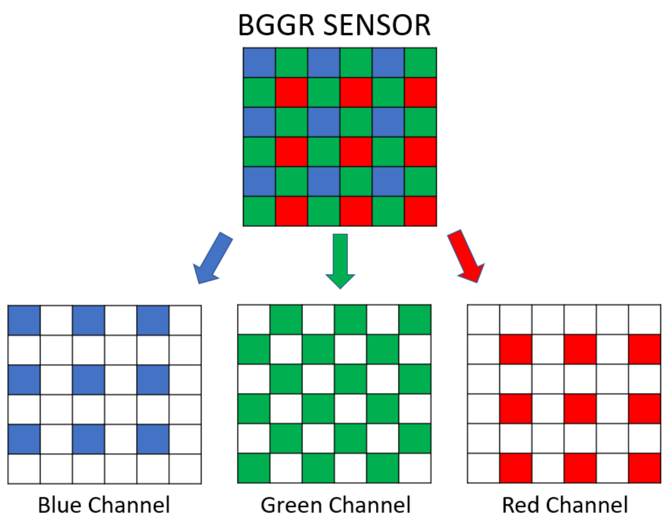


Figure 8: BGGR (Blue, Green, Green, Red) Bayer Sensor Array

There are several properties that must be looked at when choosing a camera including resolution, frames per second, field of view, and cost. Resolution is the number of elements called pixels that make up the sensor of a camera. The more pixels the better the quality or crispness of an image. This is important to our project as we will be tracking a line as it shifts pixel position. However, frames per second (fps), the frequency in which a camera can capture an image within a second, must also be taken into consideration. Table 10 lists the mapping resolution and speed specifications for our basic, advances, and stretch goals and the corresponding frames per second needed for each combination using $fps = (63360\, x\, speed)/(3600\, x\, resolution)$.

Table 10: Resolution and Speed Specifications

Specification	Frames per Second
4 in Resolution at 10mph	44
4 in Resolution at 20mph	88
4 in Resolution at 30mph	132
2 in Resolution at 10mph	88
2 in Resolution at 20mph	176
2 in Resolution at 30mph	264
1 in Resolution at 10mph	176
1 in Resolution at 20mph	352
1 in Resolution at 40mph	528

The camera's field of view determines the maximum area that can be captured. To map the road's surface, we are tracking a horizontal line; therefore, the horizontal field of view is the focus of this project. Our basic goal is to capture the projection of the laser line of at least 6 feet. As the length of the line increases, the field of view must also increase. We will be able to compensate for a larger field of view by increasing the distance the camera will be from the ground.

Table 11 shows a list of features of the two cameras that were researched and features compared. Due to design constraints and specifications ELP-USBFHD085-MFV was chosen for the prototype.

Table 11: Features of ELP-USBFHD085-MFV and ELP-USBFHD03AF-A100

Feature	ELP-USBFHD085-MFV	ELP-USBFHD03AF-A100
Pixel Size	2.0 um X 2.0 um	3.0 um x 3.0 um
Image Area	5440 um X 3072 um	5856 um X 3276 um
Frames per Second	260	100
Resolution	640 X 360	640 X480
FOV	100 degrees	100 degrees
Price	$77.00	$50.99

Even though the ELP-USBFHD085 is more expensive, the features outweigh the cost. The increase in frames per second is the biggest advantage in selecting this camera. This increase will allow us to achieve a much faster mapping speed which in turn will make this device safer and more convenient to use. The higher frame rate is key to achieving some of our advance and stretch goals. There are other cameras with even higher frames per second, some have even greater resolution, but they cost substantially more money and are out of reach with our current budget. These more advanced cameras are also bulkier and would be more cumbersome to attach to the back of a car. They would also represent a significant theft risk to the end user. The pixel size is smaller which for our purposes is an advantage. The smaller the pixel size the greater the spatial resolution the sensor has while the larger the pixel size the greater the dynamic range the sensor has. Therefore the smaller pixel sizes will allow us to measure smaller increments of change in the laser line's profile. While the dynamic range is usually important for clear images, we are not concerned in maintaining the image quality. For this project, we need to know how the laser line shifts in the camera's image space as a means to track the ground elevation changes. This may result in an image that is unclear to the human eye but perfect for digital analysis. The image resolutions are very similar. Both have 640 pixels in the horizontal, which means that we will have a possible 640 points of measurement for our transversal resolution. This is about the standard for cameras that meet our frame rate and budget constraints. The vertical resolution is related to the height resolution of the system. A greater vertical resolution means that we can measure greater changes in the elevation of the road. In this regard the ELP-USBFHD03AF-A100 would be more advantageous. This advantage however is not significant enough to make it the more suitable camera. In fact this advantage comes with its own disadvantage in the memory cost of each frame. The greater number of rows of pixel, the larger the file size of the recorded video.

3.4.3 Cylindrical Versus Powell Lens

This section will discuss what type of lens to use to generate the line that will be tracked to make the road's surface. There are two lenses that were considered, a cylindrical lens and a powell lens. Cost, uniformity and possible length generated were examined.

A cylindrical lens is composed of at least one optical surface having different radii in the x and y direction, or in the shape of a cylinder. The shape of the lens causes the incoming light to defocus or focus light in only one direction. A single or multiple cylindrical lens can be used to shape a beam of light to the needed dimensions. For example, two cylindrical lenses can be used to circularize the beam, one lens to collimate light horizontally and the other lens to collimate the light vertically. Another common application of a cylindrical lens is for line generation. A plano concave lens will shape a beam of light into a line. Figure 8 shows how a plano-concave cylindrical lens can be used to create a line.

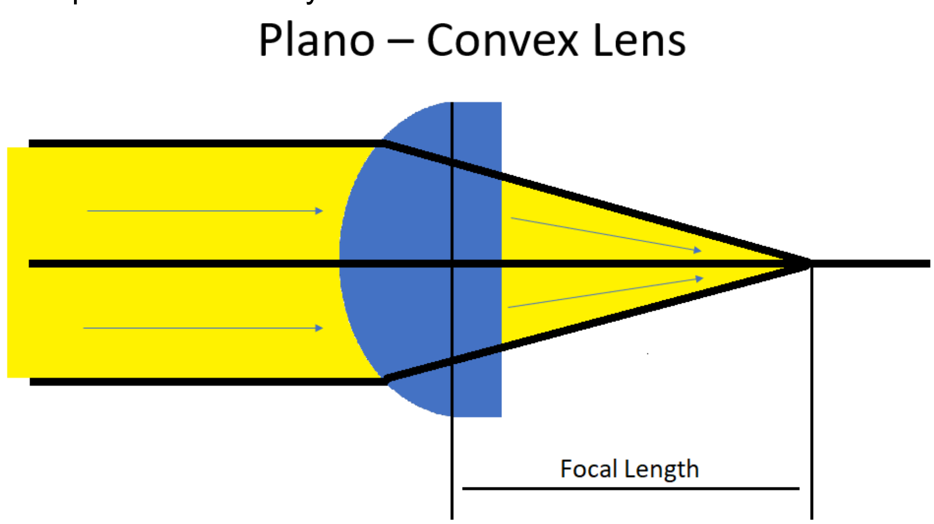


Figure 9: Plano-Convex Cylindrical Lens

Cylindrical lenses are lenses that have different radii in the x and y axes of the lens. These lenses typically have one curved axis and one flat axis. These asymmetrical properties give a cylindrical lens its unique properties. Cylindrical lenses are used to focus or expand light in one axis only. This differs from the typical spherical lenses that affect both the vertical axis and the horizontal axis. This single axis effect allows cylindrical lenses to focus a laser into a line instead of a point. The line is the circular spot of the laser elongated perpendicular to the cylindrical axis of the lens.

Cylindrical lenses suffer from chromatic aberration the same as spherical lenses do. Chromatic aberration is a color distortion that stems from the refractive index of the lens varying with wavelength of different colors of light. The varying refractive indices result in the different wavelengths being focused to different spots. The asymmetrical properties of cylindrical lenses can result in some manufacturing errors in the lens. Due to this lack of symmetry, the cost of a cylindrical lens can be expensive as the manufacturing process requires precision when shaping the lens. Three such errors are wedge, centration and axis twist. Wedge is an angular deviation between the planar side and the cylindrical axis of the lens. Ideally the planar side of the lens and the cylindrical axis of the lens should be parallel. If the two sides of the lens are not parallel it will result in an image shift along the non-power direction. Another manufacturing error is called centration. Centration is an angular deviation of the optical axis in respect to the edges of the lens. This will result in beam deviation and make alignment of the lens in the system difficult. Axis twist is the third possible manufacturing error. Axis twist is a rotation in the cylindrical axis that results in it not being parallel to the sides of the lens. This will cause a rotation in the light passing through the lens which would have to be corrected by rotating the lens. These errors all stem from the manufacturing errors such as misalignment during the polishing process. This means that manufactures need to closely monitor the manufacturing processes which also results in a higher cost for cylindrical lenses.

A powell lens is another type of lens that will shape incoming light to project a line. It is in the shape of a prism that has a rounded "roof" and converts a beam of light into a uniform line. The fan angle is determined by the refractive index of the lens and the angle of the roof. An increase in the steepness of the roof or the refractive index will increase the fan angle which in turn increases the length of the generated line. The width of the generated line is dependent on the incident beam. A narrow incident beam that is parallel to the roof of the powell lens will yield a thinner line width than a wide incident beam perpendicular to the roof of the powell lens. However, many powell lenses are optimized for a 0.8 mm diameter incident beam. Figure 9 displays a beam incident on the roof of the powell lens, the light traveling through creating a fan angle.

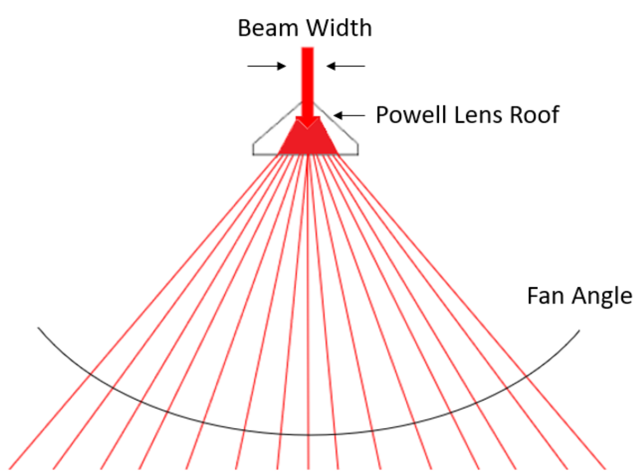


Figure 10: Powell Lens Fan Angle Generation

It’s important to note that due to powell lens properties, the system is able to take an incoming Guasian beam and convert it to a flat beam of light. When light passes through the lens, it produces large amounts of spherical aberrations which reposition the light along the line. The line generated by the powell lens is uniform in intensity by redistributing the bright center to the ends of the line. The uniformity created by a powell lens is not absolute as there will be some variations throughout the line. These variations are dependent on characteristics of the lens's aspheric surface and even the fan angle. Another property to consider is contained power. Eighty percent of the line generated from a powell lens contains 80% of the power. If less than 80% power is contained, the ends of the line will increase in brightness. Figure 13 shows a Guassian input distribution that is incident on a powell lens and the new output distribution that is relatively flat. The output distribution has good levels of contained power as the peaks are minimized.

A cylindrical lens can generate the same line as a powell lens; however they differ in line intensity. A cylindrical lens produces a nonuniform Guassian beam while a powell lens will produce a uniform beam. Figure 10 shows the difference between the line formed using a cylindrical lens versus a powell lens.

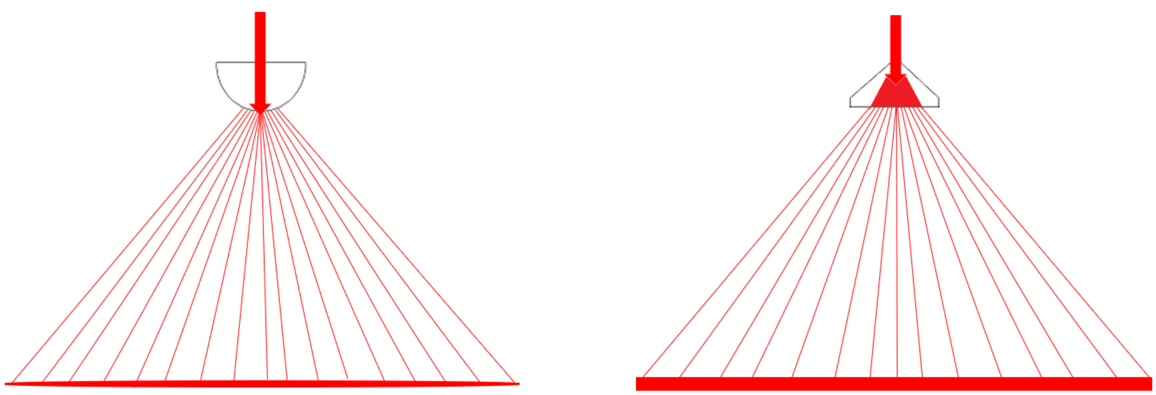


Figure 11: Cylindrical Versus Powell Lens Line Generation

The figure on the left shows a beam of light incident on a cylindrical lens. The cylindrical lens will create a beam in the shape of a line. However notice the intensity is strongest in the middle and weakest on the edges. The figure on the right shows the same system but a powell lens is used. Notice the powell lens distributed the intensity equally throughout the beam line.

Table 12.a is a decision matrix that helps determine which lens to use and table 12.b defines the criteria. In this instance the criteria that was chosen was cost and line uniformity were used to determine whether to use a cylindrical lens or powell lens for line generation. A powell lens will be used for the project prototype.

Table 12.a: Line Generator Lens Decision Matrix

Decision Factors		Cylindrical Lens	Powell Lens
Criteria	Weight		
Cost	3.0	1.0	2.0
Uniform intensity	3.0	1.0	2.0
Weighted Total		6.0	12.0

Table 12.b: Criteria Definition for Table 12.a

Criteria	Definition
Cost	The cost of the line generating lens
Uniformity	The uniform intensity of the generated line

After determining that the line generating lens used for the prototype is a powell lens, we looked for one that would meet the requirements of the project. One of our basic goals is the ability to map the width of 6 feet of road with an advance goal of mapping an entire lane (11 feet horizontally). With these goals in mind, a powell lens with a fan angle of 110 degrees was found. However, there are cons when using a fan angle greater than 20 degrees. As the angle increases the uniformity of the line decreases. It was decided that any distortion that occurs will not affect the end result of the project. The powell lens selected is a BK-7 Powell lens with a 110 degree fan angle sold by sunshine electronics.

3.4.4 Communication

To accommodate our advanced goal of providing user feedback we will need some sort of communication between the vehicle operator and the device. For this goal we need a system which tells the user whether the device is ready to record or not. The feedback system should have no effect on the function of the rest of the device.

This can be done in two forms, the first form is the device having a cellular connection where it can communicate with the server and store the device's status. The second way this goal can be achieved is through a Bluetooth connection with the users phone that displays status on an application. There are a few differences between these two methods.

Bluetooth is a technology that allows wireless communication between devices in a short range area, the original purpose of Bluetooth was to connect devices together without the need of a wire. Bluetooth range is usually only up to the 10 meter range or about 33 feet. This technology operates on the electromagnetic spectrum at 2.402 GHz to 2.48 GHz in the ultra high frequency radio waves area. The international telecommunication union set aside this frequency range for Bluetooth, WI-FI and ISM bands, which are bands set aside for Industrial, Scientific and Medical purposes, this frequency is globally unlicensed meaning you do not need a license to use bluetooth technology.

Bluetooth operates by using a method called frequency-hopping spread spectrum. This method is one where the communication signal frequently changes to different frequencies that both devices, the transmitter and receiver are aware of. This technology is also used to avoid interference and to prevent people from listening in, as you would have to be aware of all the frequencies being used to get all of the information from the broadcast. Bluetooth technology is packet-based with leader/follower architecture, the leader shares a clock signal with the followers which establishes an order of communication. The leader only transmits on even clock slots and receives on odd ones, while followers transmit on odd slots and receive on even ones. Packets being transmitted through Bluetooth may be multiple slots long.

Cellular technology is what mobile phone networks are based on. Cellular technology has multiple parts to make it work. The underlying technology that connects cellular users is the network of cell towers scattered around the globe. The cell towers as well as our mobile devices include a transceiver that is capable of both sending and receiving data. These cell towers are also connected to the public switched telephone network in order to connect users to a wider telephony network. Mobile data is handled by a packet switched network while calls and texts are handled by a core circuit switched network. Cellular frequencies operate in the ranges of 806-947MHz and 1700-2000MHz. In terms of connecting to a cellular network one would need a subscriber to the network, subscribers are sometimes given a subscriber identification module or a SIM card in order to connect to the network. Subscribing to a cellular network is not free. In terms of this project we will mainly be interested in the data services provided by cellular networks to transfer information to and from our device if we choose this technology.
The first difference between the methods is the use of the server to store device status, with the cellular connection the status of the device is only seen when the device has a cellular connection. This is problematic for situations where cellular service may be spotty or non-existent. With a bluetooth connection the status of the device can be seen at all times without being affected by a lack of cellular signal. The feedback system will have no effect on the device's function, that is the device will still run properly whether or not the user can see how the device is doing.

The second difference between the two methods is cost. The cellular connection requires the user to pay for a subscription to the cell service as well as the parts necessary. Bluetooth operates a little differently in that it does not require you to subscribe to the network before you can access it, in this regard the only cost associated with implementing Bluetooth into our system is the cost of parts.

The third difference between the two methods is speed of the connections. The bluetooth module which we are looking at boasts a speed of 2 Mb/s whereas the cellular connection only has speeds of 158 Kb/s. Though both of these are more than adequate for giving the user simple feedback of how the device is doing.

The final difference between these two methods is difficulty/complexity. The criteria for this is what the user has to do to maintain and use either of these systems as well as what we have to do in order to implement them. For a cellular connection the user must remember to pay for the connection before the service expires, this is not the case for a bluetooth connection. To use the bluetooth connection the user must connect through bluetooth to the device, such as connecting to a pair of bluetooth headphones, this is not necessary for a cellular connection as it should automatically connect to cell towers. For implementation of either method we have to consult how other projects used these technologies. More projects implemented a bluetooth connection with their designs meaning we know it is possible, and there must be adequate documentation of how to use Bluetooth modules. Since less projects are using a cellular connection we might have a harder time finding documentation and getting this system to work. Table 13.a is a decision matrix that helps determine which communication device to use and table 13.b defines the criteria.

Table 13.a: Communication Decision Matrix

Decision Factors		Bluetooth ANNA-B112-70B	Cellular Connection BC660KGLAA-I03-SNASA
Criteria	**Weight**		
Cost	High	$9.96	$13.86
Speed	Low	2 Mb/s	158 KB/s
Difficulty to implement	Medium	Low	Medium
Difficulty to maintain	High	Low	High

Table 13.b: Criteria Definition for Table 13.a

Criteria	Definition
Cost	Cost of the module and its implementation
Speed	Amount of data transferred from device to user
Difficulty	Effort needed to implement and effort needed from end user to use

As a result of the time constraints on this project and a few of the setbacks we did not attempt to include our advanced goal of communication in this project.

3.4.5 Data Transfer

Data transference is important to this project because we need a way to populate the database with data gathered from each use of the device. There are a few methods for this which include cellular connection, bluetooth or saving data to a physical device and uploading it to a computer later. Transferring data through a cellular connection is not ideal because areas without service will not ever be uploaded to the database. Using bluetooth for data transference will allow for having parts serve multiple purposes. For the purpose of not having the device lose data we will not be considering having a cellular connection to transfer data to the database. For these two methods of transferring data between device and database there are a few differences that are important.

The first difference between local storage and a bluetooth connection is where the data is stored. With local storage there is a dedicated storage device for the data gathered about the road. With the Bluetooth connection the data would be stored on whatever device it is connected to whether it be a phone or a laptop, this is problematic because most times a phone or laptop is not used for only one purpose meaning other applications may use up storage space. If there is not adequate storage space for either of these methods the extra data would be lost. Losing data is something we want to avoid at all costs, and managing how much storage is used on a device with a single purpose such as an SD card in our device is much easier than storing data on the user's phone which can have variable storage space, as well as other applications that utilize that available space.

The second difference between these two methods is reliability. Reliability here is defined as the consistent and accurate transmission of data gathered from the device to wherever it will be stored. With a bluetooth connection data reliability is entirely dependent on the Bluetooth link between the two devices. Ways for data to be lost between the device and the database include but are not limited to: connection failure, interference, weak signal and loss of storage device. With a local storage device such as an SD card or USB drive we eliminate the loss of data due to connection failure, weak signal and reduce the chance interference corrupts the data. In a Bluetooth connection, connection can fail for some simple reasons such as the user's device turning off or malfunctioning. In our case weak signals may be ignored as a threat to reliability as a Bluetooth device will be able to communicate with the user's device from anywhere reasonable around a vehicle. Interference may threaten both systems but it would be far more common for Bluetooth interference as many of today's devices and vehicles have and utilize Bluetooth, drivers on the roads we will be scanning might be using Bluetooth to connect their phone to their cars infotainment systems meaning this increases the chances that other devices may be operating on the same frequency as our device. Having other devices operating on the same radio frequency closeby can introduce packet collisions, leading to a loss of packets. The last threat to storing data safely affects both storage methods and is not as big a threat as some others and is mainly due to human error.

The third and final difference between the two methods is the work required to use each method. Transferring data to a separate device using Bluetooth requires connecting our device to the users device, this step is already taken when we implement the user feedback system. Transferring data using a physical device such as an SD card requires remembering to physically insert the SD card into the device and removing it from the device after operation. Both methods are simple to execute but introducing human error may be missed.

The final difference between both of these methods of transferring data is cost. The cost of an SD card system is largely dependent on the size of the card. For 128GB SD card storage it will cost about $22, the bluetooth module we were looking at in the previous section costs about $10 but this expense is already accounted for within the user feedback system whereas the SD card's main use would be to store data gathered from our device. Table 14.a is a decision matrix that helps determine which data transferring method to use and table 14.b defines the criteria.

Table 14.a: Data Transfer Decision Matrix

Decision Factors		Local Storage	Bluetooth
Criteria	Weight		
Cost	Medium	$26.00	$9.96
Reliability	High	High	Medium
Work	Low	Simple	Simple
Storage location	Medium	On Scanner Device	On User Device

Table 14.b: Criteria Definition for Table 14.a

Criteria	Definition
Cost	Cost of the storage method
Reliability	Consistent and accurate transmission of data gathered
Work	Effort required for user to use this method of storing data
Storage location	Location of which data from the road scanner will be temporarily stored

In our final implementation we …

3.4.6 GPS module

GPS locational data is important to this project because it fulfills one of our goals which is to GPS tag road damage. The purpose of tagging the location of road damage is to accurately map where the damage is on a map for visualization. The two methods to determine this accurately is to either have a GPS module onboard our device or to gather GPS data from the user's phone once it is connected to Bluetooth. One issue that might arrive from both of these solutions is that when GPS connection is lost we will not have locational data to tag any road damage meaning we will have to come up with a method to maintain locational data even when GPS is not available. We have 2 GPS modules in mind to compare to our other method of using the user's phone. There are a few differences between these methods including price, reliability and how long to start a GPS connection.

The first GPS module is about $9 and about half the price of the second GPS module at $22. Using the user's device to provide GPS data is free since a Bluetooth module is already required for communicating with the user to provide feedback of the device's status as discussed in section 3.4.

The second difference, accuracy, is more important to our project than the cost of the three different methods. Accuracy is defined as how close a GPS's locational data is to the device's actual location. The first GPS has an accuracy of 2.5m CEP and the second GPS module has 2m CEP accuracy whereas using the user's phone depends on the device the user has. CEP stands for Circular Error Probable meaning that if you drew a circle with a radius of 2.5m around where the GPS said its location is there would be a 50% probability that the GPS is in fact in that area for the first GPS module. Between the two GPS modules and collecting GPS from the user's phone, the second GPS module is the most accurate to the GPS's actual position.

The third difference between these methods is reliability. Reliability in this context refers to situations where locational data may be lost or corrupted. With the Bluetooth connection sending GPS data to the device we risk losing locational data if the user's phone dies, disconnects from Bluetooth or otherwise the Bluetooth data becomes corrupted for whatever reason. All three methods risk losing GPS locational data if the GPS link is lost, but they differ slightly at the strength of the connection they can support. Just like accuracy, reliability is completely dependent on the device the user has for the Bluetooth connection case. The first GPS module can support tracking and navigation down to -166dBm and the second GPS module supports only down to -147dBm. A lower dBm rating for this means the module can support a connection with a weaker signal. With this knowledge this shows us that the first GPS module supports a slightly weaker signal than the second module. Supporting a weaker signal is beneficial for us because it may reduce the number of instances where we have to rely on other methods of gathering locational data such as calculating the time between two individual Locations to estimate the speed at which the vehicle was traveling and the associated physical location of any road scans.

The last difference between the three methods is the time it takes the module to get an initial GPS fix. This is important to this project because it determines when the device is ready to start recording road damage, in other words how long the user has to wait before they can start driving to collect data. The first GPS module has a cold start time of 26 seconds and the second device has a cold start time of 29 seconds. Collecting locational data from the user's phone purely depends on how quickly the user can connect to the device, we believe connecting to the device through Bluetooth will take longer than the other two methods and therefore this difference is less important to us than others since regardless if we use the user’s phone to collect GPS data we are still connecting to Bluetooth to provide the user with feedback from the device, in other words it is expected that the user will take more time to get started than it will take for the GPS modules to initially connect with a satellite.

One difference between the two GPS modules is the datasheet that is provided with both of them, the second GPS module has a more detailed data sheet and provides a schematic as well as a block diagram. These included materials will make using and understanding the module that much easier as the specifications and the pin assignments are given directly on the second module's datasheet, reducing research time and possible troubleshooting that may occur. This factor is very important as it gives us more confidence in implementing this module in a timely manner. Table 15.a is a decision matrix that helps determine which GPS module to use and table 15.b defines the criteria.

Table 15.a: GPS Module Decision Matrix

Decision Factors		GPS 1	GPS 2	Users Phone
Criteria	**Weight**	**LG77LICMD**	**377-MAX-M10S-00B**	
Cost	Low	$9.07	$22.21	$0.00
Accuracy	High	2.5m CEP	2m CEP	Unknown
Reliability	Medium	-166dbm	-147dbm	Unknown
Cold start	Low	26s	29s	Unknown

Note: in reliability lower dBm is better, this means this is the weakest signal that can provide a positional fix

Table 15.b: Criteria definition for Table 15.a

Criteria	Definition
Cost	Cost of the module and its implementation
Accuracy	How close the device's calculated position is from the truth
Reliability	Cases where locational data may be lost or corrupted
Cold start	Time for the device to start gathering locational data

3.4.7 Microcontroller

For this device to provide many of the features we will need a device capable of controlling it all, this is where microcontrollers come in. A microcontroller is a compact integrated circuit that is designed to control specific operations in an embedded system. Two microcontrollers are compared in this section, the msp430fr6989 and the raspberry pi zero w. The MSP board is familiar to many students at UCF, critical to some embedded systems classes in understanding some basic functions of computers and embedded systems. Some functions such as timers and serial communication were covered in these classes using this very same microcontroller. This means as students here at UCF we have a very good understanding of the features of this board and how to utilize them. On the other hand the raspberry pi zero is a device with which we have no real life experience in programming and using its many features. The two boards are actually quite different from each other, the MSP board is a simple microcontroller while the raspberry pi is a full on computer. The MSP board is a 16MHz RISC architecture processor, and the raspberry pi is a 1 GHz 64 bit ARM processor. ARM (Advanced RISC Machine) is a part of the RISC architecture which means Reduced Instruction Set Computer. The MSP CPU is roughly 625 times slower than the raspberry pi board based on processor speed alone.

Another difference between these two options is that the raspberry pi zero provides useful features that we will need for some of the goals of our project. One such feature that the raspberry pi zero has is Bluetooth, this reduces the complexity of connecting a Bluetooth module to a microprocessor as we would need to do if we choose the simple msp430 board. Another feature the raspberry pi zero includes is an integrated SD card slot in the device. As per the Data transference section (3.5) of this paper we prefer having local storage of the road data for increased reliability and simplicity therefore having a dedicated SD card slot already built in will also simplify the work we have to do. The last useful feature that the raspberry pi zero has is the two micro-usb ports on the device, this is useful to this project because the camera we are looking to get has a usb plug, and to connect the camera to the device we will simply need a male micro-usb to a female usb-a cable. This also reduces the need for us to design a way to connect the camera to our device. Some other features the raspberry pi zero include is a wifi module and an hdmi output but these might not be features we will necessarily use.

In comparison the MSP board is pretty basic compared to the raspberry pi zero, this is partially because the raspberry pi zero is meant to be a computer, it even has its own GPU. One drawback of the raspberry pi zero is that since it is a computer it needs an operating system in order to run and the Raspbian OS take about 8GB of the SD card's storage capacity, this might be a non issue because the official documentation from raspberrypi.com states "the boot partition on the SD card must be 256GB or less otherwise the device will not boot up", meaning even if the system takes takes 8GB we still have over 240GB to store our data which is more than we presume we will need.

One similarity between both of these devices is neither includes a GPS module so we will need to implement that individually in both cases to fulfill one of our project goals. With the MSP board this increases the complexity because we will need to design and support a total of 5 components. On the Raspberry pi zero w we need to design and implement only the GPS module and the power system.

To summarize the main benefit of the raspberry pi zero system is that it already includes many of the features we are looking to include within our design. Having these features included reduces our workload and reduces the cost of parts we will need. The raspberry pi zero w was originally marketed at only $15 to make it available to many users, us implementing a Bluetooth communication system alone would cost roughly $10 in parts and some effort in programming the system to work. In the raspberry pi zero system this is all taken care of making it a good deal at a price of $15. Unfortunately this device is sold out on many websites for this price and can only be found on other sites for close to $50 that said it is still a pretty good deal as it reduces our workload on just getting the system to work with all of its parts correctly, this can help us focus on getting the device to do its job earlier than with the MSP board. Table 16.a is a decision matrix that helps determine which microcontroller to use and table 16.b defines the criteria.

Table 16.a: Microcontroller Decision Matrix

Decision Factors		MCU 1	MCU 2
Criteria	**Weight**	MSP430F2418TZCA	Raspberry Pi Zero W
Cost	High	$17.28	$47.90
Features	High	• 2 timers	• usb-c port • SD card slot • Bluetooth
Familiarity	Low	Moderate experience	Zero experience

Table 16.b: Criteria definition for Table 16.a

Criteria	Definition
Cost	Cost of the device
Features	Features that are useful to our project.
Familiarity	Experience with the device, in terms of use and programming

3.4.8 Power Supply

In the electrical configuration sense of our device there are many different possibilities of how to build and maintain our goals with the most efficient parts. The first decision to be made is what kind of power configuration would provide the best operation. The goal of this device is to begin with a power supply that generates the laser configuration as well as the camera to detect and save images through the process of driving a vehicle on the obstructed road. This data then needs to convert to a digital system to be read by the software. The software portion will create a website with a visual representation of what the laser and camera collected. In order to decide which form of power supply will operate our device we need to understand how each option performs. These options were previously discussed in the technology comparison section. As researched these applications apply to both sections, but in this instance we will discuss further the decision factors such as cost and performance.

Our first option is an AC-DC converter which works by converting the incoming AC voltage into stable and regulated DC voltage that can be used to power electronic devices. The AC voltage is rectified using diodes converting the alternating voltage into a pulsating DC voltage. This DC voltage is filtered using a capacitor to create a stable DC voltage. Voltage regulators can then be used to maintain a constant output voltage by adjusting the current flow. AC-DC conversion is known as a good option for power supply because of the compatibility/flexibility in terms of voltage and current levels that can be supplied. The AC-DC converter is also highly efficient, with power efficiency of over 90%. With this power efficiency, very little power is wasted during the conversion process resulting in a lower energy need. With the result being a conversion to a DC voltage, this is highly reliable and safe because DC is safer at the low voltage levels and does not have the same potential for electric shock. However, this AC-DC converter is not always the best option in terms of power supply because of the complexity of a simple battery powered device or direct DC power. This can make design terms in the schematic and SD2 more difficult to troubleshoot. Electrical noise is also a large factor about AC-DC. This can affect the performance of sensitive electronics. Finally this method can be inefficient when powering a device that requires only a small amount of power. In our case for our model the converter could end up wasting more power than necessary making the product inefficient.

The next option is a DC-DC converter which works by converting one level of DC voltage to another level of DC voltage. This type of power supply is used to step up or step down the voltage level of a DC power source to match the load requirements. The input stage of the DC converter is passed through an inductor and followed by a switch, such as a transistor or MOSFET, to control the flow of current. The output stage passes through an inductor to step up or step down the voltage level. A diode converts an AC voltage back into a DC voltage to then be filtered to smooth out ant noise. In terms of power supply DC-DC is a very popular option. The efficiency level is higher than 95% meaning very little power is wasted in the conversion process. As of safety and reliability, there is not as high of a potential for electric shock and it has been proven highly reliable. The most important advantage of DC-DC conversion is it provides good noise immunity which is important when the load is sensitive to voltage fluctuations and electrical noise. The weight and portability makes it a popular option for automation electronics. For the design of our project this can seem like a very good contender for the build of our power supply. Although the advantages seem promising there are several disadvantages that cause us to not adhere to specific electrical standards. DC-DC converters can generate electromagnetic interference which affects the performance of nearby electronic devices. Being that our device will be mounted on a vehicle we want to ensure the least amount of interference. The cost of the device can be on the more expensive side as well compared to other options and it can be seen as more complex to design rather than a simple battery.

Our third option is a voltage regulator. This is a device that is used to regulate the output voltage of a power supply, ensuring that it remains constant regardless of changes in the input voltage. There are linear and switching voltage regulators. A linear voltage regulator uses a variable transistor to regulate the output voltage. These are relatively simple and inexpensive but are less efficient than switching regulators and are used for lower power applications. A switching voltage regulator works by using a switching method, such as a MOSFET, to turn the input voltage on and off at a high frequency. This generates a high frequency AC which is then filtered into a constant DC voltage. Switching regulators can be more efficient but are more expensive and complex than other options. Voltage regulators have many advantages such as high efficiency and stability. These are designed to maintain a constant output voltage and provide a stable reliable power supply. Regulators also provide low-noise power supply which can be important for applications in which electrical noise would affect the performance. There is also the ease of use, this option requires little to no external components for design, causing them to be suitable for a wide range of applications. While voltage regulators can be a good option there are plenty of drawbacks including heat dissipation and limited voltage range. In many cases voltage regulators may also not be able to provide enough current for high power applications with the design of a limited current capacity. Another disadvantage would be the higher cost compared to other power supply solutions.

Finally our last option for the power supply is a battery approach. Using batteries is using a device that converts chemical energy into electrical energy through a chemical reaction. When a battery is connected to a load, the chemical reaction between the anode and cathode generates an electric current which flows through the load to provide power. As the process continues the materials are consumed and the battery’s voltage decreases until the battery is dead. The amount of power available is dependent on the chemistry of the battery, the cells and the load. The capacitance of the battery is the amount of charge that the battery can store and deliver over time. These are a popular choice because of its rechargeable capability as well as it being portable. The portability factor ensures that these will operate without needing another source to cause a reaction such as a wall outlet or another device. Because these can provide consistent power as long as they are charged they can be a very reliable option for uninterrupted power. There is minimal risk associated and they are known for being highly efficient. The last top advantage is the sustainability of batteries because they can be reused many times, reducing the concept of waste. However, there can be some disadvantages to the use of batteries for power supply. Batteries do contain a limited capacity and can only provide a certain amount of power before the need of recharge or replacement. This is an issue if the device is on a continuous operation. The charging time can also impose an issue if the device needs to be used again immediately but the battery has not been fully charged. If the batteries also need to be replaced very often the cost of the type of battery and the amount of replacement can add up to be more expensive than other power supply options. Compared to the other options the drawbacks of the battery powered option is not as significant as the other. In the case of our device we will be moving forward in the design process with using the battery option.

For a more concise overview of the decision of how to power the laser driven device a table 17.a is provided below with the decision factors including criteria and weight, while table 17.b provides the definitions for the criteria.

