UCF Senior Design

Scanner for Automated 3D Modeling of Small Objects

Department of Electrical Engineering and Computer Science
University of Central Florida
Dr. Lei Wei

Group B CREOL

Cary McEwan Computer Engineer

Sommer Hilliard Electrical Engineer

Isaias Velez Electrical Engineer

Sam Benjamin Photonics Engineer

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1.0 Executive Summary

Three-dimensional metrology and manufacturing have evolved significantly over the past decade, and the latest technology has adapted it for individual use in the form of 3D printers and scanners. Science labs and professional engineering firms are already using these to simplify production of specialized hardware in experiments and commercial products, and even hobbyists have begun to make use of them in projects of their own. Specialized hardware components that once had to be ordered and shipped over a period of days can now be printed and installed in a matter of hours at little cost or hassle. Creating a custom 3D-printable file of a real-world object, however, does pose a significant issue for some. Design software such as SolidWorks and AutoCAD require specialized knowledge and extensive practice to use effectively, and even with training it can be tricky to duplicate complex geometries in a reasonable amount of time. Our aim is to design a desktop scanner that is user-friendly and can produce scans of submillimeter quality that are useful in professional STEM-related environments.

There are many ways 3D scanning can be implemented. Ultrasonic emitters, visible-wavelength LEDs, infrared LEDs, laser diodes, grid projections, speckle field projections, and photogrammetry are all viable options. Our implementation uses an active line scan architecture, where a laser diode's beam is passed through a cylindrical lens to project a vertical line of illumination into a fixed plane. The line of illumination creates a profile of the scanned object's contour, and an image is subsequently captured from an angle at which the contour is pronounced. The image is passed into a series of processing algorithms that filter out extraneous information such as static background and unnecessary color channels. The beam profile's center is determined in terms of pixel array coordinates; once this process has been repeated for the entire vertical profile, the useful real-space coordinates are triangulated from the pixel array data. A point cloud of the coordinates is generated in the form of a text file, which is run through a meshing process and output in the form of a standard 3D-printable file.

This method uses low-cost hardware and, best of all, it utilizes open-source image processing software so that price is further minimized and the user does not need to purchase expensive third-party software. Similar to a 2D desktop scanner, this will be a product that can be unboxed, plugged in, and immediately put to use. Wireless transmission of the output file to a computer via Bluetooth will be optional, and a touchscreen user interface will be built into the product so that the user has access to an options menu as well as a native visual display of scan results.

This report documents the design process in its entirety, beginning with selection of general methods and documenting all relevant research, down to the final official schematics. Subsystems and their interactions will be thoroughly detailed, and mitigation of design flaws will be documented as potential technical issues become apparent.

2.0 Project Description

A generous amount of thought and care was placed in selecting a project that would utilize the knowledge and strengths of each team member, while still imposing a challenge on each individual. This project will incorporate photonics, computer, and electrical engineering to produce a challenging yet rewarding project. The motivation and goals of the project were outlined initially in order to properly proceed into the research, design and implementation phases.

2.1 Project Motivation

Ever since 3D printers became affordable to a broad market, they have become increasingly cheap and user-friendly. Duplicating 3D objects, however, still presents a multitude of challenges that make it impractical or unaffordable for the everyday hobbyist to make quality 3D copies. One method hobbyists can use to duplicate an object is to learn to use open-source professional modeling software to construct a simple object from scratch. Alternatively, they can spend as much money for a quality 3D scanner as they did for the printer alone, if not more. The motivation behind this project is to develop a fast, low-cost, easy-to-construct, and user-friendly desktop 3D scanner whose resolution is on par with more expensive scanning devices currently available.

2.2 Project Goals

As 3D printing continues to gradually decline in costliness, public interest in 3D scanning technology is not lagging far behind. In its current state, the market for these devices offers a surprising diversity of scanning methods. Unfortunately, most of the practical scanners commercially available today are targeted toward businesses, organizations, and entrepreneurs who stand to make profit off of using the technology. As a result, these high-tech scanners boast impressive features including submillimeter resolution in outdoor lighting, the ability to scan from small handheld devices with dynamic distances and orientations, structured light, time-of-flight sensors with subnanosecond sampling frequencies, and full-color rendering. On the other end of the budget/quality scanning spectrum, an abundance of informal hobbyist literature can be found online for DIY 3D scanners. While cheap, these devices almost always utilize relatively low-quality hardware with a complete absence of image processing. They are slow, inconvenient to use, and less than durable. Most often, the resulting replica printouts appear to be chunky quasi-imitations of their original counterparts.

The primary goal of this project is to create a relatively lightweight system for rapid 3D scanning at millimeter-level resolution. Market-wise, its purpose is to fill the gap between the high-end and low-end scanning products previously discussed. It is imperative that throughout the development process and as the project advances, we constantly evaluate the tradeoffs between the accuracy, efficacy, size, and price.

2.3 Project Functionality

The device would be equipped with a stationary line-profile laser that scans an object on a rotating platform at a fixed distance in front of it. Specifically, the desired object will be placed on a turntable within a controlled-illumination environment. The housing and platform for the project will be portable, meaning that its weight and size will be limited. The scanned images will be of at least submillimeter resolution. Furthermore, it will be an affordable design as opposed to those on the market. These functions are clearly defined in the house of quality, with specific design requirements. Moreover, the specifications are described further in the next section.

2.4 Requirement Specifications

- A laser diode will be used to illuminate the object’s vertical profile
    - Output regulated by the power distribution section of the PCB and/or a multipurpose microcontroller to prevent diode burnout
    - Red wavelength will be between 635nm and 650nm
    - The output waveform will be a linear with a vertical ray fan of 60º
    - Width of laser’s output line approximately 100µm
    - Focusing optics will be built into housing
    - Laser will only operate when scanner is closed for eye safety
- A CCD or CMOS array must be used to capture image data
    - Pixel density must be high enough to resolve details on the order of millimeters
    - Must sit at an angle between 20º and 100º with respect to laser
    - Aberration caused by the receptive focusing lens must be minimized
    - To aid in determining the point positions accurately in the z-direction, a checkerboard pattern of known dimensions will sit opposite the camera at a fixed distance
- One microcontroller will execute a program that converts the profile image into point cloud xyz data in a text file
    - Must have sufficient memory to store large text files containing thousands of data points
    - Must be able to deliver text files to a device via Bluetooth or Wi-Fi
- A second microcontroller will regulate the voltages and currents of several electrical hardware components, performing the following conditionals
    - If the scanner is open, the laser must be switched off
    - If a scan has been initiated, the turntable motor must rotate at least 2º every time a contour profile is imaged and digitized
    - If a scan is in progress, switch on a green external LED
    - If Bluetooth connection to an external device is successful, switch on a blue LED as long as the connection is maintained

    - If the object being scanned has been jostled around by external forces or placed significantly off-center, halt scan and illuminate a yellow LED
- The device must be small enough to fit on a desk and light enough to carry
    - Should be able to fit well within a circle 3ft in diameter
    - All electronics and sharp edges must be insulated and covered
    - Should weigh less than 20 lbs
    - Heat radiated by the device's electronics must be well insulated and/or kept to comfortably low levels
- The total cost of developing the device should not exceed $500

2.5 House of Quality Table

An important part of any type of engineering design is factoring in the marketing requirements. The house of quality table lists the marketing requirements of a laser based scanning device as well as its corresponding engineering requirements with specific targeted values for those engineering requirements. It provides a means to explore the tradeoffs between each market requirement and engineering requirement, as well as, how they affect one another. The up and down arrows represent a positive and negative correlation amongst the two.

		Quality	**Cost**	**Dimensions**	**Resolution**	**Weight**
		+	-	-	+	-
Portability	+		↓↓	↓↓		↓↓
Cost	-	↑↑		↓	↑↑	↓
High Speed	-	↑	↑↑	↓	↑	↓
Operation Ease	+	↑	↑	↓		↓
High Resolution	+	↑↑	↑	↓		
Targets for Engineering Requirements		> 70%	< $500	2x3x3 feet	≤ 2 millimeters	< 20 pounds

Figure 1: House of Quality - Engineering Specifications

2.6 Project Block Diagram

The following diagram shows a high level overview of the major parts within the project. Each part is color-coded based to indicate the individual who is responsible to construct or implement the task. Single arrows specify that there is only a one-way connection or communication within to modules, while the double arrow pointers specify that there is communication between both modules. All of the modules are implied to be within a containment unit or chassis that is designed and implemented by the entire group.

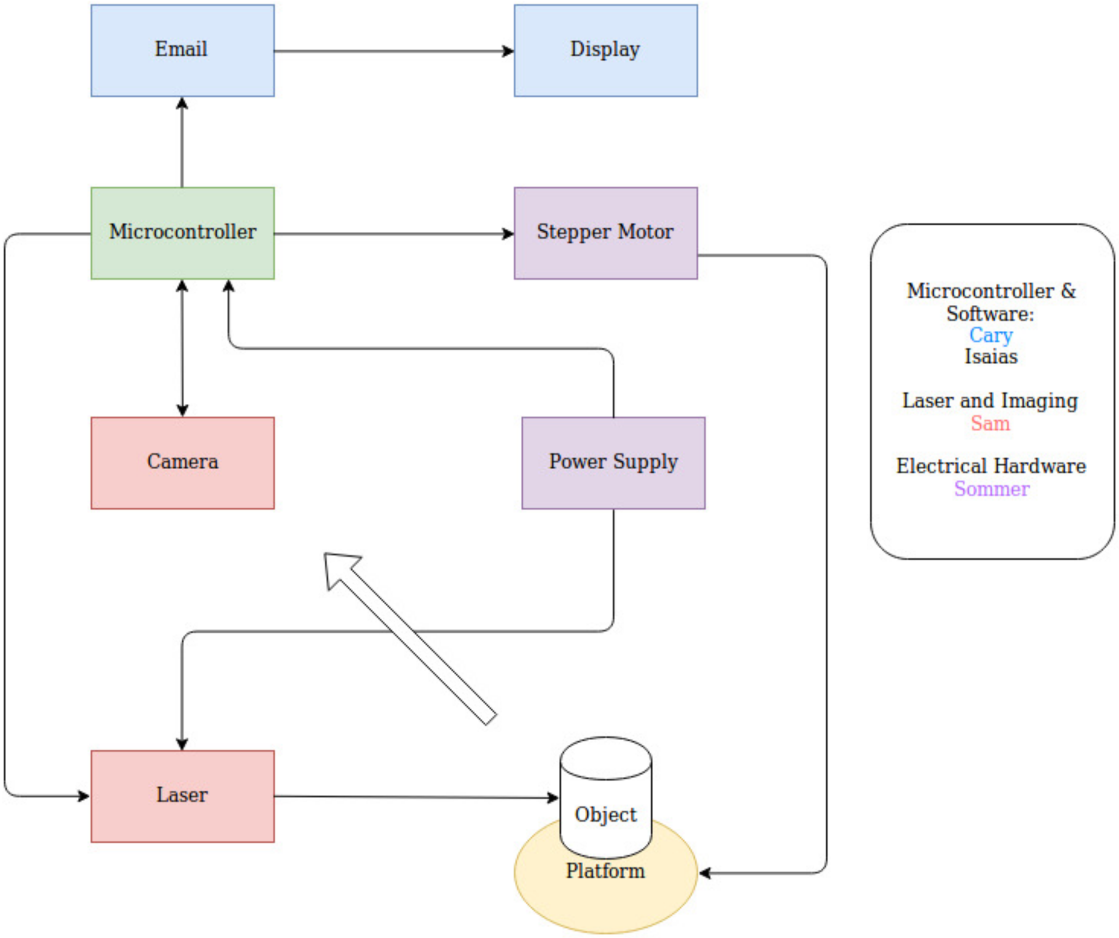


Figure 2: Project Task Breakdown

The project tasks that each individual is responsible for accomplishing are as follows:

- Laser Diode and Camera: Sam
  - Responsible for the research and integration of the laser diode and the camera that will profile the scanned object
- Microcontroller: Cary
  - Responsible for the open source software implementation to collect, process, and display the data from the laser
- Display: Cary
  - Responsible for the research and integration of the display with the microcontroller and system results
- Platform: Isaias
  - Responsible for the design and implementation of the mounting device for the scanner
- Power Supply: Sommer
  - Responsible for research and integration of power supply and proper power distribution to each component of the project
- Stepper Motor: Sommer
  - Responsible for the research and implementation of a sufficient motor to carefully rotate the platform with enough precision for high quality 3D scanning
- PCB: Sommer and Isaias
  - Responsible for researching, design, ordering, soldering, testing, and implementing the PCB design for the entire project
- Containment Unit: Group
  - Responsible for collaborative research and design on how the entire system will be contained into a final unit with attention to project requirements, such as; price, weight, and size

3.0 Research Related to Project

Quality research is a crucial step in the right direction towards a successful project. In the proceeding section there is thorough research provided for each component of the project. Furthermore, there are valuable comparisons made and conclusions drawn in regards to which components will be utilized in the final design.

3.1 Existing Methods for Scanning

The three existing methods for traditional scanning and imaging technology are Radar, Sonar/Ultrasonic, and Laser based technology. Each of these methods operates with similar principles that utilize short or continuous pulses of different types of waves utilizing a transmitter and then receives the reflected signals through the receiver. All three methods coexist in modern science and technology, but are used in different scenarios or project types, which leverage the unique properties to create accurate imaging or scanning technologies.

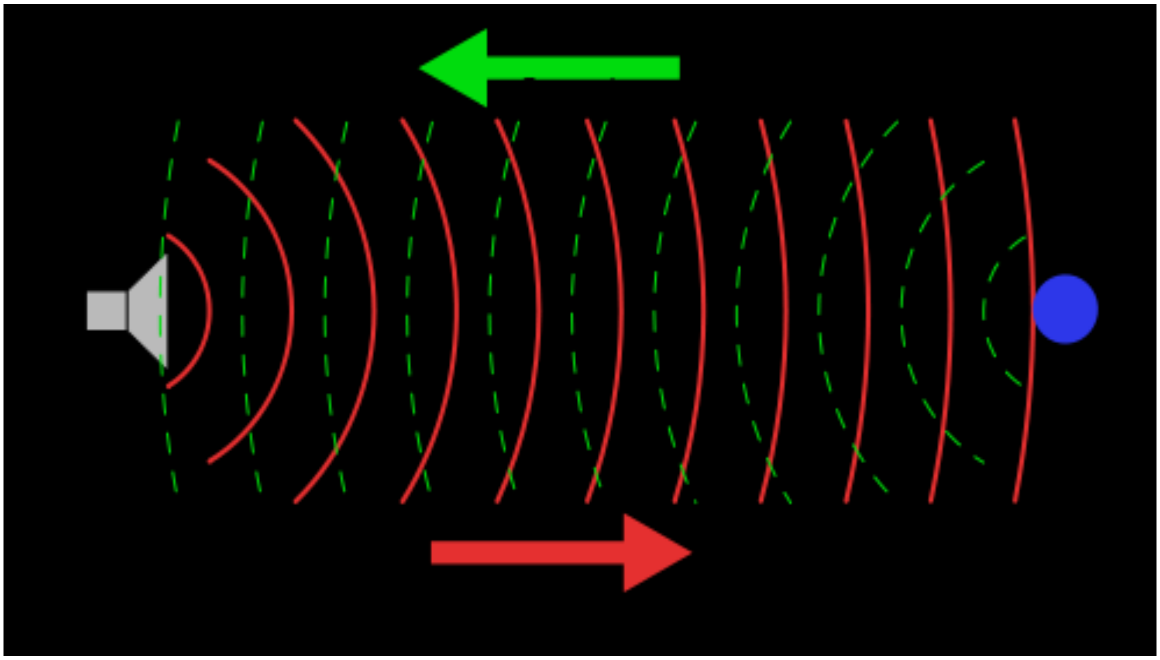


Figure 3: Time-of-Flight Ranging for Light or Sound (used with permission from Creative Commons licenses)

3.1.1 Radar

Radar stands for radio detecting and ranging and is a detection system that uses radio waves to determine the location and range of an object. It utilizes electromagnetic waves in the radio frequency as a short-pulsed wave, which can be reflected back by an object in the wave’s path and received by the radar receiver. In order to use radar based sensors successfully, several intricate components are required, such as; a magnetron, antenna, and dish array. The benefit of radar is due to the weak absorption of radio waves it the propagation medium. The radio waves do not suffer as heavily as other electromagnetic waves at different wavelengths, which are more strongly attenuated to ambient conditions. Radar is used in many areas, particularly in aerial traffic controls and meteorological weather forecasting.

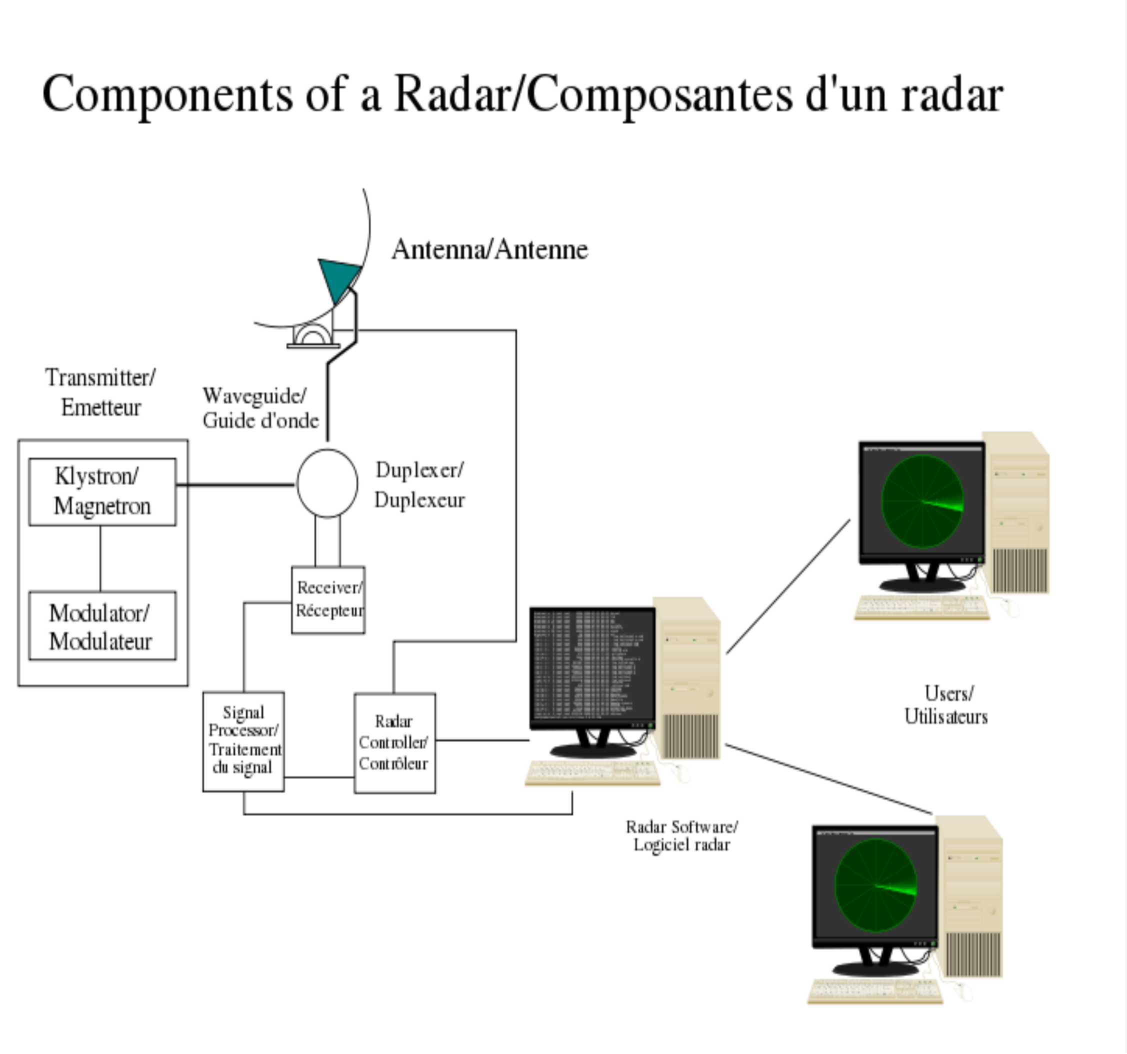


Figure 4: Components of Radar (used with permission from Creative Commons licenses)

3.1.2 Sonar and Ultrasonic Sensors

Sonar stands for Sound Navigation and Ranging. Sonar uses pulses of sound waves to determine object range and locations. Sonar is split into two main types: active and passive sonar. Active sonar uses pulsed waves to determine the range or location of an object by using both the transmitter and receiver in the design. Passive sonar on the other hand only detects noise from objects and must be used with other devices, such as, passive listening devices to measure range. Location in a passive system must be used with multiple devices to allow for triangulation. In water the speed of sound is nearly five times faster than in air (1500m/s versus 330m/s) as such it is great for water-based applications. For air based sonar the accuracy isn’t as precise due to ambient/external noise and thus it requires more pulses to extract information. Due to the fact that low frequency waves travel much more efficiently in water than in air sonar is especially effective in naval military applications and ocean surveillance systems. Ultrasonic sensors employ similar methods to sonar, while also dealing with high frequency sound ranges and calculating the time interval between generating and receiving an echo from the sound pulse. Using this principal allows sonar and ultrasonic applications to reconstruct images based on the time between pulses. The more accurate the apparatus is coupled with its access to better processing equipment, allows for reconstruction of more complex images.

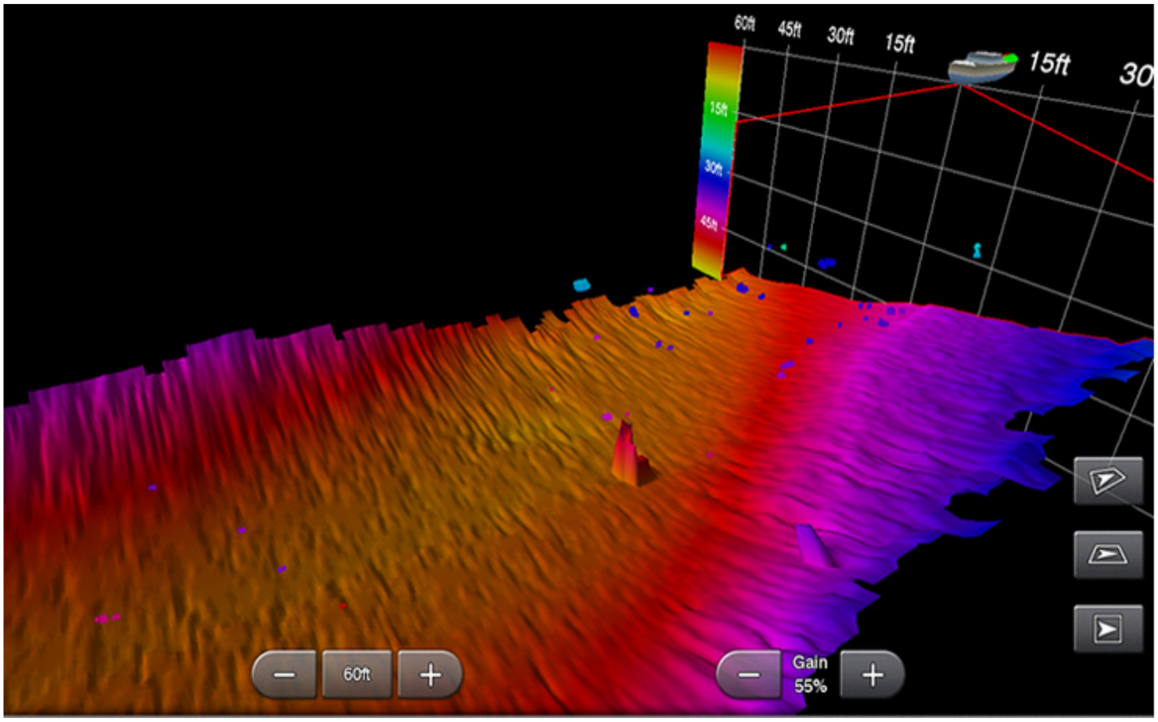


Figure 5: Visualization of Highly Detailed Sonar-Based 3D Data (permission pending from Garmin)

3.1.3 Laser Sensing

When considering light sources, lasers stand out among the rest due to four of their unique properties. First, their output is highly directional. Whereas an LED or light bulb casts its photons almost uniformly in all directions, the laser concentrates all output photons in a single direction, illuminating only a small area while leaving the surroundings relatively dark. In scanning applications that require high contrast, this is a desirable trait. The second reason lasers stand out is a consequence of the first. Due to the confined nature of a laser beam, the intensity of the light on a given surface (measured in W/cm^2) is relatively large compared to the input power, which makes more efficient use of electrical power. The third reason lies in its spectral properties. Nearly all non-laser light sources generate a broad spectrum that is centered around its characteristic wavelength.

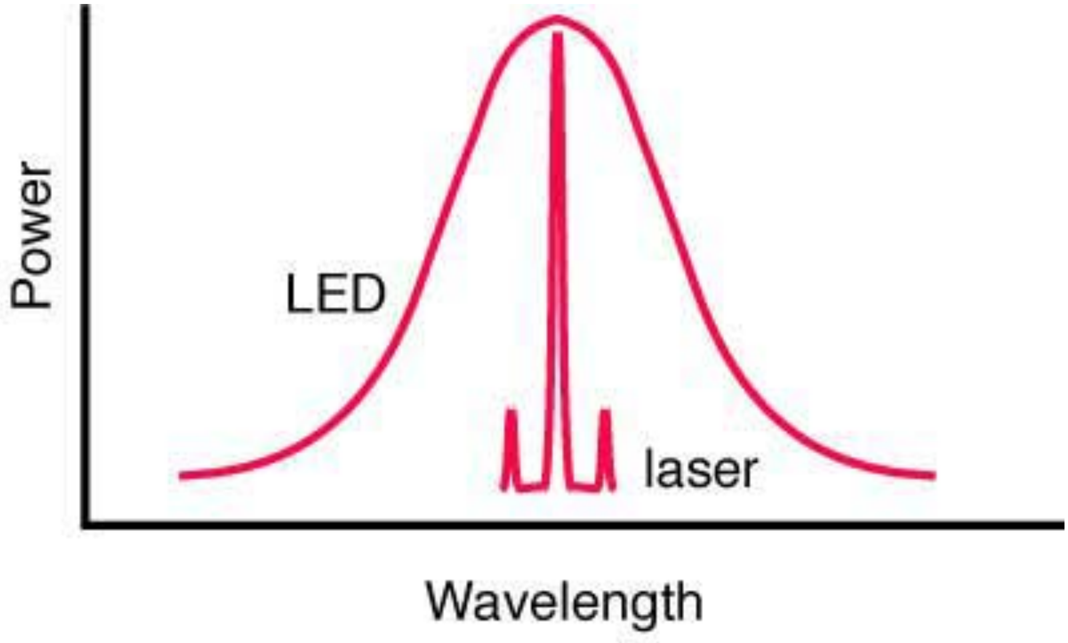


Figure 6: Comparison of Laser and LED Spectral Power Distribution

Lastly, the laser is often desired because of its coherency, a subtle but important characteristic. When talking about light, coherency refers to the fact that all output photons are in phase with each other, are of roughly the same wavelength, and are polarized in the same direction

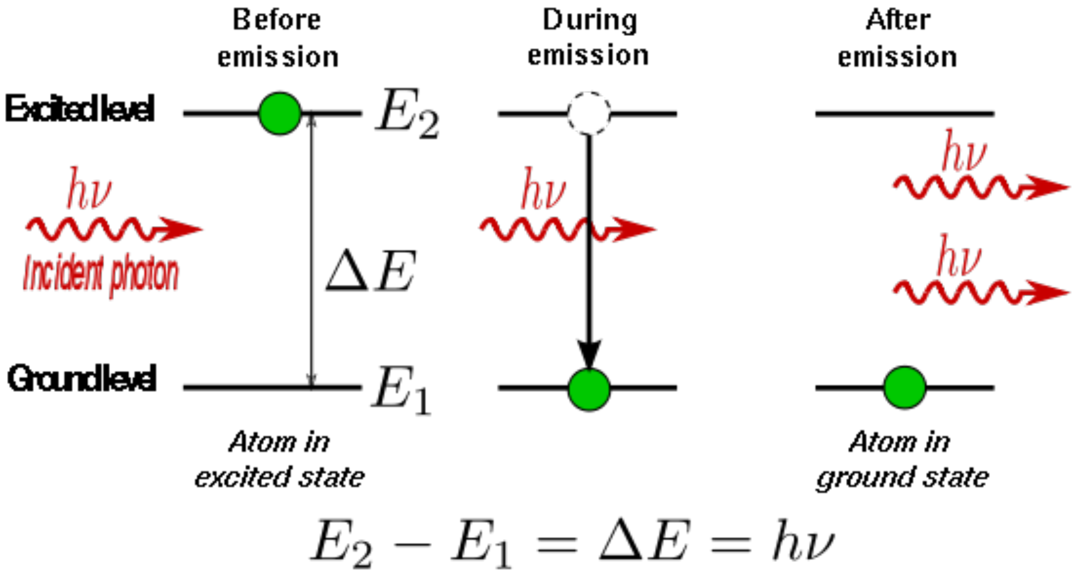


Figure 7: Synchronous Phase and Polarization In Lasers

In the context of this 3D scanner design, coherence from the light source can be advantageous, as it would allow us to attenuate the light with a single polarizer in the case that the object being scanned is extremely reflective. This can be done with incoherent light as well, but an extra polarizer would be necessary for the task.

