Road Surface Mapping (RSM)

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***ABSTRACT* — This project aims to create a road mapping system that can quickly and easily detect and analyze road damage such as potholes. The current system relies on commuters reporting damage, which is slow and labor-intensive. Initially, a scanning LiDAR design was considered but faced technical and budgetary challenges. The project shifted to machine vision which involves creating a device to map the road surface using a laser line projected onto the road, which is recorded by a camera. Software analyzes the video to calculate the shift in the road's surface. The new system proved feasible within the time and budget constraints, although the prototype may have lower resolution and limitations.**

***Index Terms* — Computer vision, point cloud rendering, powell lens, reflected light, GPS, NMEA, power supply efficiency**

I. Introduction

A group of engineers including two optical, two computer, and one electrical developed a surface mapping device. Car owners often encounter uneven road surfaces and potholes while driving and are forced to either safely make evasive maneuvers to avoid them or stay the course and hope their vehicles don't get damaged. Currently, the Department of Transportation relies upon commuters to report incidents of road damage. However, issues on many backroads and country roads go unreported as they are less traveled. The device aims to safely and efficiently locate road damage by using a surface mapping device attached to cars. Image processing techniques are used to analyze digital images captured by a camera attached to the car. The device consists of an emitting system, made up of a laser diode and a powell lens, and a detection system, consisting of a spatial filter aperture, bandpass filter, and camera. As the vehicle moves, a laser line is projected onto the road's surface. Any change in the elevation of the road will result in a shift of that line up or down. The video data is collected in a removable memory source, an SD card. Once uploaded to a computer, the data is processed by an algorithm to create a road map, identifying damaged areas which are displayed on a website for easy visualization.

This project has potential applications for the Department of Transportation, Google, and the government, providing benefits such as identifying repair locations, alerting drivers to road damage, and potentially securing more funding for lower quality roads.

This paper will discuss the design approach of the individual subsystems of the road surface mapping system, along with how each subsystem is integrated to create a working prototype.shown above.

II. Illumination System

The illumination system of the device consists of a laser, a focusing lens and a powell lens. This system generates the laser line on the surface of the road. There are many constraints on this system, such as safety, visibility, and budget. All of these constraints led to the decisions below.

A. Powell Lens

Initially, two lenses were considered to generate the line that would be tracked on the roads surface, a powell lens and cylindrical lens. Cost and uniformity were the attributes examined which lead to the selection of a powell lens. Cylindrical lenses were found to be more expensive as the manufacturing process requires precision to shape the lens and many errors may occur during the polishing process. The line generated from a cylindrical lens is a nonuniform Guassian beam which results in a non uniform intensity.

A powell lens is able to take an incoming Gaussian beam and convert it to a flat beam of light due to the large amount of spherical aberrations created by the lens which repositions the light along the line. This ensures the line generated uniformly in intensity by redistributing the bright center to the ends of the line. Powell lenses can be expensive, but for the needs of our device a fairly cheap one was found which solidified our choice. The lens selected is a BK-7 powell lens with a 110 degree fan angle sold by Sunshine Electronics.

A property of the powell lens that will affect the overall design of the illumination system is power distribution. The uniformity in power distribution is not absolute, causing variations throughout the line. Ten percent of both ends of the line contain less power than the rest of the light causing a decrease in brightness and less photons for the camera to capture. Therefore the line generated should be longer than the line captured by the camera.

The placement of the powell lens in relation to the road's surface was calculated using the angle of the powell lens. and the desired line length of 2 feet captured by the detection system. With a powell lens angle of 110 degrees and at a height of 3.67 ft from the road surface and line length of 10.48 ft can be generated, well over the basic goal of a line generated of two feet. However, an obstacle that was not initially considered arose once the bandpass filter was added to the detection system which will be discussed more in detail in the next section. The end result was a line of 2.4 feet with uniformity throughout 2 feet of the line. Even though a 10.44 foot line is projected the goal of 2 feet is captured by the detection system.