Table 17.a: Power Supply Decision Matrix

Decision Factors		AC-DC Converter	DC-DC Converter	Voltage Regulator	Battery Power
Criteria	Weight				
Portability	low	medium	high	medium	high
Noise	medium	medium	medium	low	low
Cost	medium	$8	$8	$6	$4
Efficiency	high	low	high	medium	high

Table 17.b: Criteria Definitions for Table 17.a

Criteria	Definition
Portability	Can the size of the part travel well and compactly in our device
Noise	Electrical noise interference
Cost	Cost of the hardware
Efficiency	Ability to achieve end goal with little to no waste of power

All options are known for their reliability and efficiency but with the specific requirements and specifications of our design the main two applicable are the DC-DC converter and a battery. For the portability necessity on the road mapping system, it is in our best interest to choose the use of a battery. The device at this moment does not require a specific voltage that the battery cannot provide, and the DC-DC converter could introduce inefficiencies and add weight/complexity to the device. The rechargeable, portable and self-contained power source, the battery is the final choice into which we can now break down the options to secure a choice for which chemical reaction would suit our device best.

3.4.9 Battery

Using the above reasoning and further research to decide which option between the DC-DC converter and a battery is better, we have come to the final decision of a battery for the power supply configuration. Because of the portability, noise and rechargeable options we found that a battery is the best solution for a device that would be mounted on a vehicle without an outside power source such as a wall outlet providing current at a consistent rate. The next objective is to now decide which chemical reaction in a battery is preferred for the resulting lifespan and voltage. The options we will explore are lead-acid, lithium-ion, nickel-cadmium and nickel-metal hydride batteries.

Lead-acid batteries are a common choice for high-powered applications. These are inexpensive but have a lower energy density than other batteries so this makes them heavy and bulkier. Lead-acid batteries are also sensitive to temperature and require regular maintenance. The specifications can vary based on the size and capacity but some common values are, they typically have a nominal voltage of 2 volts per cell. A typical 12-volt lead-acid battery contains 6 cells. The capacity of a lead-acid battery is measured in ampere-hours (Ah) and can vary from a few Ah to several hundred Ah. For a common 12-volt battery these can weigh around 30-50 pounds because of the chemical compounds. Relative to the weight, the size can be generally large as well. There are small sealed batteries and large industrial options for heavy duty applications. The full charge time depends on the size and charging rate, but typically takes several hours. One of the benefits of the lead-acid battery is they can provide a high current discharge rate for short periods of time making them suitable for high power applications as well as a self-discharge rate of 1-3% per month. Lastly, the average lifespan is typically ranging from 3-5 years if it is well maintained. Overall, lead-acid batteries are reliable and cost-efficient for applications that require high current discharge but these have a lower energy density and shorter life span.

Lithium-ion batteries are another popular option due to their high energy density, low self-discharge rate and long lifespan. This rechargeable option has several specifications to differentiate it from other chemical reactive batteries. Lithium-ion batteries have a nominal voltage of around 3.7 volts per cell. The average cycle life is the limited number of charge/discharge cycles that the battery can compute before it degrades. For the lithium-ion option, it typically has around 300-500 cycles or a 2-3 year lifespan. This depends on the quality of maintenance and usage throughout its lifetime. The full capacity charging time is from 3-5 hours but has the option to reach 80% charging capacity in 1-2 hours making it a quick and efficient choice. The difference of lithium-ion compared to lead-acid is the discharge rate. Lithium-ion batteries have a self-discharge rate, which means they retain their charge for longer periods of time without the need for recharge. This self-discharge rate is around 1-2% per month. Another specification of this type of battery is the operating temperature. This can be seen as a disadvantage because the performance can be affected by high temperatures resulting in a reduction of their capacity and lifecycle. The optimal operating temperature would be around 68-77 degrees Fahrenheit.

Nickel-cadmium batteries are the third option being explored, as it can be used as a rechargeable and portable application. The specifications include the nominal voltage of 1.2 volts per cell and a capacity that ranges from 300 mili-amphere-hours (mAh) to 500 mAh depending on the size. The cycle life is normally 500-1000 charge/discharge cycles and an average lifespan of 2-5 years. The self-discharge rate is faster than the lithium-ion option but is still slower than the lead-acid, this is at a rate of 10-20% per month. The nickel-cadmium battery has temperature ranges for each transition and use including the operating temperature of -4 to 122 degrees Fahrenheit, the charging temperature range of 32 to 113 degrees Fahrenheit and the discharging range of -4 to 149 degrees Fahrenheit. This battery can be a better option compared to the lead-acid because of the size and weight options that range from very small in the weight of grams to large cells at the weight of several kilograms.

The last battery option we will discuss is nickel-metal hydride batteries. These are most commonly used in digital cameras and portable audio players. Some specifications of the nickel-metal hydride batteries are that they have the nominal voltage of 1.2 volts per cell which is slightly lower than alkaline batteries whose nominal voltage is 1.5 volts per cell. The capacity range is typically from 500 mAh to 5000 mAh and they should be operated at room temperature for optimal performance. NiMH batteries have a higher self-discharge rate compared to the lithium-ion and nickel-cadmium options. The rate of the nickel-metal hydride is up to 30% of loss of charge per month. An advantage to the use of these batteries is the charging capabilities. These can be charged using a variety of charges such as fast chargers and smart chargers. The charging rate depends on the battery's capacity but averages around 1-5 hours. The cycle life of the NiMH is around 500-1000 charge/discharge cycles and it has a lifespan of 2-3 years. Another advantage is this battery is considered less harmful to the environment than other types because it does not contain toxic heavy metals such as lead or cadmium.

Table 18, below will show a comparison between the available battery options to help demonstrate the final decision. Due to design constraints and specifications a Lithium-Ion battery was chosen for the prototype.

Table 18: Battery Specification Comparison

Specifications	Lead-Acid	Lithium-Ion	Nickel-Cadmium	Nickel-Metal Hydride
Average Lifespan	3-5 years	2-3 years	2-5 years	2-3 years
Total Voltage (per cell)	2 V	3.7 V	1.2 V	1.2 V
Size	Large	Small	Small	Small
Discharge Rate (per month)	1-3%	1-2%	10-20%	30%

Using the knowledge gathered above regarding the types of rechargeable batteries, the final decision for the best option for our device's configuration is the Lithium Ion battery. Based on the currently known power requirements we have chosen a 9 volt lithium battery, whose average cost is around $4 per unit. The manufacturer has not been determined yet but could be any generic brand such as Energizer or Duracell.

3.4.10 Server

To host a website on the internet, a server is needed. A server is a fancy name for a machine that is always on and open to a network. Therefore, a server can be as small as a PCB or as large as a desktop tower. In considering how the server should best be organized, the behavior and parts are of importance. The server’s behavior is described qualitatively. Conversely, the server’s parts are described quantitatively. From humble beginnings, the server for this project is hosted on a Raspberry Pi 4 Model B (“RPi4B”). Scaling the computing power or storage of the server is possible by either upgrading the individual hardware or paying for cloud resources. These options are organized in table 19. Due to design constraints and specifications a RPi4B was chosen for the prototype. Table 19 compares qualities between a 2015 raspberry pi model, a 2019 raspberry pi model and Amazon Web Servers.

Table 19: Server Decision Matrix

Decision Factors		RPi2B	RPi4B	Cloud (AWS)
Criteria	Weight			
Overall Qualities				
Reliability	High	Prone to grid blackouts	Prone to grid blackouts	Nearly 24/7, 365 service
Availability	High	Low	Low	High
Cost	Medium	$67.55 (from amazon)	$197.90 (from amazon)	$15/month
Capability	Medium	Pitifully low	Passable	Abundant
Security	Low	Weak	Weak	Tough
Flexibility	Low	Low	Low	High
Scalability	Low	Low	Low	High
Hardware Specifications				
Architecture	High	ARMv7	ARMv8	ARM Neoverse
CPU	Medium	900 MHz quad-core	1.5GHz quad-core	1 core
RAM	Medium	1 GB	8 GB	1 GB
I/O	Low	4 USB 2.0	2 USB 3.0, 2 USB 2.0	100 GB Transfer

Reliability and availability are tied for highest weight in the decision matrix. This is because an unreliable server is a useless server. That is to say, the website being accessible 24/7 is not an ideal but a bare minimum. The RPi4B lives in a bedroom. As such, it relies on the power of Florida's local grid. To combat blackouts, an intermediate storm surge battery is in place to power the Pi for an hour if the grid momentarily fails. As for availability, there is no server if there is no server hardware. As of March 2023, the RPi4B is out of stock from all approved resellers (“Cytron Technologies” and “ThePiHut”). However, it is available on Amazon for $197. Only 560% more expensive than the MSRP ($35).

Which transitions well into the criteria of cost. There is a serious consideration for hosting the website with Amazon’s “Lightsail” due to the economic cost and convenience. At $15 a month, hosting the server with Amazon Web Services (“AWS”) for ten months – almost an entire year - is cheaper than buying the RPi4B. However, the computing power of the $15 plan is laughable. Amazon offers 1 GB of RAM, a single core processor, and 40 GB of hard drive space for $15 a month. Even though the capability of the RPi2B is described as “pitifully low”, the RPi2B comes with equivalent RAM, a quad core processor and a micro-SD card slot (which currently houses a card of 128 GB capacity). The RPi2B was released in the beginning of 2015 which means the $15 per hour plan is worse than hardware from eight years ago.

Of course, that judgment assumes AWS’s single-core processor is as old as a Cortex-A7 chip. In reality, it is a chip specifically designed to handle the strenuous loads of a server. These chips, like those seen in Intel’s “Xeon” series, vastly outperform chips designed for consumer desktop use with at least a magnitude or up to five magnitudes of improvement in computing power. On flexibility, as well, nothing beats the cloud. By design, cloud computing is modular. This is reflected in Lightsail’s “pick and choose” style of server design. For example, instead of the $15 deal mentioned above, a virtual server running on a Linux operating system can be bought for $10 per month. The 1 GB memory is upgraded to 2 GB and the storage capacity is upgraded from 40 GB to 60 GB. To easily increase storage capacity, $3.20 can be added to the $10 per month for another 32 GB. That’s $13.20 now for an extra gigabyte of RAM and an extra 52 GB of storage.

Additionally, hosting the server on the cloud provides unparalleled security and scalability. Trying to hack into the cloud involves bypassing multiple layers of enterprise-level networking. Trying to hack into a server hosted in somebody’s bedroom involves running a password cracker for a day. To remedy this discrepancy, following the best practices outlined in the NIST 800-123 will help bolster the server’s defenses. If the prototype camera’s resolution or frames per second were increased, the server’s capacity would need to be increased. This can be done by connecting a hard drive to the server via a SATA to USB cable. Or, much easier, a command can be typed into a console to allocate more resources to a virtual server. This is the way of the cloud. Some of Amazon’s plans even dynamically scale resources based on the server’s load.

If hosting a server on the cloud is economically superior, easily customizable, and secure, why choose locally hosting? Being a senior design project, the honest answer is curiosity. The experience is answering the question: how is a server hosted from the ground up? In other words, exploration is being prioritized over efficiency. With the benefits of centralized computing power becoming ever more apparent, the future of hosting servers is convincingly in the cloud. However, it doesn't hurt to know.

Finally, the hardware. The server's architecture has the highest weight because of compatibility concerns with the server's core processes. Its database, for example, only runs on 64-bit x86 platforms. This renders 32-bit architectures, like the RPi2B's ARMx7, incompatible. The CPU is of medium weight since the main purpose of the server is to process HTML requests and serve content. Eight gigabytes of RAM are useful for the server-side calculations necessary to translate camera data into visual maps and geotags. The I/O is also worth mentioning since the RPi4B supports USB 3.0 ports. USB 3.0 ports can transmit data up to ten times faster than USB 2.0 ports. Pragmatically, this means the RPi4B can read and write to external hard drives up to a magnitude faster.

Since the RPi4B has a 64-bit architecture, 64-bit operating systems are supported. The Raspberry Pi Foundation recommends the “Raspberry Pi OS”, but the server will be run on “Ubuntu Server 22.04.2 LTS”. This is because Ubuntu is a familiar option. Ubuntu Server is also lightweight, only requiring a 1 GHz processor and 1 GB of RAM to run. The entire OS takes up around 2.5 GB. Although the RPi4B is fully capable of running Ubuntu Desktop, the purpose of the server is to host a website. Thus, all the flavor of graphical interfaces is unnecessary.

3.4.11 Database

The purpose of the database is to store the data generated from the camera. In academia, there are two popular database management systems: MySQL and MongoDB. MySQL was released in 1995 and organizes data according to a relational model (mainly). After almost three decades, it has become well-established in full-stack applications. On the other hand, MongoDB was released in 2009. MongoDB organizes data in collections of “documents” instead of relational tables. Despite MySQL's widespread adoption, MongoDB has become a staple in modern tech stacks. For this project, MongoDB is used. Why MongoDB was chosen in comparison to MySQL is summarized in the decision matrix below in table 20.

Table 20: Database Decision Matrix

Decision Factors		MySQL	MongoDB
Criteria	**Weight**		
Intuitivenes s	High	Medium	High
Flexibility	High	Medium	High
Capability	Low	High	High
Security	Low	High	Medium

One database is not a direct upgrade of another. In other words, the database management system should be chosen based on the use case. The use case of this project is storing images taken from a camera and storing GPS data. To illustrate how MongoDB is "intuitive", here is an example: The database will need to store data generated from the camera. This data might be in the form of a grid of raw pixels. The pixels might be represented as a three-tuple (e.g., r, g, b) or a four-tuple (e.g., r, g, b, a). This is easily represented in MongoDB as an object that has three or four {key: value} pairs. Each pair represents the red, green, blue, and alpha of a pixel. This is what is meant by "intuitiveness." The shape of the input data translates almost directly with how it is stored in the database. In comparison, instead of thinking in terms of {key: values}, MySQL relates the intersection of a "red" column and a number in a row to the red value for the pixel that row represents.

As implementations change to satisfy the project's requirements, so does the structure – or "schema" - of the database's input data. MongoDB elegantly handles this by allowing documents of different shapes to be stored in the same collection. For example, a document that is missing longitude and latitude values can be stored with other documents that have GPS data. If it is discovered that a new input needs to be stored in the database, it will not be necessary to create a new collection. Generally, MongoDB is useful for managing semi-structured data such as the data sourced from the GPS sensor and camera.

As for capability, both MySQL and MongoDB are efficient at storing and querying data. MySQL, by default, uses the "InnoDB" database engine to perform CRUD operations for the database and MongoDB uses the "WiredTiger" database engine. The discussion of which database engine is more efficient becomes convoluted such that blanket statements such as "1 GB of data in MySQL is equal to 1 GB of data in MongoDB" quickly lose meaning. As such, the weight of capability is low. To answer the question of which database management system has higher performance: both are sufficient in storing and retrieving the data for this project.

Originally, MySQL was only capable of organizing data relationally. Structured data, like waiver forms or credit card information, fits nicely into the relational structure. As people took on new challenges, like facial recognition, individual data points became less meaningful. In response, MySQL not only handles structured data, but it is now also capable of organizing semi-structured data like the Binary Encoded JSON (“BSON”) documents seen in MongoDB. In other words, its flexibility in recognizing and managing different data has increased over time. Additionally, MySQL fundamentally implements data authentication and secure socket layer (SSL) security. In terms of flexibility and security, MySQL provides many attractive features. Overall, however, the intuitiveness of MongoDB’s document-based approach is the deciding factor in being the chosen management system for this project.

3.4.12 Front-End Frameworks

The “front-end” in a full-stack app refers to what the clients see. Front-End frameworks are libraries that seek to accelerate the development process of transforming data to a graphical interface by advocating for codebases to adhere to a certain paradigm. By following a certain structure of code, optimizations can be made by the framework to minimize re-renders, synchronize state changes, and enhance code semantics. For example, following the “declarative” paradigm of the “React” library allows for websites to be rendered using the “Virtual DOM.” The virtual DOM greatly enhances the performance of a website by calculating what elements change in response to an event and re-rendering only those changed elements instead of the entire website. Table 21 is the front-end framework decision matrix. Due to design constraints and specifications React was chosen for the prototype.

Table 21: Front-End Frameworks Decision Matrix

Decision Factors		Vanilla	React	Angular	Svelte
Criteria	Weight				
Documentation	High	Well documented	Well documented	Well documented	Sparse documentation
Familiarity	High	Familiar	Familiar	No experience	No experience
Development Speed	High	Slow	Quick	Slow	Quick
Performance	Medium	Terrible	Quick	Quick	Quickest
Flexibility	Medium	Flexible	Flexible	Rigid	Flexible
Scalability	Low	Terrible	Good	Best	Good

As visualized in the preceding decision matrix, the most important factor in choosing a front-end framework is ease of use. All these frameworks are different shapes of the JavaScript programming language. Ancient and monolithic stands Vanilla JavaScript, JavaScript without a framework. Although not a framework, it is included for the sake of comparison. Being the quasi-source of web scripting, Vanilla JavaScript is the best documented. This includes decade-old Stack Overflow questions, the professional Mozilla Developer Network ("MDN"), countless forum posts, and tutorials on personal blogs. Coding in Vanilla JavaScript is fun until finding a function becomes equivalent to whacking the grass with a machete in an attempt to traverse a jungle. This is because Vanilla JavaScript source files quickly degenerate into a wasteland of global variables and functions. After 300 or so lines of code it becomes cumbersome to keep working on a website coded in Vanilla JavaScript. Website state represented as global variables also takes a big hit on performance as the browser struggles to stuff everything into the client's RAM.

This is where front-end frameworks step in. The front-end framework used in this project is React. React was created by Facebook developers and released as an open-source library in 2013. Although this section is about front-end "frameworks," React describes itself as a library. The difference is a framework enforces an, often rigid, structure on a codebase. React JavaScript, on the other hand, can be flexibly interwoven into Vanilla JavaScript. It can be sprinkled in with or without accompanying libraries like JavaScript XML ("JSX"). Instead of using React here and there, however, it is more common for an entire codebase to follow React's declarative paradigm, bundling code into structures called "components."

A component is a small, reusable building block of a user interface that can be composed to create more complex components. React components have their own state and can manage their own rendering based on that state. This solves the Vanilla JavaScript problem of everything being global. Framing the website in terms of components also increases scalability as, once a basic component like a "counter" is defined, making as many counters as desired is as simple as typing "<Counter />" in the code.

React uses a Virtual Document Object Model ("DOM") to efficiently update and render components. The Virtual DOM is a copy of the actual DOM that React uses to keep track of changes in the state of the application. WHen there is an update in the state of the application, React compares the Virtual DOM with the actual DOM and makes the necessary changes in the actual DOM, which results in an instant update of the user interface.

React is lightweight, fast, and easy to learn, which is why it has become one the most popular front-end frameworks in recent years. It also has a huge community of developers that constantly contributes to the growth and development of the library. The "State of JS" took a survey of 39,472 JavaScript Developers in 2022 and 82% of the 39,472 developers said they use React. React's usage statistics in comparison to other front-end frameworks is included below in figure 11.

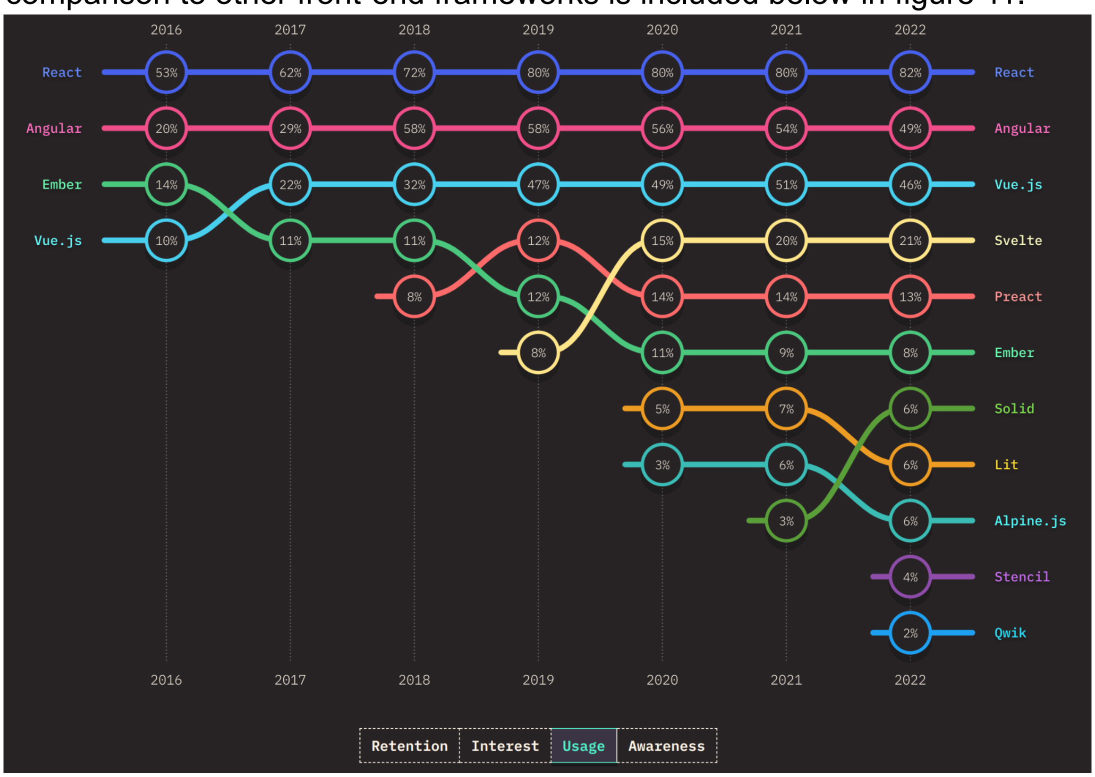


Figure 12: Front-End Framework Usage Statistics from 2016 to 2022

Like React, 100% of JavaScript developers in the State of JS survey reported they were aware of Angular's existence in 2022. Angular is a comprehensive open-source development framework used for building modern web applications. It is developed and maintained by Google. Its popularity and enterprise support allow many examples of Angular code to be found online. By design, Angular is used to create dynamic and responsive single-page web applications that offer an improved user experience. Unlike React, Angular uses TypeScript, a more strict and strongly-typed language. Angular is also different in having its own templating language. These features make Angular more attractive for large-scale, enterprise-level projects. Relating back to the small scale of this project, the robust nature of Angular becomes more of a hindrance than a feature.
The differences in React and Angular make it perhaps the most important part in planning how data is presented in this project. To go into more detail, there are seven key differences between the two: architecture, learning curve, performance, reusability, state management, development speed, and community support.

The architecture of React only provides a set of tools for building user interface ("UI") components. Angular, on the other hand, is a full-featured framework that provides a more opinionated approach to building web applications. Both are capable of building complex single-page applications, but React gives developers more room for integrating the codebase with other tools. This aligns more with the uncertainty of this project as the team gradually agrees on what works and what is unnecessary.

The learning curve of React is relatively easy to learn compared to Angular. React uses JavaScript and JSX, which are both familiar to most developers. JavaScript is a high-level scripting language that, when written well, can be understood without any documentation. That is, it can be read as if it were prose. JSX mirrors HTML which, adjunct to JavaScript and CSS, was the backbone of the web since the 2000s. Angular, however, has a steeper learning curve due to its complex architecture and TypeScript syntax. TypeScript is akin to a compiled language like C where programmers are required to specify the data type of a variable. This allows for extraordinary compile-time optimizations and easier debugging at the trade-off of slower development. Since ease of use is more important than scalability in this project, React's lower learning curve is a better fit.

In terms of performance, React is fast and efficient because of the virtual DOM. Angular also uses a virtual DOM, but its change detection algorithm is more complex and can sometimes result in slower performance. Performance is important for our project's website because of the data that is being presented. The semi-structured data sourced from the camera and GPS will require more “creative” means of presentation compared to something like strings, for example. Modern web browsers have come a long way mainly thanks to monumental leaps in hardware. While full 3D games can be played in the browser, something akin to how a stretch of road might be visualized with all its curves and elevations, performance is largely dependent on the client’s machine. To ensure the project’s website runs on as many computers as possible, leverage of a framework’s rendering optimizations is key.

React’s components are more reusable than Angular’s “directives” because they are simpler and more flexible. React components must be pure (a certain input always maps to the same output) and are encouraged to be as “atomic,” as conceptually straightforward, as possible. For this project, there will likely be a few types of objects repeated millions of times. For example, pixels or GPS locations. Without reusable and flexible components, coding the UI would be a nightmare.

Even in Vanilla Javascript, an interactable website exists in one of many possible states. For example, a website that displays a counter that counts from zero to infinity has the state where the counter is one, counter is two, ad infinitum. React formalizes the idea of state by providing a function that initializes and updates a component’s state. As the logic of a website increases, however, managing state becomes increasingly complex. React does not provide a built-in solution for managing application state, but there are several popular libraries such as Redux and MobX. Angular has its own built-in solution called RxJS, which helps to manage application state and handle events. For this project’s website managing state will not grow to be overly complex. The purpose of the website is to visualize data sourced from the camera and GPS. It will query the database and render the queries. As such, the state of the “world” (the website’s 3D coordinate space) is pre-processed and immutable to the client. However, the camera’s 3D orientation as well as any transformations on the world will need to be stored as state.

A particularly important factor for this project is development speed. React allows for quick and iterative development because its library of components is lightweight and easy to use. Angular, however, takes a more structured approach and requires more time to set up and configure. React provides an easy way to hit the ground running by typing the command “npx create-react-app” into the console. After this command is executed, a directory with an already-working app is available. From there, the developer can simply insert their code to create the app they want. What enables a full app to be created with create-react-app is the provision of a complete toolchain. A toolchain in a bundle of programs that work together to optimize, organize, and modularize a project. Exploring what tools comprise the toolchain is interesting but complex. For the scope of this project, the default toolchain is sufficient. Many great features like content hydration from the server, however, are not possible without configuring the toolchain.

As an open-source project, React has a large and active community. Angular also has a robust community, but it is smaller compared to React. Both React and Angular are powerful and well-established front-end frameworks, each with its own strengths and weaknesses. For React's strengths in flexibility, development speed, and community, it is the chosen front-end framework for this project.

While React and Angular have been the most popular front-end frameworks for almost a decade straight, there are many other front-end frameworks with high performance and unique features. One of these that is worth exploring is Svelte. Despite releasing four years after React and Angular, 21% of JavaScript developers used Svelte in 2022. At 70%, Svelte is also the front-end framework most JavaScript developers are interested in. Figure 12 shows the front-end framework interest statistics from 2016 to 2022

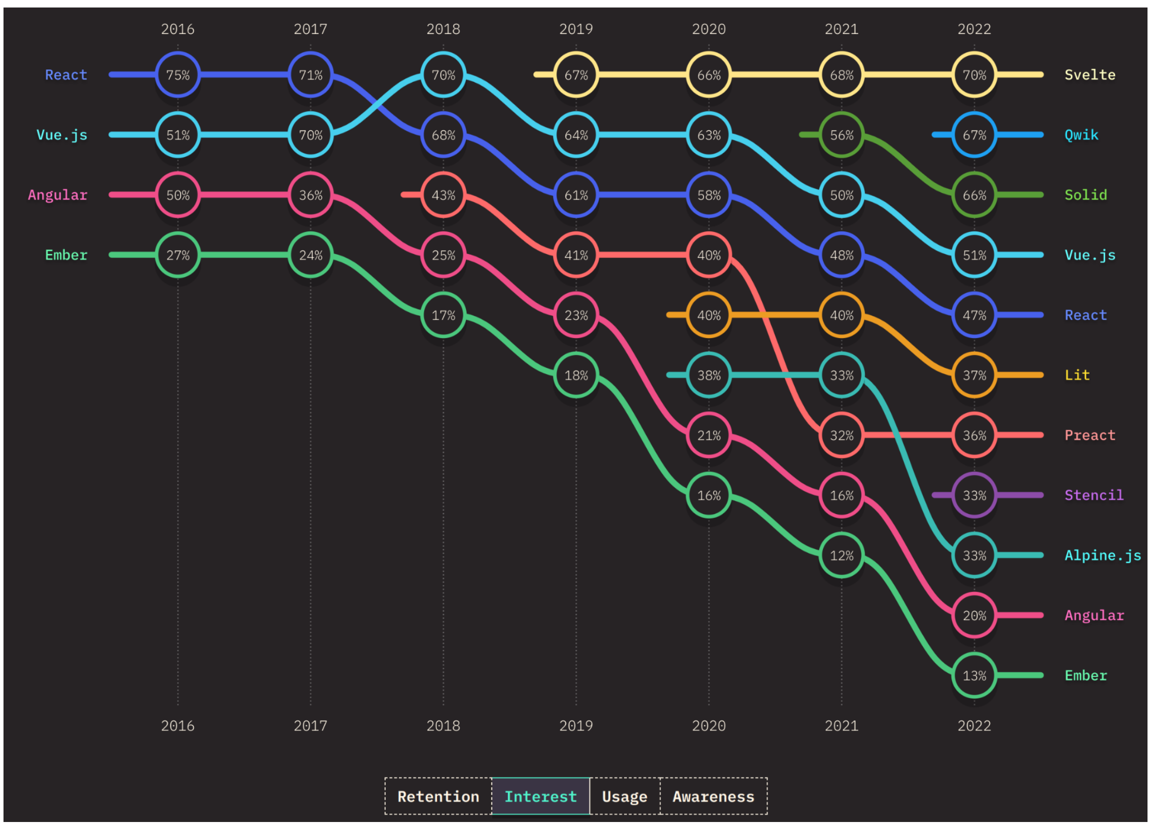


Figure 13: Front-End Framework Interest Statistics from 2016 to 2022

In general, Svelte is a new-generation JavaScript framework designed to create reactive, dynamic, and fast web apps with ease. It boasts a simplistic approach and is different from React and Angular, which rely on a virtual DOM, as Svelte compiles code at build time and eliminates the need for a virtual DOM. Svelte focuses on moving the logic of a web application away from the runtime and into the compile-time, offering better performance as it converts code into highly efficient Vanilla JavaScript. This minimizes the amount of code sent to the browser, leading to faster load times and better performance.

Svelte simplifies the development process of web apps, thanks to its intuitive templating engine, which enables developers to manipulate the DOM with declarative syntax. This is similar to reusable components in React. Svelte also allows developers to include CSS or any other text-based files directly into their components, reducing file size and easing the development process.

In terms of functionality, Svelte supports reactive programming, allowing developers to create web apps that react to user interactions, data changes, and other variables in real-time. It also integrates well with other technologies such as TypeScript, making it easier to incorporate into existing projects. This makes porting React or Angular code to Svelte easy.

Although the legends of Svelte's compiler-based approach being faster than React or Angular are enticing, it ultimately was not chosen because of its lack of support. There exist many more tools for React. If performance becomes an issue in the future, porting the codebase to Svelte would be a painstaking but possible solution.

3.4.13 Back-end

If a website has code that queries a database injected into its source file, the website would crash. If that did work it would be both hilariously and infuriatingly easy to extract anybody's information. To prevent this, encryption and connection protocols have been defined to provide data security and data integrity. In a "full-stack" application, these protocols are implemented in the "back-end" of the application. The back-end is an abstraction representing a suite of programs that connect the front-end to the database. In the project, the back-end involves "Express" and "Node". By the end of this section, all parts for the project's online application will have been discussed. Figure 13 shows the flowchart for the front-end, back-end, and database.

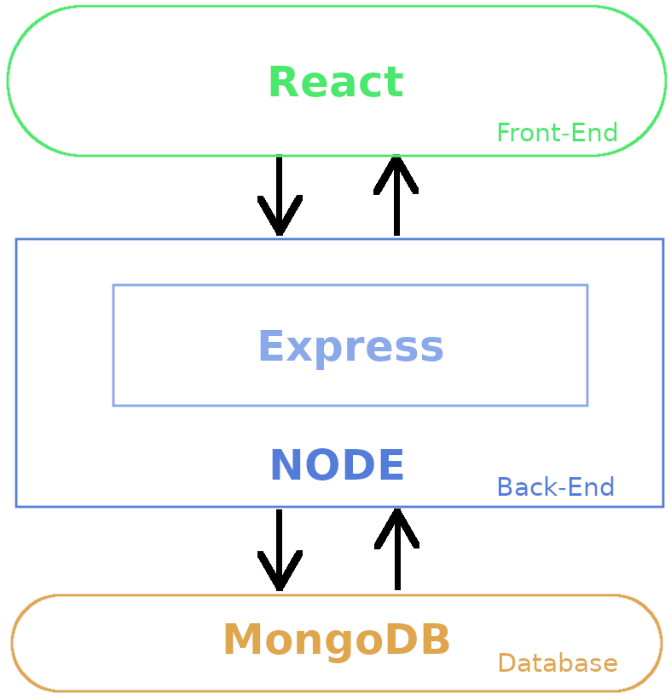


Figure 14: Front-End, Back-End, Database Flowchart

Originally, JavaScript was designed to enable interactivity in websites. That is, JavaScript was simply a script that linked a mouse click to an HTML element in a client's browser, for instance. This was in 1995. It was not until 14 years later, in 2009, when JavaScript was able to be run outside the browser, as a process, through Node. Node, often referred to as "node js", is an open-source, cross-platform JavaScript runtime environment. Before Node, full-stack applications used scripting languages like PHP (e.g., the "LAMP" stack) to connect the front end to the database. In the past decade, web developers have expended great effort to centralize all of web development under one language: JavaScript. The techstack used in this project, the "MERN" (MongoDB, Express, React, Node) stack has 75% of its components implemented in JavaScript.

Centralization of web development under JavaScript allows for a faster development cycle as the same JavaScript fundamentals underlie all parts. Learn one language to know the basics of most of the stack. Express, often referred to as "express js" runs inside a Node server. Express is a fast, unopinionated, minimalist web framework. Express can be described as the "middleware" of the application, handling requests, responses, and routing application logic. It provides powerful models for handling data exchange via the HTTP protocol. Adjunctly, the TCP/IP protocol is followed to ensure all data arrives at the destination in order and without gaps. Alternatively, the UDP protocol can be followed to exchange packets over a network. With less overhead, UDP is faster than TCP; however, the extra speed comes at the cost of data integrity. Most commonly, a client is satisfied waiting a little while longer, maybe a difference in milliseconds, to ensure they receive 100% of their requested data.

At the end of Senior Design II, it was decided to go serverless by uploading all website data to an Amazon S3 bucket. This substantially abstracts navigating tables and collections into a single JSON file. In exchange for a monthly cost, Amazon will provide the computational resources needed to perform database functions and simplify pulling data from the S3 bucket by providing a one-line key to access the bucket.

4 Standards and Constraints

4.1 Standards

While researching, creating, then building a prototype engineers must adhere to certain standards put forth by the government, such as OSHA, or other industry governing organizations that produce National Consensus Standards. Table 22 outlines standards that our group must follow when producing the LiDAR Surface Mapping System.

Table 22: Standards

Standard	Description
ANSI Z136.1	Safe Use of Lasers
ANSI Z136.6	Safe Use of Lasers Outdoors
IEC 60825-1	Safety of Laser Products
IEEE 802.15.1	Bluetooth Communication Standard
RFC 9110	HTTP Standard
ICD-GPS-200C	Signal Specification and Performance Standard
NIST 800-123	Best Practices for Hosting Secure Servers

4.1.1 Laser Safety Standards

There are many standards formed by agencies that apply to laser safety. For example, the American National Standards Institute (ANSI) facilitates consensus based technological standards in the US. Within ANSI the Laser Institute of America worked with a government agency OSHA, the Occupational Safety and Health Administration, to produce standards to ensure a workplace would be safe from any laser hazards. When building our prototype we will have to take into account ANSI Z136.1, safe use of lasers, and ANSI Z136.6, safe use of lasers outdoors. The International Electrotechnical Commission (IEC) is an international organization that produces standards for electrical and electronic technologies. ICE 60825-1, safety of laser products, will also be followed during the design and build phase of the project.

ANSI Z136.1 classifies lasers and laser systems based on the biological harm they may cause. Table 23 below shows requirements for each class of laser denoted by 1, 1M, 2, 2M, 3R, 3B, and 4. Classes that are denoted with a M are only hazardous when viewed through any optical device that will magnify. Class 1M and 2M replaced Class 3A. Class 3R lasers have relaxed rules as this class does not require the same safety standards as Class 3B or 4. Another ANSI standard that will affect our project is Z136.6, which puts forths guidelines for using lasers outdoors specifically when using an open beam.