3.1.4 Comparison

Out of the three major sensors, the best method for this project would be a laser-based implementation. The aim of this project is to produce a cost effect implementation of a mapping device that can allow a user to visualize an object. For this to be viable, there are constraints that limit the size and effectiveness of the implementation. In accordance to the constraints and standards specified for this project, radar does not work. Radar requires the use of antennas along with a more complex transmitter and receiver that would require more power. In order for the power to be increased, a larger power supply would need to be implemented thus violating the necessary portability constraint. In addition, sonar was not a viable option either due to the fact that sonar was more useful in water. The only solution to using sonar-like application was based on ultrasonic sound waves, which provided less accuracy at farther distances. The receiver for the sound waves would be highly sensitive to ambient noise and would require an extensive array of analog or digital filters to extract the relevant information. Furthermore, extracting the information from the sonar or ultrasonic transmitters would be difficult to represent in a computable format.

The primary reason that a laser-based implementation was chosen for this project is because of the ease at which it turns the data collected from the laser into a computable representation. Using a laser allows the profile of the laser to be recorded by a simple camera interface, which can be saved onto a variety of formats. The profile of the object due to the laser and angle of the camera can be turned into what is known as a point cloud format. This allows the profile to be visualized as a series of points in a three dimensional grid which can be rendered onto a screen or an image. Furthermore, using a laser drives down the cost and size of the implementation due to the amount of components that are required to operate radar and sonar. The small amount of necessary overall parts also makes a laser-based mapper the ideal implementation because of the smaller amount of components to consider in the design phase.

3.2 Existing Products

The current market for 3D scanning products boasts a wealth of scanning methods to choose from. Not all methods are equal, so it is important that the options are weighed thoroughly before committing to a certain method. This section will briefly summarize the existing scanning methods and evaluate their strengths and weaknesses with respect to the project goals. The information gathered here will help to identify potential budget traps, avoid critical design flaws, and give a strong foundation of ideas to aide in the development and design of this project.

3.2.1 Popular 3D Scanners

This section will address popular 3D scanners that exist on the market. This type of research is helpful in any project in order to optimize the design. By evaluating already existing designs, the pros and cons can be extracted in order to come up with an entirely new and better solution.

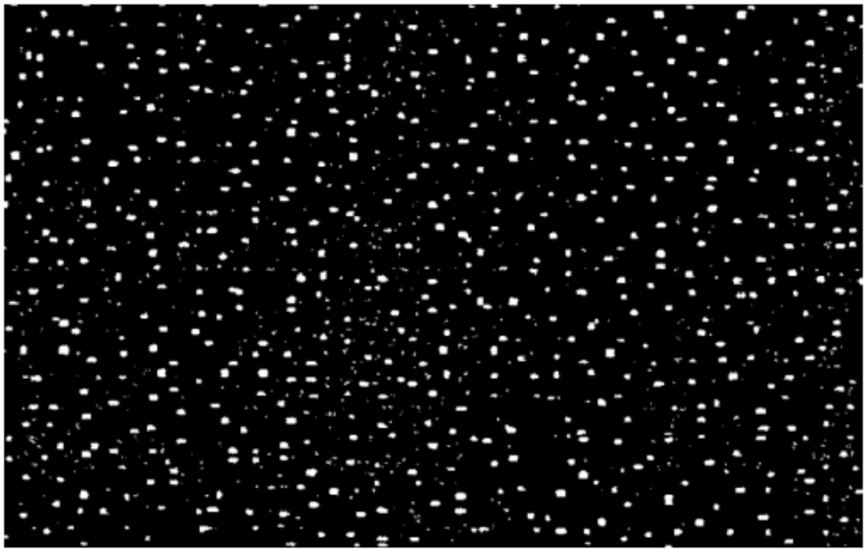
3.2.1.1 Xbox Kinect

This scanning software makes use of a piece of hardware called the Kinect, which was designed by Microsoft primarily for the purpose of tracking movements in interactive gaming. The hardware requirements for this device, coincidentally, are also sufficient for a certain type of 3D scanner. Two depth-sensing methods are used simultaneously by the Kinect’s ReconstructMe software. There are a handful of DIY project that can be found online that utilize the Xbox Kinect in the design. It provides more simplicity to the design; being able to buy a component that is known to work and to work very well at that. For the senior design project, it is important to apply skills and knowledge attained in the classroom to design this component rather than buy them already made. However, it is very helpful to research existing components on the market

Figure copied from Kinect for Windows SDK Quickstarts

Figure 8: Optics Utilized by Xbox Kinect (used with permission from Kinect)

Both of these methods rely on a speckle pattern as seen in figure 9, which the Kinect projects into its field of view (FOV) in infrared light. This falls under the broader category of scanning based on structured light, where a known pattern such as a grid or a speckle field is projected onto an object, and depth is determined by how the object distorts the pattern. The first depth-sensing technique is the parallax method, where two cameras separated by a known distance simultaneously capture images of the same object. In the Kinect's case, the speckle pattern is used as a reference. As an object moves closer to the device, a comparison of the two simultaneously captured images will show an increasingly greater shift in lateral position of speckles projected onto the object.



Shpunt et al, PrimeSense patent application
US 2008/0106746

Figure 9: Infrared Speckle Field Projected by the Kinect (used with permission from Kinect)

In conjunction with the parallax method, the Kinect uses a clever twist on a relatively common depth-from-focus method. Depth-from-focus sensing analyzes the point-spread function (PSF) of objects in an image. It quantizes the blurriness of objects throughout the image and compares those quantities to a value representing the sharpness of objects in the focal plane of the particular camera being used. The difference between the blurriness observed at focal length and the blurriness observed at an unknown position corresponds to a specific axial distance from the focus, which can be calculated without much trouble. The clever twist on this method used by the Kinect is that it has an astigmatic lens, meaning the lens has two different focal lengths: one for the x-axis, and one for the y-axis. This turns each speckle in the FOV into an ellipse, where the physical depth of a speckle corresponds directly to the orientation of the ellipse's major axis. Such a system actually eliminates the need for PSF analysis, but is still considered to be a depth-from-focus technique. Ultimately, structured light and parallax methods may prove useful and cost-effective to our project due to simplicity and proven effectiveness. The Kinect's scan quality, however, still fails to meet our submillimeter resolution requirement, therefore, further methods will be researched and considered. Depth-from-focus and its variants, while resourceful, require special lenses and/or intense processing power for image analysis, so they will be avoided if possible.

3.2.1.2 Autodesk 123D Catch

Autodesk 123D Catch is a 3D scanning application, which can be used on most mobile devices. The software makes use of your device's camera to implement a scanning method known as photogrammetry, where multiple images of an object from different perspectives are used to extrapolate a 3D representation. This method has obvious advantages in terms of portability and affordability, but it is not desirable for our project for two reasons. First, it would severely limit the creative element of our project because it lacks hardware, and such a software-heavy project would be better suited for a team composed entirely of computer engineering students. Secondly, the scan resolution is highly dependent on lighting conditions and the optical hardware of the mobile device being used, both of which are factors often outside the user's control. Our standards will require much more consistency in terms of resolution, which points us toward a desktop design where the scanning is performed in a dark, enclosed space.

3.2.1.3 Matter and Form 3D Scanner

The Matter and Form 3D Scanner is a popular desktop turntable scanner currently available on the market. This product, unlike the ones previously discussed products, uses laser triangulation to extract depth data on a small object. Similarly to the parallax method used by the Kinect scanner, laser triangulation involves simple trigonometry, where a known distance between two elements is used in conjunction with image data to calculate depth. This scanner can be seen in the figure below.

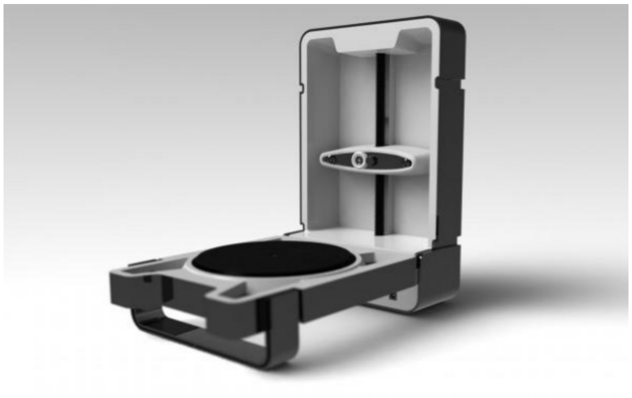


Figure 10: Matter and Form 3D Scanner Turntable (permission pending from Matter and Form)

One advantage laser triangulation holds over the Kinect's parallax is that it requires only an inexpensive laser diode and one imaging device, whereas the Kinect requires two imaging devices, an infrared emitter, and a special diffusive element to generate the speckle pattern. Also, unlike the previously discussed scanners, this product's fixed desktop configuration removes many complications such as variable illumination and tracking of dynamic position/orientation. Because of this fact, it consistently achieves a resolution of 0.43mm, which meets and exceeds our stated goal of creating a scanner with submillimeter resolution. Clearly, laser triangulation is a practical option for making high quality scans on a limited budget.

3.2.1.4 Time-of-Flight Ranging Scanners

Although time-of-flight (TOF) scanners are relatively rare on the personal 3D scanner market compared to photogrammetry and triangulation scanners, TOF is a well-known ranging method and as such will not be glossed over in our considerations. A brief overview of the physics behind TOF sensing reveals why these scanners are much more practical for geographical surveys and similar meter-scale applications rather than scanning smaller objects as our scanner will be designed to do.

On the surface, TOF scanning is appealing because the calculations involved are the simplest among ranging methods. A pulse of laser light is emitted, and the time is measured between the moment of emission and the moment when the reflected pulse arrives at the detector. The distance can be calculated with the simple formula seen below.

$$D = \frac{c*t}{2}$$

Where c is the speed of light (3×10^8 m/s) and t is the total time between pulse emission and signal detection. Typically, such a system can only provide meaningful data if the laser's pulse duration is shorter than the time it takes for the light to make a round trip to and from the target. This limitation allows us to calculate the minimum laser pulse duration necessary to meet our submillimeter resolution goals:

$$D = \frac{c*t}{2} \Rightarrow t_{min} = \frac{2*D_{min}}{c}$$

$$t_{min} = \frac{2*(1mm)}{3*10^8(m/s)}$$

$$t_{min} = 6.67\ ps$$

As the math clearly shows, the pulse duration necessary for millimeter-resolution scanning using TOF ranging is on the order of picoseconds. Such rapidly pulsed lasers are available for purchase, but even the most inexpensive picosecond models cost several hundred dollars. If we were to rely on the TOF method for our scanner, we would need to spend an exorbitant amount of money to reach an acceptable scan quality. Submillimeter resolution can be achieved for a fraction of the cost using other well-documented methods. For this reason, TOF ranging can confidently be eliminated as a viable scanning method for our design.

3.2.2 Selecting Triangulation

Out of every implementation reviewed, triangulation presents the best set of challenging yet attainable goals toward which all group members will be able to make significant contributions. Not only does this method meet our group's needs, but also it appears to be quite popular in practical products due to its high precision at relatively low cost. We will opt for desktop/turntable architecture similar to that of the Matter and Form 3D Scanner. To further improve upon its design efficiency, we will use triangulation by line-plane intersection as seen in figure 11, instead of the line-line intersection method employed by the Matter and Form 3D Scanner. This requires extensive calculations that all group members will contribute in finding the most optimal solution. This method will surely take a lot of trial and error prototypes and testing procedures, but persistence will be met with success for the most optimal 3D scanning design.

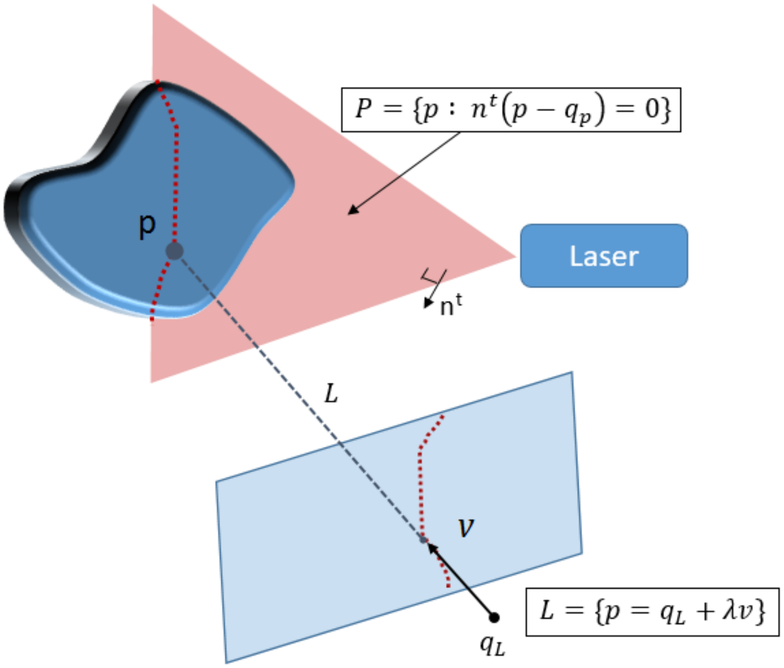


Figure 11: Triangulation by Line-Plane Intersection

Line-plane triangulation simultaneously captures all points along the object's vertical profile each time an image is captured. An arbitrarily defined global coordinate system is then used to define the intersection of the plane created by the laser and a ray extending from the camera to each point.

3.3 Wireless Transmission

The 3D Scanning System requires a method of sending the point cloud data, generated by the microcontroller, to the user's desktop or PC, which will receive and process the information. The following sections will explore various wireless transmission technologies, assess the trade-offs with each option, and define the option that is optimal for the 3D Scanning System. The information gathered here will allow for an increase in the efficiency of the system, potentially reducing the latency between point cloud generation and production of the 3D image.

3.3.1 Why use wireless technology?

Implementing wireless technology in the 3D Scanning System allows for more overall flexibility for the user. A system that requires a direct connection to a desktop or laptop increases the amount of constraint on the overall use of the product. Especially, a 3D Scanning System, that can sometimes have very lengthy durations, which makes it unpractical to have the system directly connected to the user’s device of choice. In addition to this, the size of the system would be a big eye sore to users and potentially inhibit them from directly using their desktop/laptop. Lastly, wireless technology, such as Wi-Fi or Bluetooth are more consistent in terms of compatibility between different devices and are found in all modern PCs. With recent advances of USB technology, some devices no longer support the traditional USB 3.0 and have transitioned to only USB 3.1 or as it is more commonly referred to as USB Type-C. Therefore, implementing wireless technology in our system allows for increased compatibility due to the consistent adoption of both Wi-Fi and Bluetooth technologies.

3.3.2 Wi-Fi Direct

Wi-Fi allows for local area networking with devices that are compliant to the IEEE 802.11 standards. It is a trademark under the Wi-Fi Alliance, which restricts the usage of calling a device Wi-Fi certified. It is necessary to be part of the Wi-Fi alliance in order to be certified by having a product tested by them. Typically Wi-Fi operates at around 2.4 GHz in the ultra high frequency band and 5 GHz in super frequency industrial, scientific and medical (ISM) radio bands.

While Standard Wi-Fi is has been widely adopted across the globe, its counterpart of Wi-Fi Direct, formerly known as Wi-Fi peer-to-peer, is known and used by few. Wi-Fi Direct offers the similar data transmission rates as Standard Wi-Fi, however this is accomplished without the use of an access point. Therefore, Wi-Fi Direct allows the transmission of data from one device directly to another similar to the likes of Bluetooth or NFC.

Wi-Fi uses network protocol specified by the IEEE 802.11 standard and follows the Open System Interconnection (OSI) model for network communication, which specifies communication layers with different protocols. Each layers packs or transforms specific data until the data payload is delivered. The lowest layers consist of the data link and the physical layer, which assigns unique address to devices such that information packets can be transmitted and received reliably. This also allows for multiple connections.

Wi-Fi Direct offers data transfer speeds ranging from 100 to 250 Mbps (Megabits per second). This is extremely useful for systems that require mass data transmissions at optimal rates. Systems that implement video streaming for instance benefit greatly from the potential speeds achieved with Wi-Fi Direct. The Open System Interconnection model can be seen in the figure below.

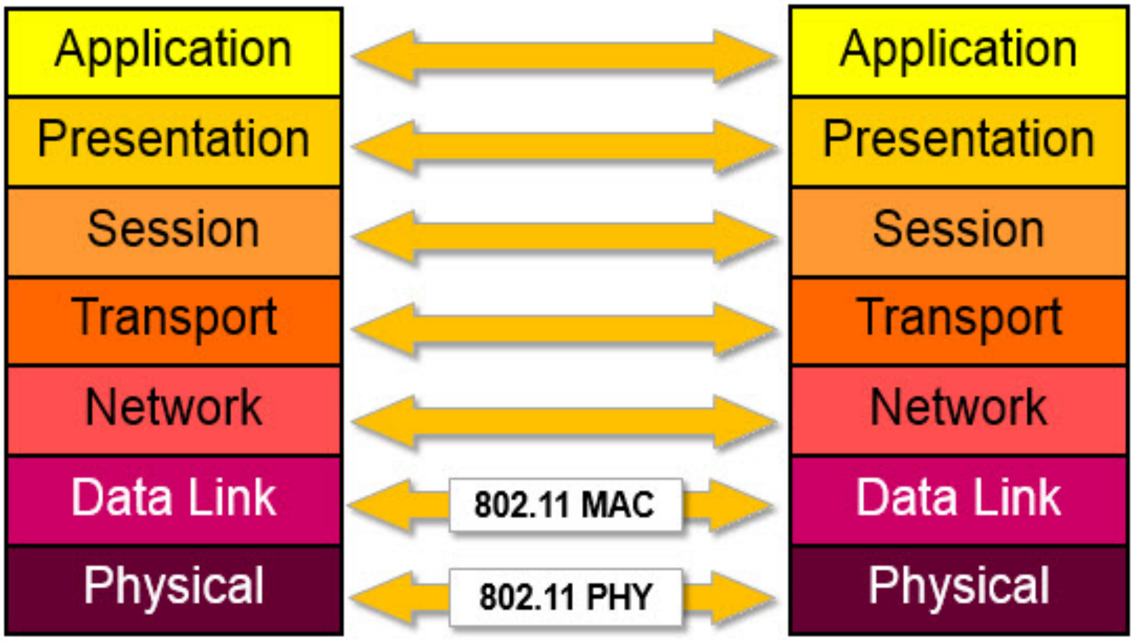


Figure 12: Open System Interconnection Model (permission pending from CWNP)

In addition to its strong data transmission rates, Wi-Fi Direct is also capable of transmitting to devices that are within a range of approximately 200 feet. Although useful, this comes at a cost of increased power consumption and decreased battery life. This may be a deciding factor, depending on the strength of the battery used in the system.

An additional feature to take into account is the security of the technology. Depending on the use of the system, security may be instrumental in the affectivity of the application. Wi-Fi Direct provides a high level of security, using 256-bit encryption, which exceeds the requirements of most uses. While it can provide security, interference from other signals and devices can be problematic. The more access points clustered in a single area the more likely the signal to noise ratio will increase and cause degradation of the signal being transmitted.

3.3.3 Bluetooth Classic

Much like Standard Wi-Fi, Bluetooth Classic has been widely adopted and can be found in almost all cell phones across the globe for the many years. Bluetooth Classic offers a direct transmission that bypasses the need for an access point shared by devices. Bluetooth utilizes short wavelength ultra high frequency radio waves that are in the industrial, scientific and medical (ISM) radio bands. The ISM band ranges from 2.5 to 2.485 gigahertz. Bluetooth utilizes a packet-based protocol with a master-slave structure. Essentially, the packet switching groups all of the data being transmitted into blocks composed of a header and payload. The master-slave protocol is a device or process that gains unidirectional control over one or several devices. A typical Bluetooth master/slave topology can be seen in the following figure where multiple slaves can connect to one master, but a master can be linked to many slave connections.

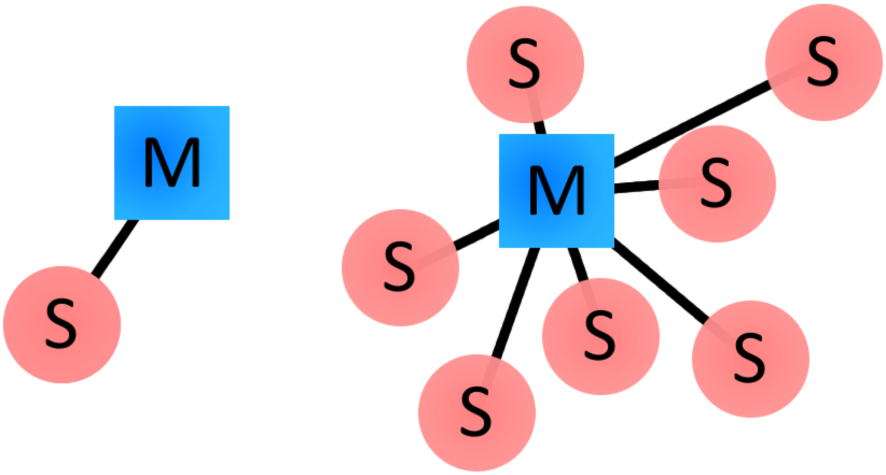


Figure 13: Bluetooth Topology (used with permission from Sparkfun)

Bluetooth Classic is capable of reaching transmission speeds of an almost miniscule 2 to 3 Mbps. Although incapable of streaming video with any decent quality, these transmission rates are sufficient for the likes of streaming audio. This can be found implemented in many automobiles, allowing users to stream music from cell phones to the automobile’s sound system. In order to send packets, Bluetooth uses a modulation technique called frequency-hopping spread spectrum. This allows signals to be transmitted by switching a carrier signal across many frequency channels. Both channels must be common and known between the transmitter and receiver for it to work. The primary advantages of spread-spectrum transmission are that signals become highly resistant of narrowband interference by spreading out the interfering signal through recollection, causing it to fade into the background. The other advantage is that spread-spectrum transmissions can share a frequency band with numerous types of transmissions signals with minimal interference and as a result the bandwidth usage efficiency increases.

Bluetooth Classic offers a maximum range of connectivity of approximately 50 feet. This, however, allows for a much longer battery and vastly reduced power consumption compared to the likes of Standard Wi-Fi or Wi-Fi Direct. With Bluetooth Classic, there are various transmitters that offer different ranges of connectivity. Class 2 transmitters, found in the majority of Bluetooth devices, support a 50-foot range, however, their class 3 counterparts are capable of reaching distances of around 300 feet.

3.3.4 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is essentially a more energy efficient alternative to Bluetooth Classic, offering the same range of transmission, while compromising transmission speed for decreased power consumption and extended battery life. BLE transmits data at a rate of 1 Mbps, significantly less than Wi-Fi Direct and about ⅓ that of Bluetooth Classic. This is because BLE is not meant for systems that are constantly transmitting data; rather it is focused on systems that transmit small amounts of data intermittently such as temperature readings.

In regards to power consumption, BLE operates at an extremely strong efficiency. Primarily developed to run on small, single watch batteries, BLE devices are capable of operating for approximately one to two years on a single battery. Since the device is meant for systems that are only transmitting data intermittently, the device is idle for the majority of the time thus allowing this increased battery life and decreased power consumption.

3.3.5 Comparison and Assessment

Outside of battery life and power consumption, it is very clear that Wi-Fi Direct is the clear frontrunner among our pool of technologies. Offering the fastest transmission rate, furthest transmission range and highest encryption level, Wi-Fi direct is an easy choice for many projects. However, the 3D Scanning System requires a wireless transmission channel, which provides a strong battery life, operating with lower power consumption, as there simply isn't space available for a sizeable battery. In addition to this, it is assumed that the receiving device will be in relatively close proximity (within 20 feet) of the 3D Scanner, therefore the range capability of Wi-Fi Direct, though appealing, is well beyond the scope of this project. Being that this Bluetooth system will be used simply for sending a text file consisting of point cloud data, the file size is not expected to exceed approximately 3 MB, depending on the accuracy of the readings. Therefore, the data transmission rates provided by both Bluetooth Classic and Bluetooth Low Energy are sufficient for this project, with a transmission time ranging between one to three seconds. Taking all of these factors into account, the Bluetooth Low Energy is the optimal solution for this project due to its sufficient transmission speed and range, coupled with its exceptional battery life and low power consumption. Being that the 3D Scanner requires very few transmissions, the BLE's idle mode will be extremely beneficial to the project. However, this decision can easily be changed considering that all of the options are aspects of the Raspberry PI 3 Model B microcontroller. If for some reason the Bluetooth Low Energy is not sufficient for the project, the other options can be experimented with. The table below can be used to reference each option based on it’s speed, range, battery life, and encryption in bits.

Table 1: Comparison of Wireless Transmission Technologies

	Wi-Fi Direct	**Bluetooth Classic**	**Bluetooth Low Energy**
Speed (Mbps)	**100 - 250**	2-3	1
Range (ft)	**200**	50	50
Battery Life	Poor	Good	**Very Good**
Encryption (bits)	**256**	128	128

3.4 Microcontrollers

Being that the 3D Scanning System is one that is heavily software dependent, the microcontroller selected will serve as a key component in the effectiveness of the system as a whole. The system will use one microcontroller to handle all operations. This includes controlling the motors used for movement of the platform, the output of the laser, and the processing of the point cloud data. In handling the point cloud data, the microcontroller will need to implement several open source libraries, typically available only on desktop operating systems. However, with the advent of newer 32-bit microcontrollers, these previously desktop restricted capabilities have now been extended to modern day microcontrollers. This is accomplished without compromising the cost and size of microcontrollers, which give them an edge in embedded systems over desktop computers. Therefore, sufficient memory will be needed to store the operating system, as well as the aforementioned open source libraries.

To achieve a visual representation that is comparable to the actual object that is scanned, the system requires a certain level of accuracy. To accomplish this, several thousand points must be generated before being processed and meshed into a 3 dimensional image. To handle the reception and processing of these points, the microcontroller chosen requires a strong clock rate, as well as RAM (Random Access Memory) to store a vast quantity of points. Sufficient RAM also allows the option of meshing the point cloud data on the microcontroller and sending this image via Bluetooth to the user, as opposed to sending a file with the point cloud data to the user, and having the data meshed and the image generated on the user’s end.