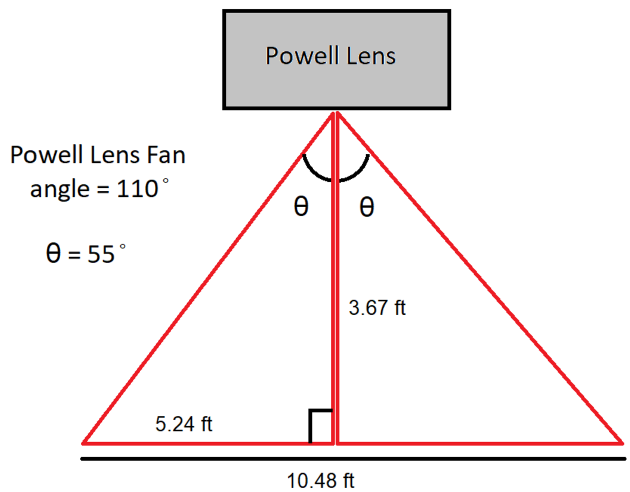

Fig. 1. Illumination System Schematic

B. Laser Selection

The laser is limited to 5 mW in an open air system, by OSHA standards. It was decided to use visible light since the detection system would be centered around a camera. Since red light lasers are cheaper than green and blue lasers it was better from a budget standpoint to choose a red laser. A red laser would also provide less of a danger to bystanders since they are more eye safe than green and blue lasers.

The laser chosen for the project was the Thorlabs CPS635 laser, a red laser with a 635 nm wavelength. It has a maximum power of 5 mW and an integrated focusing lens. The lens collimates the laser beam and generates an elliptical beam profile. This results in a beam spot size of 4 mm by 1 mm, which is ideal for the powell lens. This spot size was measured while the powell lens was 50.8 mm from the front of the laser housing, which is incorporated into the overall design for the illumination system.

III. Detection System

Originally, the detection system consisted of a camera and a cylindrical lens which would zoom in on the vertical axis of the image. This was an advantage as each pixel height would cover a smaller area of the image and a better depth resolution would be achieved. However, during initial testing of our system, it was apparent that the ambient light overpowered the scattered light captured by the camera. Adjustments were made including positioning the camera at an angle to capture reflected light. Due to cost, the cylindrical lens was eliminated from the design and instead a bandpass filter and spatial filter aperture was included in the optical design to reduce the signal to noise ratio.

A. Camera Selection

To capture light from the generated laser line on the road's surface a camera was used. When choosing what camera to implement characteristics such as frame rate, resolution and cost was considered. The resolution of the scan of the road is dependent upon both the speed the vehicle is traveling and the frame rate of the camera. The faster the car travels the faster the camera's frequency must be to maintain an usable resolution. For safety reasons the car must be able to travel at road safe speeds, so as not to become a hazard on the road. Due to time and budget constraints we determined a minimum speed of 10 mph. The resolution of the system needed to be able to detect a pothole of 2 inches deep and 8 inches diameter. It was decided that a camera with a frame rate of at least 40 Hz would be needed to maintain a 1 inch by 1 inch resolution while traveling at 10 mph.

The camera chosen was ELP-USBFHD085-MFV and has a maximum frames per second of 260 at a resolution of 640 X 360. To obtain a camera with 260 frames per second, it was more costly, but it fit our needs better.

The camera was originally positioned directly above the surface of the road. This position allowed the camera to provide a flat image for a reference frame. This made the calculation of pixel shift to depth change easier. However, this made the camera dependent on scattered light. When tested during daytime hours, it was found that the ambient light from the sun was overpowering the laser line in the camera's image. To combat this the camera was moved to collect reflected light instead of scattered light. The camera was moved farther from the illumination system and placed at the same angle that the illumination system was operating at. Now instead of a flat image of the road, the detection system is seeing the road at an angle. This reference disparity is now being handled by the processing code.

B. Spatial Filter Aperture Design

Early testing showed that ambient and scattered light overpowered the laser line resulting in the camera's detector unable to detect reflected light from the road's surface. Optical engineers calculated the black body radiation of the sun by first finding the peak wavelength which has the most irradiance.

$$L_{max} = 2.89 \cdot \frac{10^{-3}}{T} \tag{1}$$

The peak wavelength was found to be 498.3 nm. Using the black body radiation formula a distribution of irradiance to wavelength was found. At the peak wavelength an irradiance of 8.428 ⍰ 10^{4} W/m^{2} was found.