Table 23: Requirements by Laser Classification

Class	Procedural & Administrative Controls	Training	Medical Surveillance	Laser Safety Operator
1	Not Required	Not Required	Not Required	Not Required
1M	Required	Application Dependent	Application Dependent	Application Dependent
2	Not Required	Not Required	Not Required	Not Required
2M	Required	Application Dependent	Application Dependent	Application Dependent
3R	Not Required	Not Required	Not Required	Not Required
3B	Required	Required	Suggested	Required
4	Required	Required	Suggested	Required

The table above shows the level classification of lasers along with the procedural and administrative controls, if training, medical surveillance, and a laser safety operator is required.

The FDA (Food and Drug Administration) has classified lasers into groups by hazard level.
Class 1 includes lasers that are eye safe under normal operating conditions. Any laser that does not emit a level of optical radiation that would harm the eye would be considered in this class. However, a more hazardous laser could be inside an enclosed area where a laser would not damage the eye and still be considered a class 1 product. Class 2 lasers are in the visible light spectrum (400 - 700 nm). If viewed momentarily it will not affect the eyes, but extended viewing will be harmful. A Class 3 includes a laser that emits any wavelength and outputs no more than 0.5W. They do not produce significant skin or fire hazards, and should not be viewed for an extended period especially at close range. A class 4 laser system is a fire and skin hazard and will cause eye damage if directly viewed. Anything that has an output of more than 0.5 W falls into this category. Below,

table 24 describes the class numbers put forth by the FDA and IEC along with a brief description of the laser product hazard and a few product examples.

Table 24: Classifying Lasers

Class FDA	Class IEC	Laser Product Hazard	Product Examples
I	1, 1M	Considered non-hazardous. Hazard increases if viewed with optical aids, including magnifiers, binoculars, or telescopes.	laser printers, CD players, and DVD players
IIa, II	2, 2M	Hazard increases when viewed directly for long periods of time. Hazard barcode scanners 66 increases if viewed with optical aids.	barcode scanners
IIIa	3R	Depending on power and beam area, can be momentarily hazardous when directly viewed or when staring directly at the beam with an unaided eye. Risk of injury increases when viewed with optical aids.	laser pointers
IIIb	3B	Immediate skin hazard from direct beam and immediate eye hazard when viewed directly.	laser light show projectors, industrial lasers, and research lasers
I4	4	Immediate skin hazard and eye hazard from exposure to either the direct or reflected beam; may also present a fire hazard.	laser light show projectors, industrial lasers, research lasers, and medical device lasers for eye surgery or skin treatments

ANSI Z136.1, ANSI Z136.6, and IEC 60825-1 will be considered when building and testing the optical system of our project. The type of laser suitable for outdoors use will be determined and safety protocols will be put in place.

4.1.2 Computer Standards

GPS Standard

ICD-GPS-200C defines the signal specification and the GPS SPS PS stands for the Global Positioning System Standard Positioning Service Performance Standard. The fourth edition (IS-GPS-200D) defines the levels of signal in space provided to the SPS community from the United States Government which maintains the service of GPS. This standard defines the signals that are expected from the GPS satellite including which conditions tell the user that the signal is healthy or unhealthy. The performance standards provide a way for the end user to define for themselves the performance they can expect for their application. This is important to this project since we will be needing to integrate GPS data into our design for marking the locations of road damage. Thus these standards are important to us in determining whether or not a certain GPS signal is accurate enough to mark locations, the frequency in which we will be receiving a signal, the format of the message we will be receiving as well as many other things.

The ICD-GPS-200C defines the accuracy of the transmission of data. The way it defines this accuracy is through relating the GPS time to the UTC (Universal Time Coordinated). This standard states that the GPS time provided will be within 90 nanoseconds of UTC. This standard also states that with other known delays such as time transfer error this gets increased to 97 nanoseconds. The final place that error can occur is from the GPS signal propagating to the device which is specific to the user. Having accurate data is important in accurately mapping locations of damage, which is one of our design requirements.

This standard defines the frequency which the GPS signals will operate in. These frequencies are defined as 1575.42 MHz for L1 and 1227.6 MHz for L2; these frequencies are derived from a common frequency source within the satellite. As a note the GPS module we are looking at only supports L1 signals meaning we will not be receiving any information from the L2 frequency.

This standard also defines a user range accuracy, this is a statistical indicator of the ranging accuracies obtainable with a specific satellite. This indicator includes all errors in the navigation data of the transmitting satellite for which the Space and Control segments are responsible for. This user range accuracy does not account for the error obtained from the transmission medium. The user range accuracy index which is reported in the message corresponds to the maximum value of user range accuracy anticipated over the fit interval. The satellite is undergoing normal operations whenever the fit interval flag is set to zero. Knowing the satellite is not under normal operating condition can give us the choice to not trust the information from it to protect the accuracy in our system.

This standard also defines how weeks are numbered in the message. It states that the week continuously increments and never resets, counting from a start date January 6th 1980. The standard defines the 10 most significant bits to correspond to the week's number in modulo 1024 bit representation. This also means that the week number information provided within the message might not correspond to the current week number due to rollovers. Rollovers happen about every 20 years and the government warns the public of this happening before it happens. The latest rollover was on April 7th 2019 meaning a rollover will only affect us if the device becomes successful and is still in use in 16 years

This standard defines a frame of the message structure as 1500 bits, each frame includes 5 subframes where each subframe is 300 bits long. Under this definition and knowing messages are transmitted at 50 bits per second we can calculate that it takes 30 seconds to transfer one frame of the message. This directly determines how quickly the device can start gathering locational information or "cold start".

HTTP Standard

RFC 9110 defines the semantics for HTTP also known as the Hypertext Transfer Protocol. HTTP is important because it provides a uniform way to interface with a resource by sending messages that manipulate or transfer representation. We will be using HTTP in order to create a web application that gives the end user a way to see the damage that was captured on the road. Having a web application is useful to this project because it allows clients easy access to the data. This database and web application will communicate through HTTP in order to send messages back and forth for the end user to see.

This standard defines that each message transferred on HTTP is either a request or a response. Responses can include status codes and the message from the server. Status codes are useful in this project because they provide the user and the developer with useful information, whether the information was successfully received, or if there was some sort of error like authentication. The message is what we ask the server for for our project. This message can include all of the data stored in the database as well as information from a map interface. This standard will help us when creating the website in providing us with documentation of HTTP syntax and reminding us of the important features of using HTTP.

Bluetooth Standard

IEEE 802.15.1 specifies Wireless Personal Area Network (WPAN) standards for bluetooth v1.1 devices. Bluetooth is short-range radio operating unlicensed in the 2.4GHz ISM frequency band, which ISM stands for Industrial, Scientific and Medical. This is important because it creates a standard way for Bluetooth communication that all Bluetooth devices should use in order to work well. This is important to our project as we will be incorporating a Bluetooth connection to the end user's phone to give them the status of the device such as when it is ready for operation, with the possibility of transmitting data to the user's device for storage.

This standard identifies many things that make up the bluetooth technology that make it consistent to use. Bluetooth has the ability to do frequency hopping amongst the 2.4GHz band it is given in order to reduce interference with other devices and to provide some more security with a hopping pattern that is unique to each device. Frequency hopping along with time-division duplex architecture allows for bluetooth communication to act as though it is full duplex meaning, transmitting and receiving at the same time. This standard also states that the host of the bluetooth system and the controller of the bluetooth system communicate through a Host Controller interface. Having a host controller interface provides us with some standard commands in order to call to execute bluetooth activities. Along with giving us commands it also states that the controller cannot buffer requests limitlessly.

This standard also identifies which blocks are responsible for what actions, such as the device manager is responsible for connecting to other devices, the link controller is responsible for encoding and decoding the packets. One important part of a bluetooth device is the ability to connect to other bluetooth devices and making the device discoverable to other devices, this functionality is handled by the device manager. This device manager information is important to us because we will need to connect to our personal device to fulfill our goal of providing the user with feedback.

It is also identified that the data can be transmitted multiple ways, framed data and unframed data. Frames are not necessary when the signal includes in-stream framing or when the data is a pure stream. For our application though we will be utilizing framed data, as error detection, identifying which device receives the signal as well as a bit for acknowledgement which are all important features in our project for correct data transmission.

Two devices use a shared physical channel for communication. To achieve this, their transceivers need to be tuned to the same frequency at the same time. A device can use only one of these physical channels at any given time. Time division multiplexing is used in order to utilize multiple channels for concurrent operation. With a limited number of radio frequencies used for bluetooth it is possible that two devices may use the same channel at the same time and therefore causing a physical channel collision.

Inquiry is the process of discovering nearby devices or allowing other devices to discover it. Inquiry is carried out on its own special channel and has to be balanced in terms of the commitments the connection already has. We expect the user's device to be the inquiring device in this case and the road mapping device to be the discoverable device that will listen for inquiries once it is turned on.

Another important feature of bluetooth is the ability of the device to switch roles between being a leader and a follower. This is important when establishing a bluetooth link to other devices as the initial device to establish the connection is the master until a role switch happens. Once a piconet has been established, master-slave roles may be exchanged.

The bluetooth standard defines three power classes for devices. The first power class outputs at a power of 100mW and its advertised range is 100 meter. The second power class operates at 2.5 mW and has a range of 10 meters. Power class 3 outputs at less than 1 mW of power and has a range less than one meter. figure 18 below shows these power classes more clearly. For the purposes of this project power class 2 is the sweet spot since we do not expect the device to be more than ten meters away from the user's device. The advantage of using power class two is that it will take less power to use it, simplifying our power system. Figure 14 shows the power classifications of bluetooth and their associated range.

Power class	Transmission power level	Advertised range
1	100 mW	100 meters
2	2.5 mW	10 meters
3	< 1 mW	< 1 meter

Figure 15: Bluetooth Power Classes. Reprinted with permission from Larry Rudolph and Albert Huang.

The standard states “Each IEEE 802.15.1-2005 device shall be allocated a unique 48-bit device address. This address shall be obtained from the IEEE Registration Authority”. These unique device addresses are used in determining the frequency hopping pattern which tries to avoid packet collisions in turn improving the reliability of the connection. The standard also states that all transmissions include a devices access code, a channel access code and an inquiry access code, all of which are derived from a part of the devices unique address. The channel access code helps mitigate unwanted effects of two devices operating on the same frequency at the same time as it is the first information sent in the transmission.

Another useful feature defined by this standard is that packets sent through this connection may be larger than a single time slot. This is important to our project as if we choose to transmit the data from the device to the user through bluetooth we expect the data to be quite large as it will include an image as well as some other information. Figure 15 shows the generic packet structure we expect with bluetooth.

Physical channel access codes	Packet header	Payload header	Payload	CRC

Figure 16: Packet Structure

This standard includes a section on interface primitives that can do things such as create a connection request, reading data and writing data and many more functions. These primitives are important to use as we will have to use them to do the things we want to do with the bluetooth connection as well as to help us debug the device if there are issues. This section defines the service, the parameters and what the output will be.

4.1.3 Electrical Safety Standards

There are many standards in the application of lidar development. In the case of electrical there are two aspects found through research. These applications are based on the sense of safety measurement requirements. In the sense of safety there are several different developments of standards related to our project. IEC (International Electrotechnical Commission) produced a standard specifying the importance of measurement requirements for electrical safety testing. This standard outline's that when testing or producing a product there should be the use of electrical safety equipment to ensure the laser sensors are installed and operating safely. There are multiple sections that make up the basis of what is required for ensuring that the device provides accurate and reliable readings. These are demonstrated in table 25 below.

Table 25: IEC Safety Standards

Section	Title	Description
Part 1	General Requirements	General Requirements for measuring instruments used for electrical quantities in low voltage installations
Part 4	Instruments of Harmonic Distortion and Power Quality	This section covers the instruments used for measuring and analyzing power quality and harmonic distortion in electrical installations
Part 5	Equipment for Testing, Measuring or Monitoring of Protective Measures	Guidelines are provided for testing and measuring the effectiveness of protectives in the electrical system
Part 6	Multifunctional Measuring Equipment	Multifunctional measuring devices that can measure multiple electrical quantities such as voltage, current and power
Part 7	Digital Communication Protocols	Outlines the protocols used for transmitting measurement data between devices
Part 8	Equipment for Testing, Measuring or Monitoring Specific Parameters	Guidelines for measuring specific parameters such as temperature, humidity, vibration, and speed

The basic definitions or what is included in the guidelines is provided in the table. The IEC does outline a further step by step requirement to meet the needs of ensuring safety when using testing equipment on electrical equipment.

Another international safety standard that applied to the electrical, electronic and programmable control equipment is the IEC 61010. The standard is a development by the IEC and is designed to ensure that the equipment is safe for use in a wide range of settings, including laboratories, medical facilities, and industrial plants. IEC 61010-1 specified the general safety requirements for electrical equipment intended for professional, industrial process and other laboratory use. This covers equipment that operates with a supply voltage not exceeding 1000V for AC or 1500V for DC. The equipment must be designed and constructed to minimize the risk of electrical shock, fire and other hazards. There are also specific requirements for protective measurements such as insulations, grounding and overcurrent protection. IEC 61010-1 also requires documentation, marking and instructions for the use, including equipment's intended use, installation, and maintenance.

The next standard we should take into consideration is ISO 26262, which specifies safety requirements for automotive system use. Because our device is designed to be mounted onto an automotive vehicle for its final demonstration or for its intended use, this standard should be met. This international standard provides guidelines for the development of safety-related systems in road vehicles, including passenger cars, trucks and buses. The ISO 26262 covers the entire safety lifecycle of a system. Included in the standards descriptions is guidance on how to assess safety risks and implement safety measures throughout the development process, including identifying potential hazards, defining safety goals and requirements, designing safety-critical components, and testing and validating safety systems. Many regulatory agencies require compliance with the standard and it is often a prerequisite for doing business in the automotive industry. Table 26 below includes the ten parts of which the standard covers for functional safety.

Table 26: Electrical ISO Safety Standards

Section	Title	Description
Part 1	Vocabulary	Define the key terms and concepts related to functional safety
Part 2	Management of Functional Safety	Outlines the management processes and activities required to achieve functional safety, including risk management, safety planning and safety monitoring
Part 3	Concept Phase	Provides guidelines for the early stages of the development process, including hazard analysis and risk assessment
Part 4	Product Development at the system level	Covers the development of safety-critical systems and components, including design, verification and validation
Part 5	Product Development at the Hardware Level	Covers the development of hardware components, including electronic control units and sensors
Part 6	Product Development at the Software Level	Covers the development of software components, including software requirements, design and testing
Part 7	Production, operation, service and decommissioning	Covers the production, operations and maintenance of safety-critical systems
Part 8	Supporting processes	Covers supporting processes such as configuration management, change management and supplier management
Part 9	Automotive Safety Integrity Level (ASIL)	Oriented and safety-oriented analysis. This provided guidelines for safety analysis, including hazard analysis and risk assessment
Part 10	Guidelines on ISO 26262	Provides additional guidelines on how to apply ISO 26262 to specific systems and components

In the next electrical listed standard ANSI/UL 61010, which was formed by the American National Standards Institute and published by the Underwriters

Laboratories, specifies the requirements for the electrical equipment use in the laboratory, industrial and healthcare settings. There are guidelines and requirements that are set to ensure the safety of the device when used in its intended environment. With our device's purpose of being used in an outdoor environment the environmental hazards can pose a large threat if our device is not properly protected. As well as the environmental aspect, our device needs to be (easy to work). With the hopes that this machine could be used by the Department of Transportation for road safety, the device needs to have all electrical and mechanical hazards designed to prevent harm of a general/untrained user. To ensure this, the device must be properly secured on its mount with conductive parts properly grounded and moving parts or sharp edges must be covered.

Demonstrated below in table 27 is the list of the hazards we must be aware of according to the ANSI/UL 61010 for laboratory, industrial or healthcare settings when handled by a general user.

Table 27: ANSI/UL Electrical Standards

Type of Hazard	Description
Protection Against Electrical Shock	Equipment must be designed to prevent electrical shock to the user. including protection against contact with live parts ensuring that accessible conductive parts are properly grounded
Mechanical Hazards	Equipment must be designed to prevent mechanical hazards to the user, including protection against moving parts, sharp edges, and other hazards
Fire Hazards	Equipment must be designed to prevent fire hazards including protection against overheating, ignition of materials, and other potential sources of fire
Environmental Hazards	Equipment must be designed to prevent environmental hazard, such as exposed to water, dust, and other potentially damaging substances

The ANSI/UL 61010 standards also cover specific types of equipment, including electrical measuring and test equipment, laboratory, and medical equipment. In addition to outlining the requirements of the equipment itself, the standard also includes guidelines for the installation, operation, and maintenance of the equipment to ensure ongoing safety. Overall this standard is important to ensure that the electrical equipment used in the laboratory, industrial and healthcare settings is safe for the users and meets the detailed safety requirements.

The last applicable standard to our project would be the FCC Part 15, which is a set of regulations established by the Federal Communications Commission in the United States. The regulations established govern the operation of unlicensed devices that use radio frequency energy, such as consumer electronics, industrial equipment, medical devices and other equipment that emits RF energy. The purpose of the FCC Part 15 is to limit the amount of RF energy that unlicensed devices can emit and to prevent interference with licensed communication systems. The technical standards and testing requirements relating to unintentional radiators, such as the lidar sensors, are to ensure the minimization of harmful radio-frequency interference with other electronic devices. If our device will be used by the DOT in the future it needs to meet the requirements for consumer or industrial applications to eliminate the harmful cause of interference with other electronic devices when being used on the road. The regulations included in the FCC Part 15 include:

- Personal computers and peripherals
- Wi-Fi routers and access points
- Bluetooth Devices
- Home automation systems
- Low-power devices such as remote controls
- Industrial equipment and machinery
- Wireless microphones and receivers

To comply with the regulations, devices must undergo testing and certification by an accredited testing laboratory to ensure it has met the specific technical standards for RF emissions and susceptibility to interference. The device must also include proper user instructions to ensure the user is aware of any limitations to their use and for personal safety. This standard is applicable to our project because of our inclusion of a wireless or Bluetooth device to transmit the captured data to an app or website for user viewing.

4.2 Constraints

This section will review the types of constraints our project faces and how it will affect our prototype. These constraints include safety, economical and time, environmental, manufacturability and sustainability, and power.

4.2.1 Safety Constraints

In a previous section, laser safety standards were investigated. Due to potential side effects to eyes and even skin, it was determined that a red laser with power less than 5 mW would be used. Class 1 and 2 lasers are considered eye safe due to the aversion response. A wavelength in the red spectrum will also be used due to possible effects of infrared radiation of green light or possible negative biological effects of blue light.

4.2.2 Economical and Time Constraints

This project has economical and time constraints that will affect the quality and precision of our project. This project must be completed in two semesters, one of them being a shorter semester in the summer. This constraint may not allow us to reach some of our advance and stretch goals as there may not be enough testing time. Also some additional features such as finding the volume of the pothole may not be incorporated. This project also is self funded as there is no sponsor involved. Companies such as Luminar, and the Department of Transportation were written to but no sponsorship was acquired. Since students will be funding the project, staying on budget is very important and will have effects on the level and performance of equipment that can be purchased.

In reference to the constraint in time it is wise for us to lighten the workload in places that we can in order to allow more time in places that it cannot be lightened. One such method to lighten our workload is to use a microcontroller system which already has many of the features we want. The raspberry pi zero w is a perfect example of this as it has Bluetooth, a micro-usb connector, an SD card slot as well as WI-FI and an HDMI port. Choosing this board will reduce the amount of time we spend on simply implementing these features and instead give us more time to spend incorporating such features. Having an SD card slot built in reduces the number of hours we have to spend implementing and coding a storage system such as NTFS as the raspberry pi board already has its own file system implemented. Reducing the time needed to implement this means we can focus on using it and transferring data between our device and personal computer. This is true for the other features this device already has, with the Bluetooth we will spend less time figuring out how to connect a Bluetooth module to our microcontroller and more time using it in the way we want.

We can also utilize our time effectively in choosing programming languages with which we have some familiarity in. One such programming tool we can use comes in the form of an application programming interface known as WebGL. Having taken some computer graphics courses at UCF we are confident that utilizing this technology can reduce the amount of time needed for a learning curve on a new technology or starting from scratch. WebGL is great because it offers all the useful features we need and is really straightforward once you know how to use it.

4.2.3 Environmental Constraints

This project also has a few environmental constraints. While designing the surface road mapping prototype, we need to minimize the harm that could occur to living animals and plant life on the road. Safe levels of power and wavelength of the laser will be used. Components must also stay attached. We do not want to cause any debris on the road that could cause damage to other vehicles.

Optical systems can be affected by environmental factors such as rain, fog, dust and other obstructions. These factors can cause the signal to scatter or attenuate, resulting in a decrease in accuracy. Some devices have multiple beams or adaptive filtering to compensate for the interference. In the case of our devices being mounted on top of a vehicle, it is susceptible to temperature, humidity, and vibration, so the electrical systems must be designed so that the accuracy is not impaired with these circumstances. In the case of temperature, these devices can have fluctuations in the output signal. The device's commands can expand or contract with the temperature changes affecting the accuracy of the data. It is noted to ensure the device is operated during the desired temperature range.

4.2.4 Manufacturability and Sustainability Constraints

Manufacturability constraints describe parameters on how the system will be built while sustainability constraints point to the resources that are available for manufacturing. A major impact on our project is budget. Materials for the prototype are bought solely by group members and it is very important to stick to our budget. For example, cameras can be very expensive ranging from the hundreds to the thousands of dollars. Since we are not funded, the camera will not have all the specifications to reach some of our advance and stretch goals. Our budget only allows a camera under one hundred dollars. A camera within our budget was chosen but we had to weigh the pros and cons of the camera's specifications. Resolution of the system is in a large part determined by the frames per second of the camera. This was one of the major features that we had to consider when searching for the camera. Some concessions were made to keep the cost within the constraints of the budget. The camera selected for the project is ELP-USBFHD085-MFV which runs at 260 frames per second. This camera runs fast enough to reach some of our goals while not costing thousands of dollars that many of the higher quality cameras on the market run. It achieves this by running at a lower resolution than the more expensive cameras.

Another manufacturing issue is related to the time constraint imposed upon this project. Due to recent supply chain problems that have been occurring around the world it has made getting the materials for manufacturing the device more difficult. An emphasis was placed on finding parts and materials that are readily available. Some parts have had to be disqualified from use due to delays in receiving them from factories around the world. For example the powell lens being used in the project took three weeks to arrive which is one reason it was purchased way ahead of time. The raspberry pi zero w is not in stock on many websites and has become a popular choice for resellers. The board we purchased was about fifty dollars when it is marketed as a board for everyone at fifteen dollars. Such price gouging would make manufacturing this system on a large scale a logistical nightmare.

Laser Safety is also a constraint put on our system. The system requires that the laser outputs enough power so the camera can pick up the projection of the line. However there are limitations on what classification of laser that is deemed safe as discussed previously. For this prototype, the laser beam will not be enclosed as it will be projected on the surface of the road. A laser with power output less than 5mW was selected so there would be no eye or skin injury if the system malfunctioned. It was also determined that a red laser color would be best so as to avoid safety issues that come with a green or blue laser. The red laser is also cheaper to procure than green or blue lasers.

The device needs to be contained within a case that will allow it to be weather resistant and safely mounted to the truck. This case will have to protect the sensitive electronics and optics held within. For this project due to time and manufacturing constraints the case will have a 3D printed exterior that will provide weather protection. It will have a support frame on the interior that will provide structural support and provide mounting locations for the electronics and optics being used. The case will be mounted to the top of a SUV. The case of the device will be attached to the rail running the length of the SUV's roof. The body of the device will be split between two main components. The first component will house the electronics and will be secured to the roof of the vehicle using the storage rails. The second component will connect to the first using a PVC pipe that will run to the back of the vehicle. This pipe will support the second component that will house the optical elements. It will be adjustable to ensure that the proper height can be achieved for different vehicles.

In reference to the construction of the housing for this device we will need to ensure that adequate radio frequencies can penetrate it. Having a case which does not allow for radio frequencies to pass through easily will disrupt some functionality as both the GPS module as well as the Bluetooth module are important to this project. Creating a case that is transparent to these radio frequencies is crucial to our design. As a rule of thumb any dense material of sufficient size can affect GPS signals.

4.2.5 Power Constraints

Laser sensors require a stable and consistent power supply to operate efficiently. When it comes to the designing portion of this model the sensor and associated components need to be considered in the case of each power requirement to ensure the power supply is reliable. The amount of power needed to operate can increase depending on the distance to view the road when placed on a specific car or the angle it is mounted at. A higher powered laser could also require more power and have limitations on the size and weight of the system to compensate for this. In the case of the camera system to operate and process images captured by the laser this requires an increase in power. The power source itself can also be a limiting factor if the laser driven camera is used in a mapping system on the road. Because the system relies on batteries as a portable source the limitation of capacity and frequency charging arises. Overall, the power constraints can limit the capabilities and practicality of laser driven camera road mapping systems. This requires careful consideration and optimization of the laser, camera and power source components.

4.2.6 Electromagnetic Interface Constraint

Electromagnetic Interference (EMI) can be a significant constraint for a laser driven camera road mapping system. EMI refers to the disturbance or noise that affects the performance of electronic equipment and can occur due to various electromagnetic sources. This can affect both the laser and camera components. EMI can interfere with laser emission and reflection of the light causing an inaccuracy in the mapping data. IT can also affect the camera’s image capture and processing leading to noise or data corruption. EMI results from sources such as power lines, electronic devices and radio frequencies.

Measures can be taken to mitigate the EMI effects. One method is to ensure proper grounding and shielding of the device to reduce the impact of EMI on the laser measurements especially if being used on a car with the future goal of operation at 60mph. Our device is designed to emit and receive signals to create a 3D map of the road obstruction. These signals can be affected by the electromagnetic interference from other electronic devices in the vicinity of the vehicle. It is important for us to shield the device with the mount and ensure it is not placed directly near other large electrical equipment. Another method to mitigate the effects is filtering. Filtering is the concept of reducing the amount of electromagnetic radiation that reaches the laser and camera components. Lastly, another option is the frequency selection to operate the system. Designing a proper frequency that is susceptible to EMI is an appropriate measure to take. Together these can be taken to minimize the effect on the system’s performance.

4.2.7 Bandwidth Constraint

Optical devices require a high bandwidth to process and transmit the data collected. The data can be transmitted through a wired or wireless connection and the requirements depend on the amount of data collected and the speed at which it needs to be collected. Bandwidth is the amount of data that can be transmitted over this communication channel during a specified time. There are several bandwidth constraints that could apply to our device. The first is the laser driven camera captures a large amount of data in real-time, and this data has to be transmitted to a processing unit for analysis. For the system to not become overwhelmed by the volume of data the transfer rate must be high enough to ensure the mapping process does not slow down. Another issue is the mapping data captured must be processed in real time to generate accurate results in a timely fashion. To ensure this the processing speed has to be high enough to keep up with the rate of data transfer. A third bandwidth constraint is that multiple components need to communicate with each other at once to ensure it operates properly. The communication bandwidth must also be high enough to ensure data communication is transmitted quickly and effectively. To minimize these constraints we can take several approaches such as introducing data transfer protocols to reduce the amount of data transmitted to prioritize the transmission of critical data. A second method of mitigation is the use of high speed communication channels such as high speed wireless connections for data to be transmitted quickly and effectively or achieving the same goal by using a high-speed processing unit. The bandwidth can be a significant constraint for a laser driven camera system and appropriate measures should be taken to ensure this does not go unnoticed.

5 Project Hardware and Software Design

5.1 Initial Designs and Schematics

This section describes an initial design to scan the roads surface, scanning LiDAR. It reviews the reasons the group decided to change how the prototype was going to be built and what it consisted of. It then shows the overall revised project schematic for the prototype, along with the optical and software schematics.

5.1.1 Scanning LiDAR

Projects go through multiple renditions as engineers discuss and investigate different technologies, go through formulas, and choose components. Constraints and specifications are placed on the prototype and ideas on how to reach the end product change. This project was not any different. Initially the optical engineers wanted to design a LiDAR system that would scan the roads surface looking for damage. However, there were many factors working against this design. The proposed design can be seen in figure 16.

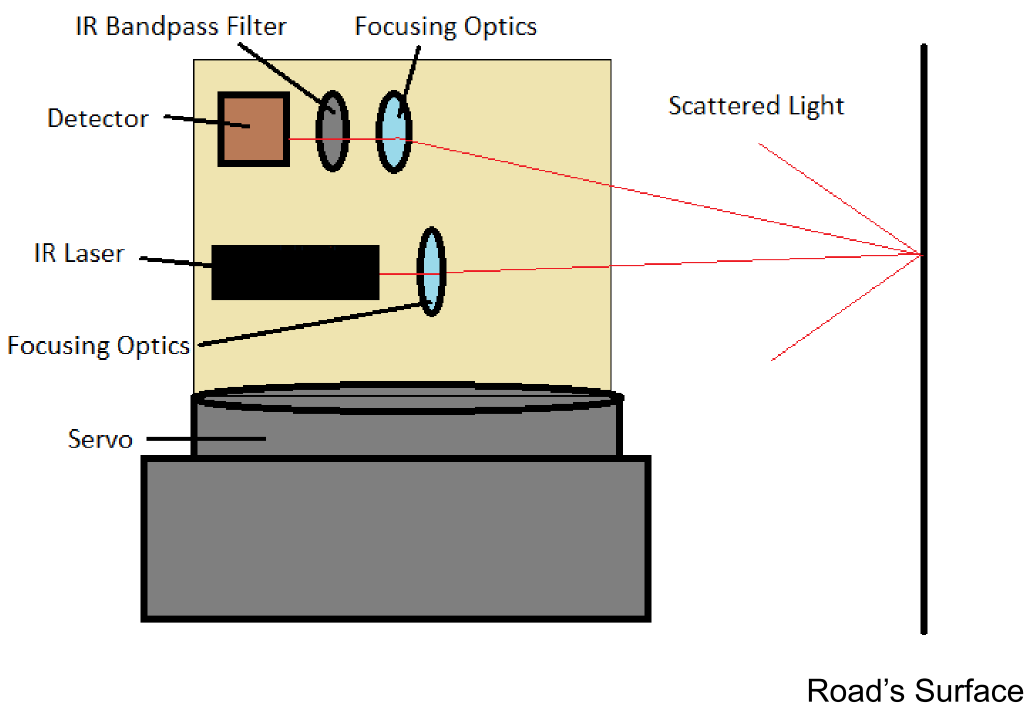


Figure 17: Initial LiDAR Design

Initially optical engineers were investigating a scanning LiDAR system as seen above. The emitting and detection optical systems are sitting on a servo. To reach our advance goal of scanning the road at a speed of 60 mph with a 1 inch resolution, it was calculated that servo would have to spin at 15840 rpm. This was one obstacle to overcome as no one in the group is a mechanical engineer and we did not know the effects spin this fast would have on the optical system or how to design a system to achieve this high of a rotation per minute.

The emitting system was designed to consist of laser and focusing optics. The laser's wavelength was selected to be in the near infrared range to avoid eye injury. It was decided that 940 nm and 905 nm were the best options for the laser wavelength because they have some special properties. There are gaps in the background spectral radiation at these two wavelengths due to the moisture in the atmosphere absorbing them. They also could be used with silicon photodetectors instead of using indium gallium arsenide, InGaAs, which are much more expensive. Also the laser must be pulsed to create individual events that can be timed. The time of flight for each pulse would be used to determine the distance traveled. The laser would have to be pulsed rapidly to maintain a viable level of resolution. With a core goal of 10 mph travel speed and 4 in x 4 in resolution, the laser would have to pulse at a rate of 2464.56 times a second. This would be relatively manageable with a continuous wave laser and use of a microcontroller to turn it on and off. It was determined that focusing optics would have to be used to create the scanning points. The optics on the emission side would need to create a narrow beam. This would allow the maximum amount of irradiance to reach the target surface, which would give the detection system more scattered light increasing the likelihood of detection.

The detection system consists of focusing optics, a IR bandpass filter, and a detector. The focusing optics collect scattered light from the light reflected from the road's surface and focus it one to the detector. Before the light gets to the detector, the light will pass through an IR bandpass filter which will filter out any light collected that is not infrared light. This will decrease the noise in the optical system. However, another obstacle that would need to be overcome is the detector's detection rate. The detector would need to be able to capture scattered light as fast as the laser is being pulsed. This required a very fast rise time, which would require an expensive detector.

A scanning LiDAR system uses time of flight to determine distance to an object. With this information an image can be formed. However, calculating these distances can be very difficult due to the spinning aspect of the system. Every pulse of the laser would occur every 6.34 degrees of rotation to achieve a 4 inch resolution. This would only work for objects directly below the emitter. For objects to the sides of the vehicle the resolution would progressively become worse as the distance to the road becomes greater. This degradation of resolution is the result of the points generated by the laser being farther away from each other as the servo rotates, as seen in Figure 17. To eliminate this feature, the servo would have to slow down or speed up at certain points in the rotation.

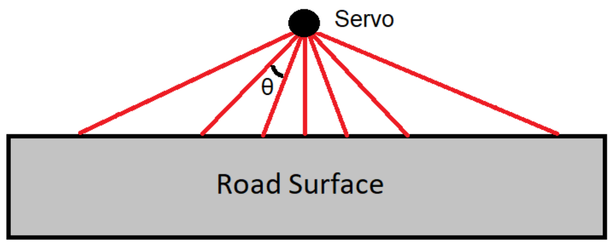


Figure 18: Servo Resolution

Once scanning LiDAR was investigated further, it was determined that this prototype would take more time and resources than were available. Other options to scan the roads surface were briefly considered until finally a new design was determined. This new design is investigated in the next sections.

5.1.2 Optical System Schematic

The optical block diagram, figure 19, includes the emitting optical system which is composed of a laser and powell lens system The lens system will generate a line on the road and images will be captured by the receiving optical system which includes a wide lens system and a camera. Figure 19 shows the optical setup from a side view while figure 20 shows a top down view.

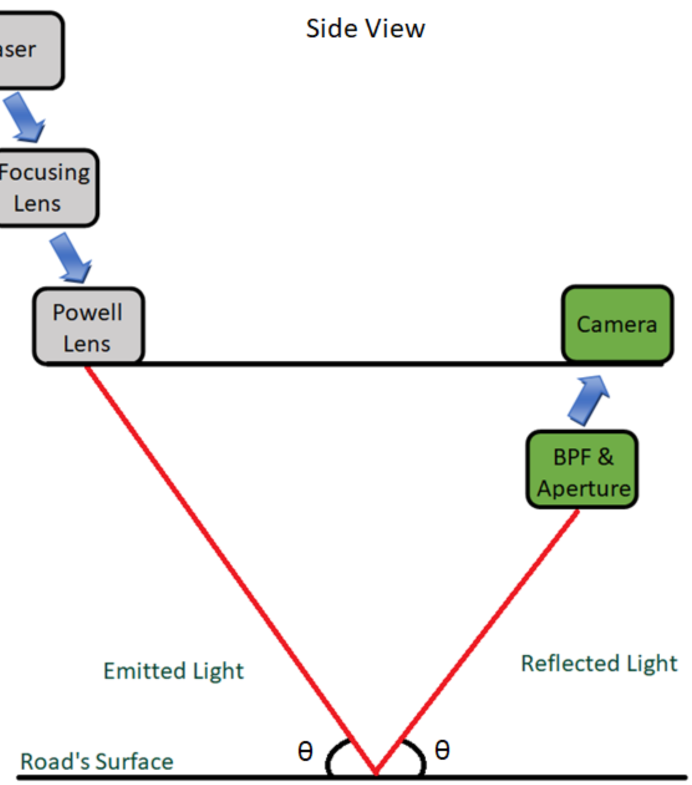


Figure 19: Side View of Optical System

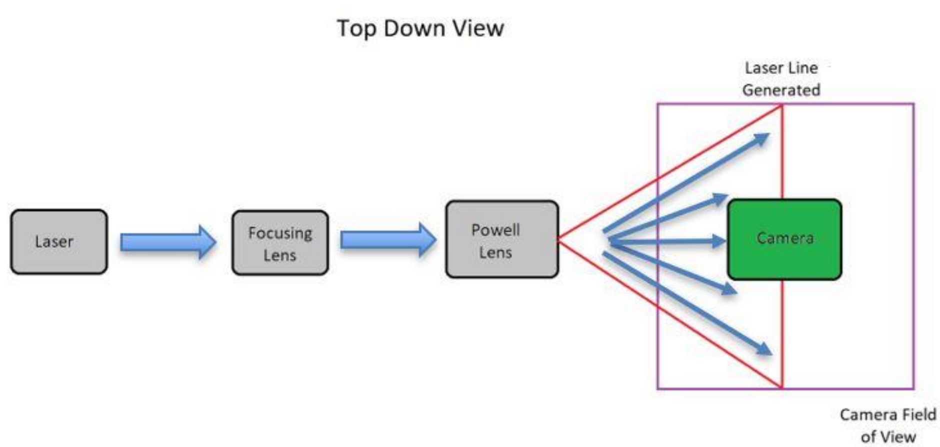


Figure 20: Top Down View of Optical System

5.1.3 Software Schematic

Figure 21 goes into more detail about how data will be interpreted and presented. The data obtained from the photodetector will be stored locally on the device on removable storage. We will then organize this data into the separate pot holes, and store the pothole data in our database which is connected to the website for user presentation. Once the data is in the database we can use that to categorize each pothole, represent each pothole and map each pothole on a real world map. The figure also explores the procedure for developing a mobile application, although this is a stretch goal.