With such a vast amount of microcontrollers available, there are several that are capable of accomplishing the aforementioned tasks. The selected microcontroller, however, must be capable of accomplishing said tasks, while not exceeding our overall budget of $500. Though tempting to select one of Texas Instrument’s microcontrollers, due to familiarity from previous coursework and accessibility on campus, this series doesn’t meet the necessary requirements. The team’s primary options then consisted of the Arduino series (used in several projects similar to this), the Raspberry Pi (extremely popular among developers) and the BeagleBone (also popular among developers). Research was done among the different series, assessing their various performance levels and features in comparison to their cost and usability.

3.4.1 Arduino

Unlike some of the team’s other embedded computing options, the Arduino is in fact a microcontroller. For the 3D Scanning System, team explored their most popular board, the Arduino UNO. It can be programmed in C, but it lacks the capability of loading and running an operating system like some of the systems in consideration. Despite this, the Arduino’s user friendliness makes it a very viable option for the 3D Scanning System. It is useful for prototyping, as it easy to connect LED’s, sensors and motors directly to the board. It also operates at 5V, the intended voltage for the system, and has 14 digital I/O pins allowing for a lot of input/output potential. The core of the Arduino UNO is the ATMega3280P microcontroller, which features 2KB of SRAM and 32 KB of Flash Memory. This relatively limited memory changes the scope of the system, in that the microcontroller would not be able to store tens of thousands of points prior to transmission to the user. The system would instead need to implement a semi-real time stream of the point cloud data, sending the data via the chosen wireless channel. The frequency at which this data is sent can be derived from the following formula.

$$\frac{\text{amount of points}}{\text{time}} \times \frac{\text{amount of bits}}{\text{point cloud}} = \frac{\text{amount of bits}}{\text{time (sec)}}$$

This frequency would be dependent on the transmission speed achievable by the selected wireless transmission technology; for instance, the maximum frequency via Bluetooth Classic would be 2-3 Mbps (Megabits per second) as opposed to the 100-250 Mbps via Wi-Fi Direct. Despite a limited 16 MHz processor, priced at $20 and with a user-friendly board, the Arduino UNO remains a suitable option for the 3D Scanning System. One thing to note is that the Arduino is highly compatible with the stepper motor driver board and stepper motor that will be used in this project. There are countless examples and references on the World Wide Web for programming the desired stepping of the stepper motor using the

Arduino. This project is software intensive, so anything to alleviate some of the programming load is valuable for the software team.

Figure 14: Arduino Uno Board (used with permission form DIYGADGET)

3.4.2 Raspberry Pi

Introduced in 2012, the Raspberry Pi is not in fact a microcontroller; it is actually a miniature computer. This embedded computing platform has served as the most popular platform among the development community. The two models of the Pi in consideration are the Pi Model A and the Pi 3 Model B. The Pi Model A is the lesser of the two models, featuring a $25 price point to go with its “credit card” sized, 3.4 x 2.1 inch build. This size is ideal for maintaining a small overall build of the 3D Scanning System. Sporting a 700 MHz Low Power ARM1176JZ-F S ARM 11 Processor, coupled with 256 MB of RAM, this mini computer is among the aforementioned embedded computing platforms capable of running desktop operating systems, typically Linux. Also useful is its 8 General Purpose Input Output pins, allowing for support of the necessary external device control. Operating at modes of 3.3V and 5V is also beneficial, as 5V is the intended voltage for the system. The newer of the two, the Pi 3 Model B was introduced in February of 2016. The model features a big upgrade from its counterpart with a very powerful 1.2GHz 64-bit quad-core ARMv8 Processor, 1GB SDRAM and 32 more GPIO pins, at only a $10 increase in price. The Pi 3 also has native support of Bluetooth Classic 4.1, as well as Bluetooth Low Energy, both of which will serve essential in implementing wireless transmission of data. The only compromise between the two models is the increased power consumption and size (4.8 x 3 in) in the Pi 3, but despite this, both models remain suitable options for the 3D Scanning System.

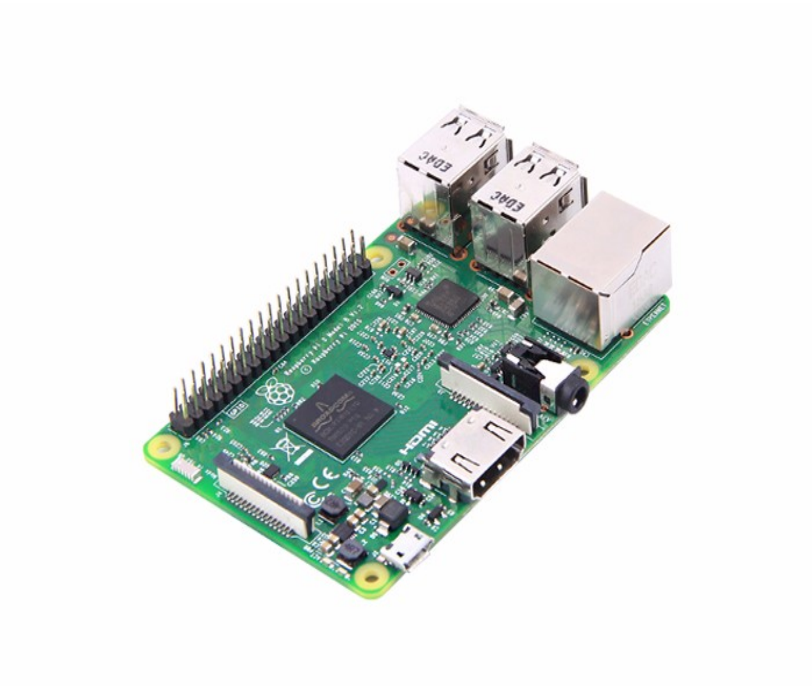


Figure 15: Raspberry Pi 3 Model B (used with permission from SeeedSTUDIO)

3.4.3 BeagleBone

Similar to the Raspberry Pi, the BeagleBone Black is actually a mini computer as opposed to a microcontroller. Backed by another large development community, the BeagleBone Black serves as another viable option for the 3D Scanning System. At $53 the BeagleBone Black is a $28 increase from the Raspberry Pi Model A and an $18 increase from the Raspberry Pi Model B. This price difference doesn’t come without additional benefits, however. Though a decrease to a 512MB DDR3L DRAM, the BeagleBone features 4GB 8-bit eMMC on-board flash storage. This allows the ability to not only load Linux, but also boot it under 10 seconds, reducing the overall latency of the system. In addition to this, the BeagleBone Black sports an AM3358 ARM® Cortex™-A8 processor at 1 GHz which is an improvement from the Raspberry Pi Model A, but decline from the Raspberry Pi 3 Model B. With its 3D graphics accelerator, the BeagleBone is capable of over 3 million Dhrystone operations per second and vector floating point arithmetic operations. This is beneficial to the 3D Scanning System as it is capable of interfacing with 3D cameras and also running image collection and analysis software such as OpenCV. With 65 GPIO pins, the BeagleBone Black provides the 3D Scanning System with a lot of input/output potential.

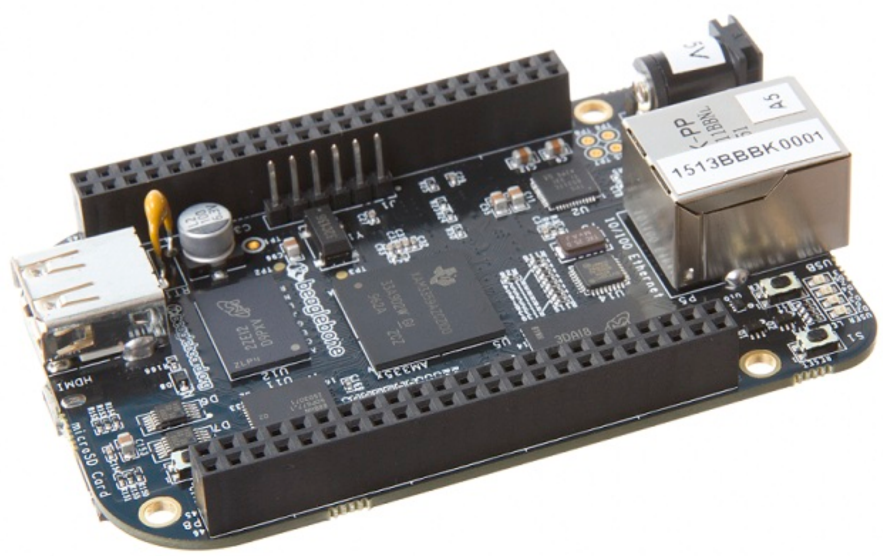


Figure 16: BeagleBone Black (permission pending form ELinux)

3.4.4 Microcontroller Statistical Comparison Tables

The following section offers an in depth comparison of the three embedded computing systems that were considered. The three will be assessed in direct relation to the 3D Scanning System, focusing on criteria of power consumption, cost, memory, input/output potential and clock rate.

3.4.4.1 Power Consumption

To keep the 3D Scanning System within reasonable size, our power source can't be excessively large in terms of physical size. This constraint in size also results in a constraint on the strength of the power source. As a result, the power consumption of each device must be taken into account as to not exceed the capabilities of the source.

Table two shows that the Arduino UNO is the top option in regards to power consumption. This doesn't come as a surprise, however, due to the peripherals included with the other options. The Raspberry Pi 3 Model B, for instance, offers both Wi-Fi and Bluetooth support. If these modules are on and running, the power consumption of the Raspberry Pi 3 will increase as a result. Another important thing to note is the operating voltage of each system. It is imperative this voltage is around 5 V as this is the intended operating voltage for the system. Luckily, all of the options in consideration meet this requirement, and don't need to be ruled out as a result.

3.4.4.2 Cost

The team's goal is to keep the overall cost of the system as low as possible, under $500 to be exact. This is to be accomplished without compromising the quality of the finished product. Therefore, although the most cost effective option is appealing, the selected microcontroller must offer a mix of both cost efficiency and functionality.

From Table two it is very clear that the Arduino UNO is the cheapest option. Selecting this option would allow for 9.5% or $20 decrease in overall budget, allowing more resources to be allocated elsewhere where they may be deemed necessary. The Raspberry Pi Model A is only $5 more expensive than the Arduino, simply 2.4% difference in overall budget percentage. A more significant price increase is seen between the Raspberry Pi 3 Model B and the BeagleBone Black, with the Raspberry Pi 3 Model B being $10 more expensive than its predecessor. The BeagleBone Black, however, ranges from being over 1.5 to 2.5 times the cost of the other options. This vast increase in price, not maintaining within the team's budget, may be potentially hard to justify with the Raspberry Pi 3 Model B offering similar performance.

3.4.4.3 Memory

The amount of memory provided by the selected microcontroller plays an influential role in the overall implementation of the system. Some of the microcontrollers in consideration have enough memory to run operating systems. This changes the team's entire approach to the problem as different types of software and libraries are able to be ran onboard the microcontroller. This creates the potential of both processing the point clouds and generating images onboard, then displaying them directly to some display as opposed to needing to send the point clouds to the user's desktop or laptop, and having them generated there.

Table two further illustrates the negatives of the Arduino UNO in relation to the miniature computers in the group. Selecting the Arduino UNO would rule out several of the available software in consideration due to its inability to run them as a result of its miniscule 2KB RAM. The Raspberry Pi 3 Model B on the other hand is the clear front-runner in this category. Its 1 GB of SDRAM vastly expands the potential of the project. Though this is still possible with the 256 MB by the Raspberry Pi Model A, this is not to the extent of the Raspberry Pi 3 Model B as the possibilities are much more limited. Another thing to be noted that is not presented in the table, is the BeagleBone Black's 4 GB of onboard storage, which makes up for the decrease in RAM between its 512 MB and the 1 GB of the Raspberry Pi 3 Model B.

3.4.4.4 Input/Output Potential

Input and output potential are other significant attributes to be taken into account in the selection of the team's microcontroller. Being that the microcontroller serves as the core of the overall system, controlling devices such as the motor, camera and laser, connectivity and compatibility hold significant weight in the team's final selection.

Table two shows that the BeagleBone Black is the clear frontrunner in terms of Input/Output Potential. Another advantage of the BeagleBone Black and the Raspberry Pi 3 Model B, not mentioned in the table, is their inclusion of both USB 3.0 and HDMI ports. This will serve extremely useful in allowing the team to expand options for selecting a camera and display tool (i.e. LCD screen) due to this increased compatibility and connectivity. The GPIO Pin Count of the Raspberry Pi Model A is significantly less than that of its counterparts, to the extent of almost ruling it out completely from consideration.

3.4.4.5 Clock Rate

Clock rate serves as an important measure due to the vast amount of calculations required by the system. An insufficient clock rate will result in a significant increase in the overall time of the system. If the time becomes too excessive, less point clouds would need to be recorded in order to reduce this duration. Taking this measure, however, would result in an overall decrease in the quality of the final image generated, due to the decrease in 'point cloud density'. Therefore, in order to meet the team's image quality standard, a sufficient clock rate is required to achieve this.

Based on the information presented in Table two, it is blatant that the Arduino UNO is incredibly lacking in this category. Its 16 MHz clock rate, ranges from being 43.75 to 75 times slower than its counterparts. This difference alone would have a significant impact in the overall speed of the system and quality of the images produced. The difference is large enough, in fact, to rule the Arduino UNO out from consideration. The Raspberry Pi 3 Model B leads the group in this category with its 1.2 GHz clock rate. Although the Raspberry Pi Model A's 700 MHz clock rate is slightly over half of its successor, this clock rate is still sufficient for the 3D Scanning System.

3.4.5 Microcontroller Selection

Table 2: Microcontroller Spec Comparison

		Arduino UNO	Raspberry Pi Model A	Raspberry Pi 3 Model B	BeagleBone Black
Power Consumption	**Operating Voltage (V)**	5 V	5 V	5.1 V	5 V
	DC Current (mA)	46.5 mA	500 mA	1000 mA	1200 mA
	Power Consumption (mW)	232.5 mW	2500 mW	5100 mW	6000 mW
Cost	**System Price ($)**	$20	$25	$35	$53
	System Price Increase (%)	-9.5%	-7.15%	-2.4%	6.19%
	Budget Percentage (%)	9.5%	11.9%	16.7%	25.2%
Memory	**RAM**	2 KB SRAM	256 MB SDRAM	1 GB SDRAM	512 MB DDR3
I/O Potential	**GPIO Pin Count**	14	8	40	65
Clock Rate	**Clock Rate**	16 MHz	700 MHz	1.2 GHz	1 GHz

Each of the previous sections illustrate that the Arduino UNO simply does not compare to the other embedded computing systems in consideration. Outside of being the most cost effective option, the Arduino was significantly inferior to the other systems in every other category, especially memory and clock rate, which frankly justifies its low price point. The Arduino serves as a suitable option for small projects, however, for one of this scope and nature, the Arduino is simply incapable of executing the tasks necessitated by the 3D Scanning System. One of the major drawbacks is its inability to run external software or libraries due to its limited memory. Being that there are many tools available, which aid in streamlining the 3D scanning process, a restriction of the tools further complicates the project to one that is outside the scope of this class.

Having ruled out the Arduino UNO, the three remaining systems in consideration were the Raspberry Pi Model A, the Raspberry Pi 3 Model B and the BeagleBone Black. All of these systems are suitable options of the 3D Scanning System, however two of them clearly stand out from the other. The Raspberry Pi Model A offers similar capabilities to the other two, however on a much more limited scale. Similar to the Arduino UNO, it is more cost effective than its two counterparts, however, it simply offers a fraction of the performance. This is evident when examining both its Input/Output potential, memory and clock rate. Another limitation of the Raspberry Pi Model A is its limited connectivity and compatibility in comparison to the other models. The Raspberry Pi Model A features a single USB Connector as opposed to the 4 provided by its successor. In addition to this, it also lacks the built in Bluetooth Low Energy and Wi-Fi capabilities offered by the Raspberry Pi 3 Model B. Though this is to be expected with a newer, more expensive model, these additional features vastly outweigh the $10 increase in price.

Upon ruling out the Raspberry Pi Model A, only two choices remained, the Raspberry Pi 3 Model B and the BeagleBone Black. Both of these options are extremely powerful embedded computing systems, more than capable of fulfilling the tasks at hand. In comparing them, however, the first thing to note is the price point. The BeagleBone Black is 1.5 fold more expensive than the Raspberry Pi 3 Model B, exceeding the team’s microcontroller budget by 32.5%. Though this price increase can be compensated elsewhere, the Raspberry Pi allows for more budget flexibility in the selection of other parts due to its reasonable price point. The BeagleBone’s 4 GB of onboard storage however saves the need of a sizeable micro SD card, which the Raspberry Pi would require, so this to an extent makes up a portion of the difference in price. Due to their extensive memory, both systems are capable of running operating systems, as well as other software and libraries, which is instrumental for the 3D Scanning System. The Raspberry Pi provides 1 GB SDRAM, which is twice as much as the BeagleBone’s 512 MB, allowing for a decrease in latency and faster processing. With onboard HDMI ports, both systems allow images to be processed and generated onboard then visualized through a directly connected display such as an LCD screen. One of the major advantages of the Raspberry Pi, however, is its wide adoption and extensive developer community. With many references and resources available, the development process becomes much smoother, especially with those concerning the popular Raspbian, a distribution of Linux built specifically for Raspberry Pi. Reducing time spent on troubleshooting, allows the team more time to focus on building the highest quality product. Therefore, backed by a strong developer community, coupled with its superior clock rate, memory, price point and built in Bluetooth Low Energy support, the Raspberry Pi 3 Model B arose as the best microcontroller option for the 3D Scanning System.

3.5 Image Calibration & Processing Software

In optics, there is no such thing as a perfect lens. Generally, a lens can only be designed to minimize aberrations and distortions, but never to completely eliminate them. This simple fact poses an issue for any type of precision camera-based scanning: aberrations stemming from the camera's focusing optics will yield inaccurate position measurements unless this problem is addressed. The degree of inaccuracy due to aberration can vary greatly within a single image depending on the position of a data point within the camera's FOV. Our scanning system will derive the positions of data points in real space directly from each data point's address within the image's pixel matrix, so we must ensure that the pixel addresses accurately reflect their positions in real space. In other words, aberration must be eliminated to meet our submillimeter precision goals.

The most widely known type of aberration is perhaps barrel distortion, more colloquially referred to as the fisheye lens effect. It can be observed in GoPro products and other imaging systems that make use of wide-angle lenses. This effect can be seen in the figure below.

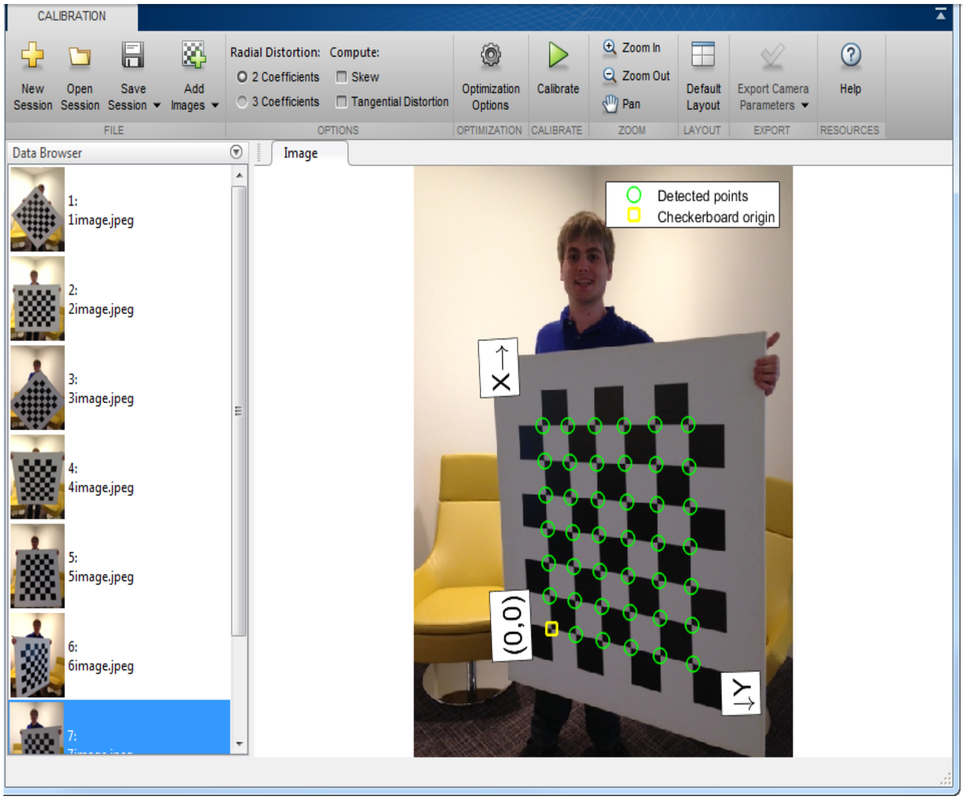
Figure 17: Barrel Distortion or Fisheye Effect (permission pending from MathWorks)

Distortion is merely one of five major spatial aberrations present in all lenses. Spherical aberration, coma, astigmatism, and field curvature will also contribute to discrepancies between image space and real space, so the problem cannot simply be sidestepped by avoiding the use of wide-angle lenses in our system's focusing optics.

As it turns out, the most practical and cost-effective way to combat lens aberration is to use software calibration to correct the image. Popular licensed and open-source software packages will be considered in this section so that we can deal with the issue as necessary.

3.5.1 MATLAB Calibration App & Image Processing Toolbox

MATLAB's Single-Camera Calibration App offers an intuitive GUI with built-in functions that simplify the calibration process to a large extent. Calibration can be performed with a live video feed, or with a minimum of seven imported images that show a checkerboard pattern of known spacing viewed from various angles as seen in the figure below.



Radial Distortion: ● 2 Coefficients ○ 3 Coefficients

Compute: ☐ Skew ☐ Tangential Distortion

Figure 18: MATLAB's Single-Camera Calibration App (permission pending from MathWorks)

If the checkerboard images fed into the calibration algorithm meet the input parameters, the algorithm scans the checkerboard pattern for apparent inconsistencies in spacing that can be attributed to aberrations. It subsequently derives from those inconsistencies a complete numerical description of the aberrations called Seidel coefficients, which are used to map the distorted image to a non-distorted space.

These coefficients do not change for a given camera, so once these parameters are obtained, they can be exported to the MATLAB workspace as an object. This object can be used for the camera in all future tasks to correct aberrations, so the calibration process does not need to be performed more than once unless another camera is used or the lens system is altered.

Another convenient feature of this app is that it offers error estimates on the corrections it makes. The error values can also be exported as an object and used in future distance calculations and 3D modeling. One drawback of this app is that your camera must be physically connected to a computer capable of running MATLAB in order to work. If the exported calibration object can be used in a script on a standalone microcontroller, the physical connection can be avoided. Even if this makes MATLAB unsuitable for the final product, it will certainly be helpful in the prototyping phase due to user-friendly GUIs and an abundance of other convenient features.

3.5.2 OpenCV Camera Calibration & Image Processing

OpenCV is a popular open source image-processing platform capable of most functions available in the MATLAB Single-Camera Calibration app. The most obvious advantage of this software over MATLAB is that it’s free to download and use. Another significant advantage of this open source software is that it can be directly installed for standalone use on a Raspberry Pi microcomputer module.

Not only can OpenCV be used to perform camera calibrations with any USB webcam interfaced with a standalone Raspberry Pi, but it can also execute the image processing algorithms necessary to reduce the volume of data being passed from the microcontroller to various other subsystems. For example, the camera’s raw output is an RGB image, containing three different color channels for each pixel in an image. Each of those channels will store an intensity value between 0 and 255 for each pixel. For the CMOS sensor array dimensions we are considering necessary for quality scans, this will produce an image occupying roughly 1 MB of data, with each scan requiring potentially a few hundred such images (say, one for each degree of the full 360º turntable rotation) to obtain a proper three-dimensional resolution.

Although MATLAB is our ideal tool for image processing, it cannot be run on a microcontroller. This means that if MATLAB were to be used as our tool for processing images and extracting point cloud data, hundreds of MB would need to be wirelessly transmitted to a computer powerful enough to do that processing. To avoid wasting precious bandwidth in this manner, OpenCV installed natively on a Raspberry Pi microcomputer can be used to break down the image into a point-cloud .txt file before passing it via Bluetooth to a computer capable of meshing together a 3D rendering. This process is laid out in the figure below.

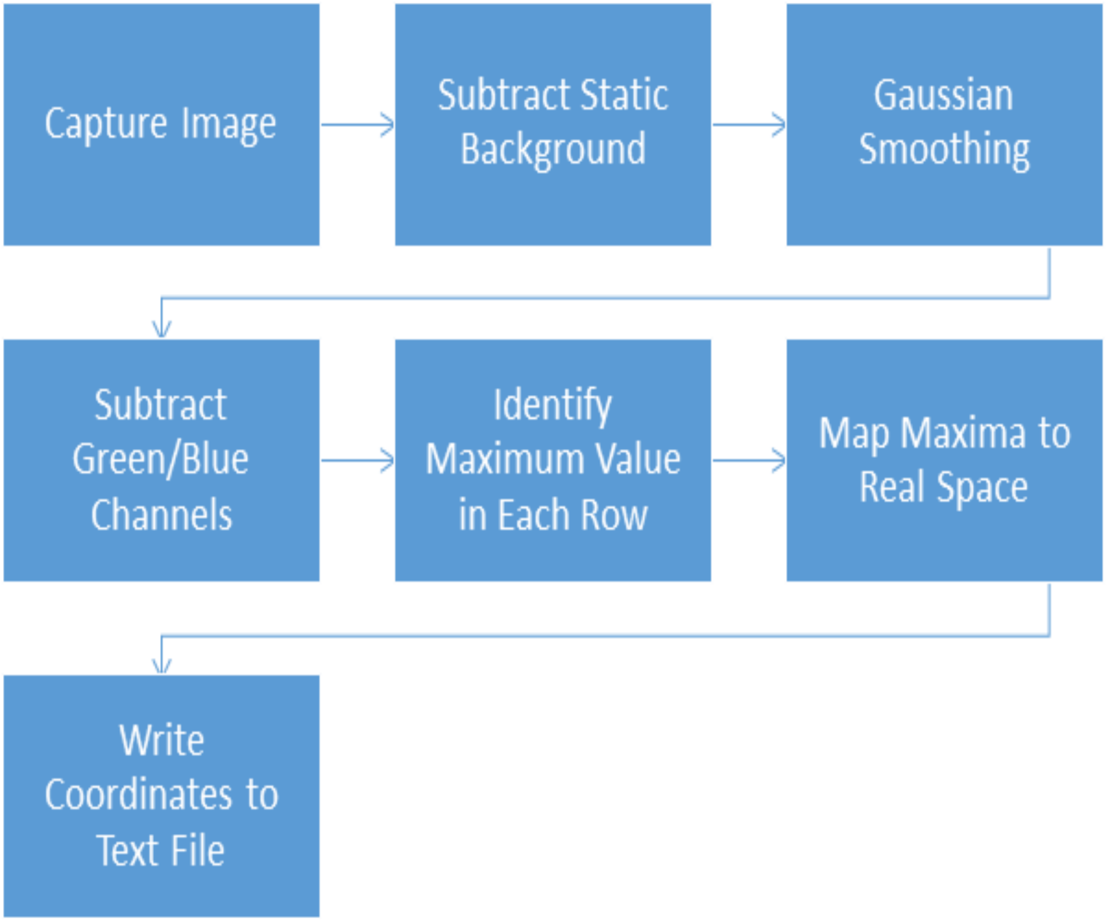


Figure 19: Image Processing Algorithm Pipeline

This is by far the preferable solution for our image processing needs, because it minimizes the volume of data transmitted and eliminates the need for the user to purchase MATLAB software to run image-processing scripts.