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

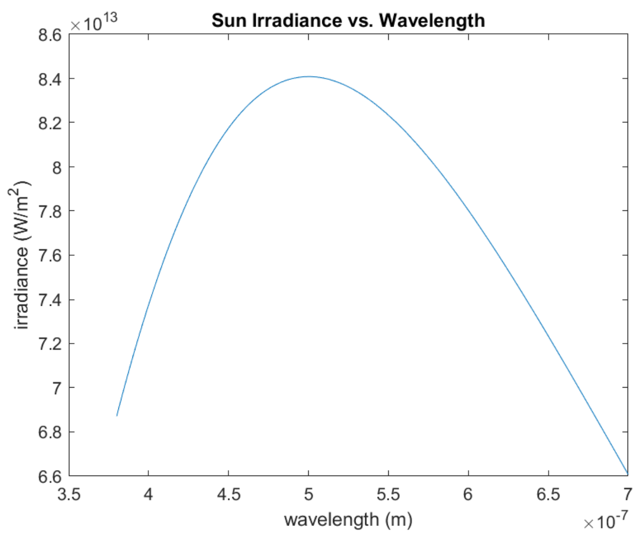

Fig. 2. Sun Irradiance vs. Wavelength throughout the visible spectrum

The total power from visible wavelengths was calculated along with the power of the laser line per square meter. It was apparent that the power from the sun overpowered the laser power which caused a low signal to noise ratio. It's important to note that as light hits asphalt 90%- 95% is absorbed, while the majority of the rest is reflected[1]. To combat the unwanted light, a spatial filter aperture is used to increase the signal to noise ratio of the system. The aperture not only has the advantage of decreasing the signal to noise ratio, but it also allows for the elimination of those areas when analyzing data. Adding the aperture reduced the amount of unwanted light to be captured by the camera's sensor, but it still was not enough to detect the reflected light from the road's surface.

C. Bandpass Filter Selection

The spatial filter aperture improved the signal to noise ratio, but not enough to detect the reflected light from the generated laser line. To increase the signal to noise ratio further a bandpass filter was added to the system. The bandpass filter is a 10 nm filter centered on 635 nm. The filter profile allows 90 percent of the light at 635 nm through. At the ends of the filter, 630 nm and 640 nm, the filter allows only 45 percent of the light through. Beyond that the filter reduces the light allowed through to 0.01 percent.

An obstacle that occurred when using the bandpass filter is the reduction in the length of the line captured by the camera's sensor. The filter is meant to be used with a 0 degree angle of incidence, or collimated light. As the angle of incidence increases, the center wavelength will shift to a lower measurement and the shape of the bandpass will change. Since the light incident on the bandpass filter is not collimated, the reduction of the detected laser line results. With more time and money a collimated optic would be added to the detection system to increase the length of the detected line.

IV. Overall Optical System

As previously stated, the optical system consists of an illumination system and a detection system. The illumination system is composed of a laser with focusing lens and a powell lens. The lens system will generate a line on the road and reflected light will be captured by the detection system which includes a spatial filter aperture, bandpass filter, and a camera.

The illumination system is set at an 80.8 degree angle from the surface of the road. This is required for the line projected onto the road to shift when the elevation of the surface changes. The camera is on the same plane as the powell lens and set to an angle of 80.8 degrees looking at the spot of the road where the laser line is projected. The 80.8 degrees was calculated from a desired 4 pixel shift per 2 inches of depth change. The detection system changed positions from looking straight down to an angle because light reflects off a surface and the same angle it is incident upon it. With the camera now collecting reflected light instead of scatter light it was able to more clearly see the laser line on the road. This shift in angle necessitated moving the camera to a position of 14.25 inches from the powell lens.