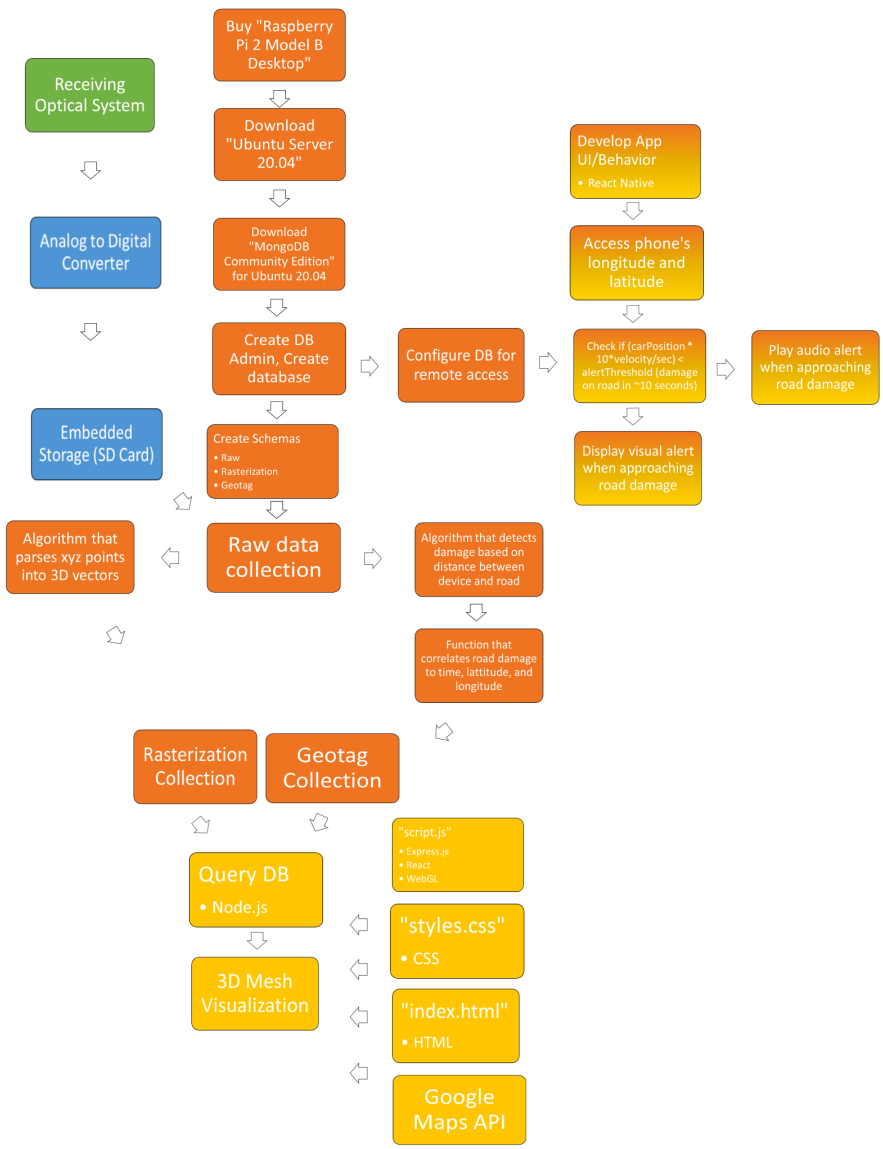


Figure 21: Software Schematic

5.1.4 Electrical Schematic

In the electrical block diagram, figure 22, this represents the components that will be included and which section they will be implemented. The battery as the power supply function will provide current to each of these modules, while Raspberry Pi will provide the instruction and hold the SD card to the data that will be transferred in a later section.

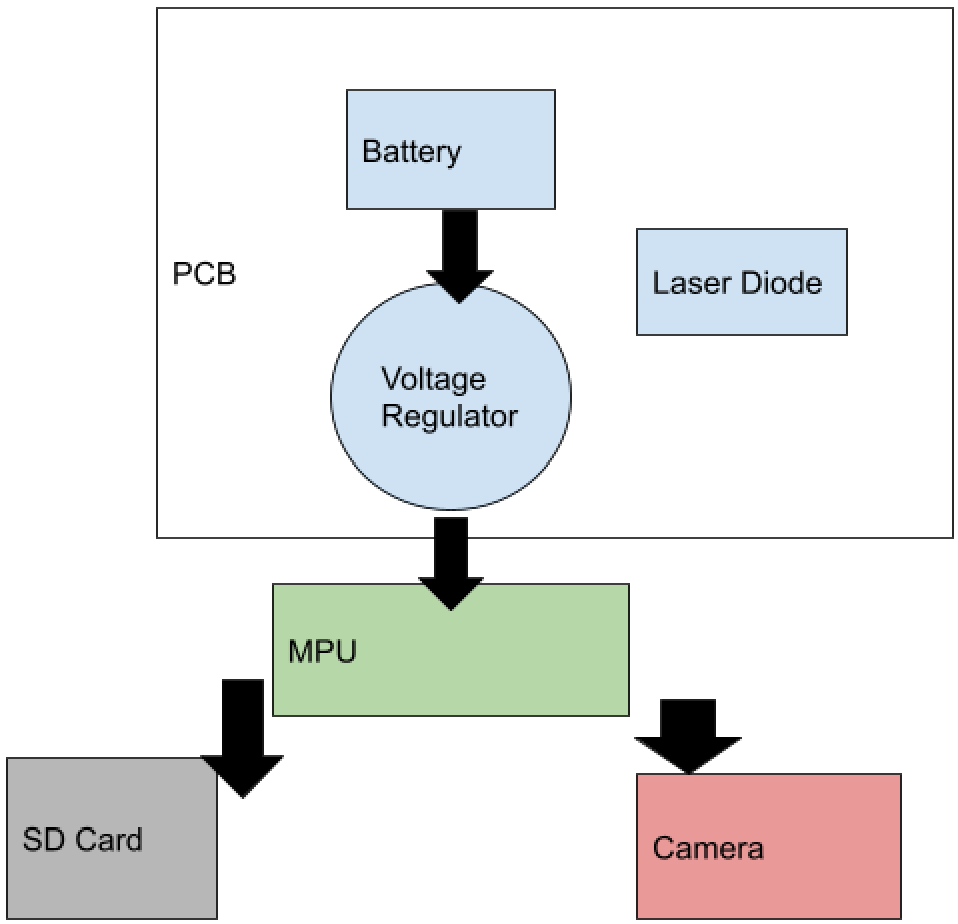


Figure 22: Electrical Block Diagram

5.2 Hardware Design

In this section, each subsection of the Road Surface Mapper will be discussed. These subsections include the emitting optical system, detecting optical system, microcontroller, GPS, data storage, and electrical system.

5.2.1 Emitting Optical System

The emitting optical system consists of a laser that will project light onto a powell lens. The powell lens will cause the laser beam to fan out along one axis creating a line that will be projected onto the road’s surface. This line will have uniform intensity across most of its length. To optimize the use of the powell lens, the laser beam size must be taken into account. The incident beam’s dimensions determine the thickness of the laser line. For a thicker line, a narrow incident beam must be sent through the roof of the powell lens, but for a thinner line, a wide incident beam is used.

A collimated laser diode forming an elliptical beam profile needs to be used to achieve the best results. Table 28 and 29 show the general specifications and the optical electrical characteristics of the laser chosen to fit the design on the emitting optical system, respectively. An important specification when choosing this laser was the beam shape and size. The shape of the projected beam is elliptical while the beam size is 4.5 mm by 1.0 mm, which is a specification of the powell lens's incident light. It’s important to note that this beam size was measured when a lens is 50.8 mm from the front of the laser housing.

Table 28: General Specifications of CPS635

General Specifications	
Housing Material	Aluminum
Housing Dimensions	11.0 mm X 40.0 mm
Beam Size	Elliptical, 4.5 mm X 1.0 mm
Operating Temperature	-10 to 50 ℃
Storage Temperature	-30 to 70 ℃
Operating Voltage	4.9 V to 5.2 V
Laser Safety Class	3R
Mounting Adapters	AD11BA, AD11F, AD11NT, KAD11F, KAD11NT
Compatible Power Supply	LDS5, CPS1

Table 29: Optical Electrical Characteristics of CPS635

Optical Electrical Characteristics				
Characteristics	MIN	TYP	MAX	UNIT
Wavelength	-	635	640	nm
Optical Output Power (CW)	4.0	4.5	5.0	mW
Polarization Extinction Ratio (PER)	-	20	-	dB
Power Stability (8 hours)	-	-	2	%
Power Stability (1 minute)	-	-	1	%
Axis Deviation	-	-	5	mrad
Beam Divergence	-	-	1.5	mrad
Operating Current	-	48	70	mA

Note: Max Axis Deviation is the parallelism between the module housing and the output beam. Also the full angle divergence is $1/e^2$ beam width

Beam divergence is an angular measure of how a beam's diameter will increase over a distance from the aperture of the laser. This is extremely important when designing the emitting system as an elliptical beam with one axis measurement of 1 mm must be incident on the powell lens for optimization. Beam divergence can be found using the below equation where D_1 is the diameter of the initial beam, D_2 is the diameter of the second beam, and L is the distance between the initial and second beam.

$$\theta = 2\, arctan\left(\frac{D_2 - D_1}{2L}\right)$$

It's important to note that for an elliptical beam, the divergence must be found in relation to both the major and minor axis of the beam.

As light travels from the laser to the surface of a powell lens, light will be transmitted through the lens and some light reflected. For normal incidence the amount of light reflected can be found using the below equation, where n represents a refractive index of air or glass.

$$R = 100\left(\frac{n_{air} - n_{glass}}{n_{air} + n_{glass}}\right)^2$$

Using this formula, if the laser outputs its maximum power of 5mW, it will reflect 4.2 percent or 0.21 mW of power and transmit 4.79 mW of power. Both the laser and powell lens will be contained in housing to ensure the maximum output power will be contained until it is transmitted through the powell lens. Therefore the maximum output power of the system transmitted outside the housing is 4.79 mW.

As previously discussed, the line generated by the Powell lens is uniform in intensity as the light is redistributed from the center and distributed along the line. However, 80 percent of the overall power is contained in eighty percent of the generated line resulting in diminished intensity in the final ten percent on each end. Therefore, to reach the stretch goal of mapping a 11 foot section of the road's surface, the generated line must be 13.75 feet to compensate for the loss of intensity at the ends. Using this information, the height at which the powell lens must be fixed from the surface of the road can be determined.

To calculate the total length of the generated line using the powell lens we must adjust for the loss of the ten percent intensity at each end. The formula below can be used where x is the total length of the generated line and r is the required length of the generated line.

$$x = \frac{r}{0.8}$$

Once the total length of the generated line is determined, the height at which the powell lens must be placed in relation to the road can be found. In the below equation θ is half the measurement of the powell lens fan angles, y is half the length of the total length of the generated line, and h is the height placement of the powell lens.

$$\tan\theta = \frac{y}{h}$$

However, after building the illumination system and testing the detection system, an obstacle arose due to ambient and scattering light. The laser line was not detected by the camera's sensor. This is discussed in detail in the detection portion of the paper. This obstacle led to the sensor being able to detect a 2 foot line when the line projected on the road's surface was 10.48 feet. Knowing this length, it was determined that the powell lens must be 3.67 feet above as seen in figure 23.

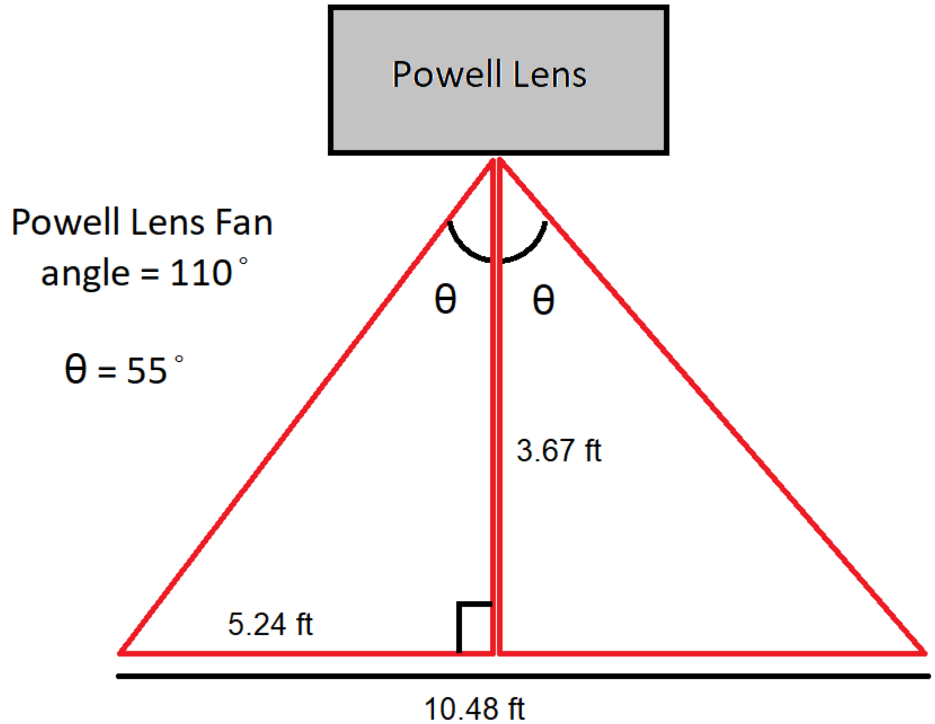


Figure 23: Placement of the Powell Lens

When light passes through the powell lens, spherical aberrations are introduced to the system which reposition the light along the projected line. A spherical aberration causes light to focus at different planes called the area of confusion, rather than a single focal plane. The spherical aberration can be either positive, light bends too much, or negative, light does not bend enough. This causes a deviation from the spherical shape as light comes in and out of focus. Usually, an optical system would be optimized to eliminate this effect; however, in a powell lens this aberration is used to create the desired effect. The unique shape of the powell lens, which is a complex two dimensional aspherical surface, uses these aberrations to redistribute the light from the center to the edge. This forms the light into a uniformly distributed line that is projected out from the lens.

The laser chosen for this project has a spot size of 4.5 mm by 1 mm at a distance of 50.8 mm from the laser housing. The 1 mm axis is the right size for use with the powell lens. This means the ideal placement for the powell lens will be 50.8 mm from the laser housing. This will allow the powell lens to generate a well defined line.

5.2.2 Detecting Optical System

As previously stated, the laser line could not be detected due to ambient and scattered light over powering the laser signal, the detection system had to be redesigned.

5.2.2.1 Initial Detection System Design

The detecting optical system was designed to consist of a camera and a cylindrical lens. The camera chosen for this project was an ELP-USBFHD085-MFV. This camera fits many of the criteria needed for the project. The most important feature was its frame rate. The ELP-USBFHD085-MFV is capable of operating at 260 frames per second. This is important because one of our main goals is to be able to operate the vehicle at road safe speeds to avoid becoming a rolling safety hazard. With the camera running at a 260 frame rate the vehicle will be able to travel at 30 miles per hour while maintaining a useful resolution.

The ELP-USBFHD085-MFV camera has a variable resolution, meaning that as the frame rate increases the resolution decreases. If the camera were set to 60 frames per second it would have a resolution of 1920 by 1080. This would give an incredible amount of detail to the scan but would negatively impact the speed at which we would be able to scan. To achieve 260 frames per second, the resolution is set to 640 by 340. This gives a viable resolution both in the horizontal axis and the vertical axis. The camera will be aligned with the road so that the vertical axis will be in the direction of travel and the horizontal axis will be across the lane of the road. The horizontal axis is directly related to the transversal resolution and the vertical axis is related to the depth resolution.

Field of View is also an important part of the detecting system. FOV is defined by the focal length of the collecting optics.

$$FOV = 2\ x\ \tan^{-1}\left(\frac{h}{2f}\right)$$

In the above equation h is the height of the camera lens and f is the focal length of the collecting optics. The camera's field of view has been measured to be 60 degrees on the vertical axis and 100 degrees on the horizontal axis. This means that the camera can image 11.44 ft in the horizontal axis and 5.54 ft in the vertical axis when placed 4.8 ft above the road's surface. The horizontal axis covers enough ground to reach our target goal of 11 feet. The vertical axis covers more area than needed. This allows us to use a cylindrical lens to zoom in on the vertical axis while not affecting the horizontal axis. Magnifying the vertical axis will reduce our field of view but it will increase the sensitivity of our depth resolution.

A cylindrical lens is a lens that functions much like a spherical lens. Both lens types use the curvature of the lens and the refractive index of the material to bend the light passing through to either converge or diverge. A cylindrical lens differs from a spherical lens in that it has a curve in only one axis. This means that the light entering a cylindrical lens is only altered along one axis. The axis that does not have a curve does not result in any change to the light path. Cylindrical lenses are typically used to correct for aberration caused in a lens or to alter a laser beam in one axis. For this project the cylindrical lens will be used to zoom the camera in on the vertical axis while leaving the x axis untouched.

The cylindrical lens chosen for this project is a plano-convex lens. Only one side of this lens is curved while the other side of the lens is flat. This gives the lens the appearance of a cylinder that has been cut in half along its major axis. The lens will be positioned so that the convex side of the lens is facing the road surface. This alignment will result in a sharper image being projected onto the camera. The lens will be aligned with the road so that the curved axis of the lens will be in the direction of travel.

Figure 24 shows a beam of light propagating from the road's surface, which is the object through a cylindrical lens, and lastly to the camera's lens at a height of 20 mm at angles of 0, 15, and -15 degrees.

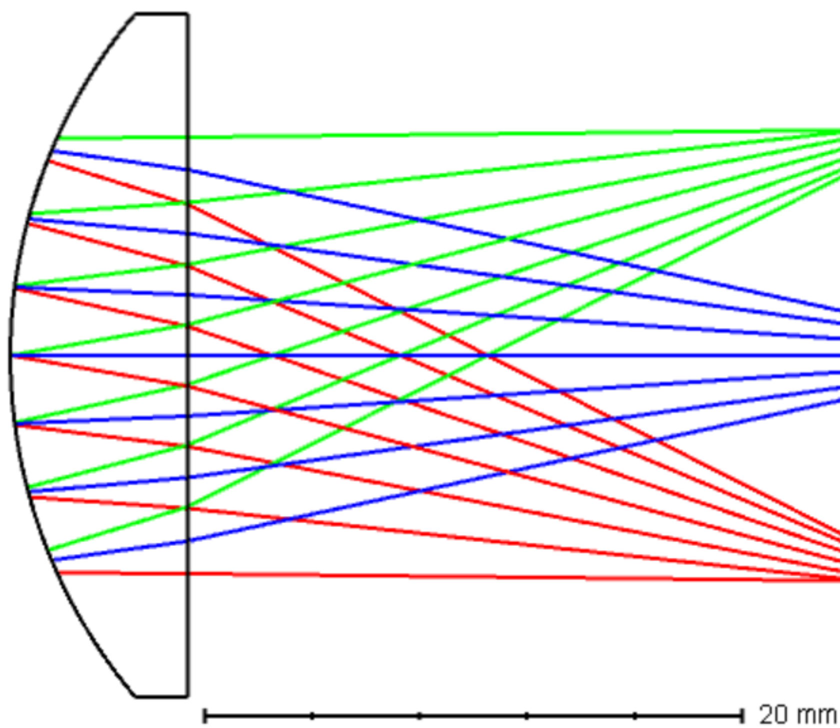


Figure 24: Zemax Design for Detection System

Zemax was used to optimize our system. The goal was to reduce the vertical field of view from 60 degrees to 30 degrees. We chose readily available plano-convex cylindrical lenses from reputable companies such as Throlabs and came to the conclusion that the LJ1765L1 would be the best fit for our goals. Below is a table on the specifications of the chosen lens. Note to obtain an image with maximum sharpness a cylindrical lens should be placed in a manner in which the curved surface is facing towards the object, in the case the road. Table 30 describes the specifications of the cylindrical lens chosen.

Table 30: LJ1765L1 Specifications:

Property	Specification
Radius of Curvature	19.7 mm
Height	25.40 mm
Center Thickness	6.6 mm
Focal Length	38.12 mm
Material	N-BK7
Refractive Index	1.517

By reducing the field of view this image will be magnified. The resolution of our camera will still be 640 X 360 however each pixel will cover a smaller physical area. This will allow us to see shifts in the pixels easier. Once the system was optimized, it was found that the plano side of the cylindrical lens should be placed 30.88 mm in front of the camera.

Spot size is the radius of the laser beam's irradiance from the center to the edges where irradiance is equal to $1/e^2$ of the maximum irradiance. In the absence of aberrations, the spot size of a point object will converge at a single point. However, in our system, a cylindrical lens will force the system to magnify in one direction. As this occurs, we can expect the spot size to stretch from a circle to a line. Figure 25 shows the spot size diagram for our system at 0, 15, and -15 degrees. The RMS radius is a measurement of the expected resolution of the system including all aberrations. Aberrations affecting this system are discussed in the next section.

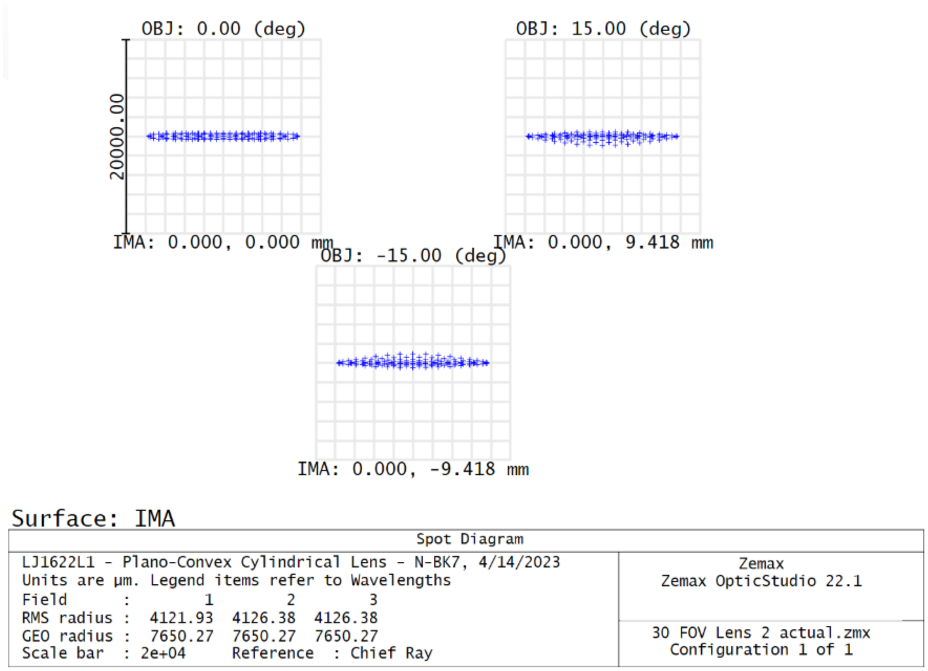


Figure 25: Spot Size

By analyzing these pictures, it can be seen that the spot size of the cylindrical lens increases along the y axis as the field of view increases. In this case it increases 0.7 um from the 0 degree FOV to the ± 15 FOV. The RMS radius values are measurements of the expected resolution of the system including all aberrations.

The detecting system includes one cylindrical lens for magnification in the vertical direction. Due to the properties of this lens, aberrations can cause the image to be blurred or distorted due to the light spreading out rather than focused to a point. Seidel coefficients describe these five aberrations which are coma, astigmatism, spherical aberrations, field curvature and distortion. This section will review the five seidel aberrations present in the optical system and describe the effect they will have on the image. Third order formulas will show how the system affects the aberrations with respect to the marginal and chief rays and ways of correcting each aberration will be discussed. Important variables within these equations are discussed in table 31.

Table 31: Seidel Coefficient Variables

Variable	Definition
A	Marginal Ray Refraction Invariant
Ā	Chief Ray Refraction Invariant.
y, u_i, u_i'	Marginal Ray Height and Angles
$\bar{y}, \overline{u_i}, \overline{u_i'}$	Chief Ray Height and Angles
H	Lagrange Invariant
c	Surface Curvature
$\Delta\left(\frac{u_i}{n_i}\right)$	$\frac{u_i'}{n_i'} - \frac{u_i}{n_i}$
$\Delta\left(\frac{1}{n_i}\right)$	$\frac{1}{n_i'} - \frac{1}{n_i}$

Coma

Coma is a type of aberration formed by rays of light that pass through a lens at an angle. The rays of light focus at different points along the image which makes the light look like a comet with a blurred tail. The below equation is for the seidel coefficient for coma.

$$W_{131} = \frac{1}{2}\left(-A\bar{A}^2 y\Delta\left(\frac{u_i}{n_i}\right)\right)$$

This equation is affected by both the marginal ray and chief ray refraction invariants. To compensate for coma, reducing the apertures of the lens will block the light rays going through the edges. Another possibility is to create a system in which the lens design is symmetrical around the center. Both of these scenarios are not an option for our system, as we can not decrease the field view of the system and extra lenses are not in the budget.

Astigmatism

Astigmatism occurs with a wide field of view and introduces blur. Within the system there is a tangential plane, containing the optical axis, z axis, and an object field point and the the sagittal plane which intersects the chief ray and is perpendicular to the tangential plane. Astigmatism is introduced into the system when the tangential and sagittal points of focus are at different planes. The equation below is the seidel coefficient for astigmatism.

$$W_{222} = \frac{1}{2}\left(-\bar{A}^2 y \Delta\left(\frac{u_i}{n_i}\right)\right)$$

This equation shows that astigmatism is based on the chief ray refraction invariant. To correct astigmatism, a three lens system must be introduced, usually using two convex and one concave lens. Again, adding extra lenses is not in the budget of this project.

Spherical Aberrations

A spherical aberration occurs due to the curvature in the optics of a system. Rays that pass through a lens near the edge are focused at different locations than the rays that pass closer to the center of the lens which causes blur. The seidel coefficient for spherical aberration is found in the equation below.

$$W_{040} = \frac{1}{8}\left(-A^2 y \Delta\left(\frac{u_i}{n_i}\right)\right)$$

This equation supports the idea that spherical aberrations are based on the angle of the marginal ray. As height increases so do the spherical aberrations. To decrease spherical aberrations in a system the marginal ray must be decreased. This can be achieved by decreasing the system's numerical aperture. However, there is a trade off; decreasing the numerical aperture also decreases the amount of light the system is able to collect. Due to the absorption of the asphalt, a maximum amount of light collected must be ensured in order for the laser line to be visible. Therefore this is not an option for our system at this time.

Field Curvature

Field curvature describes the amount the image plane curves due to the lens design in relation to the reference image plane. Due to the change in the vertical change of the field of view by the cylindrical lens, field curvature was introduced to the system. The Zemax rendition in figure 28 shows at a field of view of 15 and -15 degrees the image is not along the expected image location, but instead along an arc, similar to what would be expected of points converging outside of the reference plane. This will cause a blur in the image as the field of view increases or decreases from 0 degrees. The first graph in figure 34 shows data for the field curvature aberration. The graph shows that the field curvature tangential is 4.2995 mm. Below is the seidel coefficient equation for field curvature. Notice the first term is the equation for astigmatism.

$$W_{220} = \frac{1}{4}\left(-\bar{A}^2 y \Delta\left(\frac{u_i}{n_i}\right) + -H^2 c \Delta\left(\frac{1}{n_i}\right)\right)$$

The second term in the equation describes field curvature which is dependent on the curvature of the lens and the refractive index. Since this system contains one lens there is no corrective action that can be taken. However, if an additional lens was inserted, such as a negative field flattener lens placed close to the image surface, the design would have an opposite field curvature forcing the curvature to lessen. Due to the budget constraints, such a lens was not able to be included in the system.

Distortion

The second graph in figure 26 shows data for distortion. The maximum distortion of the image is 0.2431% at a 15 degree field of view. To correct distortion a special tilt and shift lens may be used, but these are very costly. A more practical way to eliminate this aberration would be by remapping each point to fit a rectangular grid free of distortion through programming. Since the distortion in this system does not affect us gathering the necessary data we are going to ignore this small distortion.

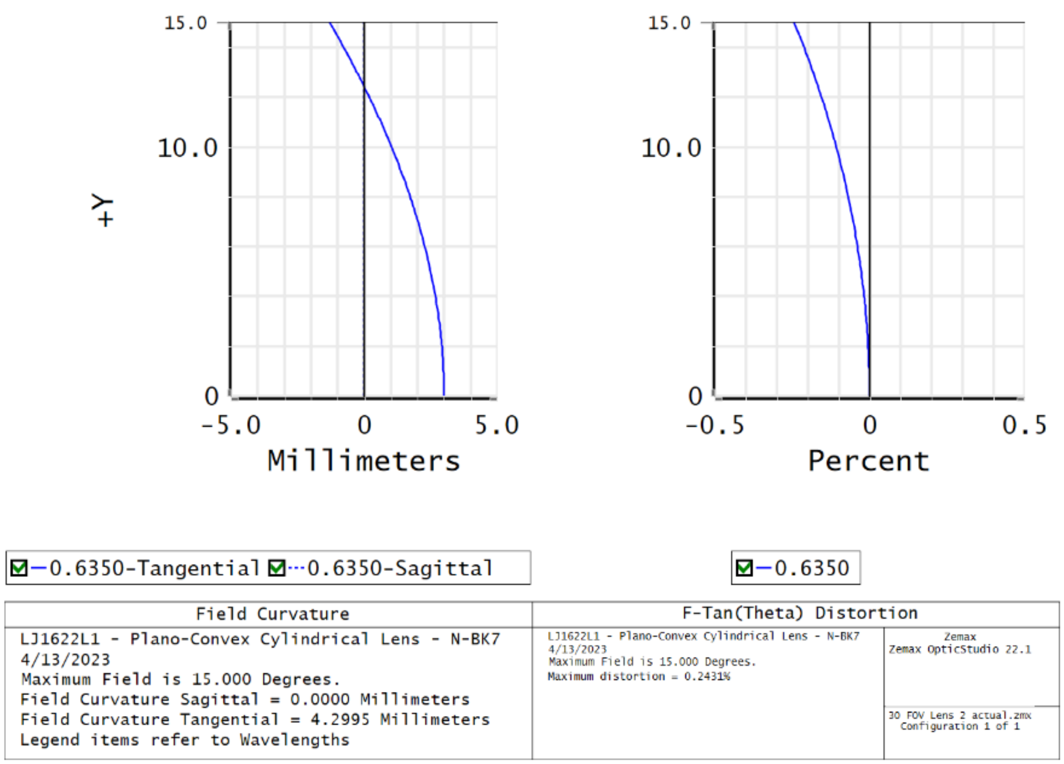


Figure 26: Zemax Field Curvature/Distortion

5.2.2.2 Redesigned Detection System

As previously stated, once the illumination system was built, testing occurred that pointed to a redesign in the detection system. It became evident that ambient and scattered light overpowered the light from the line reflected off the road's surface. In other words, we needed to increase our signal to noise ratio. First we calculated the black body radiation of the sun by calculating the maximum wavelength and then the max irradiance. To find the maximum wavelength the equation below was used.

$$L_{max} = 2.89 \cdot \frac{10^{-3}}{T}$$

The equation for the maximum irradiance at the maximum wavelength is presented below.

$$U_{max} = \frac{10^{-9} \cdot 2 \cdot h \cdot c^{4} \cdot \pi \cdot \left(\exp exp\left(\frac{h \cdot c}{L_{max} \cdot T \cdot k}\right) - 1.0\right)^{-1}}{\left(L_{max}\right)^{5}}$$

Using matlab figure 27 shows the maximum irradiance for every wavelength of visible light. Note at the calculated maximum wavelength of 498.3 nm an irradiance of 8.4240 W/m2 was found.

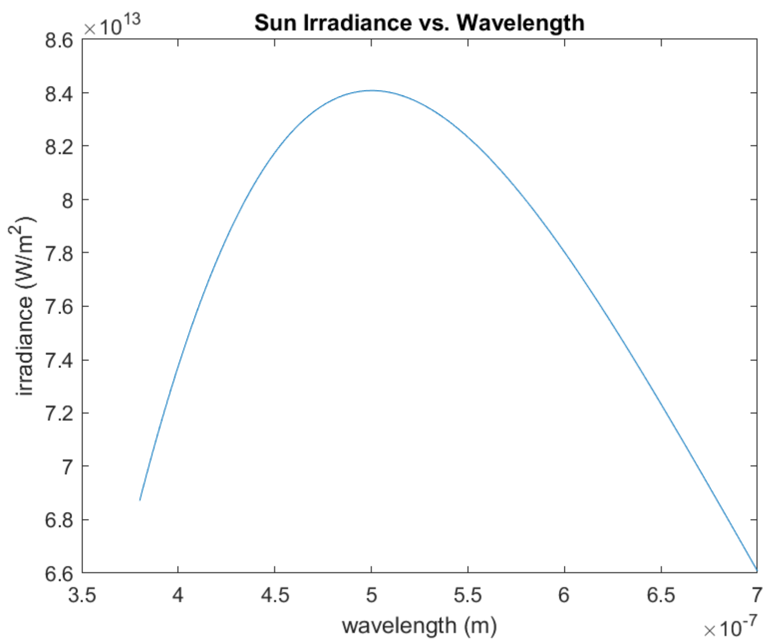


Figure 27: Graph of Sun Irradiance vs. Wavelength

The laser power was calculated to be 0.4174 W/m2 which is well below the calculated black body radiation sum. To increase the signal to noise ratio a spatial filter aperture was added which will eliminate some of the light incident on the sensor. This aperture also ended up benefiting the processing by decreasing the size of the video files but it was not enough for the camera's sensor to aperture the reflected light.

To continue to increase the signal to noise ratio of the detection system a bandpass filter was added to the detection system design. Since the laser's operating wavelength is 635 nm, a bandpass filter centered at 635 nm is ideal. The bandpass filter chosen is from Thorlabs and is a 10 nm filter centered around 635 nm allowing a 90 transmission at that centered wavelength. At 630 nm and 640 nm the transmission is decreased to just 45% while the tails allow just 0.01%. Figure 28 shows the transmission allowance at different wavelengths taken from Throlabs.