3.5.3 Point Cloud Library (PCL)

To begin with, a point cloud is essentially a three-dimensional (x,y,z) coordinate. The Point Cloud Library is a large, open source project that builds on this idea, offering a ton of libraries expanding on image and point cloud processing. Being that it is open source, PCL is free for both commercial and research use, clearly fitting within the team's budget. PCL is cross-platform and can be compiled and deployed on Linux, which is extremely useful as the intended operating system for the Raspberry Pi, will be Raspbian, a distribution of Linux built specifically for Raspberry Pi. The entire library is divided into a set of smaller libraries several of which could be instrumental to the 3D Scanning System. The I/O library contains and algorithms for both reading and writing point cloud data. In addition to this, the library has functions for capturing point clouds as well. It should be noted that PCL mainly operates using its own PCD file format, which is optimized for PCL use, however other more common file formats are supported as well. The Visualization library allows users to quickly visualize the results of algorithms operating on 3D point cloud data. The surface library provides users the ability to reconstruct surfaces from 3D scans. This library has classes, which offer smoothing and resampling if the point cloud data is noisy. In addition to this, a meshing class is offered as well, allowing users to create a surface from point cloud data at various qualities, with time as a tradeoff. With libraries capable of capturing, reading, and writing point cloud data, as well as rending images from these points, the Point Cloud Library could serve as a useful tool for the project. One of the key selling points for this library as a whole is the capability of storing and processing point cloud data onboard. Implementing this library, allows all the processing to be done on the microcontroller, only sending a rendered image via Bluetooth to the user and or showing a visual on some type of directly connected display. This essentially makes the entire system, as embedded as possible.

3.6 Camera Technologies

When building an imaging system, the most fundamental aspect to consider is which type of sensor array is suitable for the job. Charge Coupled Devices (CCDs) and Complementary Metal Oxide Semiconductors (CMOS) are the two options from which to choose, and each pose strengths and weaknesses depending on the situation. Sensor arrays can be seen in the figure below.

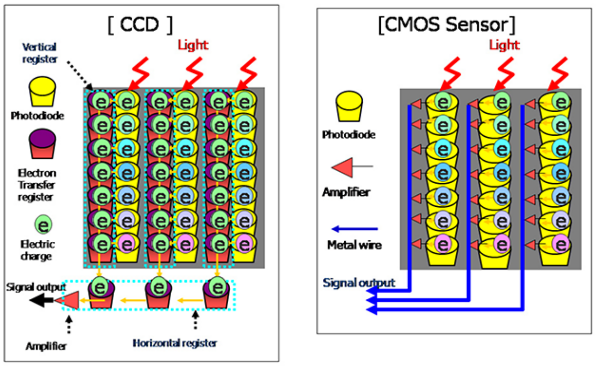


Figure 20: Structures of CCD and CMOS Arrays

CCDs are superior to CMOS sensors in terms of noise reduction and sensitive low-light applications. If extreme image clarity and detail are desired for an application, CCDs will win out over CMOS sensors almost every time. Consequently, CCD cameras are found in optics research labs and expensive custom lens systems far more often than their CMOS counterparts.

That being said, the opposite is true in consumer electronics. CMOS sensors reign supreme in the consumer domain because they are easier to manufacture, are much faster at actually producing images, and they draw significantly less power than CCD arrays. Because our imaging will take place in an illumination-controlled environment where high contrast and favorable lighting are guaranteed, CMOS-based cameras are the logical option for our scanner. Inexpensive CMOS cameras with built-in focusing optics are abundant and easy to obtain, so only CMOS cameras will be considered in our search for a proper sensor array. Below is a table that compares several CMOS cameras that are being considered for this project.

Table 3: Camera Comparison

	UCAM-II Serial Camera Module	**Sparkfun CMOS Camera Module**	**Adafruit TTL Serial Camera Module**	**Raspberry Pi 5MP Camera Board Module**
Pixel Array	696H x 496V	728H x 488V	680H x 480V	2592H x 1944V
Pixel Size	5.5μm x 5.5μm	6.35μm x 7.4μm	5.6μm x 5.6μm	1.4μm x 1.4μm
Sensor Type	CMOS	CMOS	CMOS	CMOS
Voltage Requirements	4.5V - 9.0V	6V - 20V	5V	N/A
Price	$49.99 + shipping	$31.95 + shipping	$39.95 + shipping	$22.59 + Shipping

3.7 Display

Since the microcontroller converts the laser profile data into a point cloud representation, in order to view the point cloud, three options are considered. Placing a tablet onto the containment unit of the scanner would allow a quick visual representation that can be fully integrated onto the product via Bluetooth or

USB. Another option for the display unit is to process the point cloud on the microprocessors and send a processed image via Bluetooth to a phone. Lastly, the processed data can be pushed to a computer connected via a cable to the unit to visualize the point cloud formation on a laptop screen. In order to fit the project constraints the tablet has to be small enough to fit on the containment unit of the scanner. Two tablets are considered that are both small and inexpensive enough to meet the budgetary requirements of the project. The first tablet is the Nexus 7 (2013 model) and the second being the Samsung Galaxy Tab 7.

In choosing the displays, there are several things that must be considered with respect to the design constraints and project specifications. Primarily, the size and weight of the display is of upmost concern, in order not to be too large or heavy to affect the overall design. The display primarily will be the interface between the underlying hardware and software system that can interact with the user and other user based tools such as connecting via Bluetooth to a phone.

3.7.1 Nexus 7

The Nexus 7 is a tablet manufactured in partnership between Google and Asus. It uses the linux kernel to run the Android operating system. The tablet runs on an open source derivative that is rootable, which means that an extensive community is present. This is an ideal situation because there will be a lot of documentation and material for unknown corner cases for integrating the tablet onto other projects. This allows for seamless adaption and integration on to new projects. Furthermore, the Nexus 7 boasts great specs for the size and form factor. The tablet itself weighs 340 grams and is 10.5 millimeters thick. It has integrated 1GB of NVIDIA Tegra 3 RAM with a storage capacity available of either 8/16/32GB. The Nexus 7 also has an integrated ULP GeForce GPU with Quad-core 1.2GHz Cortex-A9 CPU. The most important aspect of the tablet are the modes of communication and operating life. The tablet comes with a 4325mAh lithium ion battery and supports Wi-Fi and Bluetooth 3.0. The battery life is rated for up to 10 hours of multimedia playback, which is ideal for portability.

3.7.2 Samsung Galaxy Tab 3 7.0

The Samsung Galaxy Tab 3 7.0 is a small, 7-inch tablet that weighs 306 grams, is 9.9 millimeters. The original release date was in April 2013 and runs on Android. The Tab 3 chipset technology for the RAM is 1GB Marvell PXA986 running a dual-core 1.2GHz Cortex-A9 and a PowerVR SGX540 integrated GPU. The internal memory is only available in two options: 8GB or 16GB of storage and has 1GB of RAM. Fortunately, there is a dedicated slot of additional memory storage using a microSD of up to 64GB. The tablet has a non-removable 4000mAh lithium ion battery that provides up to 8 hours of multimedia play back. It also supports Wi-Fi and Bluetooth 3.0. This tablet does not run stock android, as only the Nexus line does, but runs on a more vendor specific Android OS made by Samsung. Due to this, it raises concerns on how configurable the system is and how well it will integrate with the overall project in the event that the Android OS on tablet must be rooted to gain access to other hidden functionalities.

3.7.3 Phone

Another display option is to use an android-based app that can be downloaded from the Google play store. This option would allow for better portability as it could be used on an android device. A phone would allow a user to leverage their existing applications to download and share the images processed by the device over mobile data assuming their is no local internet. Utilizing a phone as a display system allows the product to shed the use of an onboard tablet. In turn, this allows for a smaller profile of the overall scanner and reduces the amount of power utilized, as the tablet no longer has draw charge from the scanner power system thereby reducing the size of the power unit.

3.7.4 Beaglebone Black Cape LCD

The Black Cape is a small, 4.3 inch LCD screen that is connectable to a beaglebone black microcontroller and can directly interface or programmed such that it can display desired graphics onto the screen. It connects directly to the back of the microcontroller such that it provides the necessary power and display signal through the connection interface. The screen itself features seven different push buttons and two LEDs that show power status and user status. It requires the actual microcontroller to run a compatible Linux distribution to be useable. It also comes with the necessary mounting apparatus as part of its design to ensure easy integration onto a larger system. The compatibility with a Linux based distribution is important due to the fact that it gives more control of the overall device which is important for debugging and proper control of all the functionality. The small size provides a great low profile in terms of the entire project size and a negligible weight increase.

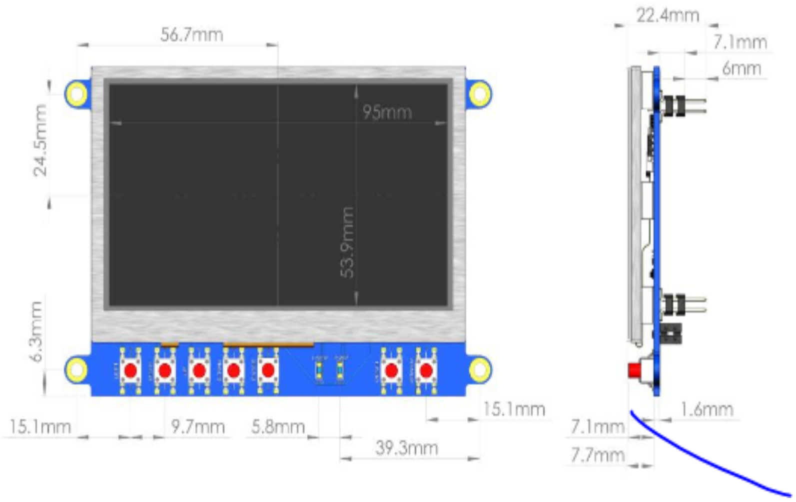


Figure 21: BeagleBone Display (used with permission form Creative Commons licenses)

3.7.5 HDMI 7 Inch 1024x600 Display

The 7 inch display screen is mini panel-mountable HDMI monitor that can be utilized with any HDMI capable device. It comes with a mountable interface so that it can offer easy integration onto any system. It features a TFP401 DVI/HDMI decoder from Texas Instruments that can receive unencrypted video and pipe raw 24-bit color pixel data. The display is ideal for small and embedded projects and devices due to the 1024x600 resolution, which is just enough to be able to run most applications and software. It is useable on Windows, Mac and the Debian flavor of Linux. The most important fact is that can it can run a Debian based distribution, which allows for maximum configurability, as access to the whole system is unrestricted. The display can be powered over a USB and require 500mA to properly work. Another important feature that has to be considered is the overall weight and this display is weighs 106 grams, which is negligible to the overall project weight.

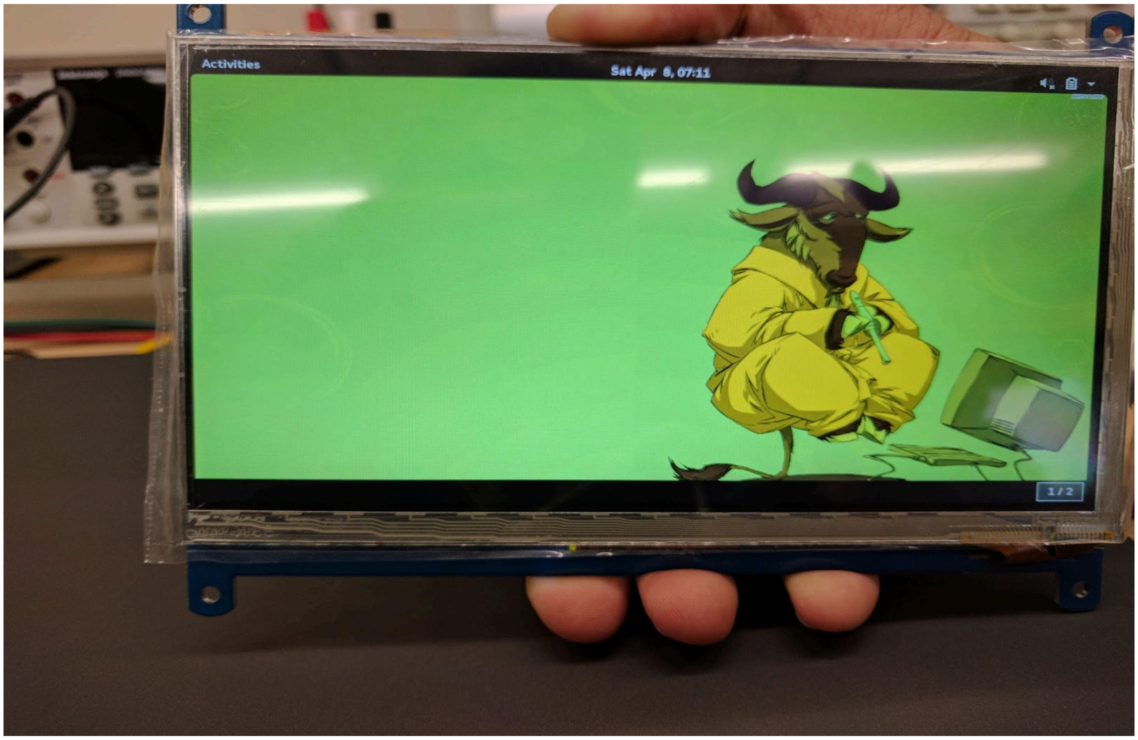


Figure 22: 7 Inch Display

3.7.6 Comparison

An important factor to consider in the display is the portability, weight, and compatibility with the microcontroller and the parts. The tablets and phone display option are good options due to the fact that they do not require power from the product and can be charged separately which reduces the overall complexity and power requirements of the project. Moreover, an onboard LCD/LED screen can be attached to a microcontroller and draw power from it, which allows it to directly interface with it. It is also important to consider the price to utility ratio of the display, for instance, in the following table LCD/LED display somewhere around half the price of two tablets. Furthermore, the tablets and phone come with much more overhead compared to a simple display. There is a lot more extra functionality added to the overall project, but it must be considered, as the project comes together - what deficiencies does the overhead of these functionalities incur?

Table 4: Display Comparison

Display	Nexus 7	Tab 3	Beaglebone LCD	HDMI Display	Phone
Bluetooth	4.0	3.0	N	N	Y
Wi-Fi	Yes	Yes	N	N	Y
Storage	16/32 GB	8/16 GB	N	N	Varies
Price	$110	$122	$65.95	$74.95	Varies

3.8 Materials for Platform

The material of the platform is an important consideration. The material itself can affect the way the entire project runs. The project has various requirements, such as; limited spending, lightweight, portable, safe, etc. It is necessary to weigh the options of materials for building the best platform for the design.

3.8.1 Aluminum

A metallic material that is non-magnetic and lightweight would provide a great a chassis and platform the project. Aluminum has a low density, high corrosion resistance, and is one of the most abundant elements on Earth. Aluminum alloys are used in variety of different areas such as in the transportation, aerospace and computer industries due to its properties. For this project aluminum was considered for making a chassis and platform to house the electronic components much like computer towers can come with aluminum-based towers. The Aluminum sheets would be ideal as thermal heat sink to help dissipate any build of heat from the components when compared to other materials.

3.8.2 Acrylic

Acrylic is a transparent thermoplastic, known by some of the common industry names as Plexiglas. Acrylic is often formed into a lightweight or shatter-resistant sheets that can be used as an alternative to glass. Acrylic comes with many different options for dyes and resins that can coat the surface the sheets to change or enhance certain properties. The use of acrylic, or plexiglass, is an ideal material for building the container and platform for the project. Acrylic is a lightweight, inexpensive material that can be easily shaped and cut. Acrylic is a non-conductive material, making it ideal for housing the electronic parts and creating microcontroller shields. Acrylic is a transparent thermoplastic that is often used as an alternative to lightweight or shatter resistant glass. It is usually transparent, but it can be manufactured in different colors or opacity. It is used in a wide variety of industries due to its strength and versatile properties.

3.8.3 Comparison

The project as a whole is split between platform and the housing unit that contains the platform and the all the electronic components. The building material for the project has to be a lightweight material and has to be easy to work with. For this reason, building material is split between a comparison of Acrylic based materials such as Plexiglass or Aluminum based materials. It is expected that the electronics and the onboard processing of the scanned objects will generate heat. The materials must be resistant to becoming overly warm by dissipated heating fast enough that it is not obviously noticeable.

It must also be configurable as such that adding the necessary ventilation to the project will be simple. Ideally, Acrylic would be the best option for this project due to inexpensive and lightweight properties when compared to the Aluminum. Furthermore, the price of aluminum becomes much more expensive as the thickness of aluminum sheets increases. In the end, it would be much more cost efficient per sheet of aluminum compared to per sheet of acrylic. Aluminum would also be more difficult overall to cut and shape into the required pieces needed to create the platform and chassis. It would require more power tools and effort to make the required forms. Acrylic can be 3D printed in various different size, colors, and textures, depending on the type of acrylic that is purchased for the printing job. There are various 3D printers on the university campus, as well as, in several locations near the campus. While 3D printing can consume hours of time, trying to cut aluminum may take days if a company is contracted to do so in the case that the team does not have in the possession the necessary tools. Lastly, acrylic is not conductive, which is an important factor in regards to the electrical components and their respective functionalities for the project.

Table 5: Comparison of Materials

Material	**Acrylic**	**Aluminum**
Density (g/cm^3)	1.18	2.80
Conductive	No	Yes
Rigidity	Rigid	Flexible
Price (Sheet to Thickness)	Inexpensive	Expensive

3.9 Power System

The power system within an electrical project is of utmost importance to the success of the project itself. The size, weight, overall architecture, electrical ratings, regulation, safety, cycle lifetime, and protection must be considered with grave detail and attention. The more common power supply is the use of batteries. All of the components of this project require different voltages to operate. The project can be powered by multiple batteries or by a single battery with the help of voltage regulators. This section will heavily weigh all of these considerations previously listed for various battery architectures. Batteries can either be rechargeable or not, but this project will be interested in utilizing rechargeable batteries. Common rechargeable batteries are amongst nickel-metal hydride batteries, nickel-cadmium batteries, lead acid batteries, alkaline batteries, and lithium-ion batteries. The electrical components of this project include a Raspberry Pi 3 Model B, 5MP Camera Module, HDMI 7" 800x480 TFT HDMI, Line Laser Module LN-60, Nema 17 Stepper Motor, and an EasyDriver. The camera and LCD screen draw power via the microcontroller. The power system is responsible for powering the microcontroller, laser, and stepper motor driver. These components require 5 volts, 3 volt, and 6 to 30 volts respectively for operation.

3.9.1 Battery Technologies

The most common type of rechargeable battery used in similar projects like this one is the nickel-metal hydride battery. This battery is popular because of its value. It is fairly cheap in relation to its capacity and weight. Furthermore, it hardly has any memory effect, which means that with each charge it will reach its full capacity. However, it’s self discharge rate is quite unfavorable and it is sensitive to overcharging. The nickel-metal hydride battery is very similar to the nickel-cadmium battery given that they both utilize nickel oxide hydroxide. However, instead of using cadmium, this battery uses a hydrogen-absorbing alloy. Also, this battery has much higher energy density than it’s counterpart. Given the same size nickel-cadmium battery, this battery will have up to three times the capacity. Each cell of the battery will charge at around 1.4 to 1.6 volts using a smart battery charger to protect against overcharging. Projects that draw a lot of current use these batteries due to their low internal resistance. The nickel-metal hydride battery is safer and more environmental friendly, because it doesn’t contain toxic materials and can be recycled.

The nickel-cadmium battery has lost its recognition to the popular nickel-metal hydride battery and the lithium-ion battery in more recent years. This can be attributed to its memory effect, causing it to lose its charging capacity if the battery if not correctly charged or discharged. Furthermore, they are more expensive than lead acid batteries due to the materials they are made out of.

They come in all types of sizes with varying capacities. At low temperatures they offer good cycle life and performance. Also, this is the only battery that can be charged quickly without negatively affecting it. The cycle life is the amount of full capacity charges and discharges it is capable of. The discharging rate can be less than one hour, which may not be sufficient for the length of a full 3D scan of a small object. The nickel-cadmium battery can be seen used in medical equipment, power tools, radios, and video cameras. Safety and environmental concerns arise given the toxic cadmium nature of the battery. Each cell of the nickel-cadmium battery is only 1.2 volts, therefore, higher voltages require a lot of cells.

The lead acid battery is the cheapest option for high capacity. To clarify, the capacity refers to how long a battery will last before fully discharging at a specified voltage and discharge rate. The lead acid battery however is very heavy in comparison to the other battery technologies. This is something to be considered given the weight limitations of this project and the addition of all of the other components and materials. Furthermore, it has a low energy density and limited cycle count. Most of the applications of the lead acid battery are related to vehicle functions or backup supplies, such as; golf carts, wheelchairs, emergency lighting, and uninterruptible power supplies. Safety and environmental concerns are prevalent due to the toxic lead component of this battery.

The alkaline battery is the cheapest overall, however, they constantly need to be replaced, which adds up in the long run. They also provide higher voltage than the nickel-metal hydride battery. Alkaline batteries are made up of a reaction between zinc and manganese dioxide. Household electronics, such as; toys, lights, digital cameras, and radios all use alkaline batteries. The cutoff voltage of the battery determines its capacity, because it slowly reduces its voltage as it discharges. The alkaline battery has a high internal resistance and cannot withstand high discharge current.

Finally, the lithium-ion battery is a more recent battery architecture that is increasingly becoming more popular. It has a very good discharge rate and fairly high capacity. Its appeal is also attributed to its lightweight nature. However, the voltages increase in increments of 3.7V, which can make things complicated. A project almost has to be designed around a specific available lithium-ion battery voltage in order to utilize this architecture. Also, it requires a protection circuit, because of various safety concerns. The battery functions by the movement of lithium ions from negative to positive electrode and back. It’s advantages are a high energy density, little memory effect, low self discharge, high cycle count, and low maintenance. The energy density is the amount of energy that it stores. The lithium-ion battery can store up to 2.63 MJ/L, while the other battery technologies have energy densities in the range of 0.5 to 1.3 MJ/L. Lithium-ion batteries can be dangerous, because they contain a flammable electrolyte. If the battery is charged too quickly it may short out and cause an explosion and/or fire.

3.9.2 Battery Comparisons

Below is a table that briefly summarizes the advantages and disadvantages of each battery technology that was previously researched and reported on.

Table 6: Battery Comparison

Battery Architecture	**Advantages**	**Disadvantages**
Nickel-Metal Hydride (NiMh)	Inexpensive, high capacity, lightweight, very low memory effect, high energy density, low internal resistance, safe, environmentally friendly	Very high self-discharge rate, sensitive to overcharging,
Nickel-Cadmium (NiCd)	Good cycle life and performance at low temperatures, not sensitive to charging quickly	High memory effect, expensive, high discharge rate, unsafe and not environmentally safe, toxic materials
Lead Acid	Inexpensive, high capacity	Heavy, low energy density, limited cycle count, unsafe and not environmentally safe, toxic materials
Alkaline	Most inexpensive, provide higher voltage than the NiMh	Consistently need to be replaced, high internal resistance, cannot withstand high discharge currents
Lithium-ion (LiPo)	Low self discharge rate, maintenance, and memory effect, high capacity and energy density, lightweight	Voltages increase in increments of 3.7 volts, requires protection circuit, dangerous, flammable

3.9.3 Battery Regulation

To contribute to the electrical complexity of this project and its printable circuit board, one battery source with voltage regulation is the power supply method that will be pursued. The power regulation must be able to regulate and provide the appropriate power to each electrical component. Logically, the power source should be in a reasonable range of the required various voltages of the project, while still being above the requirement. This is not an easy task considering this project requires 5 volts for powering the microcontroller, 3 volts for powering the laser, and 6-30 volts for powering the stepper motor driver. It is important to note that batteries themselves are never a consistent or regulated voltage. For example, the lithium-ion battery has a nominal voltage of 3.7 volts, but may reach 4.2 volts when fully charged and 3.0 volts when properly discharged.

Voltage regulators or linear regulators are used to regulate the voltage output of a batter. For example, if there were four lithium-ion batteries connected in a single pack producing 14.8 volts, a 12 volt voltage regulator can take the output of this lithium-ion battery pack as its input and produce a regulated 12 volt output. Linear regulators can be an open loop design or closed loop design that provides feedback. An advantage of the linear regulator is that it produces very little noise at the output. A disadvantage of the voltage regulator is that it tends to be inefficient, because it wastes so much power. The power lost is proportional to the difference between the input and output voltages. This power loss is in the form of heat, which requires the addition of heat sinks. It is said that perhaps linear regulators waste more power stepping down a voltage than it delivers to its intended device. Linear regulators are also unable to step-up voltage or invert it. Lastly, in is important to remember that these regulators will not work if the input voltage approaches the desired output voltage.

Unlike the linear regulators, the switching regulators are able to step-up an input voltage or even invert it. The switching regulator is much more efficient by using a switching method to maintain the same power input and output. The switching regulator uses as electrical switch to transport tiny segments of energy from input to output. These regulators are used in items, such as; cellular devices, video game consoles, robotics, camera, and computers. While the switching regulator is much more efficient than the linear regulator, on the other hand, it is much more complicated to build due to the requirement of extra components. A switching regulator is a good choice for this project, because the stepper motor requires various currents that could be affected by the inefficiency of a linear regulator. The switching regulator is slightly more expensive, but not enough to be concerned with.

Aside from voltage regulation, it is wise to implement electrolytic capacitors and fuses into the power distribution circuitry. An electrolytic capacitor will store large amounts of energy to be used in case any given electrical component suddenly draws large amounts of current in which the battery is insufficient. This is a realistic possibility and concern with the stepper motor that will be implemented into this project. Fuses will aide in short circuit protection, negative voltages, and noise protection, which are also all relative concerns, given the various operation voltages of the components in this design.

3.9.4 Battery Protection

A fuse is the most fundamental type of protection used in battery protection methods. The fuse will open when the current is high. The fuse can open permanently, meaning the battery will be useless at that point, or they can be designed to reset. An example of a resettable fuse it the positive temperature coefficient fuse. As the temperature increases, the positive temperature coefficient fuse will increase its resistance simultaneously. If the temperature returns to appropriate levels, the resistances will reduce as well. This allows current to flow only when safe. Other common names for the positive temperature coefficient fuse are the polyfuse or the polyswitch.

Another version of battery protection methods is solid-state switches. This regulator will consistently monitor the voltages and currents flowing, in order to flip the switch and disconnect the battery if the current or voltage gets too high. All of these switches will contain some type of residual resistance that will affect the voltage of the battery slightly.

There is an important concept to be aware of called intrinsically safe. It is required that all electronic devices in the realm of hazards must be intrinsically safe. This works in the same way as the fuse or solid-state switches in that it monitors the current, however not in relation to charging but instead in relation to hazardous materials. The current must be kept at a safe level in order to avoid an electric spark that could ignite the hazardous materials in the environment. There are different hazard levels that rate the type of hazard, the likelihood of the presence of hazards, the potency of such hazard, and the temperature code. The intrinsic safety codes are different depending on the location.