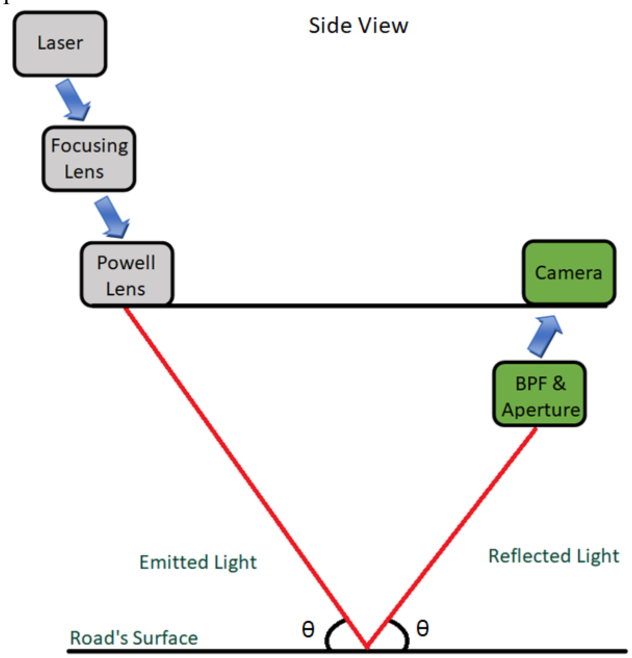

Fig. 3. Optical System Schematic

V. Power

To achieve the objectives of this project, various design decisions were made regarding the power supply system for the laser-guided camera road surface mapping system. The power supply was designed to meet the requirements of the USB and micro SD card attachments, as well as provide sufficient power to the laser diode, camera, and GPS module. This section will discuss the rationale behind the selection of the power supply and the integration of the USB and SD card interfaces. Furthermore, experimental results from our video demonstration will showcase the effectiveness of the power supply in delivering accurate and reliable road surface mapping.

A. System Components

The power supply design for the overall device will incorporate the following system components. The chosen microprocessing unit responsible for UART capabilities and supporting the required attachments such as USB and GPS module is the LPC1752FBD80, 551, operating at a 3.3V I/O voltage. This MPU offers 120mHz flash memory and high-speed operation. The GPS module, SW-GPS01, and passive antenna, KH-GPS181804-WY, combine to provide highly sensitive, accurate positioning, and low power consumption navigation solutions for the road surface mapping (RSM) device. The dual-mode navigation system operates at a 3.3V I/O level, with a 50Ω impedance antenna interface and a compatible UART rate of 9600bps. The micro SD card component, MUP-M627-1, requires a 3.3V power supply and offers seamless compatibility with our selected micro SD card. Lastly, the USB component, 916-162A1023Y10210, supports an I/O voltage of 5V, essential for supplying sufficient power to the critical camera function of our device.

These chosen components are in an overall hardware diagram to demonstrate why they were chosen, and what functions they will support. The system is color coded in representation of red for the external optical portion and green for where the computer section becomes relevant in the PCB.

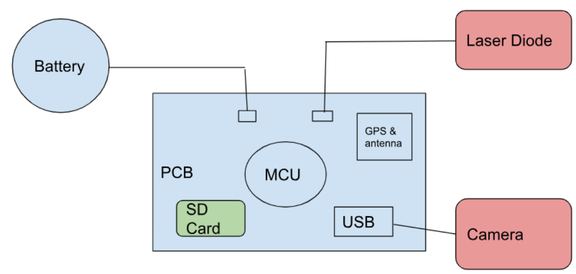

Fig 4. Electrical Diagram

B.Power and Attachment Requirements

In the road surface mapping system, it is crucial to consider the specific power requirements and attachment considerations for the successful integration of the interfaces, namely the USB, micro SD card, and GPS module. The I/O voltage for these main attachments were discussed previously. The USB interface plays a vital role as both a communication and power source for the camera, which is an essential component of the detection system. The USB adapter requires a stable 5V power source to ensure proper compatibility and functionality with the camera. The micro SD card interface serves as a central hub for data storage and retrieval, which is critical for the software component of the project. The selected micro SD interface specifically requires a 3.3V power supply to enable seamless operation. Additionally, the GPS module and its antenna attachment demand a constant 3.3V power supply. Proper integration and circuit design will be addressed to deliver the appropriate voltages to the MPU (Microprocessor Unit) and other attachments, ensuring efficient operation of the overall system. By considering the power and attachment requirements, the system can achieve reliable and efficient performance, while enabling the desired functionalities of data storage and accurate positioning. These requirements can then be used to calculate the power consumption and justify our overall system design.