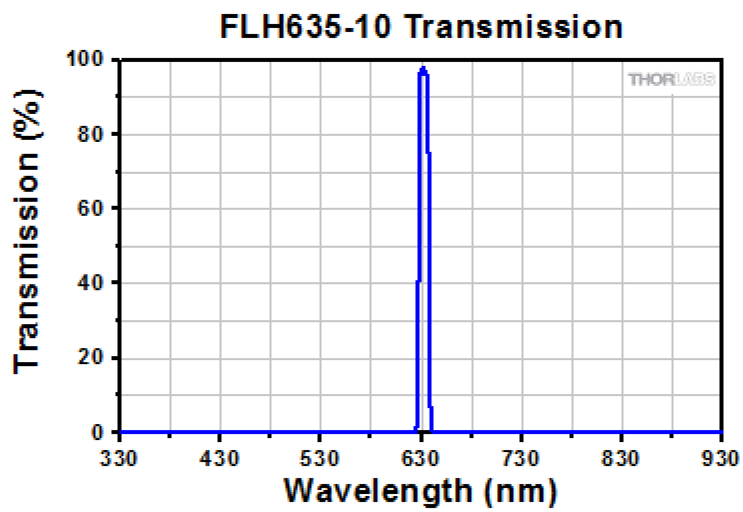


Figure 28: Transmission Allowance at 330 nm to 930 nm

Table 32 lists the general specifications of the FLH635-10 bandpass filter obtained from Throlabs.

Table 32: General Specifications of FLH635-10 Bandpass Filter

Angle of Incidence	0°
Housing Diameter	12.5 mm or 25 mm
Clear Aperture	Ø10.0 mm for Ø12.5 mm Ø21.1 mm for Ø25 mm
Mounted Thickness	3.5 mm
Operating Temperature	-40 to 90 °Ca

It was calculated that post filtering 0.3737 W/m2 was allowed through the filter which is less than the power of the laser of 0.4174 w/m2. After testing the system with the bandpass filter, the line detected by the system was only 2 feet. This is due to the fact that the bandpass filter requires incoming light to be collimated. For incident light at any other angles greater than zero degrees, the band will shift to a lower center wavelength and the shape of the bandpass changes. This causes a significant decrease in the transmittance of the passband. Figure 29 shows this effect.

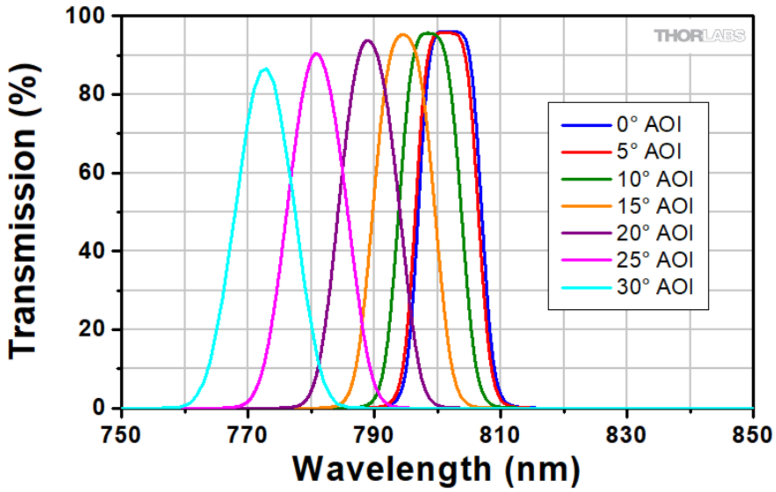


Figure 29: Transmission vs. AOI

To detect a longer line a collimator lens should be added to the detection system, however due to money and time constraints it was not added to the prototype.

5.2.3 Optical System

Initially, this system works by using geometry to detect a shift in depth of the road's surface. The laser is calibrated with the camera so that the line emitted from the powell lens is in the center of the image plane for the camera. The powell lens and the camera are positioned on the same plane which allows for a right triangle to be created by the camera, powell lens and the laser line. The angle of the laser in relation to the camera is used to position the laser in the center camera's object plane. When the road is flat the laser line will be continuous and straight from one side of the road to the other from the camera's view. When the laser hits a pothole the line will bend down in the camera's view and may be discontinuous, depending on the severity of the pothole's edge. The deformity of the line is the result of the angle that it is being projected at. Since the surface of the road will be greater than what the system was calibrated for, the line will travel farther and shift further down in the camera's view. When the line encounters a bump or an object on the road, the camera will see the laser line bend up. This occurs because the surface of the road is now closer than the calibration point and the laser is traveling a shorter distance. The figure below shows the triangle formed from the powell lens, the camera and the road surface.

Placement of the optical components in relation to one another is extremely important to optimize the system and reach some of our goals. To detect road damage, the camera must be able to differentiate between changes in the laser line projected onto the surface of the road. The below calculations are based on a detection system without the cylindrical lens. It was previously determined that the camera must be placed 4.8 feet or 57.6 inches from the road's surface. According to the Department of Transportation, a hole is considered anything greater than 2 inches. There are eleven pixels per inch based on the resolution and FOV of the camera; therefore a minimum shift of 0.17 inches, which the camera will see as a 2 pixel shift, must occur for the projected line to jump to a new line indicating a hole. Using this information and the below formula where h is the height of the camera it was determined that the emitting system must be placed at an angle of at least 85 degrees.

$$\theta = \tan^{-1}\left(\frac{h}{x}\right)$$

While the emitting system is at an 85 degree angle, the distance between the powell lens and the camera must be 5.04 inches away from each other. As the angle varies, so does the distance between the powell lens and camera. Notice these calculations only work if the powell lens and camera are on the same plane. Figure 30 shows the placement of the powell lens in relation to the camera. It also shows that to measure a 2 inch deep in the road damage, a shift of 0.17 inches must occur.

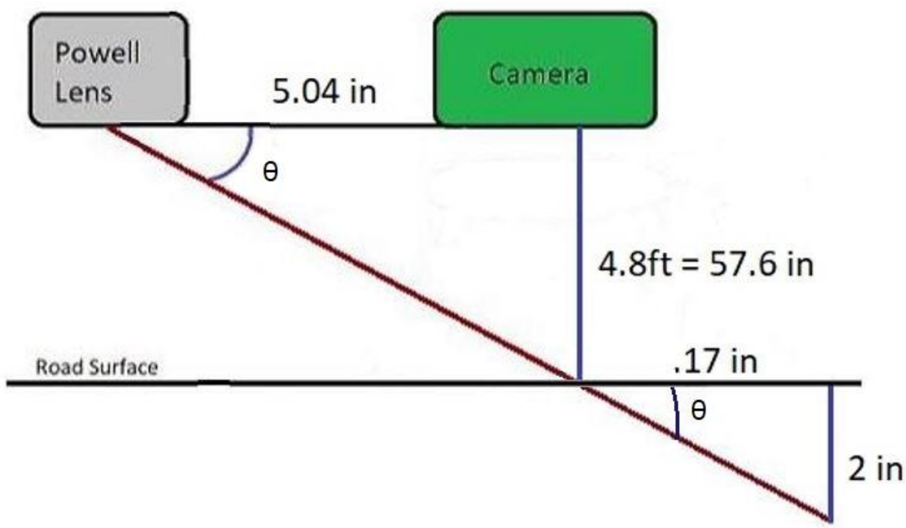


Figure 30: Powell Lens and Camera Placement

When creating the optical system, properties of asphalt became a topic of interest. Albedo is a measure of reflectivity with a scale of 0 to 1. Asphalt has an albedo of about 0.05 percent, meaning it absorbs around 95% of all incoming light. Therefore we can assume that of our max power of 4.79 mW transmitted from the powell lens, 0.24 mW will be reflected and 4.55 mW absorbed by the asphalt.

It was determined that we needed to collect more light from the laser line to combat the ambient light that was overpowering the laser in the camera. We decided to collect more light by gathering reflected light instead of scattered light. To collect the reflected light the camera was moved farther from the powell lens and placed at an angle. The camera now needed to be on the same angle as the laser and powell lens. The angle being used was changed from 75.16 degrees to 80.8 degrees to lessen the distance between the camera and the powell lens. With these new angles the camera and the powell lens required a distance of 14.25 inches between them as seen in Figure 31.

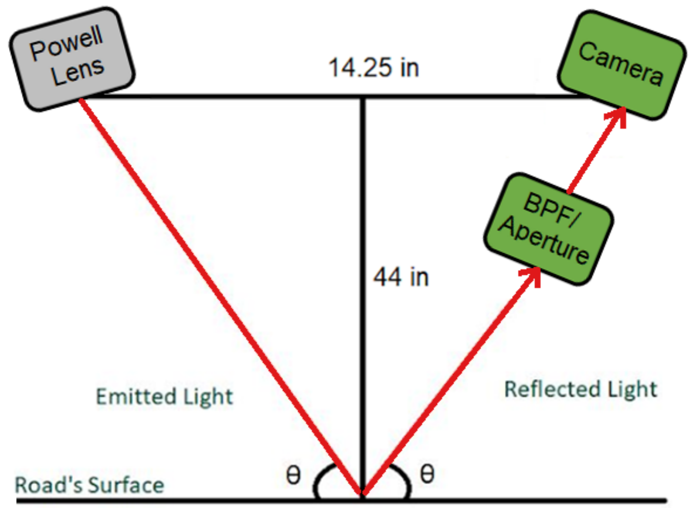


Figure 31: Optical Component Schematic

5.2.4 Microcontroller

The microcontroller section will discuss how our PCB will be configured with our controller as well as discussing the other functions of the microcontroller. The microcontroller contains a 40 pin header which we can utilize for some parts of our design, such as establishing a UART connection. UART will be the main method of communication between the GPS and the microcontroller. On the raspberry pi the pins responsible for UART communication are TX (GPIO14); RX (GPIO15). On the gps module which we have chosen the UART pins are pins 2 and 3. UART is important because it provides a quick and simple data connection with the gps module. Requiring only 2 wires to communicate with the controller is simple and can reduce our manufacturing overhead. The microcontroller has many systems and features that fit into our design. These systems will be broken down into their own sections below but they include USB communication, UART communication, Bluetooth communication, data storage and GPIO. The microcontroller in question also has its own graphical processing unit which may prove to be useful in our design.

The microcontroller is responsible for communicating with the different aspects of our design, from gathering information from our optical system, gathering information from the GPS module to communicating to the user that the system is ready to start scanning to storing all of the information gathered for use later.

First off the microcontroller will need to communicate with the GPS module located on our PCB. to facilitate this communication we will be using the established UART connection on both the microcontroller as well as the GPS module. The UART connection from the microcontroller is located on GPIO pins 14 and 15 while the UART connection for the GPS module is located on pins 2 and 3. The UART connection is capable of a maximum of 10 updates per second, this is achievable by increasing the baud rate and decreasing the number of ‘enable’ messages. Ten updates per second is not representative of the baud rate but instead represents how quickly the gps module can obtain a gps fix.

The UART connection from the microcontroller will send a NMEA signal and will receive a NMEA GGA, GLL, GSA, GSV, RMC, VTG and TXT message from the GPS module, we will then store this message to store the locational data provided within it. For our design if storage space becomes constrained we can implement a method for the microcontroller to shorten the information received before it is stored.

The microcontroller will also need to communicate with the camera module. Communication with the camera module can be done either through the GPIO pins on the microcontroller which interfaces with the PCB or we can utilize the onboard micro-usb port with the help of a USB OTG cable which converts the Micro-USB to USB-A which is the connection that our camera comes with. Communication with the camera is important because optical information is at the heart of what this project is all about.

The microcontroller will also need a way to store all of the information we gathered from the system and its various components. Luckily the microcontroller we have chosen comes equipped with a micro-SD storage system that the microcontroller uses to store its operating system at a minimum. Therefore we will be utilizing this storage system for our storage needs. Online sources state that the microcontroller can utilize 256 GB micro-SD cards at most given one partition. Though this limit might be passed using multiple drive partitions we do not expect the need for more than 256 GB. Likewise, even if our system generates enough information that we will need more than 256 GB it is better design practice to find methods to reduce our storage needs than to rely on increasing our storage threshold.

The microcontroller we have chosen also includes an onboard Bluetooth module. This Bluetooth module will be used to create a Bluetooth link to the user's phone.

This link is important because it is the first step in achieving one of this project's goals which is to provide the user of the system/ the driver of the vehicle with information about the device, that way if there are any issues they can be sorted before the user begins their drive.

Lastly for powering the microcontroller the manufacturer recommends the power source be capable of 5V at 1.2A for a total of 6 watts of power. This may need to be increased slightly if we find out that the micro-USB connection cannot support our camera at 1.2 amps. Otherwise if the method we choose to go with is the GPIO route for the camera our microcontroller will be satisfied at 1.2 amps.

5.2.5 GPS

The GPS module is the heart of the location system. The GPS module is responsible for obtaining the locational data from the GPS constellation. This system is important to this project because it tells us where the potholes are located in space which we can then display properly on a map. In this section we will be discussing the design related to the location gathering part of our project.

The GPS module will be located on our PCB as our microcontroller does not include a built-in GPS unit. The location of the module will have to be close to a mounting point for the antenna. The antenna that we have bought has a cable length of 100mm giving us less than 4 inches to mount it from the PCB. Mounting of this antenna is done with the use of double sided tape.

The GPS module is tasked with communicating with the microcontroller for the purpose of sending locational data. Thankfully the GPS module we have chosen includes a built-in UART connection which we can access through pin TXD and pin RXD. Being that TXD is an output for UART systems as well as for this GPS module we will connect pin TXD on the GPS module to pin RXD on the microcontroller, likewise we will connect pin 2 on the GPS module to pin TXD on the microcontroller. The module supports a baud rate ranging from 9600 to 921600, which is in terms of bits per second. Figure 32 will show this connection between GPS and microcontroller as well as some other connections.

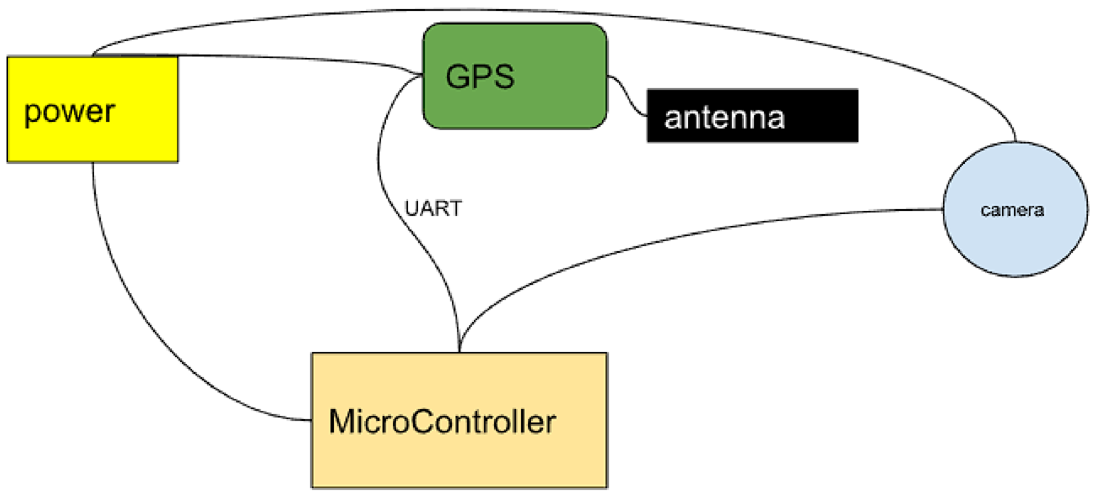


Figure 32: Microcontroller Block Diagram

The manufacturer of the GPS module recommends that the Vcc voltage be 3V and only a max of 3.6V. Another thing to consider is the ability to reset the module, this extra connection to the microcontroller may be useful to not having to restart the entire system if something goes wrong. In order to reset the module pin 9 has to be low for at least one millisecond. Resetting is done when the module has a hard time getting a GPS fix.

The figure above shows the block diagram of the components connected to the microcontroller. We can see that the power system is connected, the GPS module is connected along with an antenna for the GPS, lastly the camera will also be connected to the microcontroller. The connection between the GPS and the microcontroller being UART means we will be needing two wires connecting it.

5.2.6 Data storage

Data storage is crucial to this project as uploading data directly to the database was decided against citing some drawbacks to justify not taking that route. In this section we will be discussing things in reference to the storage of data in our device. One subsection will include a breakdown of how much data we will be expecting to store before it can get offloaded. The constraints on larger data storage are size and cost.

Location

As discussed in previous sections, offloading data as soon as it is created is not an option for this project. Therefore storing this data on the device until it can later be offloaded is crucial to this project. As for where we will be storing this data it will be on a micro-SD card connected to the microcontroller. The microcontroller has a dedicated slot for a micro-SD card that it uses to store its own operating system. This is also going to be the place where we store all of our gathered information from the various components of the device. One thing to take note of is that since we are sharing our data space with the microcontrollers operating system we must take precautions not to erase parts of the operating system when transferring data.

Space

The SD card needs to be large enough to contain the operating system of the microcontroller as well as the data gathered from scanning. We know that the information gathered from the laser sensing unit (Camera) will give us the largest percentage of data. With this in mind a precaution we can take to not generate excessive unused data would be to crop the images taken from the camera to a smaller size before we store the information on our micro-SD card. This can be done as we are really only interested in the subsection of pixels which contains the laser. Limiting it to just the pixels where the laser lies creates an image that we store that is short vertically but the full width of the frame, or most of the frame if the laser does not take up the full frame. Testing has to be conducted to determine exactly how many pixels we should expect in the final image to be useful to us. Taking this precaution alone can reduce our data input from the camera from 108 GB to 30GB for a scan of 10 minutes if we generously use 100 pixels for the perpendicular angle of the laser. Table 33 shows the calculations for storage space that will be needed. This change allows us to use our limited space more efficiently. This precaution also reduces the cost of the system by only needing smaller SD cards.

Table 33: Storage Needs Calculations

	640X360MJPEG@260fps	1280X720 MJPEG@120fps	1920X1080@MJPEG60fps
Frame size	680.4 KB Cropped: 192 KB	2765 KB Cropped: 384 KB	6221 KB Cropped: 576 KB
Frames per second	260 fps	120 fps	60 fps
Data per second	176.8 MB Cropped*:49.92 MB	331.8 MB Cropped*:46.08 MB	373.3 MB Cropped*:34.56 MB
10 min size	107.83 GB Cropped*: 29.95 GB	199.07 GB Cropped*: 27.65 GB	223.95 GB Cropped*:20.736GB
30 min size	323.5 GB Cropped*: 89.86 GB	597.2 GB Cropped*: 82.94 GB	671.8 GB Cropped*: 62.21 GB
1 hour size	647 GB Cropped*: 179.7 GB	1194.4 GB Cropped*: 165.9 GB	1343.7 GB Cropped*:124.4 GB

* Cropped to 640 X 100.

The table above does not account for possible video compression provided by the camera automatically. The numbers devised were calculated by strictly multiplying the image resolution by frame rate by the 24 bits of color per pixel, 8 bits for red, green and blue respectively.

The table above shows the frame size of each setting on the camera as well as a cropped frame size to the full width of the frame bit only 100 pixels tall for each respective setting. We can see that using a higher resolution always increases the frame size. We can also see that using the native resolution provided along with the frame rate the bandwidth or data per second is in an inversely proportional relationship with the frame rate, as frame rate goes down the increase in resolution outweighs the savings from a slower frame rate. The opposite statement is true when cropping the input, as frame rate decreases the pace of increasing resolution does not keep up meaning the bandwidth gets smaller with a slower frame rate. The table above also states that with cropping the total data for an hour of data will be less than 256 GB for all cases.

With the information provided from the table above we see that a simple 10 minute drive at our highest frame rate gives us 110GB of data to store, with cropping we reduce this to only 30GB of data. Therefore cropping is important to not waste valuable storage space.

Cropping the input from the camera is not only important in terms of physical allocation of space on the device, it also helps reduce the bandwidth of data that we need to store down as well. SD cards are limited by their speed of reading and writing data. A high performance micro-SD card boasts up to 90 MB/s write speed though this may be limited by other factors that we do not know of yet meaning a lower bandwidth is better to store all pertinent data to this project. Testing will need to be done between the microcontroller and the micro-SD card to determine how far we can push our system.

In the final implementation we did not end up cropping the input from the camera on the fly on our system, though cropping is done in the video processing program to avoid processing data which is not useful. Such data include parts of the frame which is covered by the aperture.

5.2.7 Electrical System

In this Section we will explore the electrical design. The whole idea can be represented by an example initial schematic, using the information of our output power from the PCB to regulate flow throughout our microcontroller and the camera. Figure 33 shows the beginning schematic of the basic power connections to the Raspberry Pi module. This is without the laser diode and without the other ground pins accounted for.

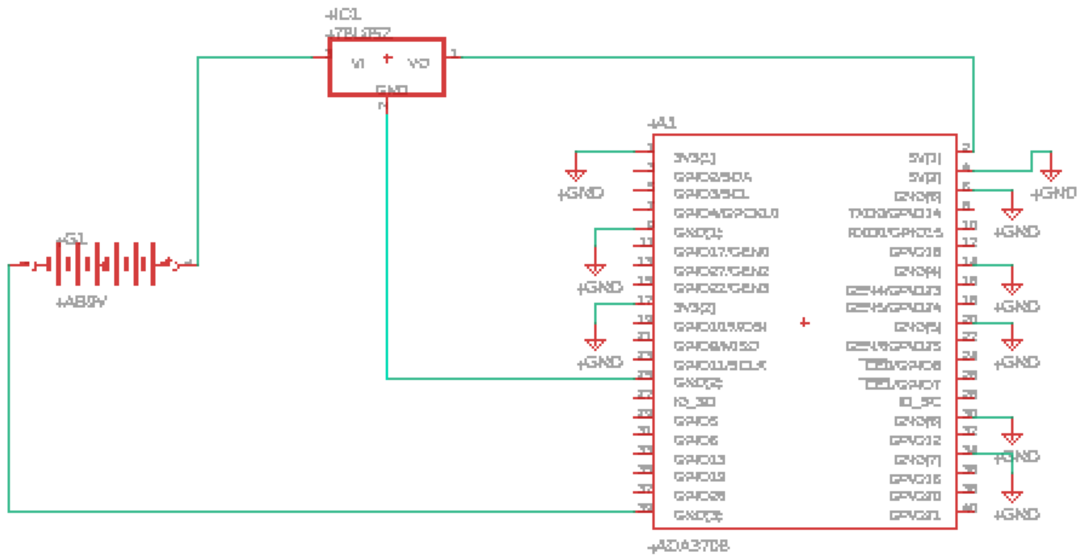


Figure 33 : Initial Electrical Schematic - LM7805

The voltage regulator is included because 9 volts is too high of a current for the Raspberry Pi to function with. The voltage regulator will step down this current, but we still need the high battery power for the camera to function at full capacity.

We must also include a circuit that can supply power to the laser modulation that can contain a high switching frequency. The signal voltage will be utilized as a voltage control, acting as the transistor switch. The high voltage is sensed and will allow full current to be supplied to the laser. If the laser is off, this is in a case for when the vehicle is not moving or the device does not need to be active yet, we will then modulate the laser at a slower rate. This will keep the laser in a “low power mode” allowing the battery to not supply energy to the laser when it is not necessary. Lastly, what will need to be implemented into the circuit is the operating voltage for the camera. This camera must be able to operate when the laser is on. This current can be fed through a receptor diode to be read easily as an analog signal. This will convert through the microcontroller to be processed by the software program.

With using several sources for Eagle symbols, pcb footprints and models, there was no available module for the specific laser diode we are using. No source has contacted me back about creating the symbol to be used in Eagle. For now we will continue implementing our project as if the laser diode will be connected through the PCB but we will need to find the symbol and footprint for a laser diode with our specifications. The camera will be connected directly through USB to the Raspberry Pi so there is no need for its inclusion in the PCB. This is especially the case since the USB cord will be used to extend the camera through the tube of our housing unit.

Because we cannot provide a full representation of our final schematic, below is a representation of how our electrical components would be placed if the diode was in use.

When developing our schematics and current thoughts about how the system should be produced and what needs to be possibly added, we considered the load calculations of each major part. Each of these ‘devices’ need a specific voltage of dispersed current to operate in the system. Using the specific part number we have found and for what has been ordered we are able to calculate the total load and voltage amount needed for our power supply to process. Below, in table 34, are the power specifications of the included parts in the electrical design.

Table 34: Power Specifications

Part	Voltage	Amps	Watts
Raspberry Pi Zero W	5 V	2.5 A	6
Laser Diode	4.9 to 5.2V	200mA	4.5 mW
Camera	5V	150 mA	12W
Battery	9 V	0.4	3.6
SD Card	2.7 - 3.6V	2.3	6-10

5.2.7.1 Electrical Design Protection

An important inclusion when designing the electrical interface is to consider the possibility of conditions such as overpower, short circuit, etc. Keeping this concept in mind we can develop measures to implement that will aid in our device having fewer future issues. Circuit protection refers to the various measures taken to prevent damage to electronic circuits or devices from electrical faults such as overcurrent or short circuits. Circuit protection is used to protect equipment using designs to break the circuit in case of abnormal conditions or limit the amount of current flowing throughout the circuit. Common protection devices are circuit breakers, surge protectors and voltage regulators. In the technology investigation section, we discussed a voltage regulator and its functions, specifically for its possible use in our circuit. This is important to prevent damage to electronic devices and ensure the safety of electrical systems. In our system we will be using the LM7805 voltage regulator for many reasons, but the design protection is a large concern. This regulator is included to ensure that every piece of equipment is dispersed with the correct consistent flow of current.

Other possibilities to keep in mind is the battery will have the ability to supply more current than needed. A way to solve this is we can include a low voltage cut off option for conditions when the unit is being operated in a steady state. For example, this is when the vehicle is not in motion and the device is still on. It would be inefficient for the device to operate at full power when the driver is stopped. This can be implemented into the PCB to save space. This will isolate the battery once the battery drops below a certain voltage, as well as protecting the Raspberry Pi from receiving an overcurrent. Figure 34 represents the possible part schematic for a low voltage cut off option while the previous initial schematic includes the 5 volt voltage regulator. The low voltage option is the inclusion of a MOSFET channel with a diode to drop the batteries available usage to a lower value for when the charge level is running low. This is again without the inclusion of a laser diode because the SnapEda part download is not available. This downloadable version for our specific diode is also not available on any other platform.

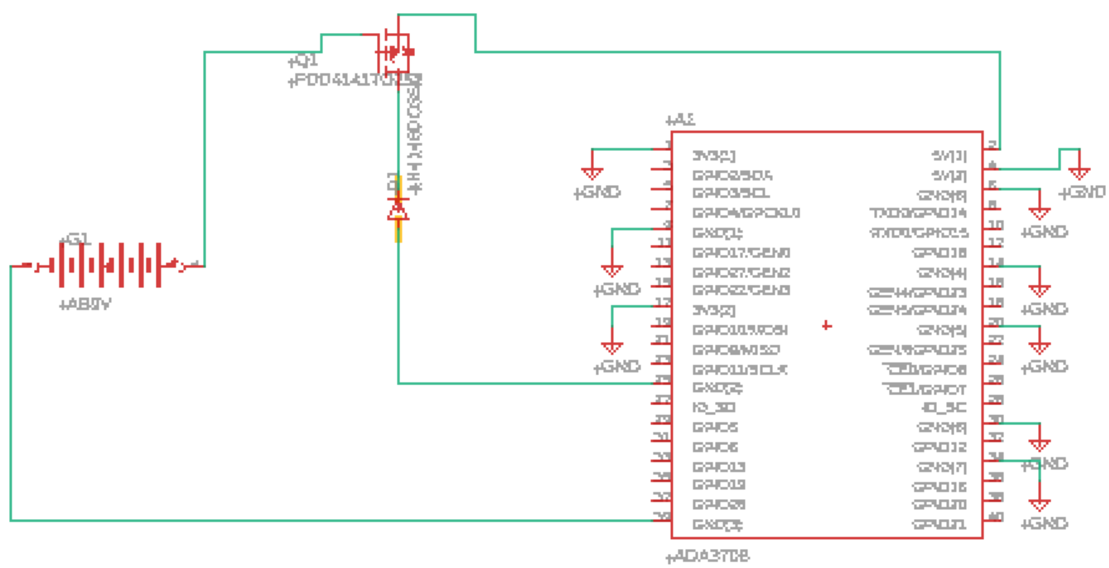


Figure 34: Schematic - MOSFET

In the case of the current option of our schematic which is very basic since we cannot include the laser diode. Because we cannot include the laser diode this affects the placement of a low voltage cut off. The only electrical protection unit we would need at this time is the voltage regulator to step down the level of supplied power from the battery. This will be our mechanism to also implement a power save mode in the final display.

5.2.7.2 Power Design

For a more concrete image of what will be represented into the electrical portion of this device, the block diagram from 5.1 Electrical Block Diagram demonstrates the process. That diagram is the order and flow of where our battery current will be supplied. Because it is directly connected to the voltage regulator, this is the device that will receive the power first. We also want to supply a current with low voltage power to the SD card even when the camera is not operating, so that the information can be relayed and exported to other devices for final augmentation. We must maintain a current to the camera and the laser diode, in a cut off manner, to ensure that when the device is immediately turned on or the car accelerates in speed, the device will power on and function properly.

The main information that needs to be implemented into this flow of current is the specification of each part we know we will be using. We must also decide whether these parts will be included on the PCB or be attached for other use. In our current plan, we have decided for the SD card to only be implemented into the raspberry pi and not the PCB, because we are wanting to have easy and consistent access to the module without other complications. A general user with less knowledge on the device should just be able to unplug the SD and insert into his personal device to directly receive the information through our portal. Developing any strict connections to the SD card could cause issues with our system when someone untrained uses this machinery. Table 35 shows the power specifications required by the Vin for each component in the power division as well as where the component will be located in our final device model.

Table 35: Power Design Specifications

Part	Vin	Origin
Raspberry Pi Zero W	5V	-
Laser Diode	4.9 - 5.2V	PCB
Camera	5V	Raspberry Pi
Battery	9V	PCB
SD Card	2.7-3.6V	Raspberry PI

5.3 Housing Design

The housing design will be built to meet the requirements and specifications of the prototype discussed in previous sections. In order to meet the budget constraint, housing for the optics and electrical components will be 3-D printed.

Figure 35 shows the Ender 3v2 3D printer.

Figure 35: Ender 3v2 3D Printer

The filament used will be polylactic acid (PLA) which is made from renewable resources. The trade off in 3-D printing the housing and using this filament versus manufacturing a metallic housing is the increase of degradability due to environmental forces and lower durability. PVC pipe will be used to connect the electrical housing to the optical housing.

5.3.1 General Housing Design

Initially the overall housing design consisted of a three dimensional case containing electrical components that attaches to the roof rack of a SUV. PVC pipe runs from the electrical housing to a second box that houses the optical components. The PVC pipe will have a coupler so the height of the optical system can be optimized to the correct height. Figure 36 illustrates a side view of the initial overall housing.

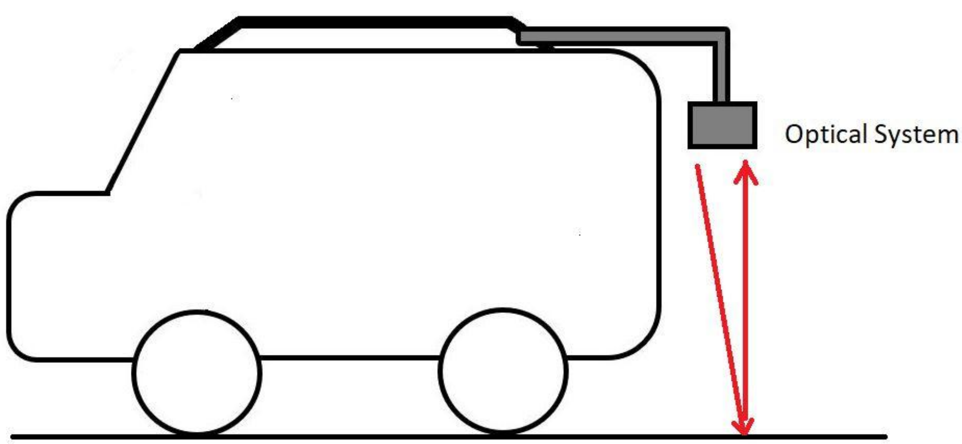


Figure 36: Side View of Housing

However, after building the prototype, it became apparent that it would be too large to hang from the roof rack of a car and a new design was implemented. A truck is used with the gate down. The prototype or road scanner is attached to a long box that is used as a counter weight and to raise the optical system to the correct height. All optical and electrical components reside inside the road scanner. Securing straps are also attached to the prototype to secure it as seen in figure 37.

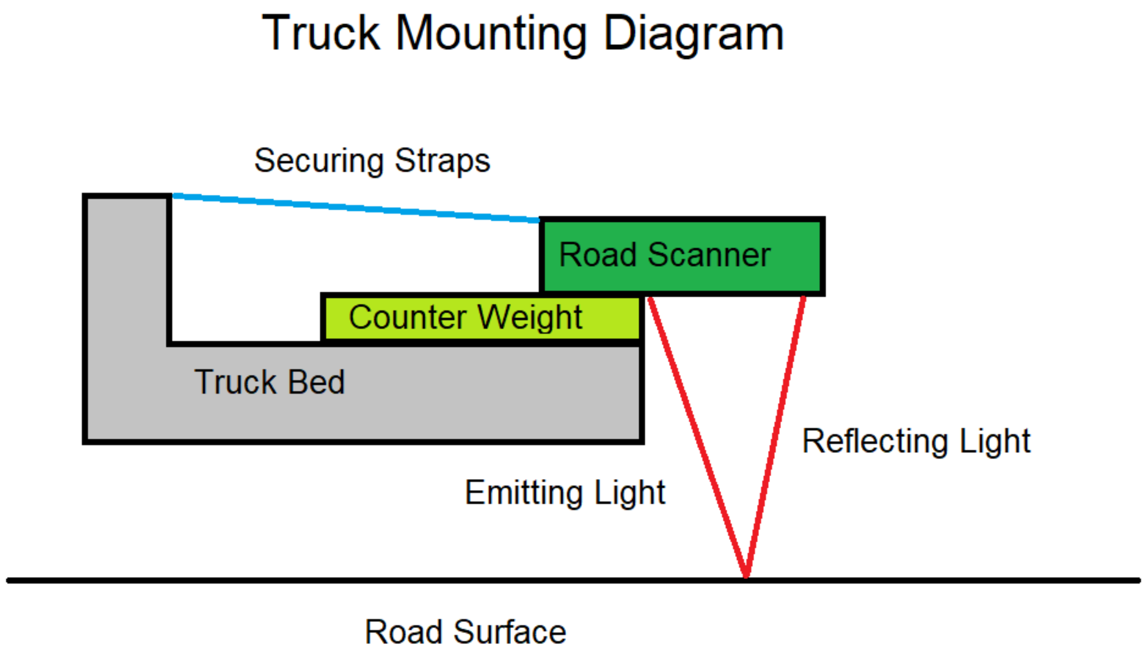


Figure 37: Truck Mounting

5.3.2 Optical Housing Design

This section will concentrate on the optical system housing design. The interior housing for the optical components will be designed in SolidWorks to the specifications of the system. Afterwards, the designs will be 3-D printed. The Ender 3 V2 has a printing size of 220 mm X 220 mm X 250 mm and has a precision of ± 0.1 mm. Printing precision is very important for the prototype as alignment of the optical components and distances between them are extremely important for optimization. The emitting system consisting of a laser and powell lens and the detection system consisting of the cylindrical lens and camera will both be contained within the optical system. Each system will be printed individually and then assembled. This prototype will be used outdoors; therefore, road conditions and environmental factors must be taken into account, specifically rain. The design should take into account that the optical components should stay dry while in use.

Initially, the main housing was to be 3-D printed in two parts to ensure accessibility to the optical components and for ease of build. However, it soon became apparent that the house was too large to be printed with the available printer and needed to be composed of a different material. Due to cost and time, the housing was made from MDF board and assembled using bolts, while the housing wedges were 3-D printed. The bottom of the main housing has a hole in the shape of a circle which allows the camera to look out and a slit which allows the laser line to project out of without any interference. Figure 38 shows the main housing designed in SolidWorks. Notice there are two circular holes on the top of the box which will allow the cables from the laser and camera to extend to the pcb for power. There is also a slat that will prevent the camera from picking up any reflected light from the powell lens.