According to the standard IEC 62133, lithium-ion cells or packs must have a built-in positive temperature coefficient, a circuit interrupt device to open the circuit when the pressure reaches 1,000 kPa, a safety vent to release gases when pressure reaches 3,000 kPa, and a separator to stop ion-flow when the core of the separator reaches 266º Fahrenheit. The previously stated protocols according to IEC 62133 are all internal protection methods. Alongside these internal safeguards are various external protection elements. The lithium-ion batteries have external protection circuits that prevent any given cell from exceeding 4.70 volts when charging. Another control circuit will cut off the current during discharging if the voltage of any given cell reaches 2.20 volts. Finally, there is an additional fuse on the outside of the battery that will also disconnect the current if the temperature of any given cell approaches roughly 90ºC (194ºF). As indicated, each cell is monitored separately. This means that as the cell count increases when lithium-ion batteries are connected in series or parallel, the protection circuits become more and more complicated. There are no safeguards to prevent any malfunctions within the architecture of the battery at this time. Aside from actual protection circuitry, there are simple common sense guidelines to follow to ensure one's safety when handling lithium-ion batteries and implementing them into electronic projects. Care should be taken when handling lithium-ion batteries to be sure not to drop, penetrate, short-circuit, overheat, overcharge, over discharge, or disassemble an already assembled battery pack. Be sure that the lithium-ion battery has a specified protection circuit specifically for that battery or battery pack as well as an appropriate charger. If the lithium-ion battery combusts for any particular reason, various substances can be used to extinguish it, such as; a foam fire extinguisher, CO2, powdered graphite, powder copper, or sodium carbonate.

3.10 Motors

The autonomous motion of the turntable requires the use of an electric motor. The motion must be occur in very precise increments and cover a range of 360º in order for the entirety of the object to be scanned. Some of the most common types of electric motors for small-scale robotic type projects are as follows; ac motors, brushed dc motors, brushless dc motors, servomotors, and stepper motors. Given that this project is powered with direct current via batteries, it doesn’t make much sense to utilize ac motors. Therefore, ac motors will not be researched in this section and can be ruled out as a possible solution. Beyond the electric motors, this section will also research encoders and drivers where necessary to aide in the functionality of each given motor under investigation.

3.10.1 Brushed DC Motor

The brushed DC motor is a simple design that offers various speeds dependent on the supplied operating voltage. Generally, a brush motor will include an armature, commutator, stator, brushes, an axle, and a field magnet. The commutator is connected to the armature to make an electrical connection and ensure current flows through undisturbed. The brushes are very important to the functionality of the motor as they ensure the conduction of current from the stationary parts outside of the motor into the moving parts in the center of the motor. Also, as the name would suggest, a stator is the stationary portion of the motor. In other words, the dc brushed motor uses two brushes to ensure that current flows from the source to the armature. The magnets produce a magnetic field that causes the armature or rotor to turn.

The brushed DC motor is used most commonly for industrial purposes. Some advantages of the dc brush motors are that they are inexpensive, lightweight, easy to control, and come in variety of forms. Some disadvantages include a plethora of noise that can affect other electronics within the project, a whining effect from its operation, as well as the wearing down of the brushes, which can produce residue and unreliability. Speed variability isn’t a pertinent factor in this project. The turntable will need to turn at accurate distances and speeds at a given interval of time. However, the inexpensive and simple aspects of the brushed dc motor can’t be ignored.

3.10.2 Brushless DC Motor

The interesting thing about brushless dc motors is that they don’t actually directly run off of a dc source. An inverting power supply is required to produce an ac current to drive the motor. The waveform of the ac current determines how efficient the motor is and how smooth the torque is. The brushes and the commutator are eliminated in the brushless dc motor, as the name would suggest. The brushless dc motor consists of an armature or rotor, magnets, and a stator with windings. The windings are connected directly to the electronics, which provide the necessary flow of current and eliminates the need for the commutator. There are one, two, and three phase brushless DC motors, but the three-phase architecture is the most common. The rotor consists of permanent magnet pairs, which increase the torque with increasing amount of magnet pairs. However, this adds to the complexity of the motor and cost. The magnets are usually rare earth magnets, which adds to the power and appeal of the brushless DC motor.

For the three phase brushless DC motor, three hall sensors are embedded in the motor to indicate the position of the stator and rotor to the controller in order to energize the windings at the appropriate time. At all times, two phases of the three-phase system are on allowing current to pass through to the motor and then return, while the third phase is open. The microcontroller determines this in order to energize the windings as needed. In order to drive the motor a microcontroller and regulated power source are required. There are drivers on the market designed for this purpose, such as the DRV8301 three-phase pre-driver by Texas Instruments. Contained on this particular driver is a step-down voltage regulator, control and protection logic, and the three-phase brushless gate driver.

Another design that is growing in popularity is the sensorless brushless DC motor. This eliminates the need for hall sensors by utilizing back electromotive force (EMF) to its benefit. The elimination of the hall sensors reduces the complexity or the motor as well as the cost. A microcontroller can use the back EMF to determine the position of the stator and rotor without the need for hall sensors. However, there is no back EMF at startup, so the motor is configured as an open loop until enough back EMF exists for the microcontroller to step in and take over control.

The brushless DC motors have largely outnumbered the brushed DC motors. Some of its applications include transportation, heating, ventilation, industrial, aerodynamic, remote controlled toys, etc. These motors are more efficient, reliable, and less noisy than the brushed dc motors because the issue of the brushes is not of concern anymore. Furthermore, they provide much more torque than the brushed dc motor compared with its size. This torque to size ratio is attractive for projects that require more power within a compact or limited region of space. However, this motor is more expensive and complicated than its counterpart and requires separate electrical components to operate.

3.10.3 Servomotor

Servomotors are very precise in rotational movements at specific angles, speeds, and positions. They can provide a very high torque within a small package. Movements are decided by electrical pulse; therefore, the motor will perform a movement and then stop and wait for the next command. Like the brushless DC motor, it requires a controller that is usually specific to the servomotor only. This aids in its precision with angular movements. This motor utilizes a feedback system that compares the output with the desired input signal and adjusts accordingly. The servo is paired with an encoder to provide this feedback for position and/or speed. If the output differs from the input command an error signal is created and the motor adjusts accordingly. When the error signal is zero the motor stops. Only when the motor is adjusting to accomplish the given command does it consume power, otherwise when the error signal is zero and the motor stops it does not consume any power. The servomotor can be thought of as a higher performing alternative to the stepper motor.

The servomotor is used in countless applications, such as; remote control planes, toys, appliances, robotics, machines, etc. The requirement of a controller and encoder add a tradeoff to the servomotor between extra costs and optimization of its performance. The standard servomotor only provides a 180º range of continuous motion, which is problematic to this project as a 360º range of rotation is required. Servos must be modified in order to provide continuous range motion, however this is more complex and expensive as more electrical components are required. A continuous rotation servo can be purchased as well, however the feedback functionality is disabled.

3.10.4 Common Servomotor Encoders

Resistive potentiometers are one option for an encoder to the servomotors, however, only for extremely uncomplicated and cheap options. The more common encoder today is the rotary encoder. The absolute rotary encoder is beneficial in that it can determine its position when power is applied to the motor, however it is not simple or cheap. Incremental rotary encoders provide this desired simplicity and are less costly by utilizing a zero-position sensor to set the position when power is applied rather than just inherently knowing that position. The brushed DC motor is very simple and cost effective, but requires extra electrical components for feedback and noise is a concern with the presence of brushes. The brushless DC motor is more complicated and expensive than the brushed DC motor, however it removes the concern of noise.

3.10.5 Stepper Motor

Stepper motors are known for their precision with position. The stepper motor can be categorized with the brushless DC motors. The simplicity of the stepping mechanism allows for proper functionality without the addition of an encoder. The motor moves in steps due to the organized sequence of multiple sections of coil windings. Each section is energized individually in sequence, producing the step effect. Using a microcontroller to program these steps can provide for very precise positioning and speed control. A stepper controller is required in order to use these instructions given from the microcontroller to control the motor.

They are used in applications that require this precision, such as in 3D printers. Furthermore, this motor has optimal torque capabilities at low speeds, contributing even more so to its precision. While other DC motors only draw power when doing work, the stepper motor continuously draws power, which limits the efficiency. Other limitations include lacking any feedback and lower torque at higher speeds. Fortunately, this project is not concerned with higher speeds. Moreover, the stepper motor provides sufficient precision without the addition of feedback.

Stepper motors come in various sizes with an assortment of electrical characteristics. When choosing a stepper motor it is important to consider motor size, step count, gearing, shaft style, and wiring. The NEMA 17 is popular in 3D printers and could be a viable option for this project. The stepper motor poses a great option for high precision applications, which is necessary for this particular project.

3.10.6 Common Stepper Controllers

A few readily available stepper controllers include the simple unipolar driver, the simple dual H-bridge driver, the Adafruit motor shield V2, and advanced CNC controllers. The simplest form of driver is the unipolar driver, which consists of a handful of transistors. The transistors are switched on and off in order to energize the phases of coils within the motor in sequence. These drivers are very simple and inexpensive to create, but they only work with unipolar motors. The stepper motor requires 2 H-bridges to run properly in order to reverse the direction. As opposed to the unipolar driver, H-bridges are more complicated to create, but there are various H-bridge ICs on the market that are very affordable. The L293D is among the most popular of these H-bridge chips. The Adafruit motor shield V2 is another H-bridge driver that offers more efficiency by utilizing two MOSFETS that enable twice the current and lower voltage drops across the system. Furthermore, each chip can drive two stepper motors at once. The advanced CNC controllers are much larger and more complicated. The boards can deliver maximum torque and speed to the motors, however they are out of range for the scope of this project. It is very important to ensure that the driver is compatible with the motor but using the simple ohm’s law to calculate the appropriate currents, resistances, and voltages.

3.10.7 Motor Comparisons

Each motor previously discussed has important features that are compatible with this project. The motors vary in terms of torque, speed, feedback availability, controller necessity, and cost. A major goal in completing this project is to provide a cost effective solution to the current 3D laser scanners on the market. It is important to conserve spending wherever possible, therefore, cost will be heavily considered. Furthermore, the project needs to be light enough to carry, so the size and weight of the motor is considered as well as how many extra electrical components are required to meet the project specifications. The servomotor seems like an excellent candidate with its precise speed and position control, as well as its feedback functionality. While precise control is necessary, the servomotor typically only has 180º range of rotation, which is insufficient for this project. If 360º rotation is desired, these servomotors are available or can be built, however they lack feedback functionality. The stepper motor provides this precise speed and motion control through individual stepping of the motor without the feedback functionality that the servomotor provides.

Table 7: Motor Comparison

Motor Type	**Brushed DC Motor**	**Brushless DC Motor**	**Servo Motor**	**Stepper Motor**
Feedback Provided	No	With an Encoder	Yes	No
Controller Needed	Optional	Yes	Yes	Yes
Torque	Variable	High	High	Average
Speed Control	Variable/Average w/ Encoder	Average/High w/ Encoder	High	High
Position Control	None	None	High	High
Efficiency	Average	High	High	Low
Cost	Least Expensive	Most Expensive	Inexpensive	Expensive

Table 7 various technical aspects of each type of motor are analyzed in an easy to see and easily comprehensible manner. The advantages and disadvantages of each type of motor can be seen in the table below. This table nicely sums up the detailed explanations of each motor in the previous sections.

Table 8: Motor Advantages and Disadvantages

Motor Type	Advantages	Disadvantages
Brushed DC Motor	Inexpensive, lightweight, simple design, easy to control, wide variety, high low-speed torque	Audible whining, electrical noise, wearing of brushes, unreliable,
Brushless DC Motor	Efficient, reliable, quiet, better torque to size ratio,	More expensive, fairly complicated, requires extra electronic components
Servo Motor	Precise rotational movements, provides feedback	More expensive, requires controller and encoder, rotational limitation under 360º
Stepper Motor	Precise position and speed control, high low-speed torque, high holding torque	Low torque at high speeds, continuously draws power, inefficient, no feedback

3.11 Possible Architectures and Related Diagrams

Although we have already selected triangulation as our 3D scanning method, there is a variety of ways triangulation can be implemented. In this section, we will consider the pros and cons of these various scanning architectures to find which one provides the best combination of speed, accuracy, power efficiency, and long-term robustness.

3.11.1 Moving Laser Methods

The moving laser method uses a series of gears and servos to move a platform with an object placed on top of it. The servos will move the platform up a step and rotate it. After one rotation the other servo will push the platform a step and repeat the process. The process is slowly repeated until the entire object has been completely scanned. This method uses a point laser that determines the distance between the surface of the object and the laser. This method is a bit more complex as the platform must rotate at specific increments while also moving the platform on a vertical axis. The downside of this method is that the time it takes longer to collect the profile of the object because of how the object has to move and rotate. It has to be at a very specific increment, preferably 1-degree rotations which subject the measurements to more disturbances. The platform would have to have a mechanism to secure an object to it.

3.11.2 Stationary Laser Methods

The second method of scanning is to bypass the additional dimensional movement on a vertical axis by passing a point laser through an aperture so that the beam can scatter and create a line laser. This method will reduce the need for two servomotors, because the function of moving the laser up and down will not be needed anymore. Only one servo will be used in order to rotate the platform in precise increments. This method offers a high quality output, because there is less noise and vibrational interference with a stationary laser. Furthermore, this method will rapidly speed up the scanning process, because the laser is now a vertical line rather than a single point. The laser can scan the entire length of an object and only need to be concerned with the rotation of the object. Below is a diagram that demonstrates how this method works with the use of a turntable, an object, a laser, and a camera.

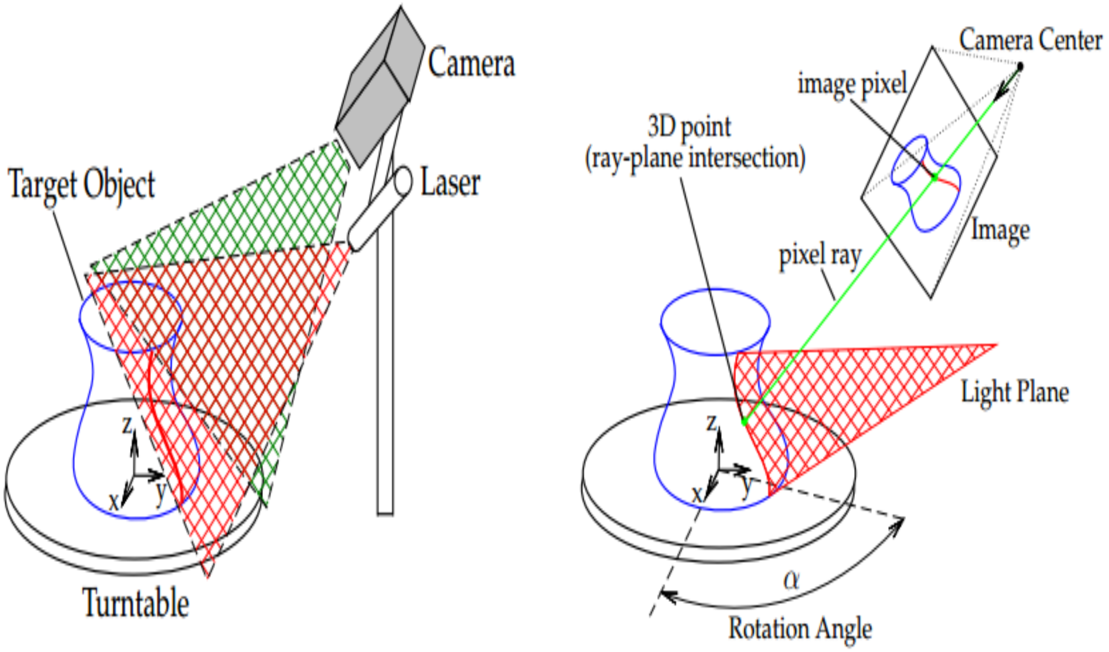


Figure 23: Stationary Laser Scanning Method

3.12 Part Selection

After extensive research into the various methods and hardware components, the table below summarizes all the physical components chosen. These components provided the best cost to utility ratio for the scanner. The table only shows the amount of parts used in the actual implementation of the scanner. More parts were ordered than what is specified on the table for the electronic components. For the voltage regulators the main reason the LM2576-ADJ was chosen was for its efficiency, features and simplicity. The LM2576-ADJ is a switching regulator, which provides better power efficiency compared to a more simple linear voltage regulator. This specific switching regulator reduces the need for a heat sink, includes built in fault protection via thermal shutdown and a fixed-frequency oscillator for cycle-by-cycle current limiting protection.

Table 9: Part Selection

Units	Item	Part Number	Manufacturer	Cost
1	Raspberry Pi 3 Model B	N/A	Raspberry Pi	35.00
1	Line Laser	LN60-635	Apinex	24.50
1	Display	7inch HDMI LCD Touchscreen	Waveshare	69.99
2	Voltage Regulators	LM2576-ADJ	Texas Instruments	N/A
1	Stepper Motor	ROB - 10846	Sparkfun	16.95
1	Motor Driver	ROB - 12779	Sparkfun	14.95
1	SD Card	N/A	N/A	N/A
1	PSU	N/A	N/A	15.99

In addition, the Raspberry Pi was the ideal microcontroller because it could act as network server and has built in Bluetooth, which makes any form of communication quite simple to integrate with the microcontroller after some manual configuration. It acts as a low powered computer, which will be important for processing the point cloud data from the laser. The additional module for the Raspberry Pi was the touch screen display to make it easy to work with as the

Linux kernel can be uploaded via an SD card onto the microcontroller. The display will be useful to mount onto container of the project as to visualize the processes that are happening which is good for debugging as well.

The stepper motor became the best choice to rotate the platform where the objects will be scanned because it allows for better incremental rotations to be performed. This is especially important to get an accurate profile of an object with the line laser. The motor along with the driver will be powered by a 7.2V rechargeable power supply. The Nema 17 stepper motor is very common in 3D printing machines and 3D scanning devices like such. The stepper motor driver was chosen because a group member had experience using that particular motor driver and spoke highly of its user friendliness and functional capabilities. However, it will be discussed later on in this document that the stepper motor driver picture will not be the one used in the final design. To further challenge the electrical team, a stepper motor driver will be designed and implemented on the PCB, rather than using an already manufactured board.

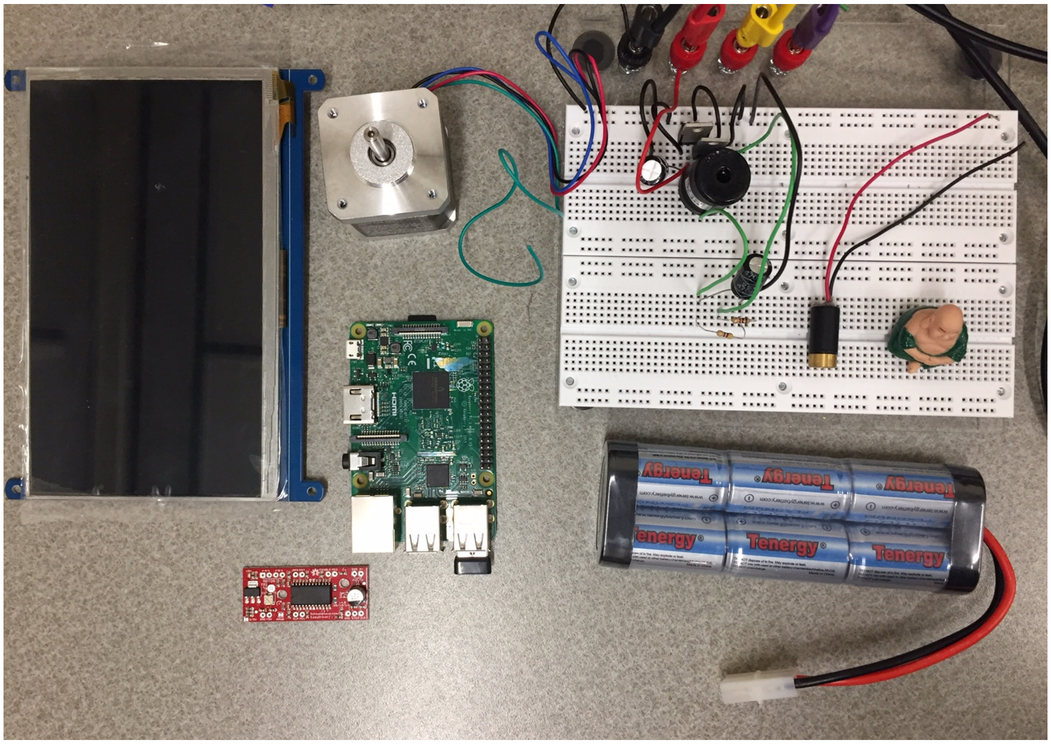


Figure 24: Project Components

4.0 Design Standards and Constraints

This section outlines the various standards that will affect the design of this project. It is very important that these standards are recognized and abided by for each technology associated with the design and implementation of this project. Furthermore, this section will address the constraints that surround the project.

4.1 Design Standards

There are a handful of design standards that must be carefully considered in all aspects of the design and implementation process of building a 3D scanner.

4.1.1 Laser Safety Standards: ANSI Z136.1

The ANSI Z136.1 standard for safe laser usage divide lasers into four classifications, and it provides specific control measures for each class. To summarize the broad range of categories and the particular hazards they pose, the following table covers each class and their subdivisions, along with the wavelengths spanned by each category.

Table 10: Laser Classifications and Related Hazards

Wavelength of Classifications				**Hazard Type**			
Class	**IR**	**Visible**	**UV**	**Specular**	**Diffuse**	**Fire**	**Skin**
1	Yes	Yes	Yes	No	No	No	No
2a	No	Yes	No	Yes	No	No	No
2	No	Yes	No	Yes	No	No	No
3a	Yes	Yes	Yes	Yes	No	No	No
3b	Yes	Yes	Yes	Yes	Yes	No	No
4	Yes	Yes	Yes	Yes	Yes	Yes	Yes

One important metric independent of laser classification is the Maximum Permissible Exposure (MPE) standard, IEC 60825. This standard defines the maximum possible time a person can be exposed to a collimated beam fully focused on the retina. The eye's absorptive properties make this hazard type heavily wavelength dependent, but as we are working with visible light, it can be assumed that all radiation will pass through the eye's focusing optics and onto the retina.

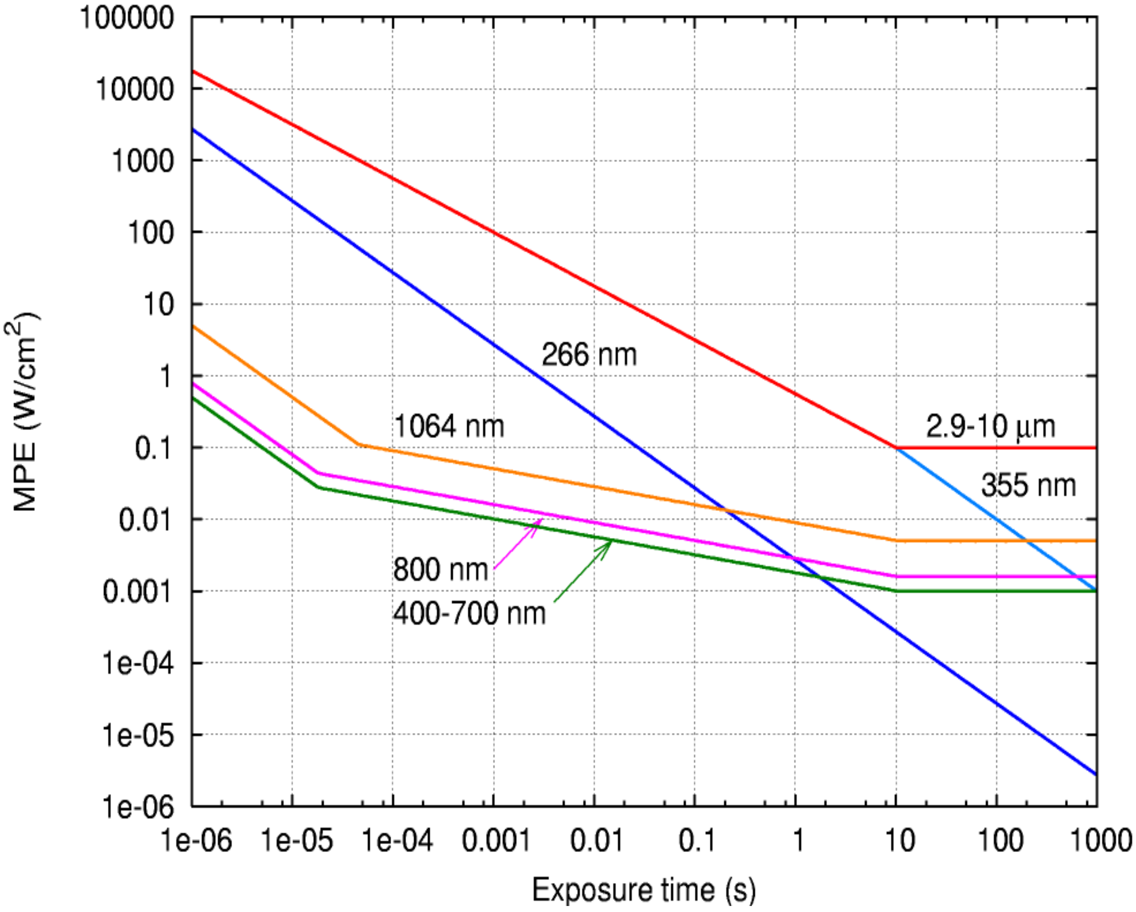


Figure 25: MPE Versus Exposure Time for Various Wavelengths

4.1.2 Class III Lasers

Class 3 laser systems are generally quite safe, which is why they're found in laser pointers and many other consumer products. Still, there are hazards to be considered when making use of them in a product. Class 3b lasers, for instance, are hazardous not only when reflected specularly, but also may pose a risk when reflected diffusely. Most objects subject to our scan can be expected to mostly reflect diffusely, so it is a positive that the laser we are using is a Class 3a device. These only pose a hazard when reflected specularly, and because our scanner will ideally be designed to scan on a wide range of reflectivities, we will use engineering controls to mitigate the specular hazard as recommended by ANSI standards. There must be an opaque enclosure around our laser when in use, so an electrical mechanism will be used by which the laser will immediately cease operation when the enclosure is opened. In addition, a warning light on the device's exterior will be activated whenever the laser is in operation.

4.1.3 IPC PCB Standards

IPC is a trade association known as the Association Connection Electronic Industries. The IPC's goal is to standardize the assembly and production requirements of various electronic parts and equipment. It is an accredited institution by the American National Standards Institute (ANSI). The IPC has a large swath of standards related to all electronic manufacturing at all steps of the process. The most relevant standard to this project is the IPC-2211 standard, which delineates the requirements for PCB design layouts, diagrams and even evaluation. Every process step is given an extensive description for testing quality and material effects. The standards that are published by IPC follow a type of tree like structure with the major branches including: General documents, Design Specifications, Material Specifications, Performance and Inspection Documents, and finally Flex Assembly and Material Standards. Each of these branches has sub standards, which go into more detail of the whole PCB layouts, designs, and specifications.

It is important to follow these standards because of the time it takes to design, order, and receive a PCB. Following well-established standards allows for an efficient and effective realization of what is needed to construct a usable PCB. This standard allows there to be a common mode of communicative design that will allow easy comparison as to what a effective and ineffective design would be.

4.1.4 Software Standards: IEEE 830

This standard is referred to as a software requirement specification that lays out a guide aimed to effectively specify software requirements and prototype effective and realistic goals for a software project. For this case, it will be necessary to implement a concrete outline and dependency layout due to the fact that project will rely on some open source software libraries to simplify the calculations. These libraries will have to be integrated into the software written by the team to gather the laser profile and will have to work with two or more different programming languages. Therefore it is important to have a clear project delineation to allow for reproducible and refactorable code.

The template of the software requirement standards can be reduced to handful of specific parts, starting with: the nature of the specification, which addresses the overall purpose of the software. It defines the functionality in multiple aspects of interaction with users and other devices or environments. The nature of the specification should define performance and response functions of the software execution. The attributes and constraints will be described as well. In this instance, the camera must begin recording in order to obtain the laser profile, which will be transformed into a point cloud form. This point cloud is processed from the collective profile of the laser on an object being rotated on the platform and returned as a numerical matrix file representing the grid.