C. Power Supply Design

The added components in our PCB configuration require a maximum voltage of 5V. Considering the consistent need for 5V power among several components, we determined that a minimum supply voltage of 6V was necessary for proper and sustained device operation. To accommodate this requirement, we chose a battery holder designed for 3-AA lithium-ion batteries due to its convenient soldering method, which features jumpers attached to the battery holder. These jumpers will be soldered directly to our assembled PCB and then placed in the housing unit for the final demonstration. To regulate the power to the desired levels for the system components, voltage regulators were selected as the preferred method. The AMS1117-3.3 was chosen as the primary voltage regulator in our circuit design, as most of the added components such as the micro SD card, laser diode, and GPS module require an input voltage of 3.3V. The selection of voltage regulators was based on the need for high power efficiency and low quiescent current, which are recommended for this application. In the circuit configuration, the voltage regulators will be directly connected to the battery as the input, and the output current of each regulator will be assigned to the corresponding system component before being attached to the selected MPU, LPC1752FBD80, 551.

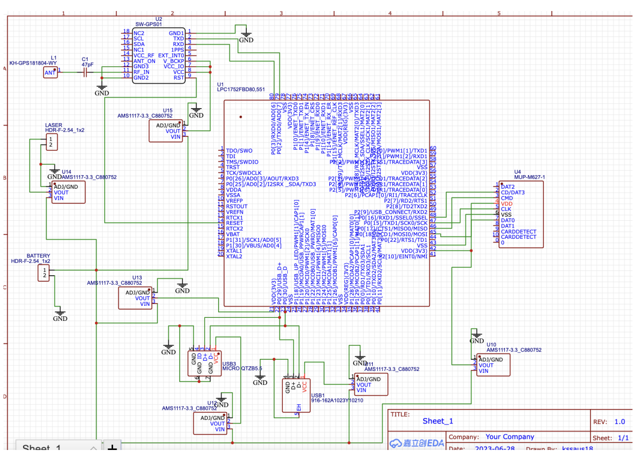

Fig. 5 Final Power Supply Schematic/Design

D. Performance Evaluation and Testing

Comprehensive tests will be conducted to assess the functionality and performance of the power supply system prior to the final demonstration. These tests will involve measuring the stability of the output voltage, evaluating power efficiency, and examining the system's ability to handle varying load conditions. This stability will be measured through the use of the oscilloscope to view the current throughout the components. This will demonstrate if each external part is receiving the appropriate and consistent voltage. The ability to handle varying loads is crucial to demonstrate the capability of achieving the outlined stretch goal. This will be tested by adding an extra external component to test if the supplied voltage will continue to provide efficient overall performance. During the breadboard test of the circuit conversion, the power supply system demonstrated reliable operation and maintained stable output voltages. The successful tested connection of the camera and laser diode to the breadboard further confirmed that the design provided uninterrupted functionality.

VI. Device Software

Building a system that is capable of classifying road damage involves gathering not only image data but also positional data.

A. GPS

A GT-U7 GPS module is used to connect to satellites via radio waves. Testing has revealed that acquiring a lock on with the GT-U7 has been a weak point. The radio waves are easily blocked by even the chassis of a car. To make matters worse, even if a connection to a satellite is established, changing the location of the GT-U7 will often break this link. Thankfully, this is a problem that is easily fixed by upgrading the antenna. Nevertheless, when a connection does persist, the GT-U7 will generate data that conforms to the National Marine Electronics Association (NMEA) standard. NMEA strings are frontloaded with conventions like “$GPGGA” which hints to the content of the rest of the string. This means parsing NMEA to colloquial terms is as easy as checking the beginning convention then reading in the rest of the data. A python program, less than 30 lines, is used in this project to read from a serial buffer, parse NMEA strings, and write to the file system for long-term storage.

B. Media Player

VLC is a free and open source media player which pairs well with the free and open source operating system used in this project. To record data from the camera, VLC takes in a bitstream via USB, interprets it, and records it all at the same time. Interpretation decodes important metadata like the camera’s resolution, frame rate, and compression algorithm. This is useful since these properties are too complex to calculate manually. VLC also has a command-line interface which enables the computer to run headless (without a monitor). While not incorporated in this prototype, it is theoretically possible to record a video by linking a button to a script that contains a VLC command. In this way, road scans could be initiated and concluded with the press of a button.