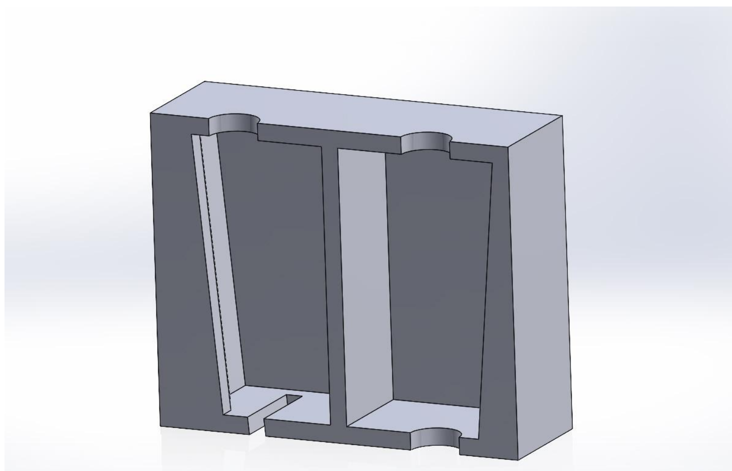


Figure 38: Main Optical Housing

Figure 39 shows a top down view of the housing. The bottom of the housing contains a slit for the powell lens's beam to project outwards and an area which allows the camera to capture the projected line on the road's surface.

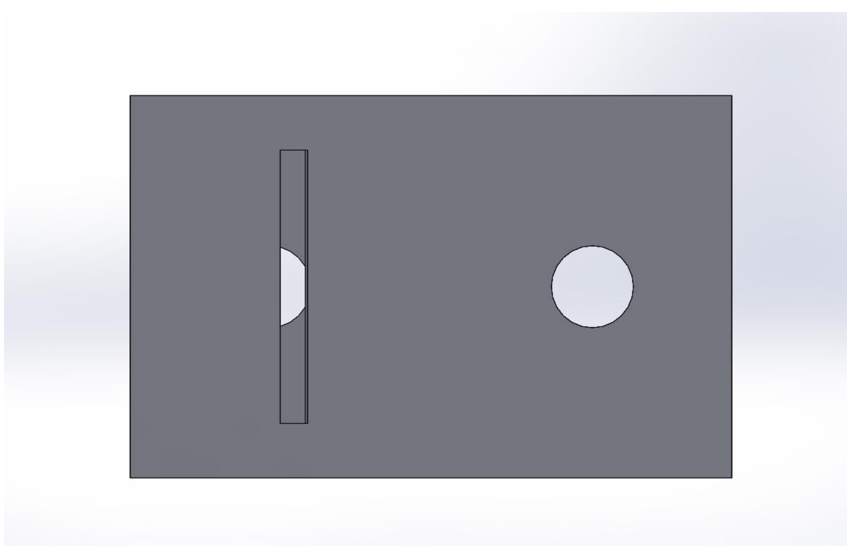


Figure 39: Bottom View of the Main Optical Housing

The main optical housing will contain the emitting and detecting optical systems. For ease of assembly, both systems will be on a rail as seen in figure 40 that will then be attached to the inside of the housing unit.

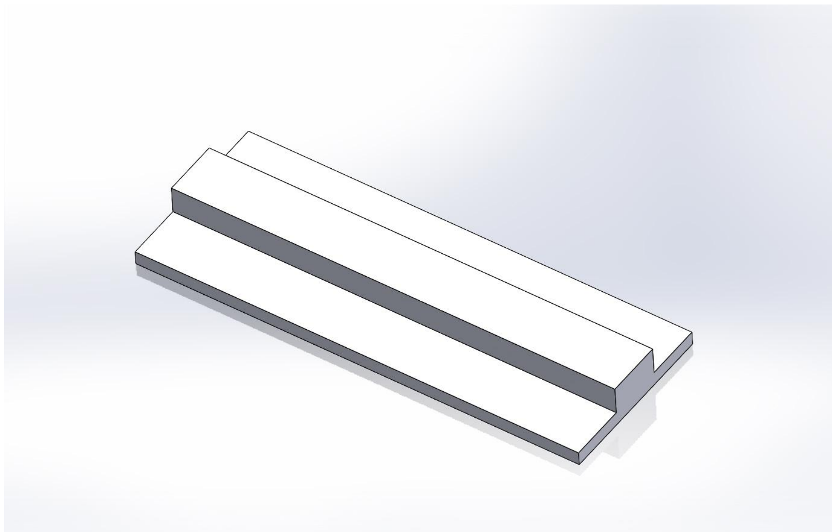


Figure 40: Rail System

5.3.2.1 Emitting Optical System Housing Design

The emitting optical system will be within the main housing of the optical system housing. It will consist of a track that will be mounted on the wedge inside the main housing, a laser holder, and a powell lens mount. When designing the powell lens mount, the shape of the exit beam transmitting through the plano side is the main obstacle. As mentioned beforehand, the shape and steepness of the roof determines the fan angle and the incident laser beam diameter determines the shape of the roof. In this case the existing beam consists of a line projected at an angle of 110 degrees. The mount had to be designed in a way so there was no clipping of this beam and its exit points. Figure 41 shows the mounts for the laser and powell lens respectively designed in Solid Works. This system will be mounted on to the wedge inside the main optical housing.

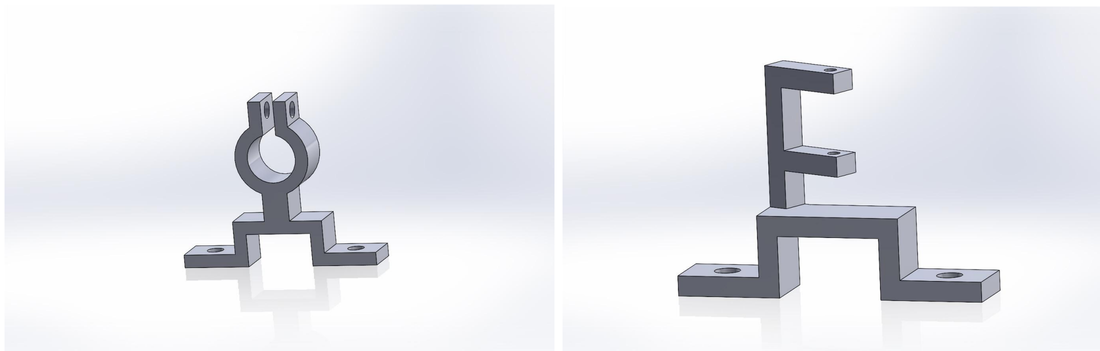


Figure 41: Emitting System Mounts

5.3.2.2 Detecting Optical System Housing

The detecting optical system will also be held within the optical housing. This system will be on a rail to make alignment of the optical components easier. The cylindrical lens mount will consist of a stationary base and an adjustable arm that will squeeze the lens against the base as a screw is twisted to tighten. The base and the arm will be positioned on the flat ends of the lens. A camera mount and cylindrical lens mount will be arranged on the rail and bolted to the main optical housing. Figure 42 shows the housing for the camera and plano- convex cylindrical lens respectively designed in Solid Works.

Figure 42: Detecting System Mounts

The bandpass filter and the spatial filter will be held in place with a mounting system that affixes them directly onto the camera lens' housing. This ensures that all of the light that enters the camera, first passes through the bandpass filter and the aperture. To achieve this a holder was designed that on one side slides over the camera lens housing and the other side has the aperture built into it. The bandpass filter is placed into the mount, which is then slid over the lens housing and held in place by a screw as seen in figure 43.

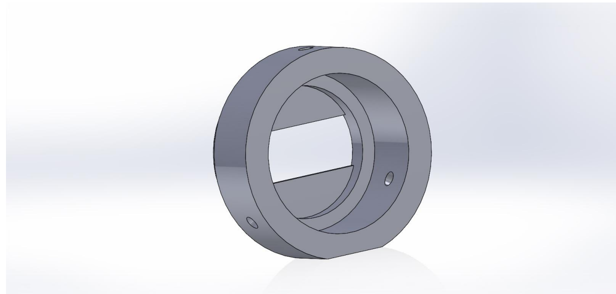


Figure 43: Aperture

5.3.2.3 Summary of Optical System Housing

Figure 44 is a schematic as to how each component of the optical system will fit inside the housing. The laser and camera will need power which is coming from the electrical housing. Wires will be connected through the hole at the top of the box and through the PVC pipe.

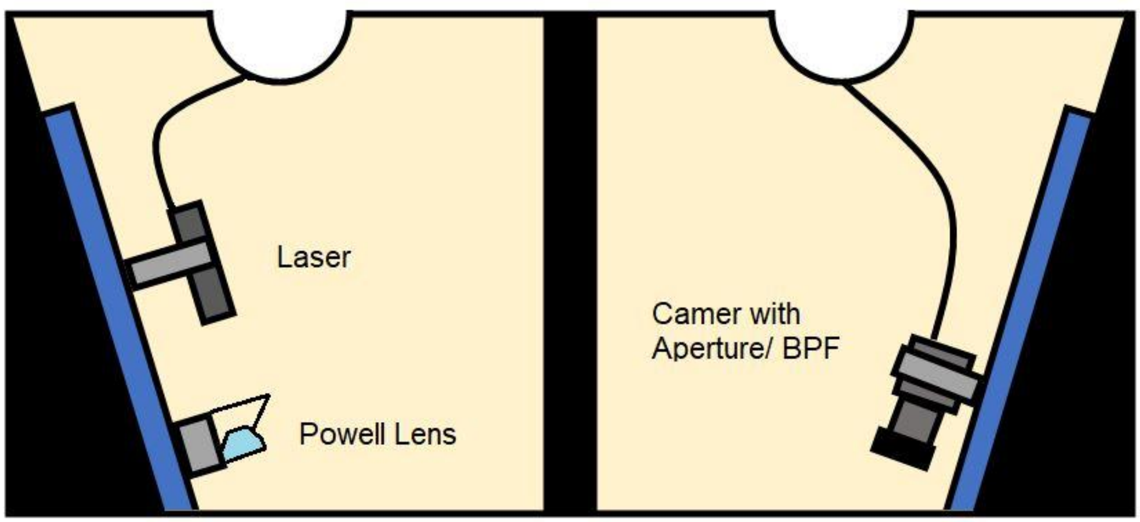


Figure 44: Summary of Optical Housing Design

5.3.3 Electrical Component Housing

The electronics housing unit will be storing the electronics associated with this project from the PCB, the GPS antenna, as well as the microcontroller. Being that the microcontroller is the device that will be holding the SD card all of our road scanning data until we get a chance to upload it, we will need a system to access the micro-SD card slot, and by association expose the microcontroller to retrieve it. With this in mind as well as unforgiving Florida rain we need to create a weatherproof opening of the housing.

The main components housed in this design will be the Raspberry Pi, the SD card, the battery, the PCB and wires leading to the optical connections located outside the central housing unit. All of these components contained in this portion of the housing unit are sensitive to ESD. This housing unit will align the components properly and maintain safety from outside environmental interferences, such as dust and rain. When mounting the device, we must also take into consideration how road obstructions such as bumps can shift or bump parts in this housing design. If the device is cushioned and mounted properly with most electrical units placed onto the PCB, there should not be as many issues. The projected designs are not final and can be re-implemented in a non-3D printed design.

In this design we will include a hinge mechanism, whose purpose is to result in the availability to open the electrical compartment to access the SD card. The SD card would be used to transfer the collected information into our program. This program will reiterate the 3D model taken by the camera to distinctly display where the road obstruction occurred. The outermost layer of the housing design for the electrical compartment will contain this hinge design. When designing this, we thought of the process in which you would open up a chest, and the contained objects are protected. What we want to accomplish with the inclusion of the hinge access top, is for any user to be able to open the housing unit and access the SD card. We are looking for little to no interference made with our hardware designs so we would like the SD card accessibility to be quick and efficient. If there is an inexperienced user in charge of operating the program and SD car we would like to ensure the rest of our is safe from casualties when retrieving the SD. With our devices going on a vehicle and the advanced goal of 60 mph, the whole design must be protected from all environmental possibilities as well as the driver's possibilities of fault. This design must be secure enough for the vehicle to accelerate and decelerate at very quick speeds, as well as being able to handle the obstruction in the road that the project is designed to map and report to the user. The current mounting concept is to attach the device to the rails on an SUV. We chose the rails of an SUV because this design can be used on many modern day vehicles and would not have to be a specific company car.
Using Solidworks, we could develop the basic understanding of what the electrical housing unit would look like. The first main portion to implement is the hinge lid of the compartment as shown in figure 45.

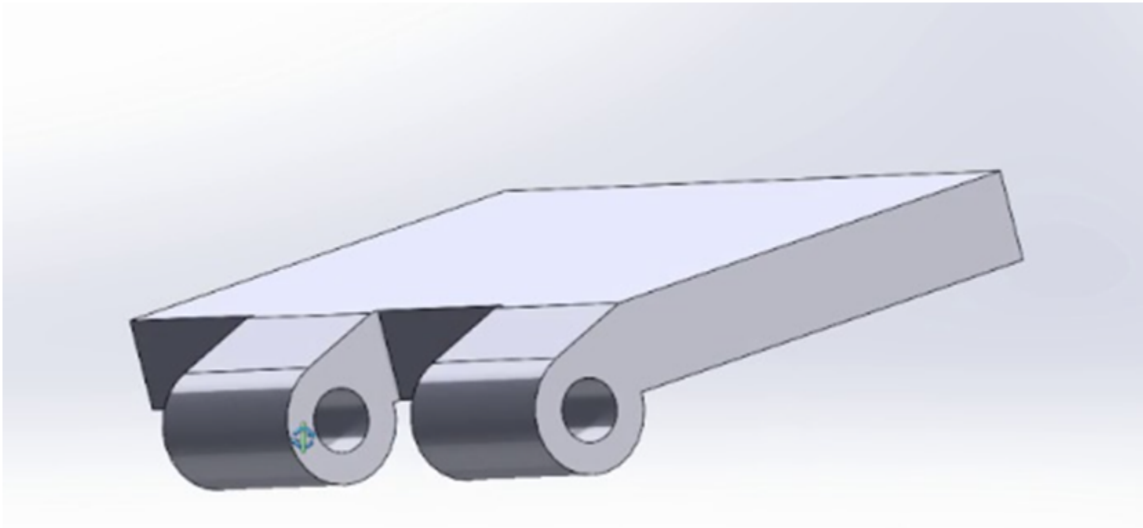


Figure 45: Electrical Housing Hinge Top

Figure 46 is a representation of the base of the figure without the notches for the hinge from the lid. The base will have a cut out square for the wires to exit through to then be sent to the optical housing unit to operate the camera and diode.

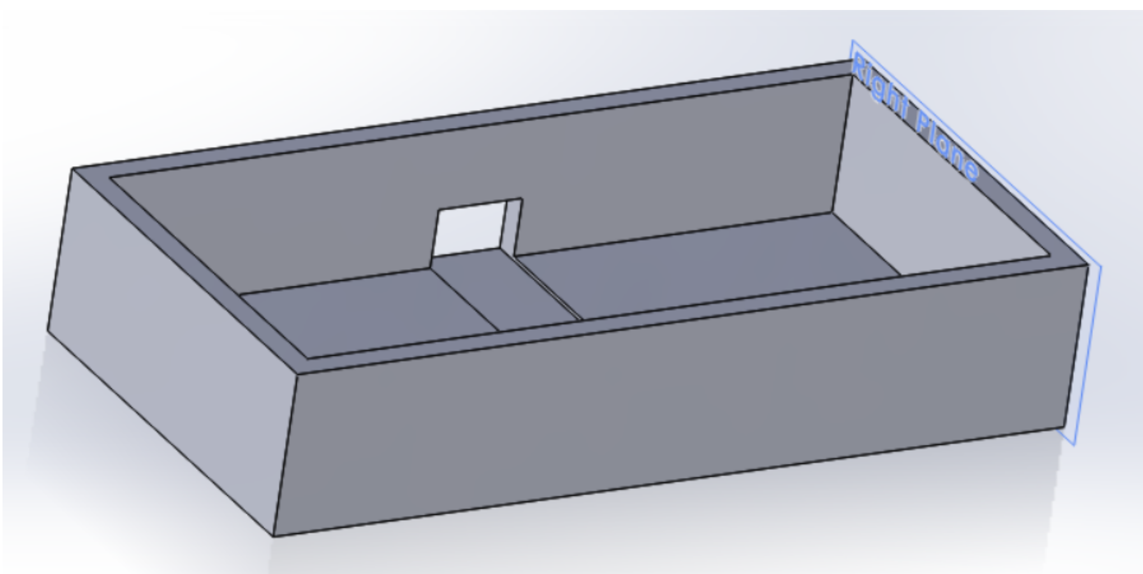


Figure 46 : Electrical Housing Base

In the final demonstration in SD2 we will be able to include a cushion protection for the hardware to not be affected by the obstruction in the road.

5.4 Software Design

The following section elaborates on the virtual tools used to satisfy the project's requirements and how they are designed to cohesively work together.

5.4.1 Video Processing and Rendering

The following sections will talk about the design of the programs which will both process the inputs stored on the device as well as displaying a fully realized road scan.

5.4.1.1 Video Processing

This section discusses the program created for processing the captured video from the device. The information captured from the device comes in two forms: video and a text file containing GPS location markers and their associated time of capture.

The program which processes the data from the device is written in C++ to take advantage of two very important libraries to this project. The OpenCV library was used for many of its features and API's. The other library which was used was the Open3D library for its API's on point clouds. A special thanks is extended to ChatGPT for its extensive knowledge on these two libraries, which sped up the process of creating the necessary functions for this project to work. The steps of this program are broken down as follows, run preprocessing and video correction on the input, run edge detection, run statistical analysis and lastly run the function which saves a user selected road scan. This program went through many revisions as the system was developed.

Firstly to start with the video correction it was initially designed to read the brightness of the video, adjust for the angle of the camera, and lastly crop the video for easier processing. Calculating the initial brightness was done in the following manner, separating the three channels in the video and only reading the red channel, taking the average of this channel on the first frame gives us the brightness for the scene. This brightness was originally used to differentiate between daytime operation and night time operation. which worked well for differentiating. It was also used partway through to dynamically calculate threshold values for the canny edge detection algorithm. For multiple reasons this code did not make it into the final production. The next part of this step was the video correction, this was done in three ways, first the video was corrected for its rotation, making the laserline more or less level as our initial testing showed the laser at a slight angle. Once our system was dialed in properly this step was not necessary. Next was to correct for the 80 degree angle which the camera is to the road. Finally the video is cropped to a 1180x650 resolution which removes the parts of the screen covered by the aperture.

The second part of the program runs the edge detection algorithm. For this code we used the OpenCV's library for both gaussian blur as well as canny edge detection. The gaussian blur runs at a kernel size of 5x5 this produces smooth edges at the canny edge detection stage, better than not using any blurring. The canny edge detection function takes in two arguments which define the threshold for the detected edges, the upper threshold, which passes any pixel brighter than it into the final and a lower threshold which passes only pixels connected to a passed pixel. any pixel below the lower threshold just becomes discarded. From our initial testing it seemed that the values to set these two values were 2.5 times the average brightness for the upper threshold. As well as setting the lower threshold to the average brightness. The initial testing conducted was done inside where the average brightness was about 36, leaving our upper to be about 90. Testing conducted outdoors at various light conditions showed that dynamically calculating the thresholds produced unfavorable results, but statically placing the thresholds at 50 and 100 showed us fewer of the edges we did not want to capture, this was due to the fact outdoor testing provided us with a much lower brightness value than our previous indoor testing. This value was measured at around 15 out of a max brightness of 255. Once the laser's edges are detected they are then sent to another function which turns a video with multiple edges, there is an edge found for both the top and bottom of the laser, to a video with only one edge. We found more consistent results with choosing the top edge of these two instead of bottom or finding an average edge.

Now that the edges of the laser line are defined as a single point for almost every column of the video, we can then do some simple math to convert these white edge pixels into a 3D vertex point. The X and Y coordinates simply are multiples of a calculated value. The calculated multiple for the Y value ends up being 2.93 inches per frame, this is based on a speed of 176 inches per second and 60 frames per second. The X coordinate is 0.09 inches times the column the pixel is in, this is derived from measuring in the real world how much space is seen by the camera, which we measured to be 59 inches for a resolution of 640 pixels. The Z coordinate was then found to be half an inch for every pixel shifted from the laser line, this was found by taking the value we found in the vertical direction of the frame and dividing it by the number of pixels which was 29 inches for 360 pixels. multiplying this value by the tangent of 80 degrees, the camera angle, we get 0.5 inches for every row the pixel moves. With these three calculations done on every white pixel in the video we get a 3d point cloud.

Now we run statistical analysis on our point cloud as well as removing a user chosen height from the point cloud. Initially the statistical analysis was used to remove points which were a result of our testing surface being smaller than our laser. As this is not the case anymore this code could probably be removed without major consequences. The statistical analysis showed better results when run twice with different values than simply running once so we left this as the implementation. This part of the code also filters a user defined height from the road, this is done as a method to ignore potholes which are too small to spend effort analyzing.

Lastly the code then segments the road scan into ten equal portions and asks the user if they want to save each. The user then presses ‘q’ on the keyboard to close the view, and types in ‘y’ or ‘n’ to signify if they want to save it. If a scan is saved the function finds the middle point of the scan, finds its associated time then looks into the GPS data record for the closest matching time. Once the closest time is found the corresponding GPS data is saved as the road scans file name, this naming convention reduces the need to come up with a clever algorithm to name road scans that are unique to the road scans in the database. As this program has no connection to the database, naming files with these unique GPS coordinates is a simple solution.

5.4.1.2 Online Point Cloud Rendering

The website which ultimately displays the road scans will be discussed in this section. The website works as follows, reading the file names of road scans it, then creates markers for each uniquely named road scan at the corresponding gps coordinate. The user then selects a marker on the map to render it, a window pops up with the point cloud rendering which can be rotated and viewed.

The mapping functionality is provided by a library called the js react maps library. This library has many built in feature ones that we used were the markers as well as the searching capabilities. A full realization of the website would be to have the road scans read from a database, due to time constraints we were not able to connect the database to the front end in this manner. The current implementation stores the road scan on the website code itself, this only allows us to render as many scans as we have uploaded to the front end.

The rendering functionality is provided by the Threejs library. This library allowed for a quick and simple rendering pipeline to be made as well as orbit controls to be added to the scene to allow for the user to move the point cloud around for better view. The renderer works as follows, first it creates the scene then adds the object as well as the lighting for the scene all before clearing it all. The point cloud file is added to the scene using the PLY file loader also provided by Threejs, once the object is loaded from the file, the coloring as well as volume calculations for the pothole are made. The coloring is based on a depth based approach where points closer to the minimum depth are more blue than they are red and points closer to the maximum are more red than they are blue, this is simply calculated using the max and min of the z coordinate for the whole point cloud. The volume is then calculated in a similar way where all points that are a certain percentage below the maximum are added to a separate min max calculation for all three coordinate axes, x,y and z. This calculation is flawed currently as the road scan may have more than one pothole in the road scan separated by any amount of lines leaving the length in the direction of travel to be inaccurate. Otherwise the finding of these maximum and minimum points gives us a rectangular prism of volume. Once the coloring is calculated as well as the volume the geometry is sent to the scene to be rendered, and the volume displayed.

5.4.2 Website Backend Design

With just the sense of sight, the processes that connect the server and client are a mystery; however, the relationship can be demystified by organizing the server and client into block diagrams. Figure 47 presents the question of how a raspberry pi can be used to serve content to computers around the world.

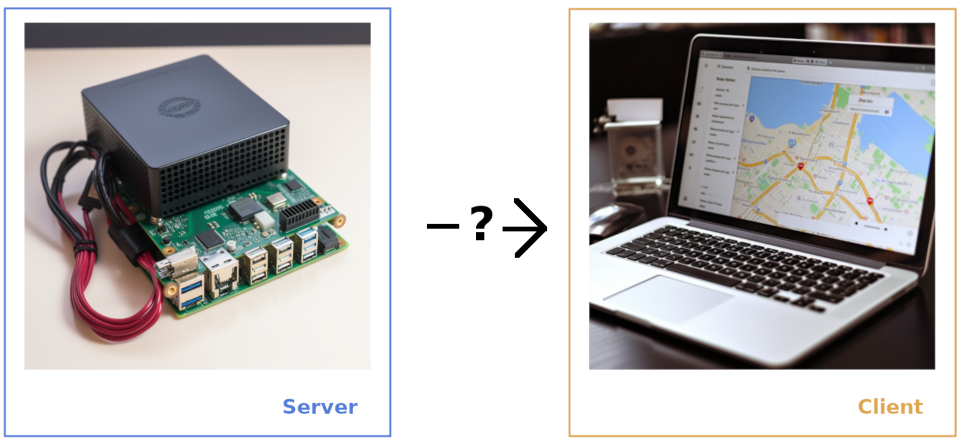


Figure 47: The Surface-Level Server-Client Relationship

On the outside, a tiny box. On the inside, there are four key technologies that allow the server to connect to the internet and serve content to clients: Node, Express, MongoDB, NGINX. Node, as already explained in the part selections section, is a JavaScript runtime environment. MongoDB is a document-based database. Express is a JavaScript library that provides useful functions that make data transfer between servers and clients effortless. What's new is NGINX. Pronounced "engine x", NGINX is a popular open-source web server and reverse proxy software that is widely used for high-performance web applications, content delivery, and API gateway. In the context of this project, NGINX is used as a web server and a proxy. Figure 48 connects server components and illustrates how they connect to serve content.

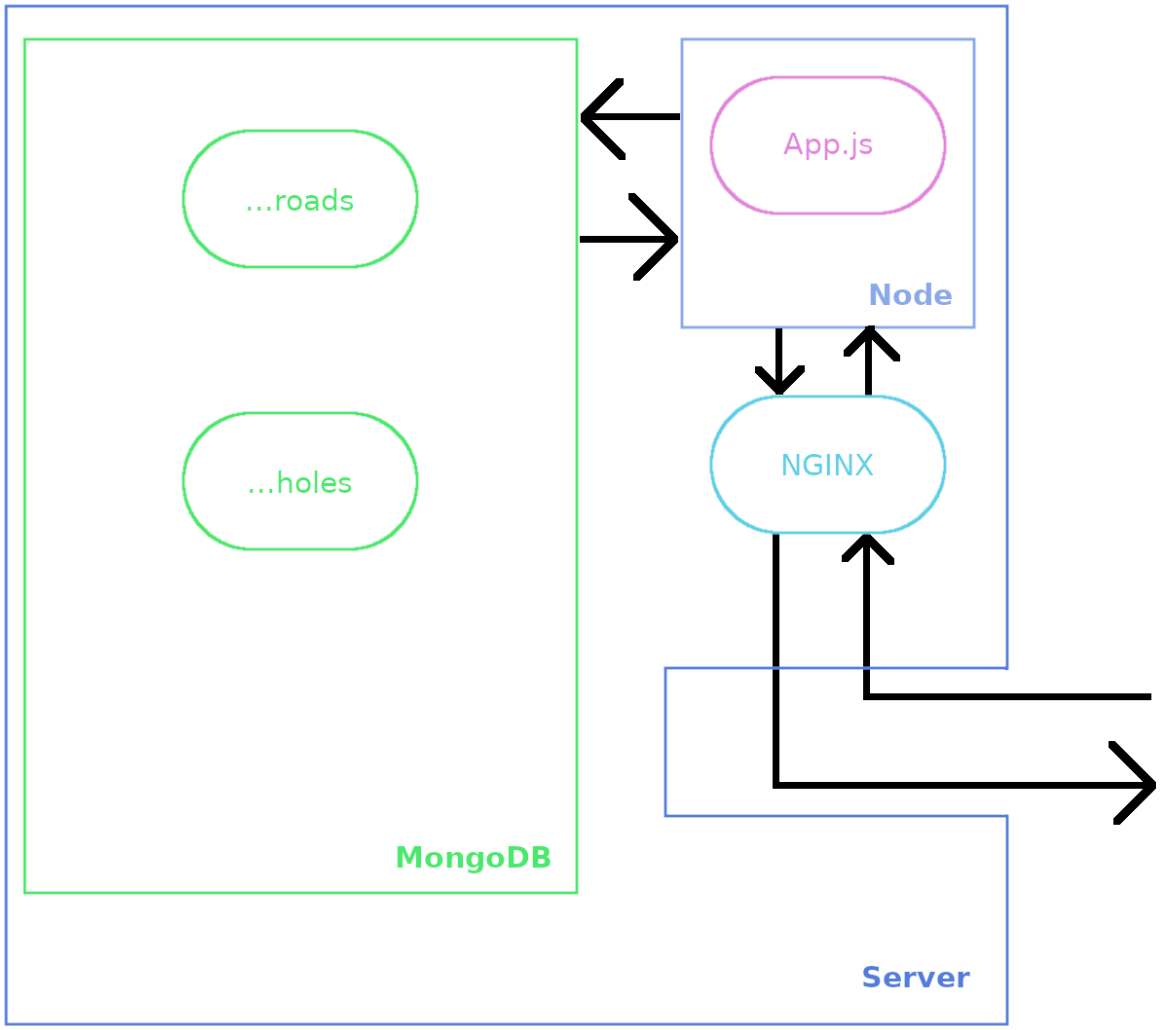


Figure 48: Server Components Block Diagram

NGINX can handle high traffic loads with low resource utilization, making it ideal for applications that require high availability and scalability. It can also be used as a load balancer to distribute incoming traffic across multiple servers to improve performance and reduce downtime. Already incorporating NGINX into the design makes scaling easier as computing power can be scaled by adding extra raspberry pis to the network. NGINX will take note of all possible computing resources available and distribute the server's load as efficiently as possible. Together with Express, NGINX is used to route traffic through IPs. The chain of events necessary to host a website is visualized in figure 49.

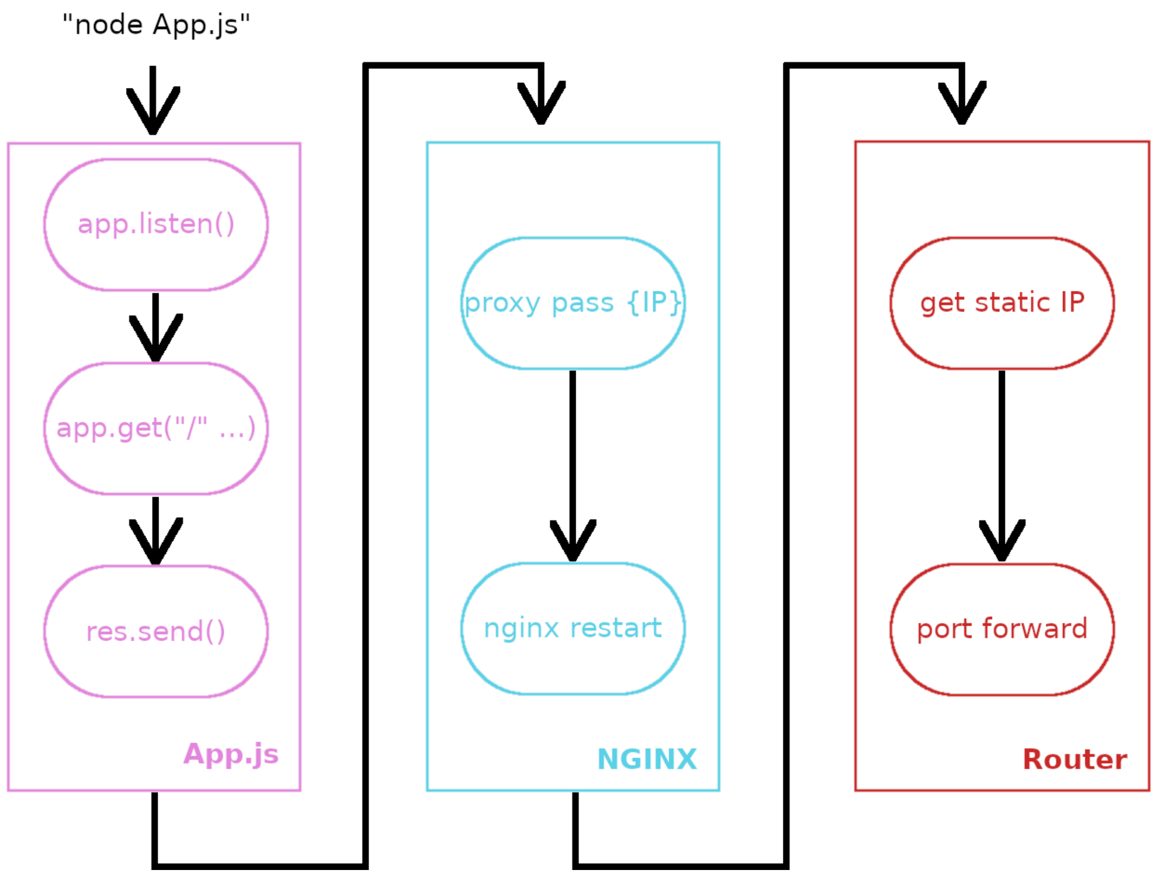


Figure 49: Website Hosting Flowchart

In the “App.js” source code lies code to initialize an Expressjs app. In this case, the express app object is assigned the identifier “app”. Then the method “listen” is called on app. The listen method instructs the Expressjs object to start hosting on a local port. It has two parameters: the port the service will be hosted on, and a callback function. The callback function is called (executed) whenever the listen method fires. The listen method should only fire once: when the “App.js” script is first executed. Either way, the callback method is useful for introducing side effects when the port is accessed. Side effects like blocking access to other ports or shutting down other services entirely.

Next, the Expressjs object’s “get” method is invoked. In this case, “get” directly corresponds to the REST API “GET” HTTP verb. Notice that the first parameter in the “get” method is a string. This string represents the GET HTTP request’s Uniform Resource Identifier (“URI”). A URI is a string of characters used to identify and locate a resource on the internet. The “/” represents the website’s root directory. Putting everything to together, the Expressjs object is sending a “GET” HTTP request to the server - itself in this tiny example - and asking for the website’s root content. The second parameter in the “get” method asks for a function. An anonymous function is passed inline to avoid defining a function that will not be reused somewhere else in the codebase. The parameters for this anonymous function include a request object with the identifier “res”.

This anonymous function with the “res” object parameter specified can be used to instruct the server to send some data back to the client. Sending an HTTP request express-style is done by calling the “send” method on the “res” object. The parameters of the “send” method are simply whatever data the server desires to send to the client. The client asked for the website’s root content so an HTML string with a greeting is passed to the “send” method. As the website grows in complexity, the root content will be a query to the Google Maps API to load a map. After, or perhaps in parallel, the MongoDB database will be queried to place pothole indicators on the map depending on the pothole object’s latitude and longitude. Each pothole indicator component will be an interactable element that raises an event on click. The “on click” event handler will use express to send a GET HTTP request to the server for the pothole’s information. Once the server sends a response back, the client can then use the data to show the user a 3D representation of their selected pothole. This is how Express is interwoven with React to create an interactive website that leverages the large memory banks and additional processing power of a server.

Although there is much going on in the JavaScript source file, the website still only exists on the local network. By running the command “node App.js” in the same directory as the App.js source file, the script runs and starts listening on “http://localhost:{port}” “Port” being in curly braces represents it is variable; in other words, it can be any number the programmer desires. NGINX and some good old messing-with-the-router are necessary to bridge a locally-hosted website to a internet-wide website.

NGINX is necessary in this design not only as a web server but also as a proxy. When NGINX is installed, its web server capability is immediately activated. After running the NGINX binary on the server, typing the server’s IP into a browser will greet the user with an NGINX screen indicating the web server is up. The website defined in App.js can be made to appear instead of NGINX’s default greeting page, by having NGINX proxy the server’s IP to “http://localhost:{port}”. After going to NGINX’s “sites-available” directory, editing the file called “default,” and adding “proxy_pass http://localhost:{port};” to the location block, the proxy is set up. Typing the server’s IP into a browser will now show the HTML response defined in App.js.

This triumph is short lived, however, when the IP address inevitably no longer leads to the web server. This is caused by two chief reasons: the server’s IP is dynamic or the web server is accessed on a network that is not the same network the server is on. When an IP is dynamic that means the Internet Service Provider (“ISP”) will periodically assign a new IP to the network. While this is good at deterring hackers, it makes hosting a website impossible. To solve the problem of having a dynamic IP, a static IP will need to be asked for from the ISP. This is not an automated process so it will take a few business days. To solve the problem of not being able to access the website on any other network other than the local area network (“LAN”), port forwarding is needed. Enter the router.