The second aspect of the standard is the environment in which the software runs in. For this, all the software requirements that may exist due to the nature of the task must be specified but impose any additional constraints onto the software. In any case, the software must be able to pipe the input of camera, control the platform and provide the necessary output controls to visualize the object to the user. The environment specifications, in short, are a form of engineering requirements that must be imposed onto the software design and implementation.

Joint preparation describes the contractual agreements and understanding of the customer and supplier. This section of the standard has less relevance due to there not being a true customer.

The project specifications for the software may need to change during the progress of the product and as such some details may be impossible to define. As such it is important to employ methods that allow for auditable code changes such as version control systems. The key part being that there should be a hierarchy or process that allows for changes to be verifiable and traceable such that the integrity of the software is not ruined.

Next, there is the prototyping section of the standard, which should elucidate the requirements and characteristics of a system in an easy to understand format. The prototyping step is important as it displays unanticipated aspects or behaviors in the system (both software and hardware) thus producing new questions and answering old questions. Prototyping for this project begins with flow diagrams for the software processes and small function testing on the breadboard model to ensure each step produces the correct outcome.

Embedding design refers to the externally visible functions or attributes of a software system and how the design describes the particular interfaces with the components. Not every specified requirement is necessarily a design and the software requirement specification species should specify, at this stage, what functions or transformations must be performed to manipulate and direct data to produce the desired results. For example, the data structures, module partitioning for files, and the communication protocols between modules.

If necessary, some requirements may severely restrict and constrain the desired design such, as security or safety requirements. As such, these constraints must be reflected as per the necessary design requirements subsection. Due to this specification in the standard, functions may need to be isolated and permitted only limited communication between parts of the program. In addition, data integrity checks must be implemented to critical parts of the program and variables.

Finally, the last specification is embedding project requirements, which should address the software as a product rather than the process of producing it. Typically, the specified parts in this should include costs and delivery schedules for the software. Quality assurance and development methods should be specified as well to satisfy previous specifications of auditable code.

4.1.5 C++ Standards

As the primary language for the project, C++ is the ideal candidate to relatively wide portability and extensive adoption across various industries. The C++ standard is governed and ratified by the International Organization for Standardization (ISO). In this project, C++14 will be the restricted subset of the language will utilize the Standard Template Library (STL) to reduce system bugs or failures. More specifically, the ISO/IEC 14822:2014 specifies the requirements for the proper implementation of C++ along with the specifications of the STL behaviors and built in cases of the language.

C++ supports multiple programming paradigms that works at both high and low level interfaces, which simplify the design process at all stages of hardware and software integration while allowing powerful abstraction. As the language is so widely used in industrial applications, it is necessary to follow coding standards and due to historical changes in the language to restrict the subset, which will be used. To reduce portability issues, the primary compiler for C++ will be the GCC/G++ compiler. By using restricted subsets of the language the group can focus on the implementation details of the project rather than underlying software gotchas. As stated, due to the legacy craft and large feature base of C++, it is important to follow the standard guidelines and established proper in-group conventions as well.

In order to maintain good modularity and refactorability in the code, all functionalities should be separated into individual interfaces and contained within separate files names. In addition, names shall be explicit so that the locations of where it a piece of code is located can be easily determined and its functionality quickly rocked. Leveraging C++ language implementations, namespaces should be utilized to ensure a reduction in naming clashes and to also improve modularity. The STL needs to be utilized extensively to reduce the usage of unsafe code by reducing the cognitive load of manual memory management. The use of Resource Acquisition is Initialization (RAII) shall be extensively used as well to ensure that the life cycle of a resource is bound to an object and when out of scope it is safely freed. Following the ISO standard and in-group standards such as this will reduce the time spent debugging and improve productivity.

4.1.6 Python

There are two major versions of Python: 2 and 3. Python 2 is set to for end of life support in the next few years and most major work is now being done for future support on Python 3. Thus, for all scripting purposes and glue code Python 3 will be the chosen higher level, dynamic programming language for the project. Unlike C++, Python does not have a similar standard, but adheres to a strict set of guidelines that should be followed by to make code pythonic, or more colloquially, idiomatic.

All coding standards for Python should adhere to the Python Software Foundation (PSF) set of guidelines known as the Python Enhancement Proposals (PEP). The PEP guidelines can be viewed on the Python main website where the most important PEP guidelines are PEP20 and PEP8. These two solidify the most common style guides for writing proper idiomatic Python and aim to simplify Python Projects through the Zen of Python (PEP20).

Moreover, Python will be used in conjunction with C++ as the primary glue and scripting language. All higher-level features should be written in Python while all low level and performance critical code should be implemented in C++. Python will act a wrapper to call the code and execute at proper time. Due to the rich features and libraries available for Python, it wise choice to increase productivity and overall time spent debugging code.

4.1.7 Power Supply Standards

The International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO) are responsible for electrical safety standards including power supply safety standards. The safety standards for power supplies are divided amongst their class. There are three classes that distinguish between the specific standards. Class I equipment utilizes basic insulation and grounding methods to protect against electric shock. Class II equipment uses double/reinforced insulation to protect against electric shock and thus does not require grounding. Finally, class III equipment utilizes a safety extra low voltage (SELV) circuit to supply power, thus no extra measures are necessary to protect against electrical shock. To further understand theses standards and classes of power supplies, the table below is provided for relevant circuit definitions.

If this project ever became on the market, these standards are very important to follow. The project is and extra-low voltage circuit design. The battery supply is rated for 7.2 volts dc, thus it is exponentially lower than the hazardous voltage threshold. Furthermore, all of the wires in the prototype will be the proper gauges in order to properly insulate the power supply throughout the circuit. These precautions will carry over into PCB design to ensure that all PCB relative standards are followed and the circuitry is properly insulated in order to protect the functionality and lifetime of the project as well as to protect the user.

Table 11: Circuit Definitions

Circuit Definitions	
Hazardous Voltage	Voltage greater than 42.2 volts peak or 60 volts dc without a limited current circuit
Extra-Low Voltage (ELV)	Secondary circuit voltage less than 42.2 volts peak or 60 volts dc that is properly insulated
Safety Extra-Low Voltage (SELV) Circuit	Secondary circuit incapable of reaching 42.2 volts peak or 60 volts dc under normal operation
Limited Current Circuits	Voltages reach or exceed 42.2 volts peak or 60 volts dc, but current is not hazardous during a single fault

4.2 Design Constraints

It is helpful to be aware of the constraints within a project in order to design around them and come up with a solid plan for implementation. Some important constraints to consider in this project include economic constraints, time constraints, health constraints, safety constraints, and manufacturing constraints.

4.2.1 Time Constraints

Time constraints could perhaps be the most limiting factor in the project as a whole. If time were not a factor, the possibilities of this project would be endless. The scope of the project would be much more extensive than it is now as well. This however is unrealistic and reminiscent of an almost utopian situation. In reality, the project is constrained to two semesters for which the idea must be created, research of topics executed, design suggested and system fully constructed and implemented. Though approximately 8 months may seem like more than enough time to accomplish these tasks, this is far from the case. Being that the team has opted for the Spring and Fall Senior Design option, as opposed to the more popular Spring and Summer, on the surface it may seem apparent that the team has additional time to work on the project, due to the addition of Summer, now extending its duration to 12 months. This, however, is also not the case as one of the team's members will be out of the state as required by an internship program. Therefore, the aforementioned tasks must be executed within the 8 months available, most importantly, without compromising the overall quality of the system. There are several abilities that could potentially be added to the 3D Scanning System, such as real time viewing of the model and 3D printing. These cannot be implemented, however, until the core functionalities have been fulfilled. These additional features, therefore, can only be added to the system if there is enough time allowed.

Another significant time constraint to take into consideration is the time it takes the 3D Scanning System to scan an object. For the system to be practical for its users, the duration of scanning an object should be minimized. Similar to the overall time for constructing the system, the time taken to scan an object should be optimized without compromising the quality of the final image produced. The quality of the final image produced is a direct result of the amount of point clouds generated. The greater the point cloud density, similar to the likes of the pixels, the greater the quality of the final image in regards to both accuracy in relation to the actual object scanned and image resolution. Obviously, the more point clouds scanned/generated, the longer the duration of the scan as a whole. This relation will need to be optimized in effort to produce a high quality image, while also meeting a reasonable scan duration time as outlined in the requirements specification.

4.2.2 Economic Constraints

The overall cost of both researching and developing the system is a major constraint to take into consideration as well. One significant factor influencing this is the fact that the 3D Scanning System team is funding the system without any additional aid from outside sources. It is a regular occurrence that Senior Design projects are funded by UCF provided sponsors such as Lockheed Martin or Texas Instruments. Some projects even receive financial assistance from private sponsors such as current or previous employers of members of the team. This, unfortunately, is not the case for the team, thus almost exponentially reducing the possibilities of the project due to the limitation of resources, as well as potentially increasing the difficulty in the process. To meet this constraint, there has to be extensive research done in order to choose the correct parts that provided a good functionality to cost ratio.

Along with maintaining a low production cost to the development team, the 3D Scanning System must offer a relatively low cost to potential users as well. Price point is perhaps the single most important factor when consumers make purchases. A Toyota Corolla, for instance, was the best selling car in the world with over 1.02 million units sold. This vehicle is extremely appealing at its base price point of $18,500. Changing its current price point to the $91,100 price point of the Porsche 911 Carrera, those 1.02 million units sold would reduce to almost 0. This is because of the low value to cost ratio the Toyota Corolla would have when presenting the same value at a much higher price point. Therefore, maintaining a low production cost allows the team to offer the 3D Scanning System at a low price point. This in turn increases its value to cost ratio and its appeal to consumers in the process.

4.2.3 Health and Safety Constraints

The project employs a laser to for scanning, thus it is necessary to consider the impact of safety on a person using or nearby the scanner. While the laser used for this project is not a particularly high-powered laser, it is crucial to still observe safety protocols like not purposefully staring into the laser. In order to design a safer system, the laser along with the platform will be shield in such away that it will not be harmful to nearby people. The design of the platform and laser anchor should be encased within the acrylic material used to create the container or chassis of the project. The chassis for the platform section would be dyed or stained with a non-transparent acrylic component such that the laser is not going through the acrylic chassis.

Moreover, a secondary concern would be in the construction process of the acrylic chassis itself. Since acrylic is a thermoplastic used in place of glass, it is important to exercise caution when cutting or shaping acrylic with tools. It is possible for the acrylic sheets to splinter and break causing shards of sharp acrylic to be scattered. It is important to utilize protection for eyes, respiration and hands while working the acrylic.

4.2.4 Manufacturing Constraints

Another constraint that must be taken into consideration during the construction of the project is reproducibility of the project. When choosing materials for building it must be taken into consideration the overall availability of the material and the impact of how long it would take to get the product into development and testing. In addition, in the case of a lack of power tools the parts must be taken to a workshop that has wide array of tools to cut, shape or mold the material as well availability for laser cutting.

4.2.5 Ethical Constraints

The primary ethical constraints surrounding the 3D Scanning System stem from the area of business ethics. One of the constraints occurs in the product’s development and the other in the product’s use. In regards to the product’s development, the team will be sure not to infringe on the copyright of any existing products or similar systems already in place. This allows for the product to potentially be patented and marketed in the future depending on the success of its development. The team has been careful to avoid this, however, does not foresee any issues in this regard.

As previously mentioned, the ethical constraint stems from the use of the system. Similar to the previous constraint, copyright infringement issues may arise due to the fact that the 3D Scanning System allows users to scan an object and, using a 3D Printer, print a copy of the object that was scanned. Though this is not an issue per say for devices such as cell phones or remotes where there is a lot going on beyond the surface of the device, objects such as small book stands or some phone cases can be replicated without losing much functionality. For instance, if a user needs five small book stands for their home, is it fair to purchase one stand and simply scan it, then print the remaining four? Though this a cost effective option for the user, is this the ethically correct one? Although the team cannot control how consumers choose to use the 3D Scanning System, this is something that must be considered in the product's development.

4.2.6 Social Constraints

The 3D Scanning System is a product that many users will enjoy the team hopes. To accomplish this, all users, not only those who have background related to computer or electrical engineering must be able to easily operate the system. This is vital also from a marketing standpoint as increasing the amount of people that can use the product also increases the amount of people that may potentially purchase the product. This only needs to be taken into account if designing an interface for the system because regardless of the complexity of the software and hardware design, the user will only interact with the interface.

4.2.7 Environmental Constraints

As the system is currently intended for indoor use, environmental factors related to the weather are not expected to serve as a constraint on the 3D Scanning System. From a more general standpoint related to the environment in which the system is being used, the build must be strong enough to endure any subtle vibrations such as people walking nearby. This is a constraint because the laser shouldn't move and the camera must be at a fixed angle during the scanning of the object. Even the slightest movements or changes in these positions would result in an inaccurate scan and a poorly reconstructed image. Should the design be implemented with a plug into the wall option for power, rather than battery power, this would be another environmental constraint. The 3D laser scanner would be limited in its usefulness to areas that contain an outlet. A power strip or extension cord may be used, but still an outlet must be somewhere in a reasonable vicinity.

5.0 Project Design

After a plethora of research, the most optimal components were selected for this project and a cohesive plan was devised in order to build a 3D laser scanner that meets the design specifications. The design can be split up into a hardware section and a software section in order to provide a thorough and comprehensible explanation of the design as a whole.

5.1 Hardware Design

The hardware components for this project include the Raspberry Pi 3 Model B (microcontroller), Raspberry Pi 3 Model B camera module (camera), HDMI 7" 1024x600 Display Backpack (display), Line Laser Module LN-60 (laser), Nema 17 Stepper Motor (motor), and EasyDriver v4.5 (stepper motor driver). These components have all been purchased, but the EasyDriver will be replaced with a PCB that will also include two voltage regulators in order to allocate the appropriate power to each respective component. The design of these components, their integration as one unit, and the power distribution will be addressed in this section.

5.1.1 Hardware Block Diagram

The hardware block diagram includes all of the hardware components and the individuals responsible for their implementation. Furthermore, it depicts the flow of the power and the respective required voltages for each component. The block diagram can be seen in the figure below. Refer to this diagram to reference the material described in the remaining sections that explain the hardware design of this project. Each component will be described further in the next section, giving more specific specs to further explain the power management of the system as a whole. Notice that the green boxes represent the software team and the blue boxes represent the electrical team. However, the electrical team will handle the appropriate power management of all the components in the hardware block diagram. This diagram is very useful in making sure that the power is allocated appropriately to each component of the project. This diagram can be referenced when powering the project. It can be used to double check that everything is connected correctly and no components will be destroyed by supplying too much or too little power. Also, It is important to use diagrams like such in order to keep on task and organized during the span of the project timeline. Furthermore, when everything is laid out in a diagram like such, each individual in the team can support each other and hold each other accountable.

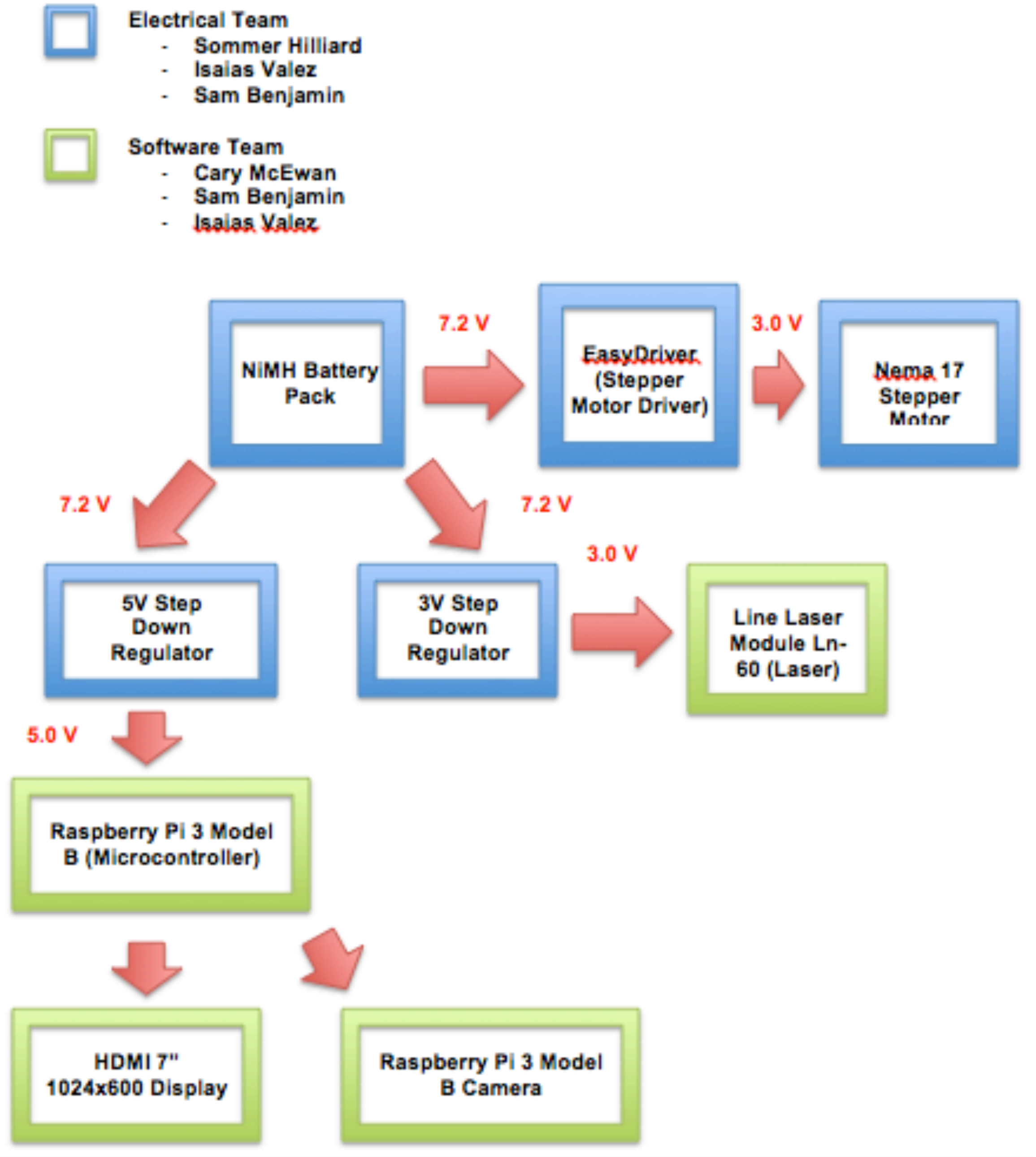


Figure 26: Hardware Block Diagram

5.1.2 Hardware Components

The hardware components for this project were listed in the previous sections and can be referenced in the hardware block diagram, however, this section will give detailed information on the electrical aspects of each component and explain how they work towards accomplishing the goals of this project.

5.1.2.1 Raspberry Pi 3 Model B Microcontroller & Components

The Raspberry Pi 3 Model B microcontroller was chosen for this project based primarily on its processing power, including its embedded systems capabilities, memory capacity, and clock-rate. Moreover, this project requires Bluetooth, a display, and a camera. This microcontroller makes the implementation of these components into the final design much more simple and efficient. The Raspberry Pi 3 Model B can run off of 5 volts and 1.2 amps for most applications without many issues, however, with the previously mentioned components integrated with the microcontroller it is wise to supply it with more power. The manufacturer recommends that 12.5 watts are supplied to the microcontroller at 5 volts and 2.5 amps. When using one battery supply, the battery should be able to provide power to all components; therefore it should have a higher power rating than any individual component. Also, it is very important that the microcontroller receives a regulated power input in order to ensure the proper functionality and long lifetime of the component. For these two reasons, a switching voltage regulator will be implemented between the power supply and the microcontroller to step the voltage down to the appropriate value and regulate its input. The voltage regulator will be able to supply 5 volts at up to 3 amps, which is perfect for this component.

The Raspberry Pi 3 Model B camera module will be powered through a ribbon cable extending from the Raspberry Pi 3 Model B microcontroller. It will draw power from the microcontroller, which is why the microcontroller will be supplied with 2.5 amps. The camera will only draw 250mA from the microcontroller. The functionality of the camera with respect to the laser will be discussed in a later section. Furthermore, the camera's controls will be addressed in the software design section. Fortunately, the implementation of the camera is rather painless for the electrical team due to the compatibility with the microcontroller.

The HDMI 7” 1024x600 Display will connect to the Raspberry Pi 3 Model B via the HDMI port. When utilizing this port, the display will draw 50mA from the microcontroller. The microcontroller will typically consume about 400mA of current running alone with no added components. With the display and camera implemented, the total current draw is nearly 1A. This leaves plenty of room for implementing the Bluetooth on the microcontroller. The USB ports on the microcontroller can draw up to 1.2A, which leaves room for implementing a mouse and keyboard for the display if desired. The other aspects of the display in respect to the project will be addressed in the software design section.

The primary, on-board display is to aid in the debugging and visualizing the processes happening on the raspberry pi. The only two functions that should be done by this display is to provide an onboard display for the Raspbian OS and allow touch screen functionality. To ensure that the display and touch screen worked the first procedure done was to connect the display to an HDMI port on a laptop and switch the primary display to the LCD screen. This allows for the actual screen to be shutoff and render the contents of the system to the smaller LCD screen. To ensure that it was working it was tested first on a laptop with an HDMI port and then after flashing Raspbian to the raspberry pi, the display was connected to the HDMI port on the board. The reason behind this order is to ensure that if the display did not work when first connected to the raspberry pi it would be simple to rule out the display not working and know that the problem may be with the boards HDMI port being faulty. In addition, to ensure the screen's pixels were all functional three PNG files were opened each containing a single color: red, green, and blue.

The final test for the display was to confirm the touch screen was functional. The specific touch screen model used for this scanner allows two modes to be used when connected. The first mode allows the user to control their primary display (no graphical content rendered to the touchscreen display) using the display as a touchpad. The second option is full use of the touchscreen capabilities while rendering graphical content onto the display as your primary monitor. The touchpad was properly calibrated, as it was possible for all touches to be registered on all parts of the touchscreen. The tests for the display passed and it was concluded that the display worked as expected. The figure below demonstrates the functionality of the display in conjunction with the camera.

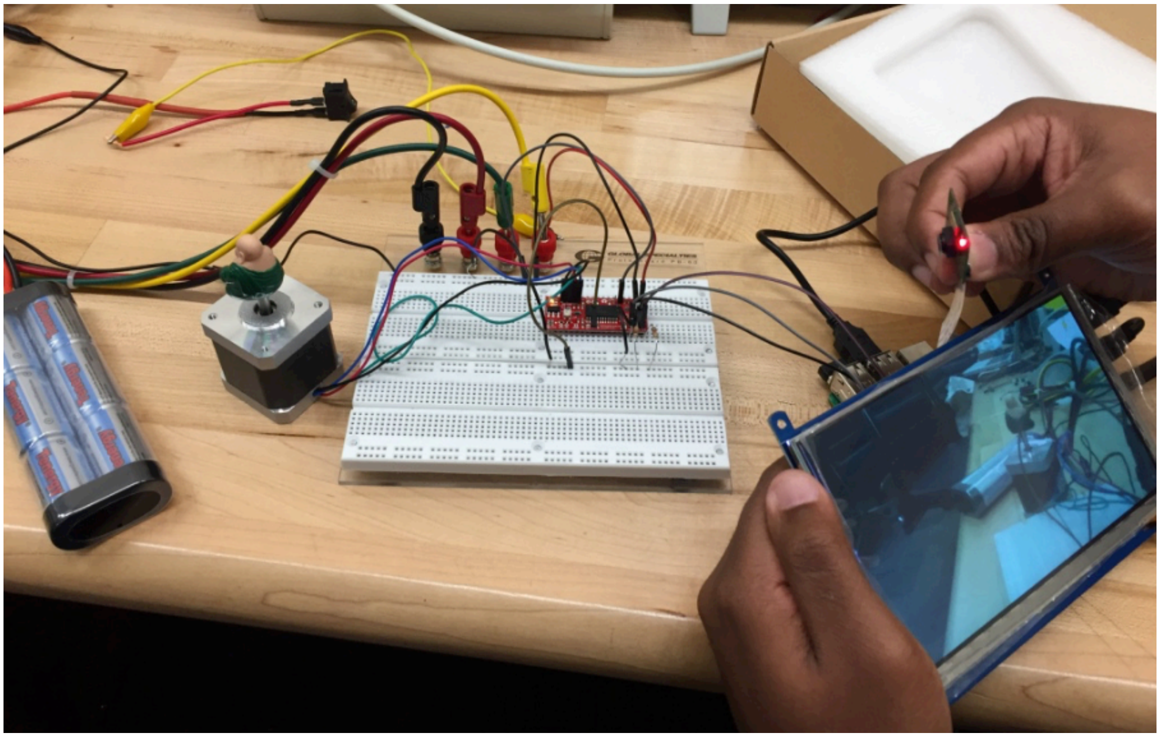


Figure 27: Functionality Testing of Display

The figure below depicts the schematic for the Raspberry Pi and respective components subsystem. The Raspberry Pi will be powered from the battery by the output of the 5V voltage regulator. More specifically, the output of the switching regulator will be applied to pins 2 and 6 of the Raspberry Pi. These are the +5V and GND pins on the GPIO pinout of the Raspberry Pi.