C. Operating System

The assistance of an operating system is essential in this project due to the high-throughput demands of recording video. Operating systems also coordinate processes in parallel by virtualizing computing resources and scheduling them according to priority. The operating system used in this project is Ubuntu. Ubuntu is chosen for the following reasons: amongst Linux distributions, it is one of the most user-friendly, it is free, and it is powerful.

Navigating the Ubuntu interface is similar to Windows where there is a "taskbar" called the "dock," the "meta" key can be used to search up almost anything on the computer, and there is a file explorer that visualizes the hard disk. Being free software, Ubuntu is easily installed and designed to be lightweight. Ubuntu Desktop, in contrast with the even-smaller Ubuntu Server that contains only a console and no graphical user interfaces (GUIs), is only 5 GB. That means the entire operating system can be passed around on a flash drive, taking up only a small percentage of capacity. Lastly, Ubuntu allows easy access to many useful tools like the python code interpreter that is used to parse GPS data. If the project was forced to be done "bare metal" (without an operating system), the 30-line python program would have to be written in assembly code which might span over a hundred lines, would be hard to read, hard to debug, and slow to learn.

D. Development Board Prototyping

When working from theory to implementation, it is often the strategy of many teams to start with what they are familiar with and start optimizing, refactoring, minifying, and so forth, later down the road. This is also the workflow that surfaced in Group 3. A way to reach the goal of portable road scanning was realized through development boards. Yet, it is still important to not use development boards as a justification for meager PCB design. The reason why a development board is still essential to the design at this stage of the project is because the learning curve for designing a PCB that rivals the complexity of a full computer with a microprocessor, RAM, SD card, UART connections, SPI connections, and voltage converters proved harder than expected. Nevertheless, it was decided that it would be better to have an implementation than none at all.

VII. Processing Software

For our project we decided to code the laser line detection software in C++ because it had many libraries which were used in this project such as opencv and open3d.

For the purpose of this presentation we will be presenting the point cloud and its associated calculations and GPS out of scanned data gathered from a one minute video.

A. Video Processing And Point Cloud Generation

The video file captured by the camera is currently uploaded to an ubuntu machine with the proper libraries installed. The input video is at a resolution of 1920x1080 in full color in any video format. The first few functions work on adjusting the video to result in a better generated point cloud. Figure 3 shows the block diagram for the video processing program.

The first function crops the video to remove portions which are covered by the aperture. The cropping is done to 1180x650 which removes 91% of the pixels. This is done to make the edge detection faster and skip unnecessary pixels. This function also encompasses the code which corrects the perspective of the image. Which is necessary since the camera is not looking at the road surface from its normal but instead at an angle.

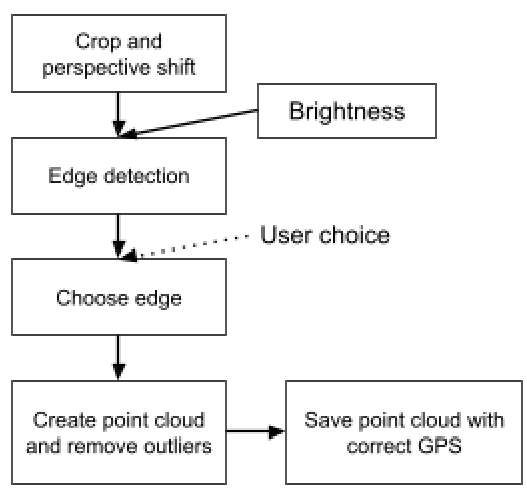

Fig. 3 Video processing block diagram

Next runs the edge detection algorithm on the cropped video. This algorithm first performs gaussian blur on the video with a kernel size of 5 and canny edge detection from the openCV library runs with the upper threshold parameter at 100 and the lower threshold parameter at 50, this captures the laser line well and removes softer edges from the input. The output will look like an outline of a laser line. Unfortunately there are some instances where the road seems to appear more red due to the laser than it should. At moments like these gaussian blur is helpful as it is used to remove high-frequency spatial components of an image through blurring[2].

The next code is the code that performs the pixel calculations and generates a preliminary point cloud file. This code handles removing points over a certain height of the point cloud, where the initial height is the position of the laser on average of the first three frames of the video.