For security reasons, a router blocks outside access (requests from the internet). This is why devices on the same network can access each other's locally hosted sites, but devices that have to go through the internet can not. Generally, port forwarding works by redirecting incoming traffic from a specific port on the internet to a specific port on the LAN. By default, NGINX starts the web server on port 80. So, the internet traffic interested in port 80 should be redirected to port 80 on the LAN. In this way, ports on a router are analogous to doors. Forwarding a port is like opening a door and letting the internet in as demonstrated in figure 50.

Figure 50: Port Forwarding Analogy

Setting this port forwarding setting in the router allows the website to now be accessed from anywhere in the world. As long as the static IP does not get its service denied, the website will be accessible for as long as the server has power. Now that the server is reliably connected to the internet, it can start serving clients. Figure 51 shows the client’s components and how they connect to send requests to the server.

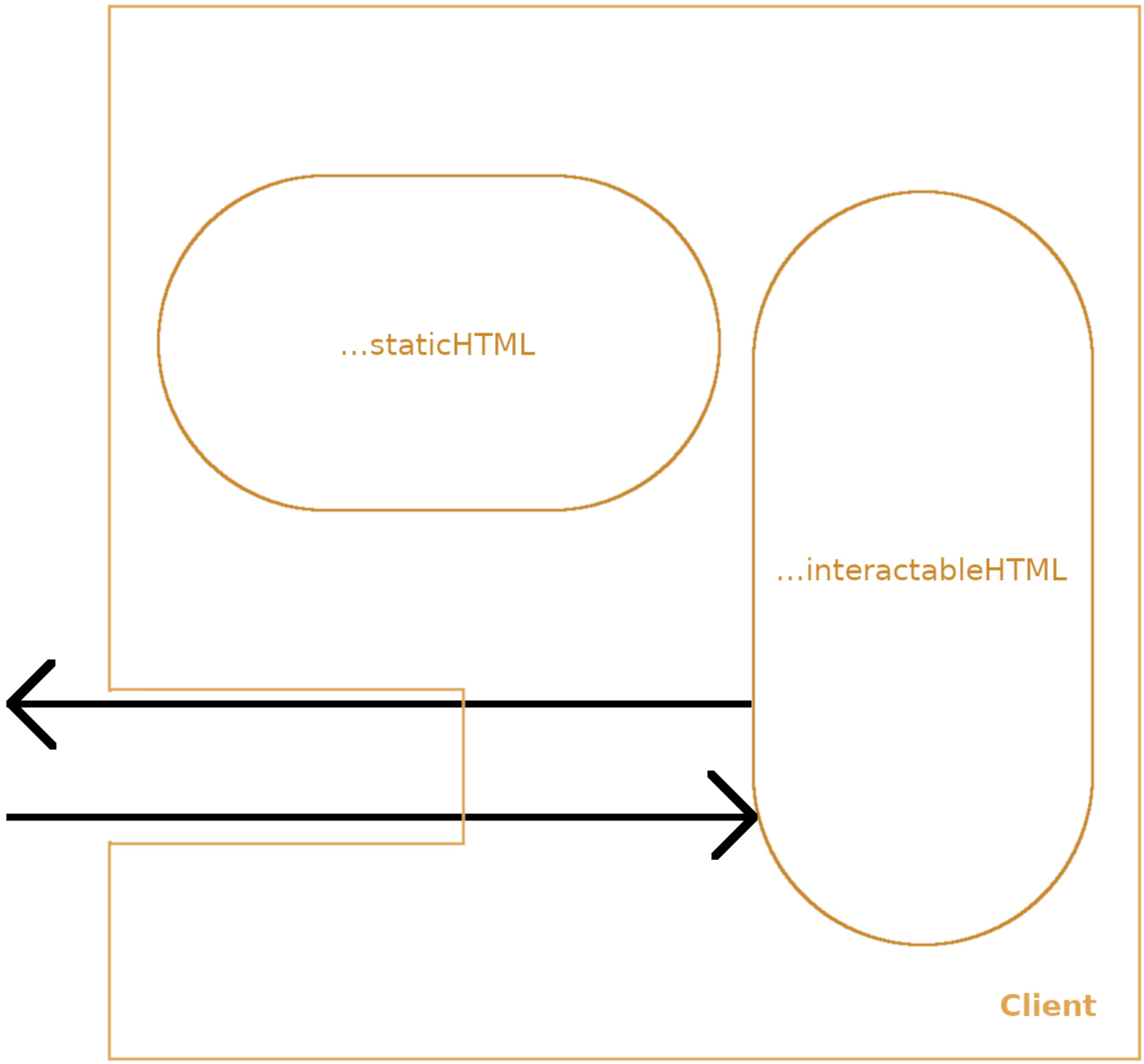


Figure 51: Client Components Block Diagram

Notice how both the server's structure and the client's structure have a little "indent" in their blocks. This indent represents a port. Since both the server and the client have a port, they are both capable of sending and receiving data over the internet. Figure 52 shows the data packets sent between client and server.

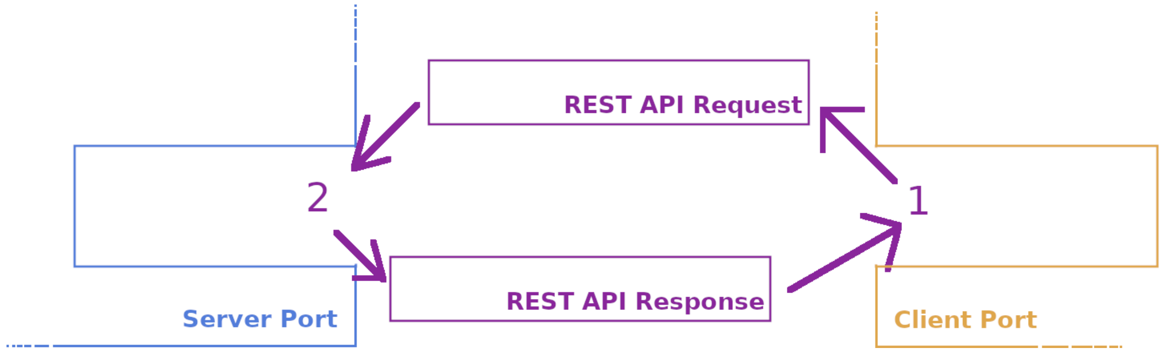


Figure 52: REST API Block Diagram

The REST API (Representational State Transfer Application Programming Interface) is a type of web service that uses HTTP requests to access and manipulate data. RESTful APIs are designed to be resource-oriented, meaning that each resource has a URI and is accessed via a specific HTTP method, such as GET, POST, PUT, or DELETE. For example, if a user is using this project's website and clicks on a pothole, the client sends a GET request to the server. GET is a HTTP method that signifies data is being requested. Like the "load word" instruction in an assembly language. The request will have an accompanying URI of the form "http://g03.com/pothole1" or similar pattern. Then, the server will query the database for "pothole1" and return a 200-level (e.g. 200, 201, 202...) code if pothole1 is found. A 200-level code indicates success. On the flip side, a 400-level code indicates an error with the client and a 500-level code indicates an error with the server.

REST APIs use a client-server architecture, where the client (not just a web browser but also mobile apps) sends a request to the server for a specific resource, and the server responds with the requested data in a format such as JSON or XML. In the example started in the previous paragraph, the REST API response would be in the form of a JSON object. This JSON object might include fields like depth and size representing how deep the pothole is and its dimensions. The client can then use this data to update its user interface or perform other operations.

REST APIs are designed to be stateless, meaning that each request contains all the information necessary for the server to process it. This makes REST APIs scalable and easy to maintain, as the server does not need to store any client state information between requests.

At the end of Senior Design, it was decided that instead of independently hosting the server, the website would be deployed using Vercel. This greatly abstracted the computational and networking concerns elaborated on above.

5.4.3 User Interface Design

This next section will discuss the elements we will display and some possible elements we can add that would improve the informational capacity of the website. Initially the design of the website will be pretty simple to make it very clear to the end user the information they are looking at. Figure 53 shows the ways a client would use the website.

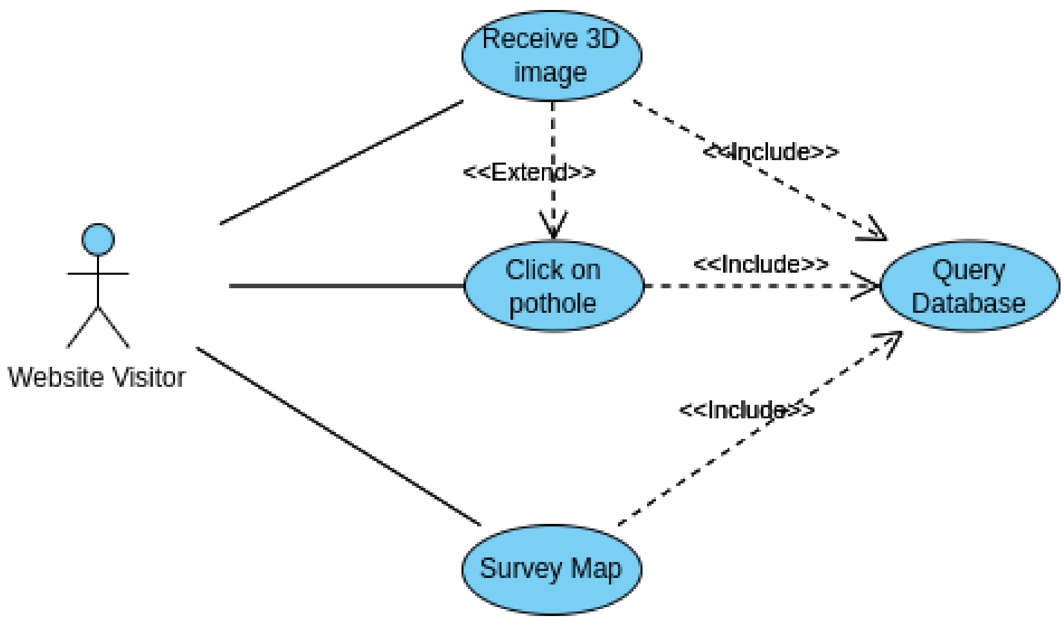


Figure 53: Website Use Case Diagram

The first element we need to have is to display the roadways. The task of displaying the roadways will be up to an api call to google maps. Calling the google maps api is important because it is a well known tool meaning the end user will know how to work with it without any instruction.

The second element we will need to have is a way to show potholes on the map itself. This is simple with the use of google maps api which allows for two methods we can choose from for this project. The first method is that of using an overlay map, an overlay map provides us with a drawing that shows up on the map regardless of how the user pans and zooms the map. The simple example google provides is to show the map tiles which on the map, for our case we will do a very similar thing and we will draw a shape representative of a pothole where everywhere our database says we have one. The second method provided for us to use is to overlay an image map. This works in a very similar way to the previous method although instead of drawing a shape it will just output an image to a particular position on the map.

The third element we will need to include is a window which displays our pothole in 3D. This window will utilize the webGL code to draw our potholes. This window element will only show up once a pothole is selected to display. To determine which pothole we will display we intend to allow the user to click on a pothole displayed on the map element. Once a pothole is selected on the map element a window should pop up showing the pothole in 3D. Having a window pop up only when a pothole is selected also reduces the stress on the user's computer as it will only render one pothole at a time.

Some elements we can add in addition to these three main elements is a table of potholes and another map element which displays all the roads that were scanned as well as a table of scanned roads. Some features the website needs to have is to import scanned roads, delete scanned roads, as well as a login page. A login page is necessary to allow only certain users to upload and delete any scans. Deleting a scan will be necessary if the pothole is fixed. Uploading scans is necessary to provide the database with new information. Lastly the choice of allowing this website to be viewable to the public is dependent on the application, for our case we will allow the public to view it but not make any changes. Figure 54 shows how the data from the database will be used on the website and figure 55 shows our initial intent on the design of the website.

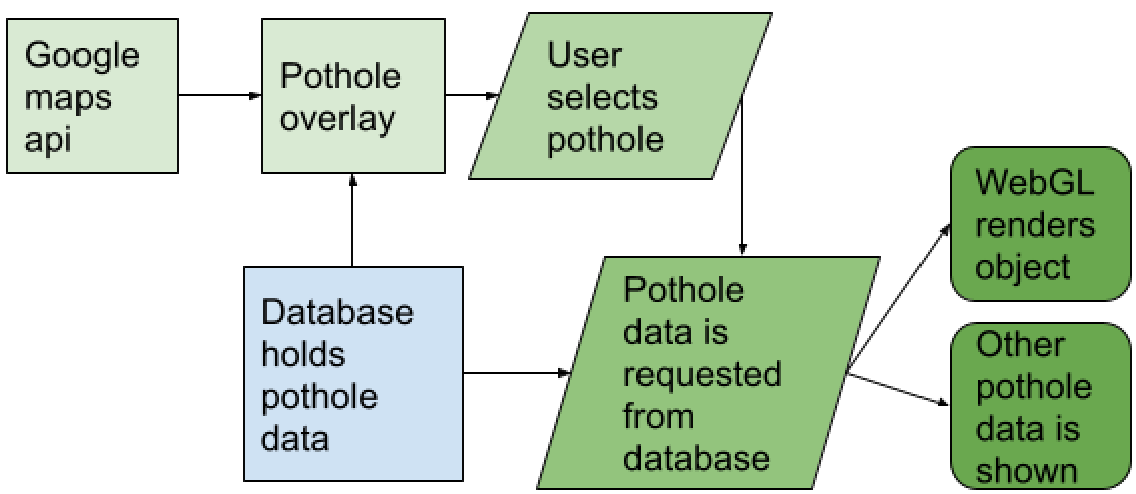


Figure 54: Website Flow: This figure depicts how data interacts with the user

Figure 55: User Interface Mockup: Mockup of the initial look of the website

The final design of the website shown below in figure 56 has a similar design to the one pictured above. We can see the mapping system on the left hand side of the screen and the rendering on the right hand side of the screen. The road scan is colored based on each vertex's calculated depth. vertices that are more blue than red have a lower depth. we can also see the volume calculation at the top right corner of the render window and the coordinates at the bottom.

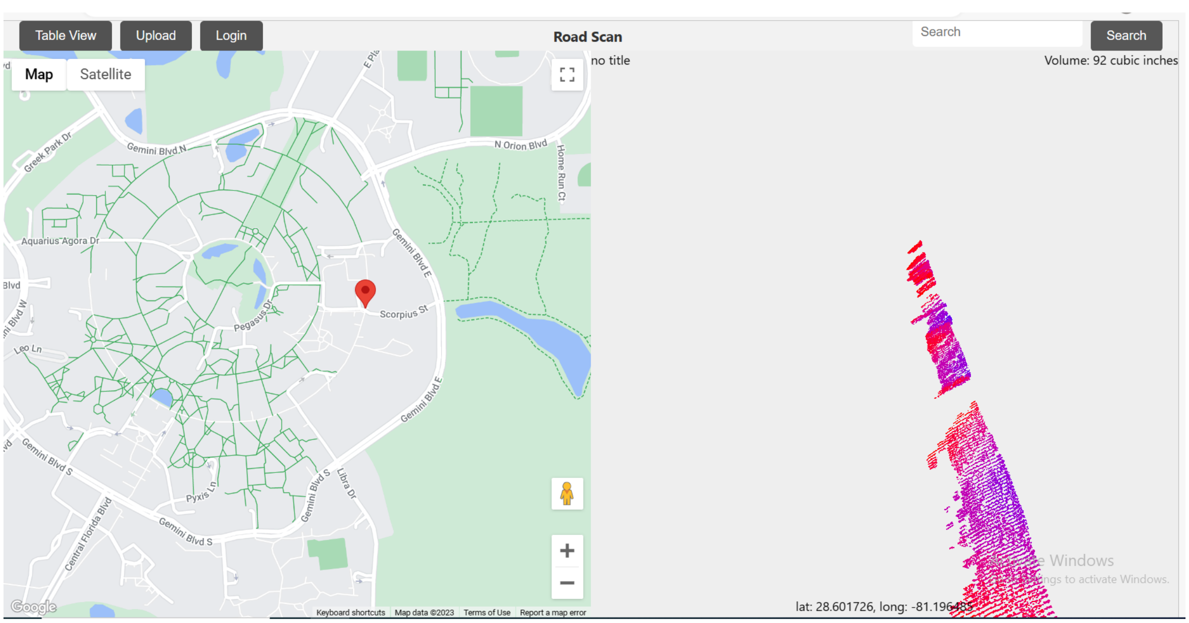


Figure 56: User Interface Final: Final look of the website

5.5 Summary Design

This section summarizes the hardware and software designs for the Road Surface Mapping prototype in Table 36.

Table 36: Summary of Hardware and Software Designs

Subsection	Design
Emitting Optics	Laser of wavelength 635 nm that emits a collimated beam with spot size of 1 mm X 4 mm and a powell lens with a fan angle of 110 degrees.
Detecting Optics	Camera with 260 fps, spatial filter aperture, and bandpass filter centered at 635 nm.
Housing	3-D Printed with PLA. General designs are complete, with the team investigating the preciseness of them
Wireless Connection Module	Attach antenna to PCB
Microcontroller	UART communication, 5V 1.2A minimum, GPIO to reset GPS, writes to SD card, communicates with user using Bluetooth.
GPS	Mounted close to antenna, communicating through UART powered with 3V
Data storage	Located on the microcontroller, 256GB capacity, with maximum write speeds available.
Theejs rendering	Simple loading of objects, simple pipeline implementation, quick turnaround time per render.
Website	Configuring NGINX, configuring local router, Map element, map overlay, 3d rendering output, login for administration, miscellaneous information provided.
Electrical System	Review specifications of each component and determine its placing for optimal efficiency in a schematic

6 System Integration and Testing

This section will discuss how different systems will be tested for optimization. Individual systems will be tested independently and then integrated to form a complete working prototype.

6.1 Testing of the Optical System

This section will discuss the testing of the optical side of the project. The optical side includes the emitting system, the laser and the lenses to generate the line, and the detecting system, the camera and the lenses to focus the images.

6.1.1 Emitting System Testing

The laser and the powell lens must be properly aligned to ensure a clear laser line projected on the road surface as a misalignment between these two elements would cause a number of problems. To ensure proper alignment, the laser and the powell lens will be aligned on an optical rail that will then be installed into the optical housing. The first step is to place the laser on the optical rail. The laser must be orientated in such a manner as to ensure that the laser spot it projects is in the proper orientation. The laser has an elliptical spot of 4.5 mm by 1 mm. The major axis of the elliptical needs to be orientated to the horizontal axis of the rail. The laser will then be aligned along the optical rail ensuring that the beam path is parallel to the optical rail. Once the laser is level to the optical rail, the laser holder will be locked into place. After locking the laser in place the powell lens can be installed onto the rail system. The powell lens should be placed at 50.8 mm since the laser spot is 1 mm at that distance, which is ideal for the powell lens. The powell lens needs to be orientated to the rail so that the roof of the powell lens is perpendicular to the rail. This will cause the line to fan out along the horizontal axis and ensure the line is projected across the road. Once the powell lens is in the correct orientation it needs to be aligned with the laser. The lens should be adjusted vertically and horizontally so that the laser beam hits the powell lens in the correct spot. The lens and the laser will be considered aligned when the laser intersects the powell lens at the center of the roof of the lens. This will ensure a clean, clear laser line projected out of the housing onto the road surface. Once the laser and the powell lens are aligned with each other the powell lens will be locked into place on the rail. With the laser and the powell lens both secured to the optical rail, the rail will be installed into the optical housing. A final check will be done to ensure that the laser line is projected out of the housing onto the surface below.

The powell lens cannot be allowed to shift or fall out of the holder. The holder must be secure enough to handle bumps and jolts of a vehicle in motion. The design discussed above will have to be tested before installation into the prototype. The holder will be tested by simulating shakes and bumps. This will be done by shaking and bumping the rail with the holder attached.

The laser must not move or fall out of the holder while the vehicle is in operation or it will become misaligned. A misaligned laser would cause the whole system to fail. The laser holder will need to be tested to ensure it will keep the laser steady. To test this the holder will be attached to the rail and a series of shakes and bumps will be simulated.

6.1.2 Detecting System Testing

The detection system will use a cylindrical lens to create a one axis zoom. This will be used to increase the sensitivity of the depth resolution. The cylindrical lens needs to be properly aligned with the camera to ensure the image is usable. The cylindrical lens needs to be placed 30.88 mm in front of the camera and mounted at the end of an optical rail. The camera will then be secured to the rail at the appropriate distance from the cylindrical lens. The cylindrical lens needs to be aligned to the same height as the camera. To avoid additional distortion of the image captured by the camera it is vital to ensure that the center of the cylindrical lens is on the same optical axis as the camera. Once the camera and the cylindrical lens are properly aligned both need to be locked in place. The rail can then be mounted into the housing.

The cylindrical lens cannot be allowed to move while the vehicle is in motion. Any shift or displacement of the cylindrical lens will render the device inoperable till it is fixed. The lens mount will be tested to ensure that it will keep the lens in place. The mount will be subjected to a series of shakes and bumps to simulate normal road conditions. The rail will then be tested in a similar way to ensure that both the camera and the lens mount are secured before installation into the optical housing.

6.1.3 Overall Optical System Testing

The angle between the camera and the powell lens controls how much pixel shift occurs with the change in elevation. The smaller the angle the greater the pixel shift. The pixel shift needs to be great enough to ensure that the camera can pick up the changes. The angle also controls the distance between the camera and the powell lens. Here a smaller angle increases the distance required between the camera and the lens. These two factors need to be balanced against each other since the device needs to be compact enough to be practical. Table 37 shows the distance and pixel shift for a depth of 2 inches from 85 degrees to 75 degrees.

Table 37: Angle VS. Laser Line Shift For a 2 Inch Depth

Angle	Shift in Inches	Shift in Pixels
85	0.174977327	1.924750598
84	0.210208471	2.312293176
83	0.245569122	2.70126034
82	0.281081669	3.091898363
81	0.316768881	3.484457687
80	0.352653961	3.879193576
79	0.388760618	4.276366801
78	0.425113123	4.676244357
77	0.461736382	5.079100205
76	0.498656006	5.485216063
75	0.535898385	5.894882233

The camera and the powell lens need to be placed on the same plane to form the triangle that makes the elevation calculations work. They will both be places so that they measure 4.8 feet from the surface of the road. The wedge that will be printed in the optical housing will ensure that the proper angle is formed by the camera, powell lens and road surface.

6.2 GPS Testing

This section will talk about the testing of the GPS module and its various facets. Important things to us is to make sure we don't provide the module with incorrect power, understand how the module communicates and to figure out what the output we will be incorporating into our design. We will discuss the initial testing of the module to make sure it is operational, powering the module to test its limits and observe how changes in power affect our system, testing of obstructions and UART system testing.

Initial Testing
The initial testing of the module provides us with information about what outputs we should expect under normal operating conditions and to ensure that the

module is functional. To test if the module is functional we will need to connect pins 1,10 and 12 to the ground of our testing setup. Connecting pins 7 and 8 to our Vcc voltage of three volts. Pin 2 which is UART output to input of our testing setup, and pin 3 which is UART input to the output of our testing setup. In this case we can do the UART testing with our microcontroller attached to a computer through a micro usb data sync cable in order to access the SSH terminal of the device. With this terminal being accessible we can then configure the device to do what we like such as reading and writing to the UART connection between the two devices. Once we have the information provided from the UART connection we can save it to a file save it for later. Another thing we can test initially is the rate at which we receive new GPS data, this is important because it will limit exactly how accurately we can track our position. the initial testing proved conclusive that the module works and outputs data in a format we can understand.

Power

Testing the power of the GPS module is important to understand what our system does in different power situations. Some power situations are the minimum power allowed by the device as well as the maximum allowed power as well as no power at all. First off we will test the GPS module at its operative voltage of three volts to ensure that it works properly. Testing the power of the module will also show how power affects different systems like UART message frequency and message quality.

UART

Testing the UART system is important in knowing what settings are the most beneficial to our application. The UART system can range from 9600-921600 bits per second. Testing the lower limit we can determine the minimum locational data we should expect from the system. Testing the upper limit of this system can help us determine exactly what the maximum amount of locational data we can access. Testing the UART communication system will also provide us with knowledge on what data is standard if any as well as how to request certain data. Testing the UART system will also provide us with information of the size of GPS data as information online is not very clear. We will need to determine the bit size of all data which we request in order to do this we will send various requests we are interested in. Some requests include getting gps fix data (class/ID 0xf0 0x00), GNSS fix data (0xf0 0x0d), GNSS satellite fault detection (0xf0 0x09), latitude and longitude (0xf0 0x01), Course over ground (0xf0 0x05). after this testing was completed we did not see an increase in the number of GPS locations per second.

Obstruction Testing

Testing the GPS module against obstructions that may interfere with radio signals is important in creating a housing for the system. Some typical obstruction we can expect for our application is metal, glass and plastic. Plastic obstructions include the housing of the device, metal obstructions could be parts of a car, and glass obstructions may be car windows in the path of the GPS signal. It is important to understand how these materials affect the system for a greater understanding of where the system can and cannot be placed. To test the effect obstructions have on GPS signals we will first cover the GPS module (antenna included) with plastic, some plastic objects that come to mind are bowls and tupperware. These objects will have very similar wall thickness as we expect to have from the housing unit we will be constructing. Next we will test the GPS signal with a glass obstruction, common household items we can use to test this includes glass bowls and glass cookware. These objects have a similar thickness to that of a car's windshield, which can give us useful data if we decide to place the housing inside the vehicle. Lastly, to test our GPS signal with metal obstructions we can use a metal pan or maybe even some aluminum foil being careful not to short any electrical connections. All tests will be conducted by sending the GPS module for the same information. A good message to send is NMEA message 0xf0 0x00, this message contains field 6 which indicates the quality of the position fix, as well as other information. Obstruction testing came back conclusive that even small obstructions such as being inside of a vehicle proved too difficult to penetrate to get a good signal.

Output Testing

We will be testing the different outputs of the GPS module. The GPS module is capable of outputting in different formats, these formats are NMEA GGA, GLL, GSA, GSV, RMC, VTG and TXT. We can test a few of these formats in order to see which output we like the best. Testing these formats will help us understand how the GPS system works, we will then be able to determine which formats we will use for our system. Starting with GGA messages we will ask for a GGA message and store the result in a file. Next we will ask for a GLL message and store that in a separate file. We will continue this process for every message type. If possible we will ask for the same data in every message as not to have differently sized data, making a fair comparison between the different message types impossible. One thing to note is that GPS testing is not possible until the GPS module is situated on the PCB. This is because the parts that we ordered came in a sealed bag stating that they cannot be exposed to certain conditions for a prolonged period of time. With this being the case we will leave the GPS module in its packaging until it is time to add them to our circuit board.

6.3 Testing of GPS Data Loss

It is expected that in certain situations we will not receive any locational data. Such instances could be due to a malfunction in the GPS module or bad conditions for the GPS signal. This next section will discuss the necessary resilience and testing of the system given a condition with no locational data.

Certain areas of roadway may be blind spots for radio frequencies such as tunnels. With a driving speed of ten miles per hour and GPS data once every second we expect normal operations to provide us with GPS data roughly every 15 feet, meaning we might have to determine where a pothole lies between two measurements as it stands. Since we will have a simple calculation to do for the two points of interest we can expand this to larger spans of missing GPS data. We must test our system for sparse locational data to ensure that a drive is not wasted due to a bad GPS signal. We must consider how our system will react to these cases. In order to do this we must provide our database or processing software with sparse GPS data. Another test we might have to perform is how this system of calculating pothole location works on curved roads.

6.4 Microcontroller Testing

This next section will talk about how we will test the microcontroller. The microcontroller we have chosen has multiple features we will be using for this project. We will need to test each system to understand the limits of our application. These systems include the Bluetooth link, data storage, UART and the microcontroller's processing capabilities.

Microcontroller Initial Testing
The initial testing needed for the microcontroller is to determine if the unit can be powered on. The device does include an LED to show activity. This LED only shines if the raspberry pi has an SD card inserted preinstalled with some pi OS. Once the operating system is installed on the SD card we can go ahead and insert it into the device. Powering the device through the topmost micro USB port we should observe that the LED will turn on, indicating to us that the device is somewhat functioning.
In order to power the system of the Raspberry Pi, we must decide what battery pack will be used. Because of the USB option we can attach a USB power bank to the system and insert the batteries necessary to reach the ongoing current of 9 volts. In the design, this power bank can be connected to a voltage regulator or DC-DC converter to set the output voltage based on its requirements of 5V at 1.2A for a total of 6 watts of power. This converter which is also implemented as a circuit protection device will then be connected to the power terminal of the Raspberry Pi. This is the micro-USB port. To determine if the board would function properly, we could connect the raspberry pi to a monitor and manually configure the WIFI using the HDMI plug in. Because we do not currently have all the equipment that we want to conduct our device with, we could only test to see if the raspberry pi would turn on and connect to a breadboard. Along with connecting the controller to a PC we could also build a basic connection by using a jumper cable to ground and a jumper cable connected to the input. A resistor can then be placed on the breadboard with a test LED light in circuit to conduct if the raspberry pi triggers the current to the light properly. During this test it was concluded that the raspberry pi worked basic function when powered on. Next,

we were able to test the capabilities with the 256 GB SD card. With testing as a power function only from a PC because we do not have the battery pack in hand, we are able to insert the SD card. We are now able to connect the raspberry pi to a secure WIFI connection, so that the pi desktop operating system can display on a computer without needing another cable source. The final step is to check whether the power can also be supplied to the camera from the raspberry pi. The camera can be inserted into one of the USB ports and with the device temporarily connected to a PC for power we can confirm that the device will power on through the microcontroller. These tests can also lead us to a conclusion of whether we need to include any regulators, resistors, or capacitors to ensure efficient power flow.

Bluetooth
The Bluetooth connection fulfills one of our advanced goals of providing the user with feedback on startup. In order to test bluetooth we must first ensure the microcontroller is functioning as the Bluetooth module is located on it. Testing the Bluetooth connection will be simple as we really do not need much from the Bluetooth connection due to our design. Therefore the testing will consist of testing the ability of the devices to discover other devices. It is important to understand how many devices the microcontroller can see at one time as if it can only see a few devices we run into the possibility that the user will not be able to connect to the device. Next we will test to see if the information sent through Bluetooth is corrupted at all. This can be done by sending a file between the microcontroller and another device then comparing the two files to find differences. As a result of not fulfilling our advanced goal we did not get the opportunity to test the bluetooth system.

Data Storage
Data storage is important to test to ensure we are capable of delivering on our design and goal of storing at least 5 minutes worth of scanning. Some limitations of data storage are both size as well as speed. Size of our data storage is well defined as roughly what it says on the micro-SD card therefore testing is not necessary. What is necessary to test is the speed of reading and writing to the SD card. We need to write to the SD card whilst scanning the road, which our camera can go as fast as 260 frames per second for a resolution of 640 pixels by 360 pixels. Needless to say without compression or other techniques to minimize the data throughput we must have a high write bandwidth. To test the write speed of a microcontroller we can store a few sets of data in the memory of the microcontroller and write through to a file located on the SD card all while timing the start and the end of this writing. Knowing exactly how much data has been written to the file as well as the time that it has taken to do the task we can work out our write speed. Though this test will not be without its flaws as writing random information to storage may slow down the write speed, random information is more indicative of the type of information we expect from the camera as pixel information will not be the same. Lastly, testing the ability of the

microcontroller to read data is not necessary as when we are done with a particular scan we expect to extract the SD card and read it on another device.

UART

Testing the microcontroller's UART system is important as it is the main communication system between the microcontroller and the GPS module. As discussed previously the limits set forth by the GPS module are 9600-921600 baud rate. We will initially need to make sure both of these rates are capable of being achieved by the microcontroller. To ensure the microcontroller can reach this speed we can simply connect the UART to an oscilloscope to measure the frequency at which it is transmitting.

Processing Capacity

Lastly it is important to test the microcontrollers processing capabilities. Processing information provided through all different inputs simultaneously is important to ensuring that all data is correct. Processing power is also important in the chance that we cannot physically store all of our information we will need to reduce its size. This means we might need the device to be able to crop images as quickly as they come in. We know the microcontroller has a GPU and this would also be helpful if we have to do more processing than simply cropping images. A line detection algorithm that runs on the GPU to detect and store only the laser line may be necessary as a further data saving method if we find out our system is not capable of writing 260 images to storage per second. Therefore in order to test these systems we could run code on the microcontroller to crop an image whilst timing it to determine how long it takes. We can perform this test with multiple different image sizes such as the three formats the camera can provide us to have the knowledge of the differences between them. Furthermore we can run code which accesses the GPU of the microcontroller and we can run a simple line detection algorithm to see how quickly that performs. Testing the processing capacity of the microcontroller was not done and was found to not be necessary for the short lengths of data which we gathered for this project.

6.5 WebGL Render Testing

The platform that we will be using to render our potholes in 3D is webGL. WebGL is important to test as a slow or insufficient rendering of our objects is not appealing. Secondly we are currently unaware of the exact geometry we will receive from the system meaning or rendering will have to perform well for objects with few vertices as well as objects with a substantial amount of points to render. This next section will talk about the testing done for the rendering of 3D objects.

WebGL is a software which accesses a systems GPU in order to accelerate processing of 2D and 3D renderings. As our final implementation of this rendering will run on a browser we should ensure that rendering is done quickly.

In order to test the speed of our rendering pipeline we can locate a few different objects with increasing vertex counts and measure the time it takes for each object to be rendered. This testing will provide us with information on just how many vertices our scan can have before our render speed gets affected in a meaningful way.

Another test we will need to conduct is to determine the lighting scheme we will be using for the final implementation of rendering. Our choices lie between using a texture, using a solid color, using normal vectors to determine the color of each fragment or a combination of all three. In order to conduct this test we will need to come up with a simple pothole model which we can render and visually observe each method individually. Some methods will take longer than others to compute and therefore we may need to retest our rendering speed with these different methods of coloring to ensure render speed is sufficient. Table 38 shows us how different objects compare in terms of their render speed, faster render speeds are better.

Table 38: Testing of Rendering Pipeline

Object Rendered	Cat	Building	Dragon
Vertices	360	134,000	453,500
Triangles	120	44,700	151,200
Render Speed Latency	5-20ms 10ms avg.	199ms avg.	30-40ms 25.4 avg.
Single Color Latency	15ms avg	170ms avg	34ms avg

The table above shows us the comparisons between differently sized objects. For the three objects I have tested the building object had the largest number of arrays included within it and took the largest amount of time to render coming in at around 200 milliseconds to render a singular frame. Although the dragon had the largest number of vertices it still rendered pretty quickly coming in at 25 milliseconds on average. The cat object had the least number of vertices and subsequently rendered the quickest at 10 milliseconds. Coming from a user experience point of view the rendering of the dragon appears really smooth, as does the rendering of the cat object. The object which does not render smoothly is the building object; this might be due to the number of arrays the object contains or the scale of the object.

We should expect rendering of potholes with less than 100,000 vertices to go smoothly. We expect this threshold to be much higher than the actual number of vertices given we will be traveling at a speed of 10mph which translates to 176 inches per second and assuming that a pothole is roughly 4 feet we expect to take 42 images to scan one pothole given a frame rate of 260 frames per second. Given these values we can assume that in one direction we will have the full resolution of the camera and in the perpendicular direction we only take 42 points. With this in mind we expect the number of vertices to be about 27,000, much lower than the value we cannot handle.

As anticipated, road scans with many points are difficult to render smoothly and result in very large files. Due to this and not having the ability to determine what exactly a pothole is in our processing program we end up dividing the road scan into ten equal partitions and asking the user to save individual road scans. This reduces the file size from originally 30MB to 3MB for each scan. This division of scans reduced the number of points which the website has to render and move smoothly.

6.6 Road Scan Position Testing

This next section will discuss the testing of a function which connects a GPS location to the center of a road scan. The testing we are concerned with is seeing how much accuracy is lost in the system.

The GPS position is gathered at most once every second and stored in a text file with its associated timestamp. Due to the nature of the one second interval we expect a maximum loss of accuracy to be one second in perfect conditions. To test our loss in accuracy we take the midpoint in our road scans and find its associated time based on frame number, we then round that value down to get the closest second which has passed. finding this time we then need to find the closest corresponding time in the GPS data file. Once these two values are obtained we can find the difference between them and multiply that by our rate of travel to find the total distance accuracy. Accuracy from our tests are shown below in table 39.