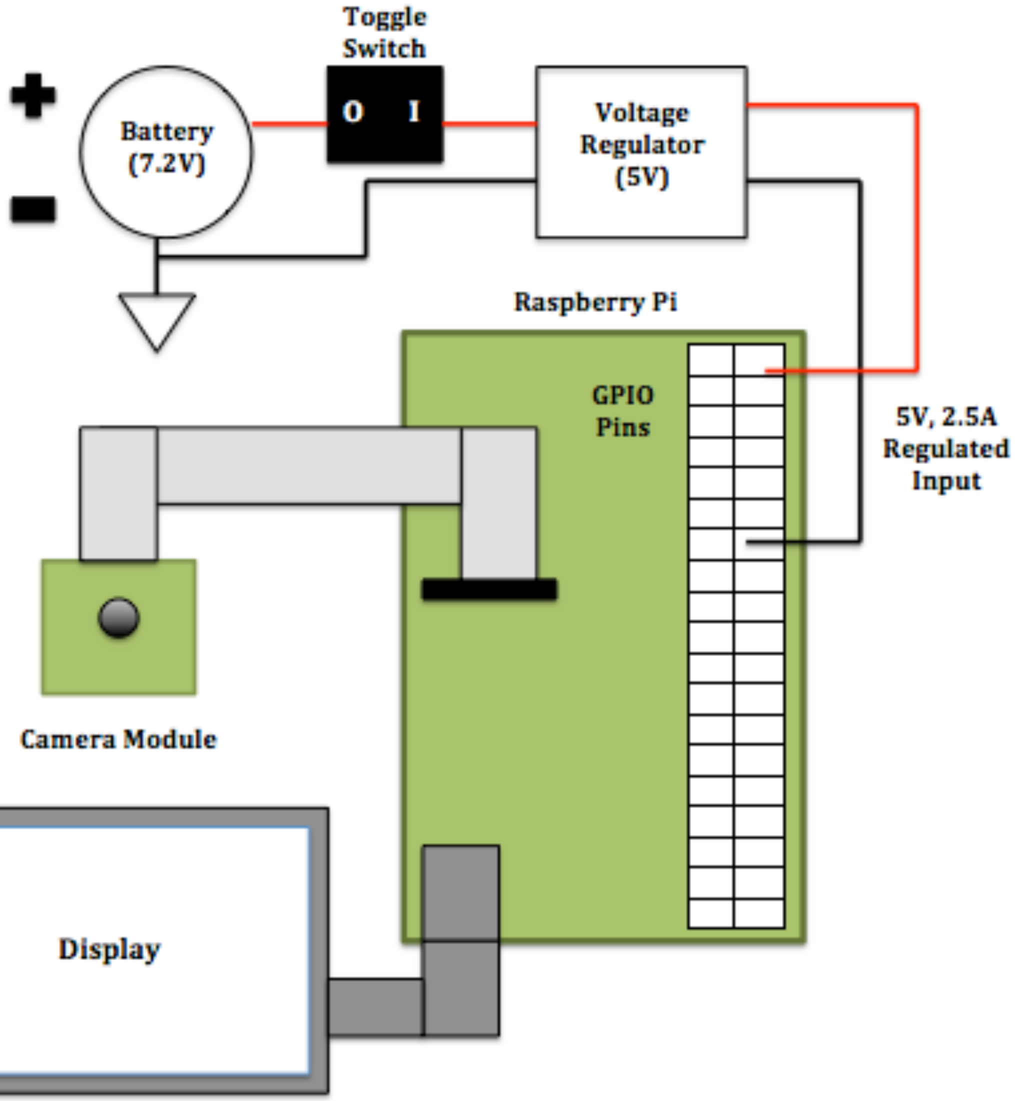


Figure 28: Raspberry Pi and Respective Components Subsystem Schematic

Testing of the Bluetooth module is a two-part test procedure as it is a built component of the Raspberry Pi. The first testing procedure is to create a script or software module that can bridge basic connection between the Bluetooth receiver of a phone or personal computer. The connection should be verified and established then be able to terminate the connection between the two devices. The test script should be able to do this process several times with various

devices. To debug this if something goes wrong it is important to open the terminal and troubleshoot or connect via the Bluetooth command tool. Using the various commands available in this allows a user to verify that the Bluetooth agent is both transmitting and listening to other Bluetooth enabled devices. To ensure that transmitter is transmitting it is important to verify the Raspberry Pi's Bluetooth MAC address is present via another device such as the personal computer. Admittedly, the fact that Bluetooth is an established standard the results of establishing and maintaining a proper connection were as expected.
After, establishing and maintain a Bluetooth connection via the onboard Raspberry Pi Bluetooth transmitter and another Bluetooth enabled device, the secondary test procedures was to see if it was possible send data. To test this several different file types with varying file size need to be transferred from the devices to measure the different times it takes transfer different files. Doing the transfers for several file types various amount of time will provide an average benchmark for the expected amount of time it will take to transfer the larger data files, which will be generated from the scanner. It is paramount that the overall transfer times will not take a large amount of time when compared to the overall process as it is important for the scan to be take a reasonable amount of time. The transfer tests should will show that an expected transfer rate for large files should be with one to two minutes and much less time for smaller files on the order of tens of megabytes.

For the Bluetooth connection the two methods to connect are through the GUI of the Raspberry Pi or through a terminal connection using bluetoothctl. A successful connection should prompt the user that the connection has been established. It is important beforehand to double check the configuration. The Bluetooth functions on very low power, therefore the Raspberry Pi will be capable of providing it with enough power via the 5V, 2.5A input.

5.1.2.2 Line Laser Module Ln-60

The line laser module draws a total of 10 mW of power with an input voltage requirement of 3v and an input current requirement of 35mA. It is desired to have a red LED as a warning light to indicate when the laser is on. This is an important feature in order to notify the user to protect his or her eyes from the red 650nm wavelength laser output. The line laser will require some type of voltage regulation in order to acquire the 3 volts necessary to power the device without burning it out.

The first and cheapest solution to regulate the power into the line laser is a series resistor and LED with the 2 volts dropout. However the voltage drop across the resistor and/or LED will not be constant, thus there will not be a regulated 3 volt input into the line laser, which could result in damaging or limiting the lifespan of the laser.
Using a diode is the next option and most likely the first instinct in this case. There is the schottky diode or the zener diode to consider. This solution is also a

cheaper solution, but the performance is not optimal in this case either. The diodes suffer from process variations and the fluctuations in output voltages can be too high or low for safe operation of the line laser. The line laser was not provided with a datasheet to specify how much fluctuation is safely allowable for the 3 volt input, therefore, it is best to stay as close to the 3 volt input requirement as possible. Both diodes can have precisions at roughly 5%, meaning the input could be as low as 2.85 volts or as high as 3.15 vols. In the testing results provided later on in this report, it can be noted that 2.85 is an acceptable input for proper functionality of the line laser, but it seemed unwise to test about the 3 volt threshold.

The more expensive option but highest performance option is a low dropout voltage regulator. The regulator that will be used in this project is the LM2576 voltage regulator from Texas Instruments. This regulator is capable of safely regulating an input voltage of up to 60 volts to a 3 volt output at up to 3A. This is perfect for the line laser that requires 3V at 35mA. Furthermore, it has a very high efficiency compared to the other options mentioned previously. The power distribution will be further analyzed in the power management & design section.

The testing procedures for the lasers were straightforward. The first test consisted of gathering the I-V characteristic of the laser through measurements to determine the threshold voltage and verify the operation voltage.

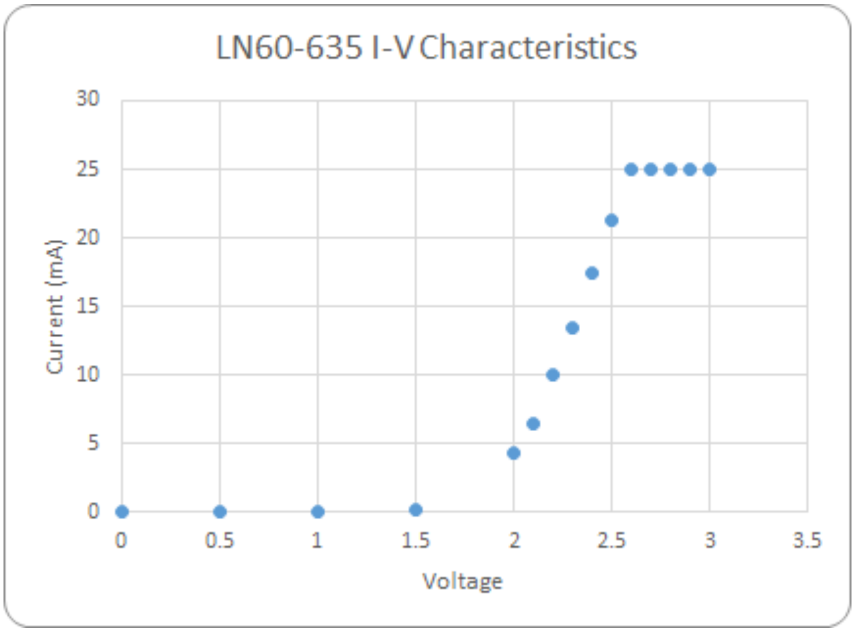


Figure 29: I-V Characteristics of the Line Laser

This was measured through the use of simple current limiting resistor circuit and power supply provided by the university lab. With the laser verified as being operational, the second test to ensure that it would work and be fully integrated into the scanner was to set as the load to the voltage regulator. Using a power supply at 7.2V, a voltage regulator was designed with an output voltage of about 3.0V. Probing the connection nodes with a multimeter the input voltage was incrementally increased until the output was 3.0V and the laser was at its operational intensity. This test can be seen in the image below.

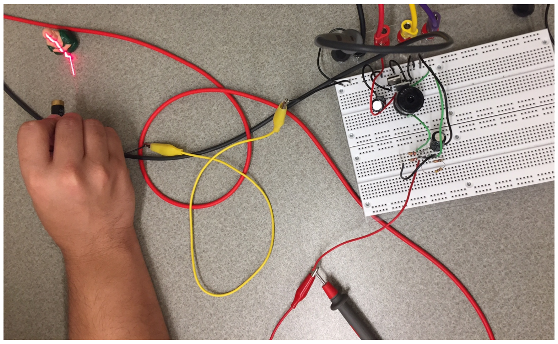


Figure 30: Initial Line Laser Testing

Two MOSFETs will be incorporated in this regulator circuit to create a switching circuit for the laser. The drain of the first MOSFET will be supplied with the 5V pin on the GPIO pins of the Raspberry Pi passing through a 1kΩ resistor. This will also connect to the gate of the second MOSFET. The gate will be connected to a 3.3V pin on the GPIO pins of the Raspberry Pi and tied to ground with a 10kΩ resistor. Finally, the source of the first MOSFET will be tied to ground. The source of the second MOSFET will also be tied to ground and the drain will have the laser connected in series to the output of the 3V switching regulator. This will enable the laser to be switched on and off through communications with the Raspberry Pi. This implementation provides optimization and ease of implementation for the software team.

5.1.2.3 EasyDriver v4.5 and Nema 17 Stepper Motor

The EasyDriver is an open source stepper motor driver that can be purchased through Sparkfun. The board was purchased for initial testing purposes; however, it will be implemented onto the PCB for the final design. While the board is open source, this project will require multiple changes in order to reduce the unnecessary components, inputs, and output on the original board and optimize the design specifically for the project specifications. The stepper motor driver can drive up to 750mA per phase. The stepper motor is a bipolar motor meaning the stepper motor driver can drive up to 1.5A. The stepper motor is able to provide 400 steps per revolution, however, the stepper motor driver defaults to 8-step microstepping mode. This means that using this particular stepper motor driver in conjunction with the NEMA 17 stepper motor, it would be possible to get 3200 steps per revolution. This is very important considering the line laser is not very thick, and in order to get the most accurate scan, the platform needs to rotate the device being scanned in very small increments. The stepper motor drive can take a maximum input voltage of 30 volts. This input does not need to be regulated, because there is on-board regulation in order to provide a regulated input to the stepper motor itself. This statistics for the stepper motor driver come from the A3967 IC chip on-board. This is the chip that will be purchased for the design of the PCB, in order to construct a stepper motor driver optimized for this project. The chip has internal circuit protection that includes thermal shutdown with hysteresis, under voltage lockout, and crossover current protection. The stepper motor driver is compatible with the Nema 17 motor as will be the PCB design using the A3967 IC chip. The figure below demonstrates how the motor connects to the motor driver, which then connects to the raspberry pi in order to allocate the proper communications and power.

This is the best way to test the prototype for this project, to ensure that it works properly as designed. This way, the PCB can be manufactured knowing that if designed correctly it will integrate into the project with ease and everything will run smoothly. If the PCB was designed without testing with products on the market that have already been verified to work, then perhaps the PCB would not work and valuable time would be wasted for lack of planning.

The stepper motor and stepper motor driver were tested using the hookup guide. The LED on the stepper motor driver indicates that it has received power. The appropriate code was uploaded onto the Raspberry Pi and the stepper motor rotated at 400 steps per revolution. An image of this testing procedure can be seen in the figure below.

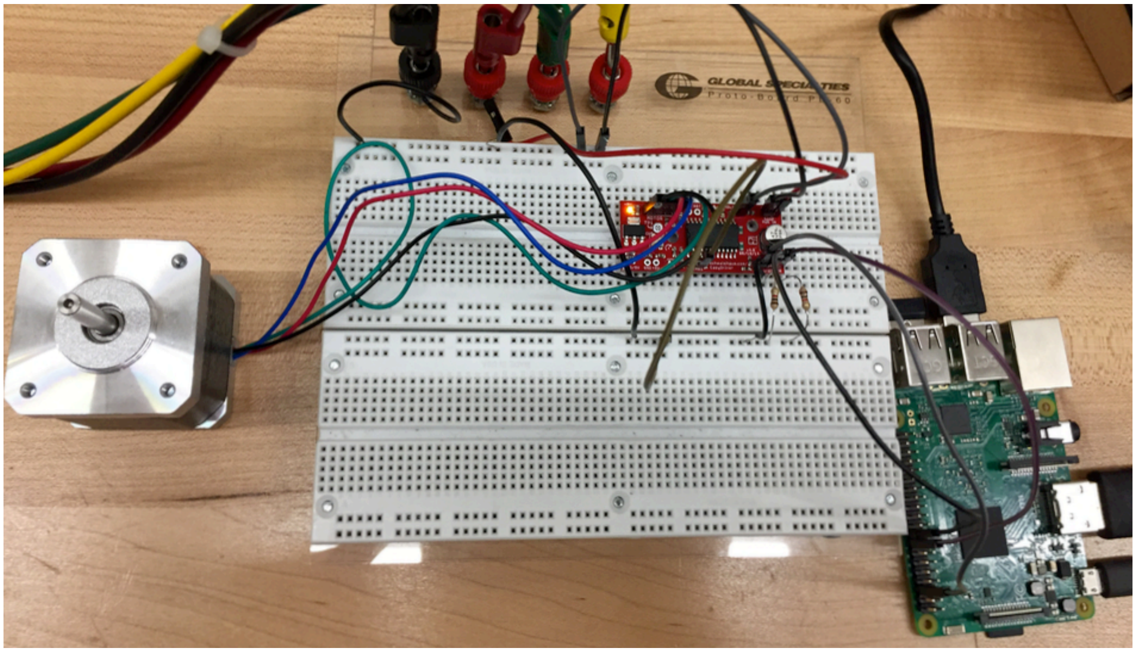


Figure 31: Stepper Motor and Stepper Motor Driver Testing

Using the A3967IC chip from the stepper motor driver pictured below, a schematic was designed using the Eagle cad software, which can be seen in figure 32. This schematic is a simplified version of the Easy Driver stepper motor driver breakout board, because not all of the aspects of that particular board are necessary to our project. Notice that in the stepper motor driver hookup guide, MS1 and MS2 are tied to ground, as well as, in the stepper motor driver schematic.

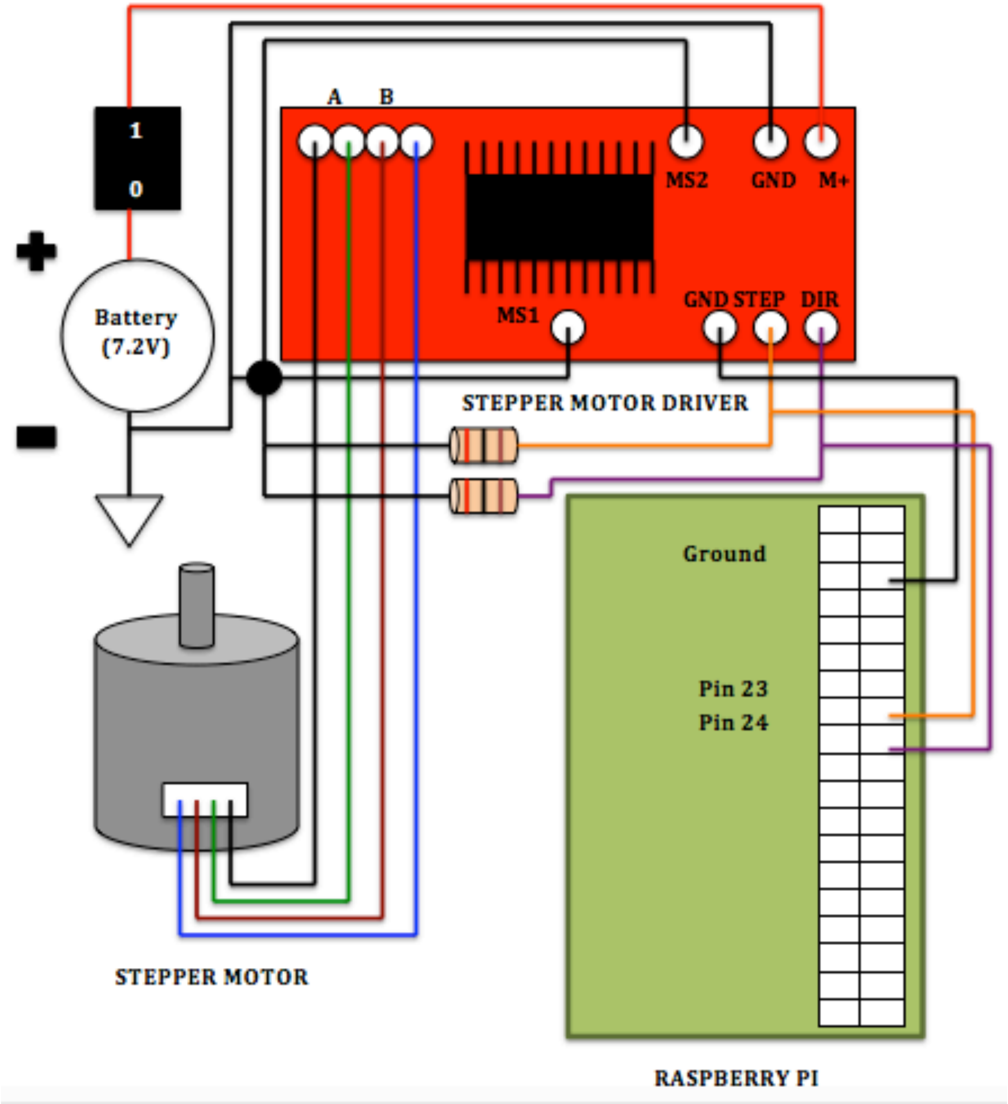


Figure 32: Stepper Motor Driver Subsystem Schematic

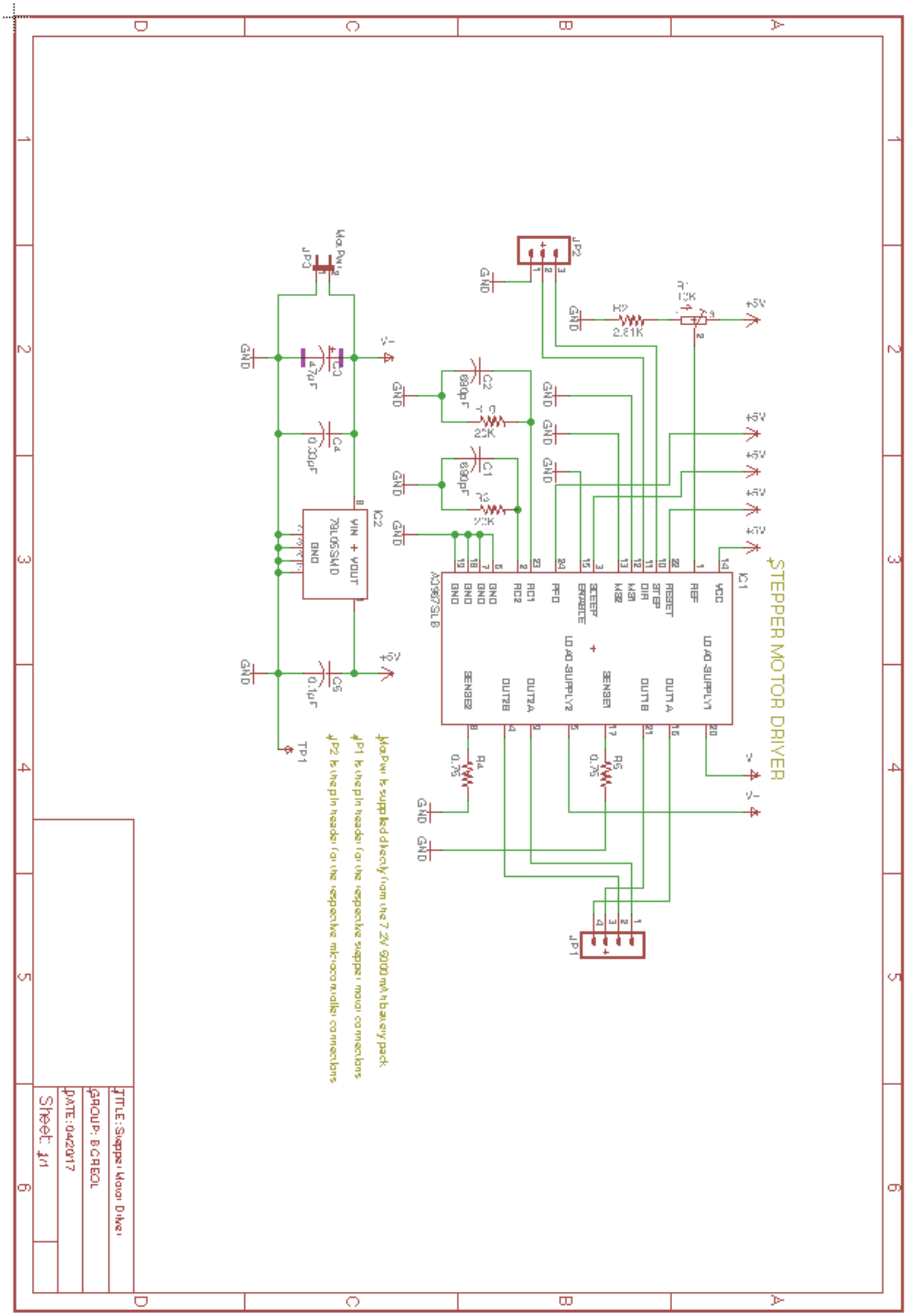


Figure 33: Stepper Motor Driver Schematic

Notice that in the stepper motor driver hookup guide, MS1 and MS2 are tied to ground, while in the stepper motor driver schematic, MS1 and MS2 are tied to +5V. As described previously, the stepper motor is rated at 400 steps per revolution, but the stepper motor driver is capable of stepping at a full step, half step, quarter step, and one-eighth step. In the hookup guide, the driver is set up to take full steps. In the schematic, the driver is setup to take one-eighth steps. This means that in the first case the motor can take 400 steps per revolution, and in the second case the motor can take 3200 steps per revolution. All tests were done at 400 steps per revolution. The schematic can be easily adjusted after further testing and analysis, if it is concluded that 3200 steps per revolution is more than necessary.

The pinout for the A3967 chip specifically designed for this project can be seen in the table below.

Table 12: A3967 Chip Output Descriptions

3D Laser Scanner A3967 Outputs	
A3967 Pin Number	**Respective Outputs**
1	Reference Input (Adj) - +5V
2, 23	Fixed Output - Bridge 1 and 2
3	Sleep - +5V
4, 9, 16, 21	Nema 17 Motor Connections
5, 20	Load Supply to Bridge 1 and 2
6, 7 18, 19	GND
8, 17	Sense Resistor for Bridge 1 and 2
10	Logic Input - Step
11	Logic Input - Direction
12, 13	Digital Inputs - ⅛ stepping mode
14	Logic Supply - +5V Vcc
15	Enable - GND
22	Reset - +5V
24	Slow Decay Mode - +5V

5.1.2.4 Power Management & Design

Proper power management is paramount to the success of this project. Without the correct power allocation to each component, nothing would work individually let alone together as one final product. Many calculations and extensive research is required in order to design the most optimal solution for power distribution. The table below depicts the major components in this project with their appropriate power ratings.

The remaining hardware components will draw power from the components listed in the table below. While the voltage regulators have high efficiency ratings, it is important to note some power will be wasted nevertheless. It is wise to estimate the maximum power rating to be higher than calculated to account for these losses.

Table 13: Power Management

Project Component	Operating Voltage (V)	Operating Current (A)	Total Power (W)
Raspberry Pi 3 Model B	5	2.5	12.5
EasyDriver v4.5 Stepper Motor Driver	6-30 (It will be supplied with 7.2)	2	14.4
Line Laser Module LN-60	3	0.035	0.105
Total Power			**= 27.005**

The Raspberry Pi 3 Model B draws roughly 400mA of current alone. The HDMI port for the display will draw 50mA of current. Finally, the camera module draws 250mA of current. There have been some issues with shipping involving the camera; therefore, another camera module may be used in its place, which will be powered through the USB port of the microcontroller. The USB port can draw up to 1.2A of current. When adding these together, the added components onto the microcontroller, plus the original current draw of the microcontroller itself results in a maximum of 1.65A of current. This is why it is recommended to supply the microcontroller with 2.5A rather than 1.2A.

The component that requires the highest operating voltage is the stepper motor driver. It requires an input between 6 volts and 30 volts. The 7.2V 5000mAh NiMH battery pack is sufficient for the power management of this project. It has a higher nominal voltage than any component in the design. Furthermore, it can provide 5A for an hour. Using the table above, the max current draw will be 4.535A; therefore, the 5A current rating is more than enough. Each scan will not take more than 45 minutes, which guarantees that the circuit will run efficiently for a full scan. The battery can be seen below where it is fully charged. The battery can be charged at a rate of 1A or 2A. The battery was fully charged at a rate of 2A and it took approximately 200 minutes. The green LED indicated a full charge on the battery pack.

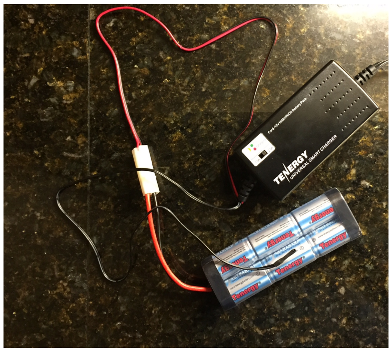


Figure 34: Battery Charging Testing

Both of the voltage regulators will utilize the LM2576-ADJ switching regulator. This regulator has fixed output voltages of 3.3V, 5V, 12V, and 15V and adjustable output voltages that range from 1.23V to 40V. Furthermore, the output current is guaranteed to sufficiently reach 3A. Lastly, the input voltage must be at least 7V. This is the perfect regulator for supplying a regulated voltage to the microcontroller and the line laser. This part is not in the Eagle Cad library, therefore a library with footprint and package had to be developed in the Eagle Cad software in order to design the schematics for each voltage regulator. The schematics can be seen in the figures below.

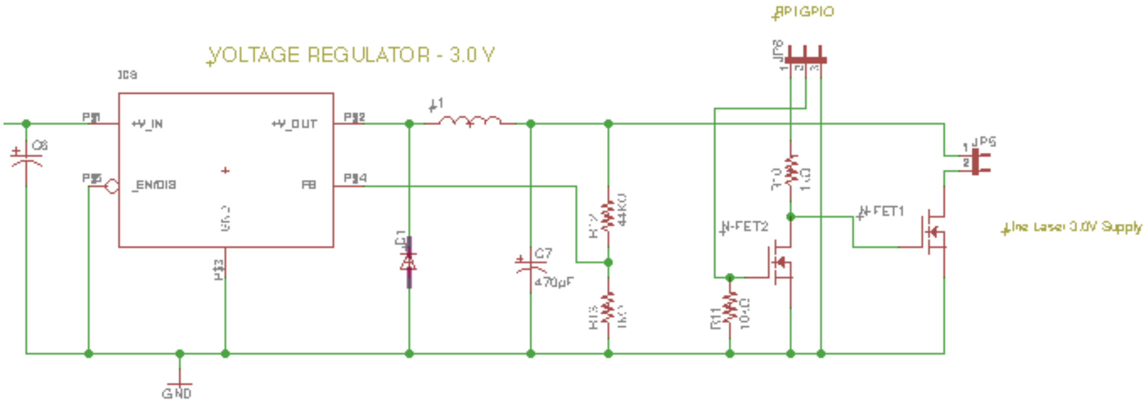


Figure 35: Switching Regulator Schematic - 3V

The LM2576-ADJ switching regulator will be designed to output a voltage of 3V for the microcontroller. The calculations to design this regulator are seen below. Note that Vref is 1.23v. Also, according to the datasheet, R1can be between 1 kΩ and 5 kΩ. For simplification purposes, this design will designate R1to be 1 kΩ.

$$V_{out} = V_{ref}\left(1 + \frac{R2}{R1}\right)$$

$$R_2 = R_1\left(\frac{V_{out}}{V_{ref}} - 1\right)$$

Using the equations above and the design specifications, the value of R2 should be 1439.02439Ω. Two 2.7 kΩ resistors connected in parallel were used to achieve a value very close to the calculated value.