The next code to run is to remove statistical outliers from the pointcloud. Being a remnant of our initial testing it is still included as it removes points in the point cloud which are statistically not close to enough other points. points found when the laser is strong do not get affected, but some unwanted artifacts are removed.

Next is the code is the saving step, the full scan is divided into 10 equally sized scans, and displays them to the user one by one. The user can then determine if the scan has any potholes in it to be saved, if so the program automatically collects the time which occurred at the center of the scan and searches the gps data for a corresponding time. Once the closest match is found the associated GPS data with that time is used to name the point cloud file.

A design change from the previous code implementation was to remove some functions for simplicity. The first function to be removed was detecting edges during the day, after reviewing this footage we agreed that it was unusable, being impossible to differentiate where the laser line is and isn't. The next code removed was connected to that, which was determining the brightness value, which without day time edge detection we can simply run the night time edge detection code. Next to go was the rotation of the video, during our initial testing this was somewhat important to produce a flat output as the laser line was not set straight. Our finished design does not have this problem, and in some cases still accounting for it proved to make the issue worse if the detected angle of the line was calculated wrong.

A. Positioning Calculation

Defining the real world coordinate space as x is a point along the width of the lane, y as a point in the direction of travel, and z as depth into or out of the road we can calculate the position of each point of our detected laser line in the following manner.

The simplest to calculate is the y coordinate or the distance between two subsequent frames, assuming rate of travel remains constant at 10 miles per hour and assuming a distance of 1.0 between two points is an inch in the point cloud. To find the distance between two frames we use the equation (1), where Δd is the distance traveled between frames, ΔI is the change in inches per second and ΔF is the number of frames per second. Given that we travel at 10 mph and record video at 60 fps we know that the distance between two frames is 2.93 inches.

$$\Delta d = \Delta I / \Delta F \quad (3)$$

The next hardest coordinate to calculate is the x coordinate. To find this we measured an object that took up the whole frame and divided its size by the number of pixels in that direction. For this we measured an object with a width of 59 inches fills our 640 resolution video when at a distance of 44 inches away.

Lastly, the hardest point to calculate is the z coordinate. In simple terms the camera takes an image of the road, the shift in pixels of the laser line in the vertical direction of the frame is characteristic of the depth. Along with the previous measurement we found that an object of 29 inches takes up the 360 pixels in height. This results in 0.081 inches per pixel vertically. Therefore every pixel that the laser line shifts in the image is approximately 0.081 inches. In equation (2) in order to calculate real world depth, ΔD, we need a shift in pixels, ΔP , and a camera angle, θ. Having a camera angle of 80.8 degrees and a pixel shift of one pixel, knowing that a pixel is equivalent to 0.081 inches, we get a depth of half an inch. With all three coordinates defined, we may generate the point cloud appropriately

$$\Delta D = \Delta P(Tan(\theta)) \quad (4)$$

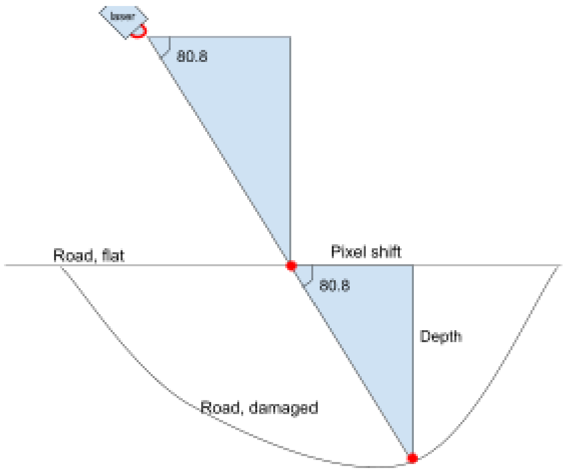

Fig. 4 road depth calculation diagram

VII. Conclusion

This two semester project helped us work together as a team and bring together many different aspects of engineering. We have learned skills such as critical thinking, time management, designing a device from specifications, how to reach goals, and how to test and adapt to changes required to produce a working prototype. It has helped us transition from an academic setting to what an industrial setting will be when we enter the workforce. Even though we have created a working prototype, there are many aspects that can be enhanced with more time and money. We are proud of what we accomplished in the time we have been given.

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VIII. Acknowledgement

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