Table 39: Distance Accuracy

Start Time	Middle time	Precision lost	Distance inaccurate
23:13:31	23:13:31.66668	0.66668s	2.9803 m
23:13:31	23:13:42.0083	0.0083s	.0371 m
23:13:31	23:13:49.3	0.3s	1.34112 m
01:24:57	01:25:00.83333	0.83333s	3.7253 m
01:24:57	01:25:08.475	0.475s	2.12344 m
01:24:57	01:25:15.225	0.225s	1.00584 m
01:24:57	01:25:24.5	0.5s	2.2352 m
01:24:57	01:25:31.3917	0.3917s	1.751 m
01:24:57	01:25:39.0166	0.0166s	0.0742 m
01:24:57	01:25:46.0417	0.0417s	0.1864 m

The data from table 39 shows that in our final implementation we have an accuracy of 1.55 meters which is better than our specification of 5 meters.

6.7 Battery Testing

The next component to test for functioning validity is the battery. The battery will be used as the main source of power supply to operate the raspberry pi, the camera and allow the SD card to function. Also included will be the future components included on the designed PCB. Our purpose of this section is to ensure that the lithium-ion battery of 9 volts can power the raspberry pi and the camera. This section is important because it will tell us how well and how long the power can be active in the system. Battery testing can be completed in several ways. We can use this power source when applied to the breadboard with a sample circuit to perform onto the microcontroller. Or we can use the battery pack method and insert the USB application directly into the Raspberry Pi and confirm that the device will power on and disperse this connection to the other devices connected. Once we create a final PCB board in senior design 2, we will be able to run an initial test before using our final equipment. This test can be completed by creating the breadboard model and connecting the camera to the microcontroller. We can then use an oscilloscope to view the wavelength of the power flow. The power source should be able to maintain its role in operating the whole system. Testing the power source in this manner will allow us to see whether additional components are needed to ensure that the voltage and currents from the power flow evenly throughout the system. Not ensuring this test, especially before final implementation of the PCB, can lead to damage to the system, battery failure, or cause only one component to receive a majority of the power without letting the other component function properly. While this method of testing will be done at a later time, for now we will use the battery pack method and see if the devices will turn on and complete basic operations. Figure 51 demonstrates the testing validity of the Raspberry Pi board powering on with the use of our battery. Our battery power is transferred through a battery pack to a USB-C connector as shown in figure 57.

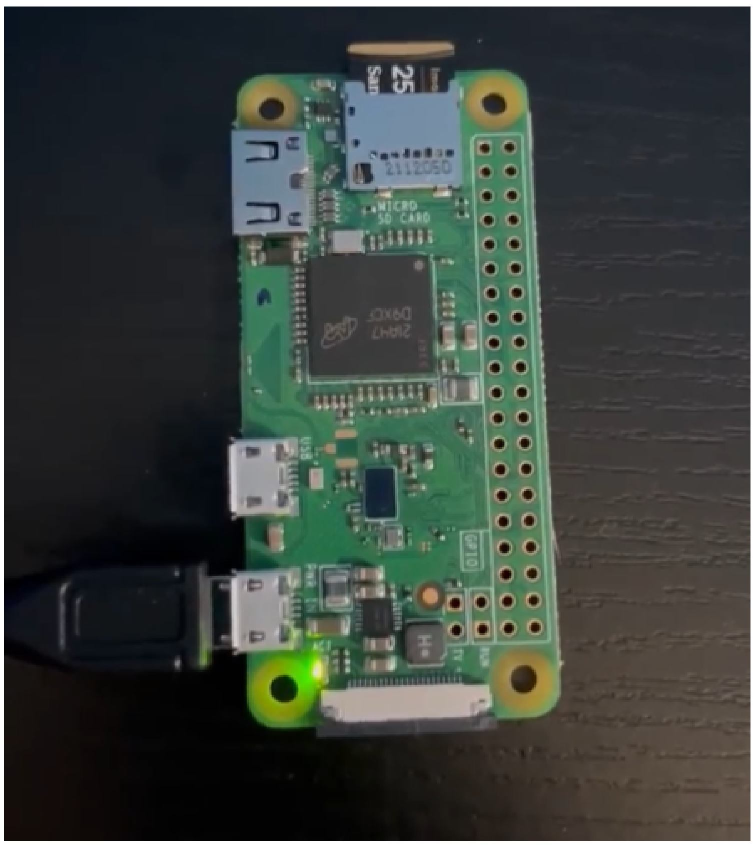


Figure 57: Battery Testing

6.8 Machine Vision Implementation

Implementing machine vision is what differentiates this project from a camera on a car and a road scanner. Implementing the logic that enables machine vision follows these three steps: image acquisition, preprocessing, and feature extraction. First, acquiring the images. A camera is used to take 260 JPEG images per second. There is an important trade off with the camera selected in this project: image processing is easier but file sizes are larger. This is because the software inherent to the camera uses Motion JPEG (“MJPEG”) compression which essentially makes each frame a standalone JPEG image. Each image, or frame, is a 2D array of pixels. Figure 58 is a frame from the camera taken from the windshield of a car.

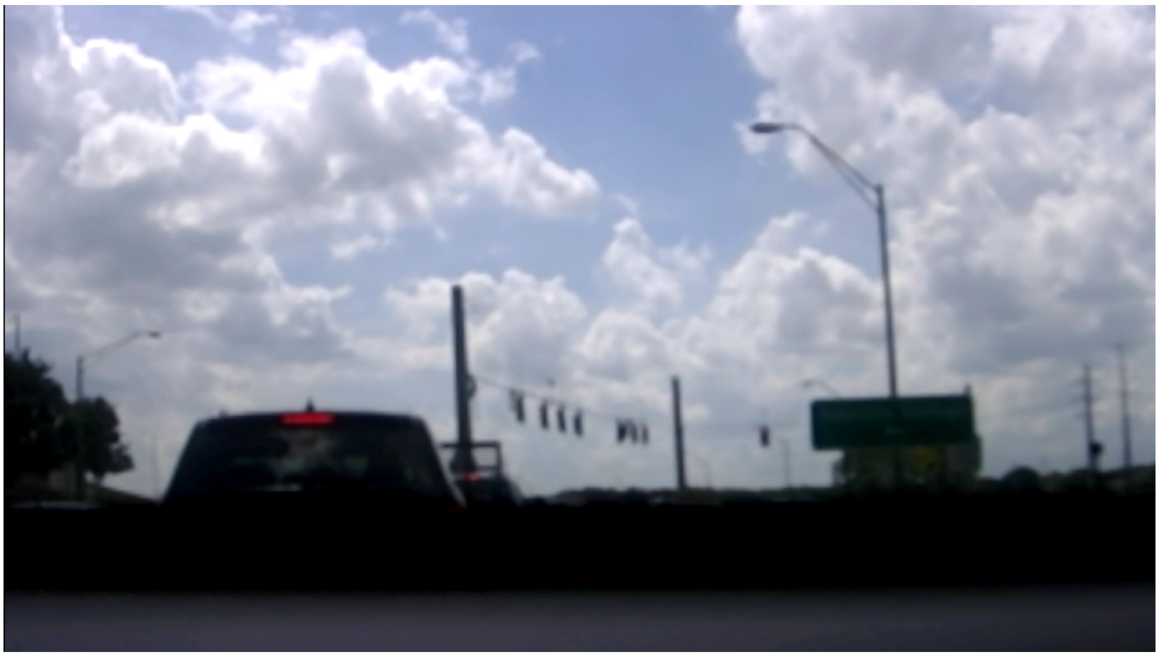


Figure 58: Sample Image from ELP-USBFHD08S-MFV

The image above has had its resolution scaled up from 640x480. Every second, 260 images that look like Figure 60 are generated by the camera. The camera will capture at a resolution of 640 by 480: 307,200 pixels per image, 79,872,000 pixels per second. Each image, or frame, is a 2D array of pixels. Figure 59 shows Figure 52 with an overlapping grid representing scaled-up pixels.

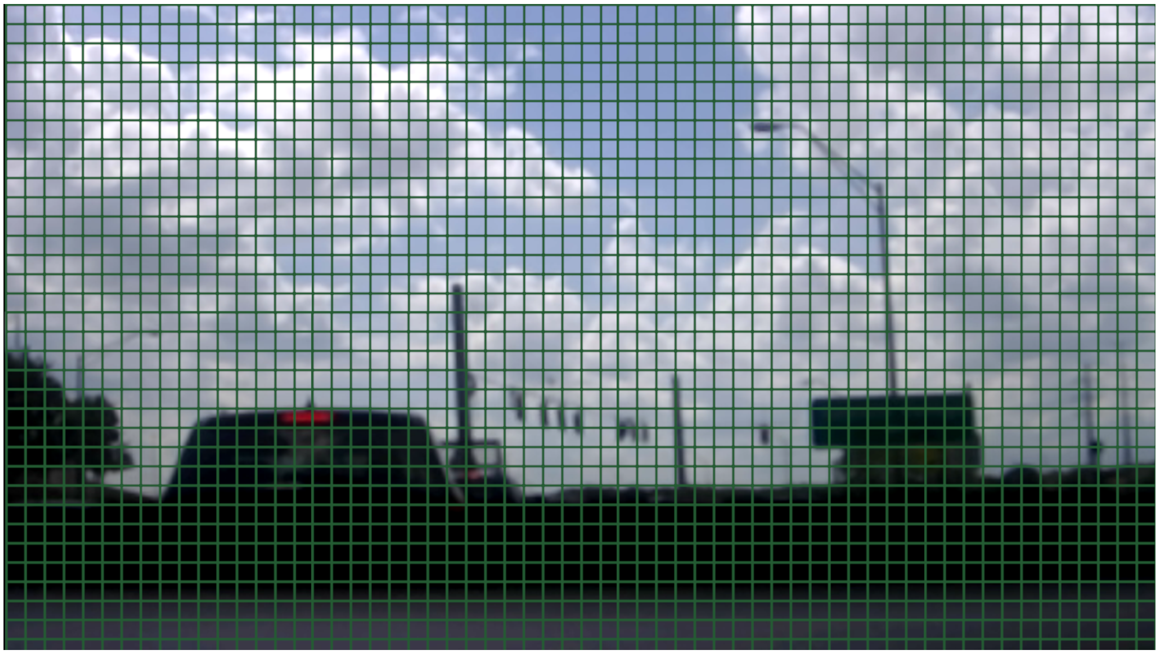


Figure 59: Sample Image as a 2D Pixel Array

As long as the camera is powered, there will be a steady stream of image data. The next step in the machine vision pipeline is preprocessing. Preprocessing involves applying algorithms to clean up any noise, enhance contrast, or adjust brightness to make the image suitable for analysis. An algorithm that is written to manipulate the pixels of an image usually would start from the top left of the image, traverse each pixel left to right in a row, then move down a row and repeat. A preprocessing algorithm follows this pattern of pixel access, applying a certain transformation to each pixel. Figure 60 shows an example of a preprocessing filter defined by a color curve.

Figure 60: Brightened and Lower Contrast

Playing with the color curve of an image can help accentuate desired features or diminish undesired features (noise). Figure 61 shows the GNU Image Manipulation (“GIMP”) window for manipulating color curves.

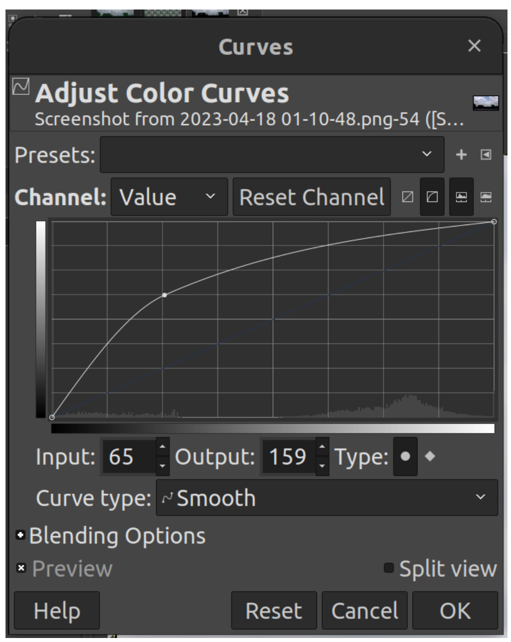


Figure 61: Color Curve GUI

The color curve visually defines the preprocessing transformation that will be applied to each pixel. For this project, preprocessing is a tool that can be used to accentuate the red of the laser on the road. Being able to programmatically distinguish the laser leads to more accurate calculations of pothole depth and pothole dimensions.

Finally, feature extraction. Feature extraction is orders of magnitude more dense and complex than image generation and preprocessing. While this is an opportunity for technical flourish, the system's simplicity makes only one thing important: tracking the laser. In other words, the feature of importance is the red line constant in all images. Figure 62 shows the group's laser on a flat, black surface.

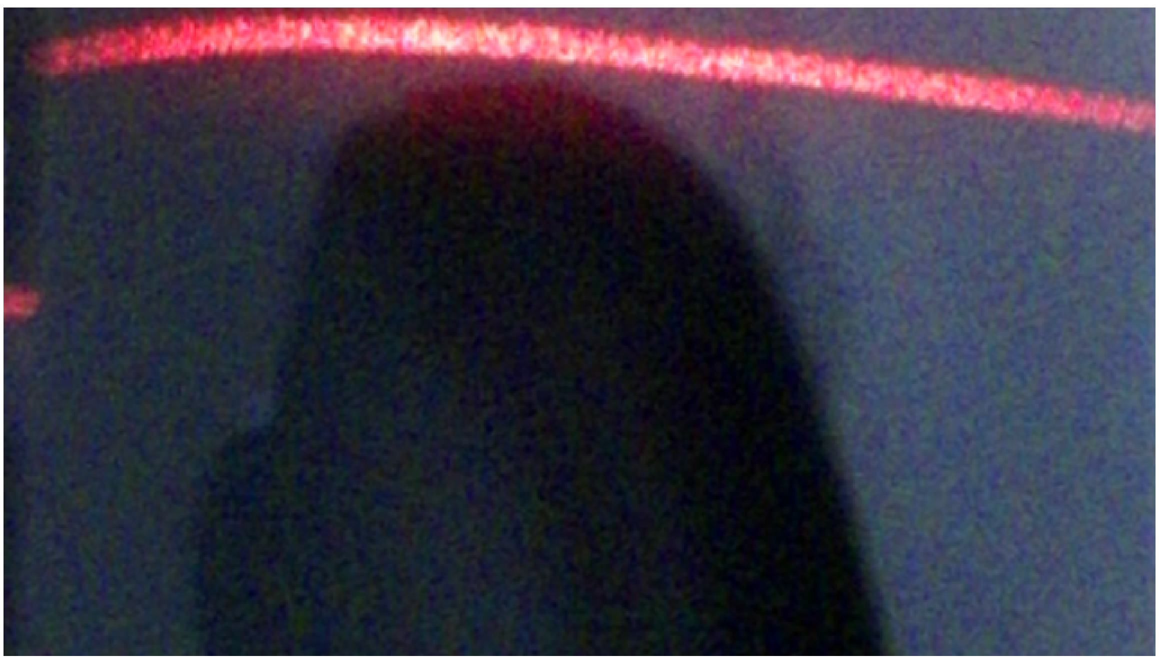


Figure 62: Laser on Uniform Depth

The laser on the road will look like something like Figure 56. Isolating the laser from the rest of the image can be done by traversing each pixel in the image and keeping pixels that match the laser's color within a certain degree of similarity. In a boolean array that matches the shape of the image (640x480), record whether or not an associated pixel is part of the laser: true representing it is part of the laser and false representing it is not. Depending on conditions like the time of day and color of the road, the laser will be colored slightly differently. Finding a reliable constant that chooses only the laser's pixels can be determined through further testing. Now that the pixels of the laser have been sorted and recorded, something meaningful can be calculated with them. Like depth and size. Figure 63 illustrates what happens to the laser when it is projected onto a non-flat surface.

Figure 63: Laser on Unequal Depth

The feature (laser) has been abstracted and represented as a boolean array. An algorithm that traverses the array and calculates the distances between true values can then be used to determine the dimensions of the hole. From the subsection where the laser is separated in the image above, the dimensions of the hole can be found. Red in the boolean array represents a value of true, white represents false. Figure 58 shows what Figure 64 would look like in code.

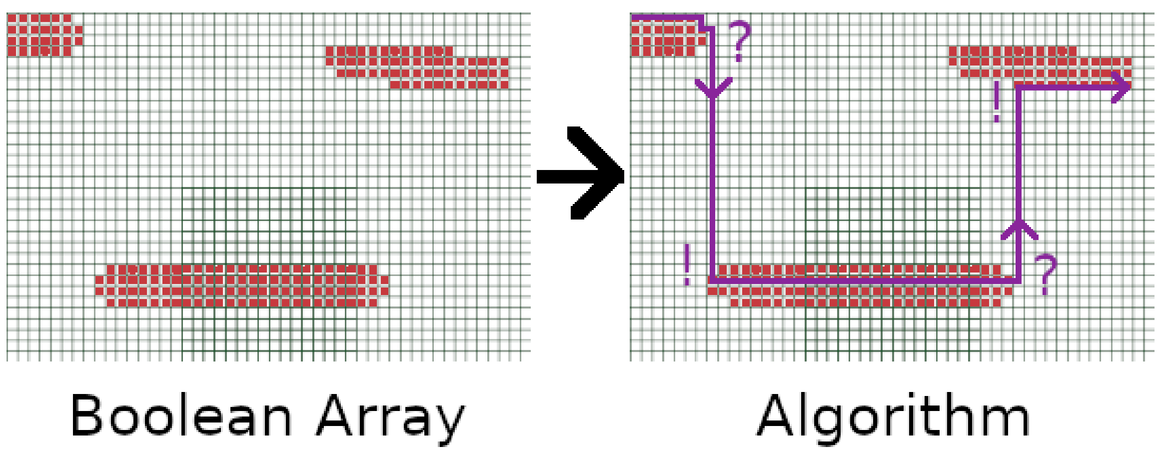


Figure 64: High-level Machine Vision Algorithm

In the algorithm above, the boolean array is being traversed horizontally until a false value is found. When a false value is found, traversal shifts from horizontal to vertical. This is visually represented by the purple question mark in Figure 66. Once a true value is found again, traversal shifts back to horizontal. This is visually represented by the purple exclamation mark in Figure 66. For vertical traversals greater than some constant (representing non-arbitrary depths), the max vertical traversal is recorded. Having a constant that represents whether the section of the laser is in a sufficiently deep depth is also useful for tracking whether to traverse up or down. Without logic to keep track of whether the laser is fractured or not, the algorithm can infinitely traverse in one direction and hang. When calculating the depth of the hole and the area of the hole, the max vertical traversal in units of pixels is used. Figure 65 illustrates a concave hole archetypal of a pothole on a road.

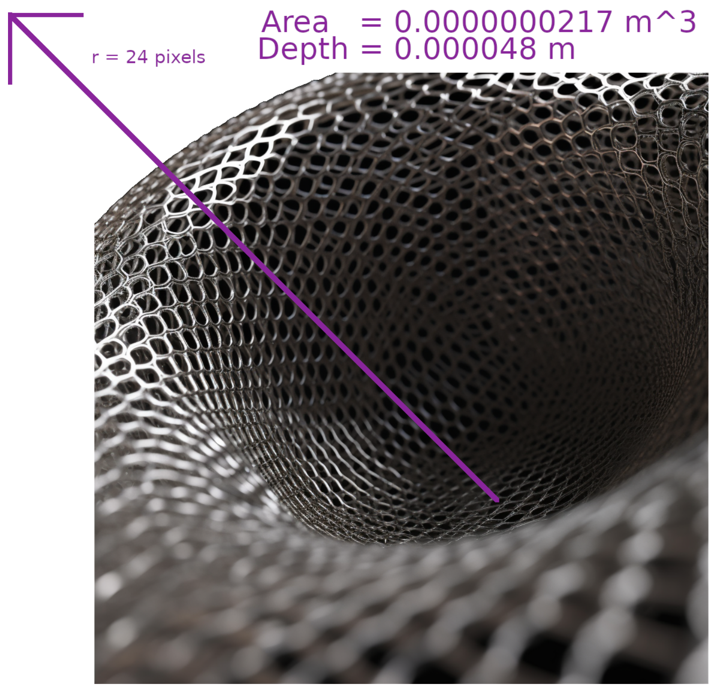


Figure 65: Area Calculations

To calculate the area of a hole, several assumptions are made. First, it is assumed the hole is of a hemispherical shape. Following the laser example and the associated algorithm, it can be seen that the shape of the "hole" represents more of a rectangle. However, it is assumed to be a hemisphere to overcompensate for materials required to fill the hole. If the area is assumed to be a hemisphere, then the hole should have a radius. Of course, real-world potholes will not have uniform radii, so the algorithm keeps track of the largest radii. In this case, the largest radii is the max vertical traversal: 24 pixels. The ELP-USBFHD08S-MFV camera has a pixel size of 2 micrometers by 2 micrometers. The pixel size is used to convert pixels to meters. Since pixels are much smaller than the grid used in these examples, the area and depths can be expected to be scaled up by at least 1000-fold.

$$Area = 3\pi r^2 = 3 * \pi * (24\, pixels * 0.000002\, meters/pixel)^2 =$$
$$= 0.000000021714688\, m^3$$
$$Depth = r = (24\, pixels * 0.000002\, meters/pixel) = 0.000048\, m$$

6.9 PCB Design and Implementation

The purpose of the PCB design for this project is to support the electrical and hardware components. The software we will be using to build this schematic is CADSoft Eagle because of the group's familiarity. Before designing the PCB, we had to incorporate the schematic research that we demonstrated earlier. In the case of our Raspberry Pi Zero W it only needs a supplied power of 5 volts, so we would need a voltage regulator to bring the 9 volts down to 5 for the input of the board. In our case with lab familiarity, we will use the LM7805 voltage regulator. The other portion of the current provided by the battery will be dispersed to the camera and laser diode. The 5-volt current is not sufficient enough to provide consistent output power for the whole system during entire operating time. Our beginning schematic of the battery, 5 volt regulator and the raspberry pi is in the 5.2.7 Electrical System section.

Our next steps in developing the final schematic to be transferred to a PCB design is to understand the specification of the laser diode and the camera that will be attached. The specific camera we are using is a 260-fps variable focus camera which includes the USB module compatible with the Raspberry Pi Zero W. The camera module can be connected directly to one of the USB ports on the microcontroller. The laser diode that will be utilized is the CPS635 laser diode with a digital interface that allows us to connect the diode directly to the GPIO pins on the Raspberry Pi. Once this is connected, we must provide directional information to the camera to capture the image for the road mapping system. We plan to complete our final PCB in SD2 to check the validity of its function with our system. Another topic to consider while designing the PCB board is to research which vendor we would like to have the board printed through. The parts must comfortably fit alongside each other with it being necessary that the board allows us to facilitate component connections without the PCB interface. This PCB will work alongside the Raspberry Pi. Though there will be updates throughout the process we have discovered several vendors to consider having the board developed and shipped to us. The main vendor that incorporates all of our needs of layers, dimensions and thickness is PCBWay. Although this brand tends to produce PCBs with a heavier total weight, we can incorporate this into our housing design to ensure it is secure enough to hold down the total force of our PCB and components.

Using the parts schematics for the items included in our design to be mounted into the housing box, we were able to create a final schematic and PCB. This PCB is a draft and can be adjusted before our final version is printed. The advanced and stretch goals should be accomplished by the battery supply of 9 volts. For added insurance the user can always switch out and implement a battery with higher capacity if a camera with higher resolution is needed or longer driving time with a faster speed is used.

Without the laser diode we cannot determine what other connections need to be supplied to fulfill the total PCB. This is something we will continue to work on for the rest of SD1 and for the duration before the start of SD2. Figure 66 is the beginning PCB representation that we implemented from our hardware. Without the laser diode available as a schematic we are unable to include it in our PCB at this moment. We are looking into the possibility of SnapEda or another source creating the diode pinout for Eagle.

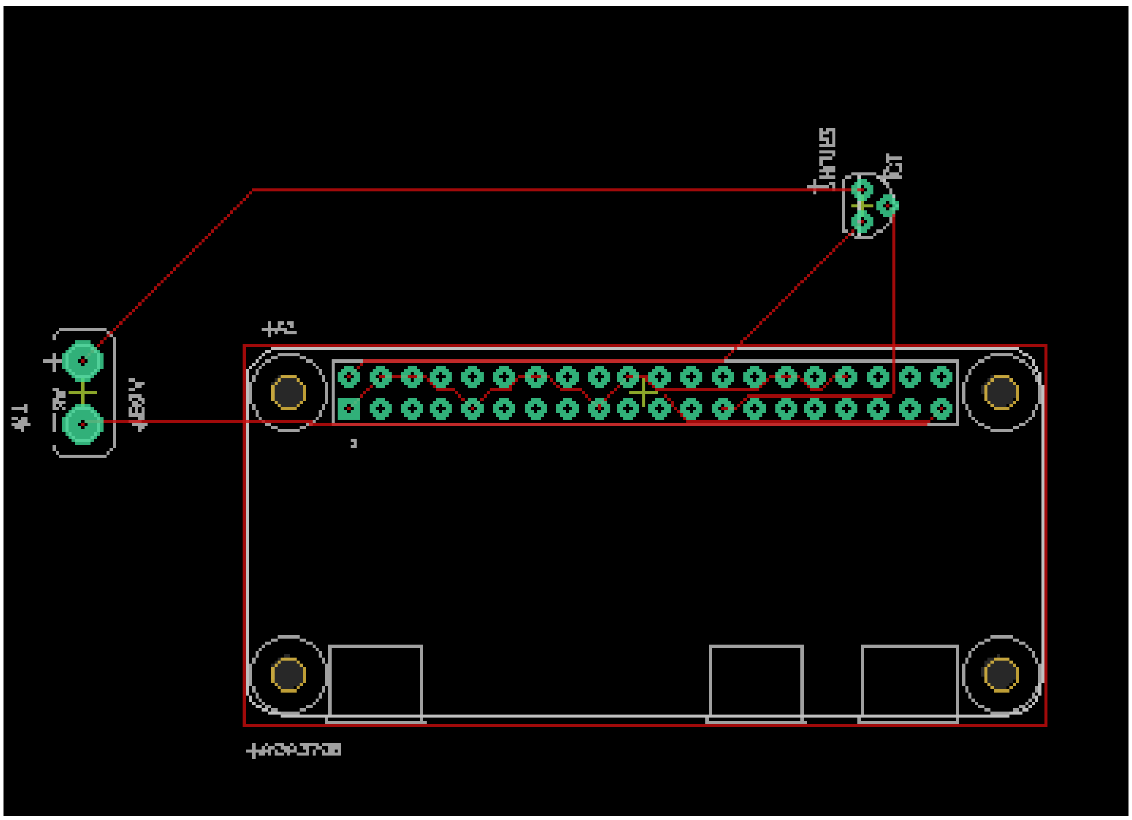


Figure 66: Initial PCB Design

Figure 67 shows the initial ground pour PCB design.

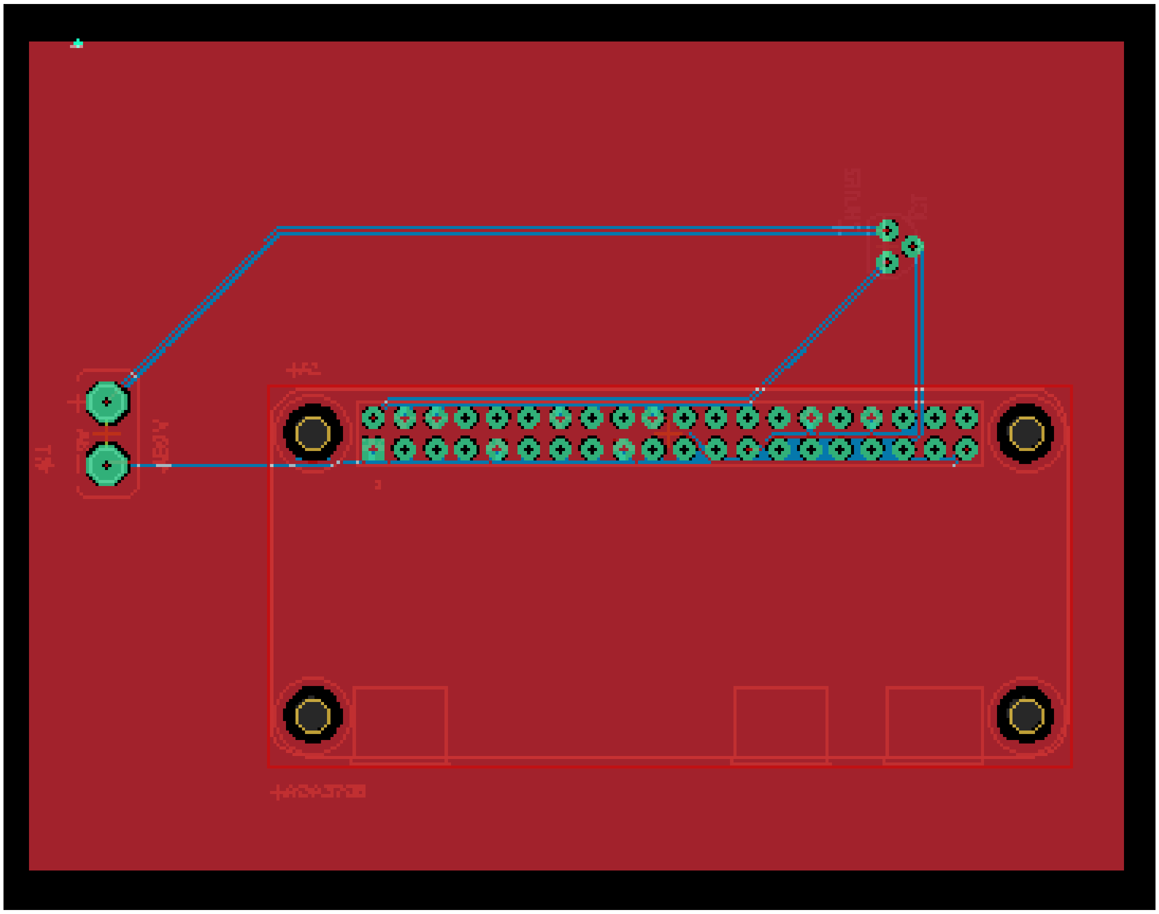


Figure 67: Initial Ground Pour PCB Design

6.10 Summary of System Integration and Testing

This section reviews the systems that will be tested individually and then integrated together to form the surface mapping prototype in table 40.

Table 40: Summary of System Integration and Testing

System	Attribute Tested
Emitting Optical System	Optical Alignment
Detecting Optical System	Optical Alignment and Light Collection
GPS	GPS signal
GPS Data Loss	Pothole location reliability
Microcontroller	Data storage and UART
WebGL Render	Rendering speed
Battery	Validity of power supply to the RaspPi
Machine Vision	Depth Calculation
PCB	Power design for electrical interface

7 Administration

This section will review administrative content.

7.1 Budget and Funding

Table 41 below lists our current estimates for what would be required to build a working prototype of the road mapping system. As of now, there is no sponsor for the project and all costs will be covered by the members of the group. Adjustments to prices and required parts are possible while methods of scanning are in discussion.

Table 41: Prototype Budget

Item Description	Quantity	Total Cost
Red Laser Module	1	$123.87
Camera	1	$75.00
Powell Lens	1	$37.28
Bandpass FIlter	1	$185.60
Wiring	1	$20.00
Battery (5 volt)	1	$4.00
PCB USB port	5	$0.98
PCB Voltage Reg.	31	$1.34
PCB Micro SD Slot	5	$2.27
PCB board / assembly	5	$94.63
PLA filament	2	$41.17
Maps api	$200 monthly credit	$0.00
SD Card (256 GB)	1	$37.00
Mounting Bracket	1	$54.37
System Casing	1	$69.48
PCB Antenna	5	$4.14
PCB Male Connectors	10	$0.37
PCB GPS Module	5	$23.21
PCB MCU	5	$37.92
PCB Micro USB	5	$0.13
	Total	$812.76

7.2 Milestones

Table 42 describes the project milestones and the duration of the tasks needed for design, assembly, and testing along with the status.

Table 42: Project Milestones

Task	Duration	Status
Senior Design 1 - Spring 2023		
Brainstorm Project Ideas	01/09/23 - 01/16/23	Complete
Project Selection	01/16/23 - 01/23/23	Complete
Divide and Conquer 10 Page Document	01/23/23 - 02/03/23	Complete
Research Component List	01/23/23 - 03/06/23	Complete
Schematic	01/23/23 - 03/20/23	Complete
Bill of Materials	01/23/23 - 03/20/23	Complete
75 Page Document	01/23/23 - 03/24/23	Complete
Final Document	01/23/23 - 04/25/23	Complete
Order Parts	02/27/23 - 05/01/23	Complete
Senior Design 2 - Summer 2023		
Assembly of Optical System	TBD	Complete
Testing of Optical System	TBD	Complete
Entire System Assembly	TBD	Complete
Assembly Testing (Stationary)	TBD	Complete
Redesign 1	TBD	Complete
Assembly Test 2 (Stationary)	TBD	Complete
Assembly Testing 3 (Mounted on car)	TBD	Complete
Redesign 2	TBD	Complete
Finalize Assembly	TBD	Complete
Final Presentation	TBD	Complete

8 Conclusion

This project started with a state goal of coming up with a new more efficient way to inspect the road ways for damage. This idea came from the group's experiences with traveling across the country and the road conditions in remote areas. At first LiDAR was thought to be the solution to rapid surface mapping, but due to technical, budget and time constraints that idea was rejected in favor of a machine vision system. It was decided that how we achieved the objective was less important than actually achieving the objective.

The optics side of this project started out with a complicated idea of using time of flight of a laser to generate a point map of the surface of the road. This is known as scan LiDAR. The LiDAR system would have required a complex system of a high rpm spinning servo with a rapid pulse laser and an extremely fast photodetector. These components raised many problems due to the group's lack of funding and experience with mechanical engineering. The group then moved onto machine vision which does not require any moving parts and can be accomplished with less expensive components. By projecting a laser line onto the road surface and utilizing trigonometry we are able to gauge the elevation shift across the road's surface. This allows the group to create a map of the road's surface in which dips and bumps can be shown.

We are satisfied with the choices we have made in terms of choosing the GPS module, the microcontroller and our data storage device. One such issue is the case of writing bandwidth of our microcontroller/ micro-SD card system. As discussed in a previous section the overall throughput of the camera may be too much for our microcontroller to handle. In the event the data received is too large we will determine try other methods of reducing the data such as cropping the images we receive before we store them on the drive, another method if this is insufficient would be to preprocess the images received with a simple edge detection algorithm to store the fewest number of pixels on our device as possible. In terms of our GPS module we believe that it was the better choice as it has a very detailed datasheet as well as supporting material to aid with using the system. With the GPS module there was a slight oversight in the need of an antenna for the system, which we have decided to buy to be safe thankfully not including shipping this only raised our budget by about five dollars.

On the software side of things, the Threejs library allowed us to create a simple and ready to go rendering pipeline to be finished quickly with only needing minor changes for our final product. The maps api that we are looking at using for the website is also promising in that it is well known and already allows for methods to depict exactly where on the map our potholes are located through the use of map overlays. Having this functionality built into the API will give us more time to achieve our advanced programming goal of displaying all of our scanned roads.

Incorporating the microcontroller with the final pcb should be as simple as soldering a 40 pin connector to both ends. Although we could get away with a smaller connector as we will only need about 4-6 pins depending on our design. Two pins for our UART connection with the GPS module, two pins for power of the microcontroller as well as possibly two more pins for data input from the camera system if we choose to connect the camera directly to the pcb.

Overall with the budget and time constraints presented, our group came to the conclusion that it is possible to create a working prototype for a surface road mapping system. Because of constraints, mainly budget, some of the parts selected are not optimal, such as the camera, but will be sufficient enough to create a prototype that will show it is possible to create a mapping system that will make it more convenient to find road damage.

Appendix A - Copyright Permissions

Bluetooth figure 18 permission

Larry Rudolph

to me, albert

You have my permission

Albert Huang

to me

Hi Ivan,

Please feel free to use that table for your report. I wish you the best,

Albert

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