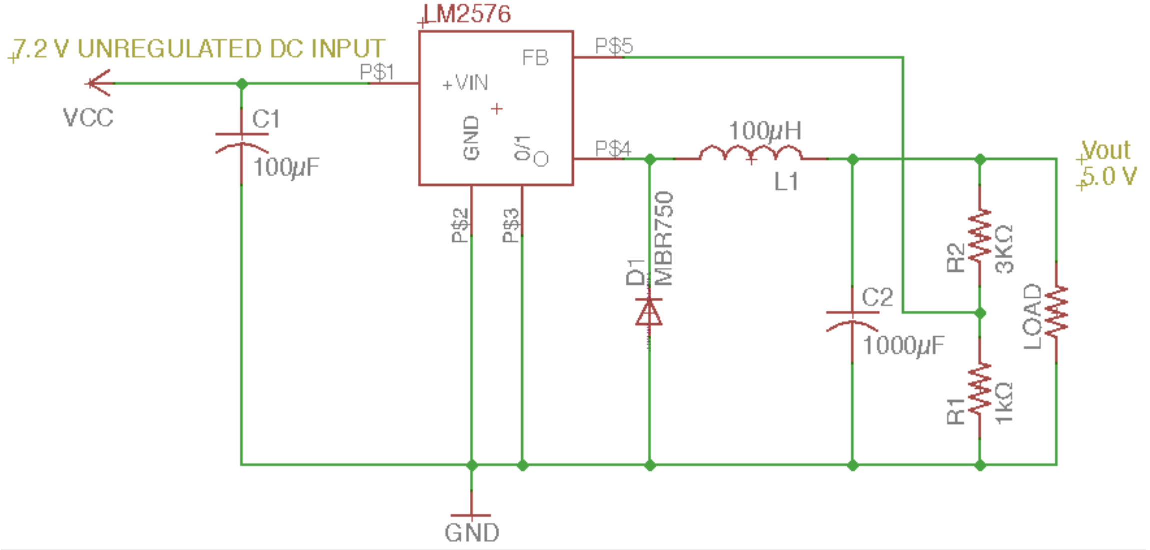


Figure 36: Switching Regulator Schematic - 5V

The LM2576-ADJ switching regulator will be designed again to output a voltage of 5V for the line laser. The same schematic is used for this design with the resistors replaced with the following calculated resistor values. Again, for simplification purposes, this design will designate R1 to be 1 kΩ.

Using the equations above and the design specifications, the value of R2 should be 3065.04065Ω. The closest available resistor value for this is 3kΩ. The figure below is the prototype version of the LM22576-ADJ switching regulator with a voltage output of 5V. Note that relevant testing results will be recorded later on in this report.

Both the 5V switching regulator and the 3V switching regulator were built on a breadboard in the lab. Various calculations were performed to verify that the designed would work properly if implemented in the overall schematic and onto the printable circuit board. Both of these prototypes can be seen in the two figures below.

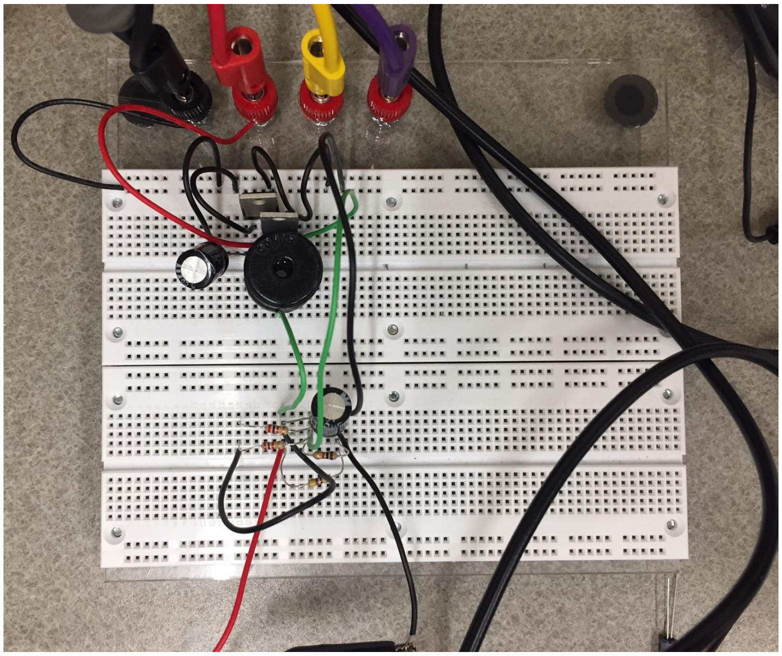


Figure 37: Swithcing Regulator Prototype - 3V

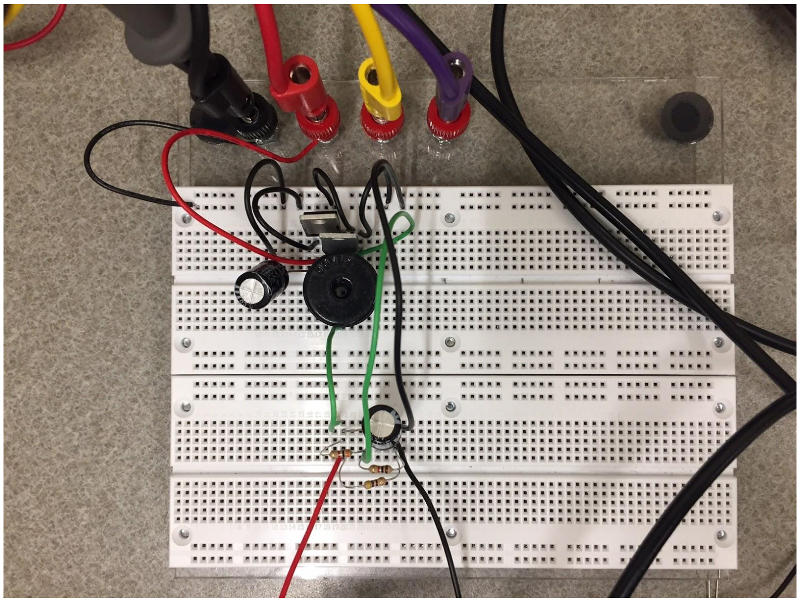


Figure 38: Swithcing Regulator Protoype - 5V

For initial testing purposes, the red LED was not included, however it will be implemented into this voltage regulator design in order to signal when the laser is on. It will be connected at the output of the voltage regulator with a resistor tying it to ground. The red LED will be parallel to the load as both the red LED and the load or the line laser both require 3V to turn on.

Thorough testing was conducted on the 5V switching regulator by stepping the input voltage up from 0 volts to 15 volts with a 500Ω load on the output. The output voltage and output current were recorded at each voltage input and the respective plots for these measurements can be seen in the two figures below.

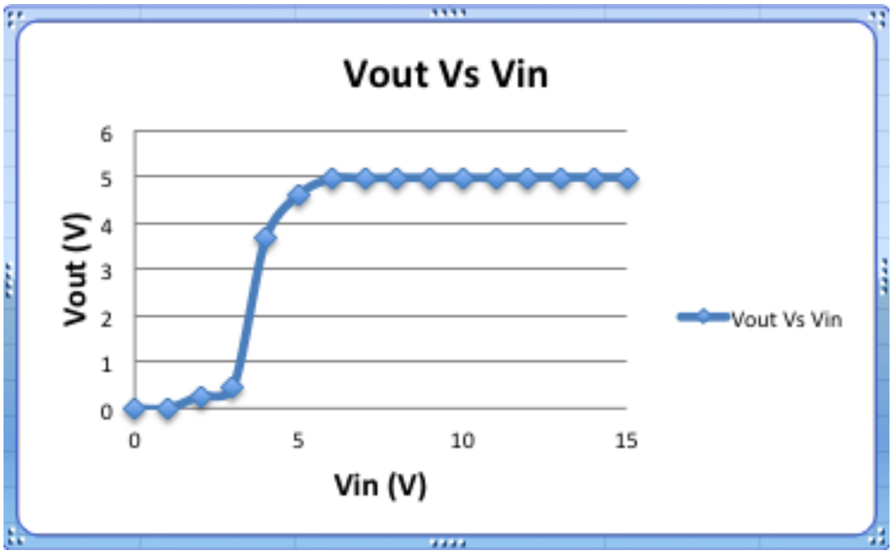


Figure 39: Voltage Regulation Testing

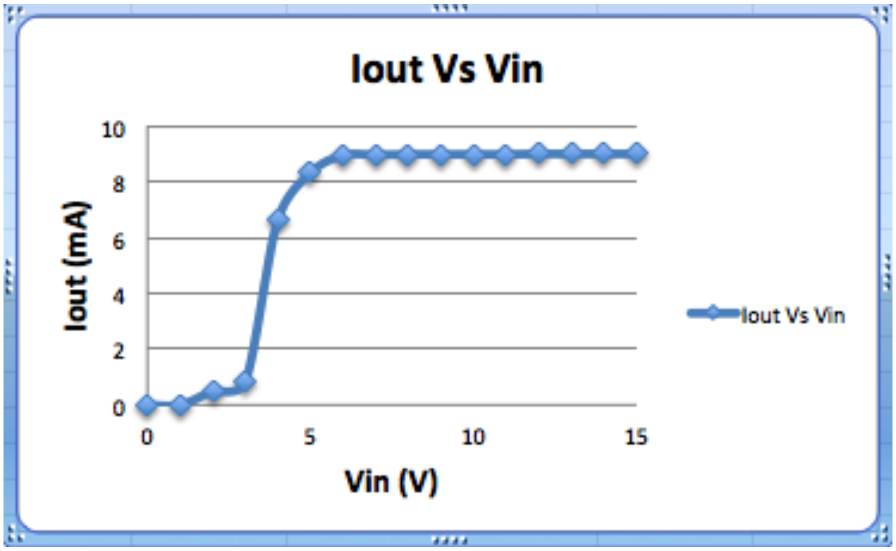


Figure 40: Current Output Testing

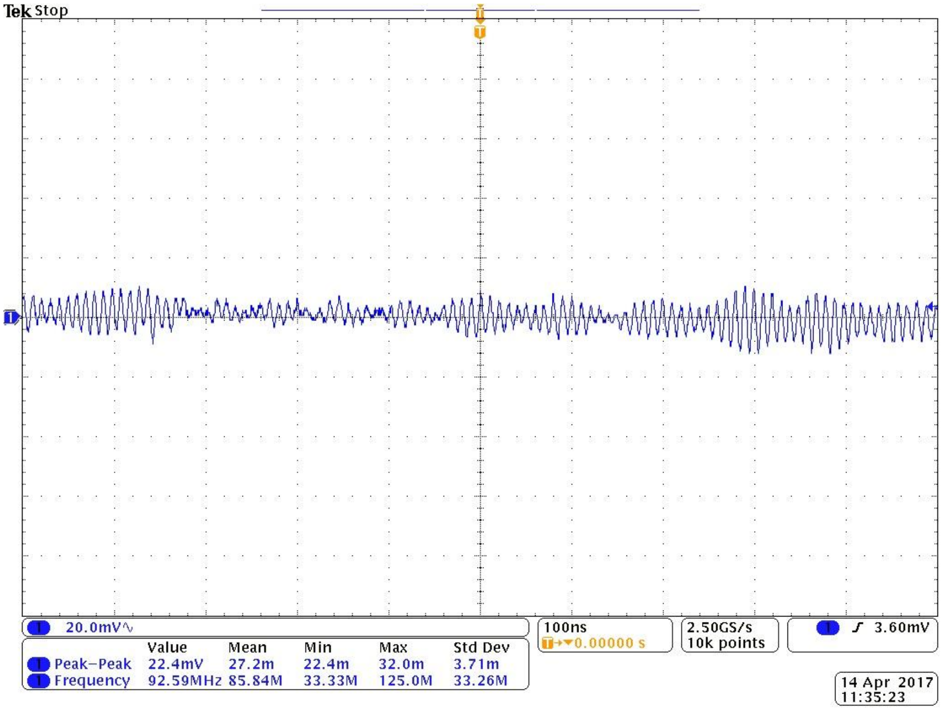
As seen in the figures above and confirmed in the datasheet, the input voltage needs to be at least 7V for proper regulator functionality. The battery will provide an input of 7.2V, which is sufficient for proper operation of the switching regulator. The tests were performed with a 500Ω resistor at the load. The fundamental Ohm's Law can be used to calculate the output current in order to produce expectations for these values. With a 5V output and 500Ω load, the output current should be approximately 10mA. As seen in the figure above, when the input voltage reaches roughly 7V the regulator will begin to function and the resistor draws roughly 9mA at the output. This is very close to the expected value and any fluctuations can be attributed to inaccuracies in the resistor values.

In addition, the ripple voltages of the LM2576 were also measured to compare against the specified value in the datasheet. The maximum ripple voltage in the datasheet for LM2576 is 50mV. To test this the output of the following steps were taken:

1. Connect the output terminal to the input of the channel one oscilloscope and ground.
2. Set the oscilloscope's setting to ac coupling to make it easier to measure the ripple voltage.
3. Set the measurements of the oscilloscope to measure the peak-to-peak voltage and the frequency.
4. Scale the output to approximately 10 mV to 20 mV to stabilize the reading of the ripple voltage.
5. Repeat this process for all the switching regulators.

The result for the ripple voltage agrees with the specified values in the datasheet. For each regulator the ripple voltage was between 20mV to 25mV, which was under the 50mV, ripple voltage value stated. More specifically in the figure below the, ripple voltage for the 3V switching regulator is 22.4 mV along with 92.59 MHz switching frequency. Similarly, the ripple voltage for the regulator with a 5V output can be seen in the figure below, depicting similar results with a slightly higher ripple voltage of 34.0mV.

Finally, the overall schematic for the power management of this project is seen in figure 46 further below. Starting on the left, it is clear that the 7.2V, 5000mAh NiMH battery pack will be responsible for powering the whole project. This is the main line that all other power will feed off of. The direct unregulated battery voltage will be applied to the stepper motor driver design that will have voltage regulation built into it to supply the motor with the appropriate power for proper functionality. Another parallel branch from the battery voltage will be fed into the 5V switching regulator to safely power the microcontroller. A final parallel branch from the battery voltage will feed into the 3V switching regulator to safely power the laser through the designed switch method using the MOSFETs. This is all clearly labeled on the schematic for reference purposes. This is the final power design at this point, but more options will still be considered to enhance the functionality and difficulties of this project.



20.0mV∿

	Value	Mean	Min	Max	Std Dev
1 Peak−Peak	22.4mV	27.2m	22.4m	32.0m	3.71m
1 Frequency	92.59MHz	85.84M	33.33M	125.0M	33.26M

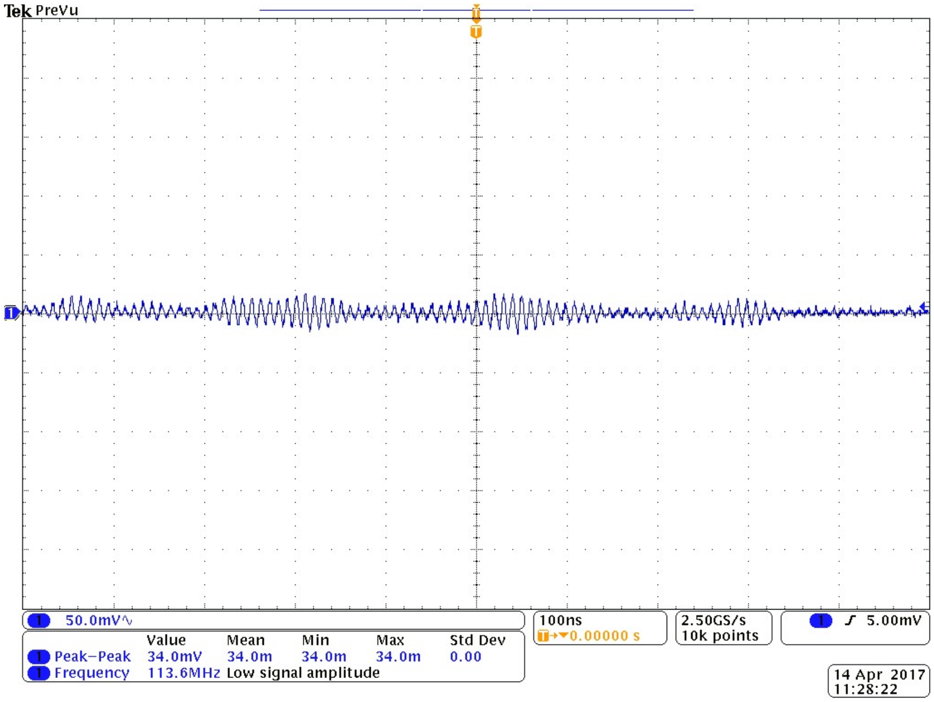
100ns
T→▾0.00000 s

2.50GS/s
10k points

1 ⨍ 3.60mV

14 Apr 2017
11:35:23

Figure 41: LM2576 3V Ripple Voltage Measurement



50.0mV∿

	Value	Mean	Min	Max	Std Dev
1 Peak−Peak	34.0mV	34.0m	34.0m	34.0m	0.00
1 Frequency	113.6MHz	Low signal amplitude			

100ns
T→▾0.00000 s

2.50GS/s
10k points

1 ⨍ 5.00mV

14 Apr 2017
11:28:22

Figure 42: LM2576 5V Ripple Voltage Measurement

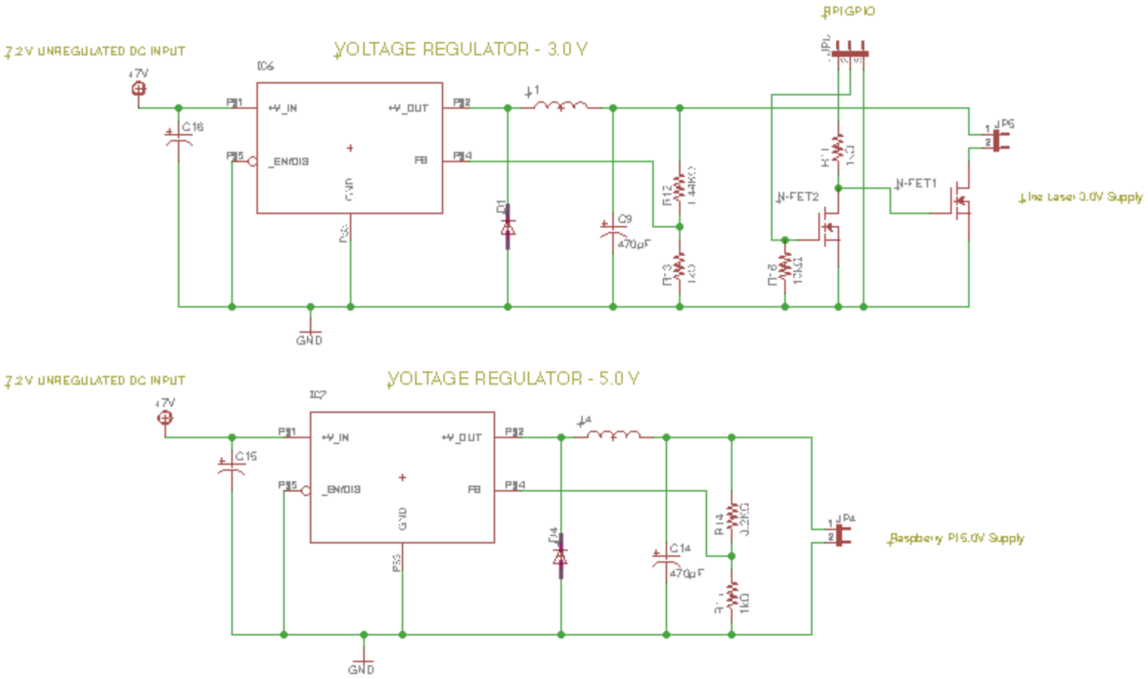


Figure 43: Power Management Schematic

5.1.3 Optical Components

Following the successful electrical testing with the laser's output being properly kept in check by the voltage-regulation subsystem, we were able to safely conduct camera tests on a small test target with the laser operating at its maximum recommended intensity. The initial topic of interest in this section was to determine whether the beam width or the camera was the limiting factor of scan's point cloud resolution, but it quickly became apparent that hardware improvements and focal length alterations are necessary to conduct such tests. As such, this section identifies those technical issues, offers viable solutions, and details how resolution testing will be performed once the proper hardware is in place.

5.1.3.1 Camera Mounts & Focal Adjustments

The first issue apparent, although it wasn't the primary focus of this test, was the lack of proper hardware necessary to mount the delicate camera chip at a reliable and reproducible angle and location. Such details are easy to overlook, but they must be accounted for in order to conduct meaningful optics tests to properly characterize the performance of our prototype. The final testing will require much more mechanical control in terms of position and orientation than our current prototype is able to provide. A high priority for our group is to create such mounting hardware as soon as possible. A protective camera housing with mounting screws has been ordered which allows simple mounting via two screws, but no adjustable mounting arm compatible with our prototype's frame currently exists. Our group lacks a mechanical engineer, so the designing of such an angle-and-height adjustable mounting arm is still in its early phases.

Presently, until we can remedy this issue, the camera is mounted somewhat haphazardly on an angle-adjustable telescoping arm attached to the prototype's frame. As this telescoping arm was designed for holding a dental mirror rather than leveling a delicate camera chip, the angle was slightly askew, as can be observed in the below figure. In spite of the issues presented by our makeshift mount, we were able to achieve the proper camera distance of three inches from the stepper motor's axis of rotation.

This test provided valuable new information regarding the camera's focal properties. This image was captured in low-illumination conditions; similar to those which will be present due to the final design's opaque enclosure. The purpose of this test was initially to determine the effectiveness of several point cloud extraction algorithms with respect to the laser diode's unaltered beam width. If the beam were determined to be too wide, a lens would be selected to narrow it. Yet another large issue was revealed, however, by the attempted test, and it must first be addressed before this test can effectively go forward.

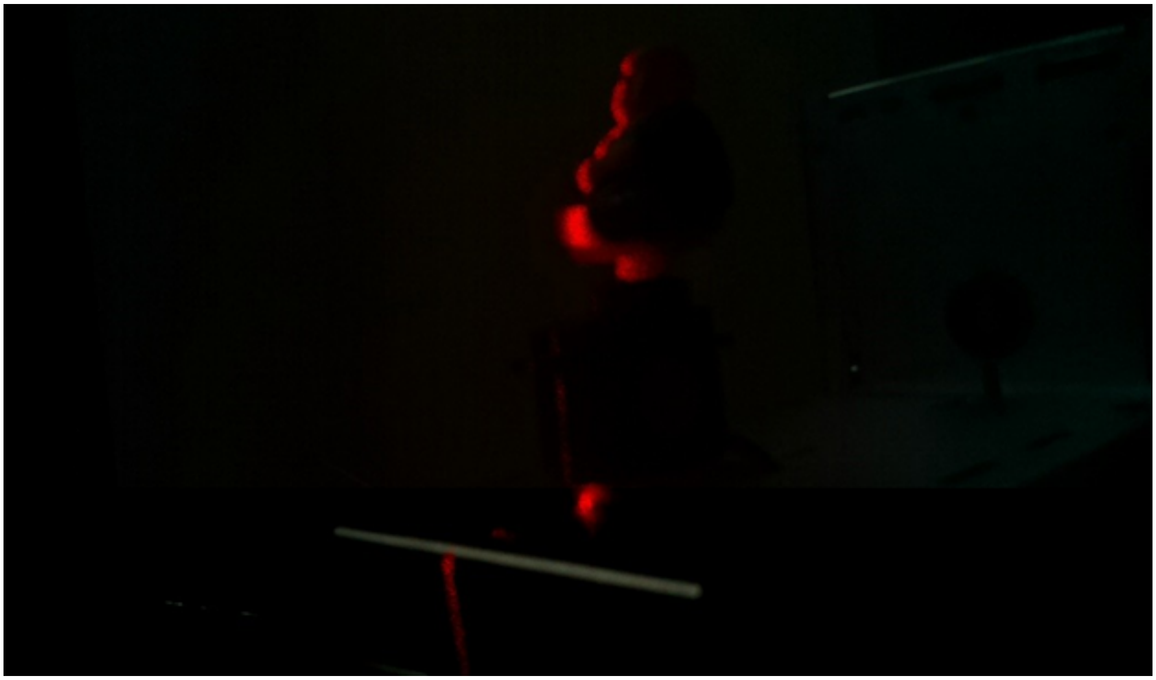


Figure 44: Hardware and Focal Issues Revealed by Image Test

The test subject is clearly out of focus, as can be seen in the figure 46. The image plane for this camera, as it turns out, is fixed [16] at a prohibitively large distance of infinity from the camera, and unlike similar models, its static lens system does not allow one to adjust the focus through software-based means. We were aware upon purchasing this model that the default focus was infinity, but a faulty assumption was made that the hardware allowed simple manual adjustment. At first glance it appeared impossible to manually adjust the camera's lens parameters due to a several dots of epoxy holding it in place. Additional lenses were considered as a solution.

Fortunately, a solution to this focusing issue exists which is far more cost-effective and time-effective than buying and mounting a new lens for each camera. A bit of research revealed that we are not the first to encounter this problem with this particular camera model [16]. Although the lens is epoxied in place, it is still mounted on a threaded, distance-adjustable lens holder. To enable adjustment of this threaded lens holder, one must first scrape away the dots of epoxy keeping it fixed in place. The lens can be adjusted such that at a minimum, its focus is as short as 2.5 cm, making our desired focal distance of 3 inches (~7.6 cm) well within reach without requiring the purchase and installation of additional optics. Several steps must be taken, however, to perform this procedure without damaging the camera's delicate frame and microelectronic components:

1. Carefully remove the epoxy holding the camera's lens in place. A fine-tipped dental scraper is recommended as shown in the figure 47, but any tool with an extremely fine sharpened end will work.

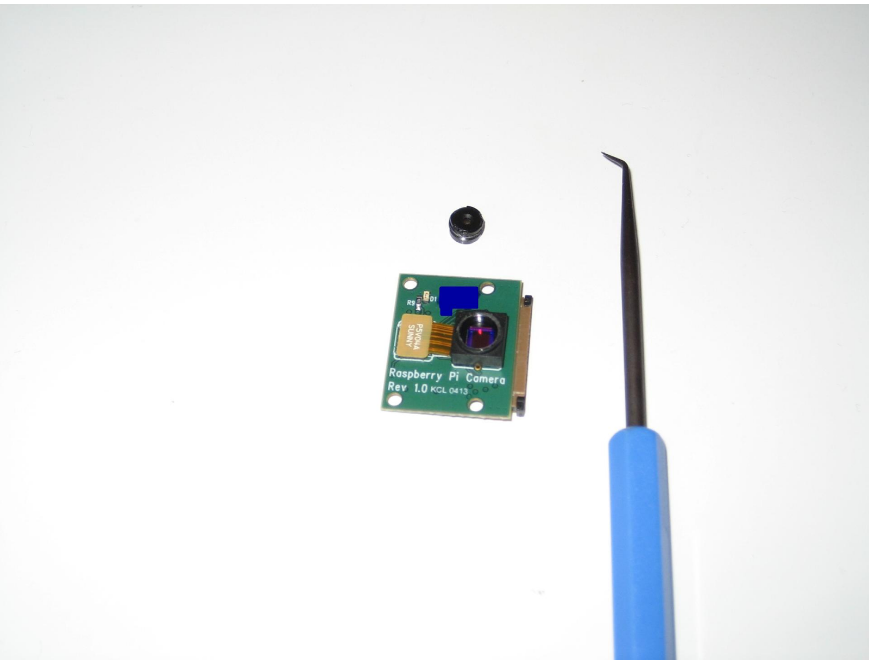


Figure 45: Removing Epoxy from Lens Assembly

2. Before rotating the lens holder about its threading, we will 3D print a special wrench with a socket custom-designed for this particular camera model and procedure. An STL file of this wrench is available for free on the popular open-source platform known as Thingiverse [17]. The tool is shown in figure 48.

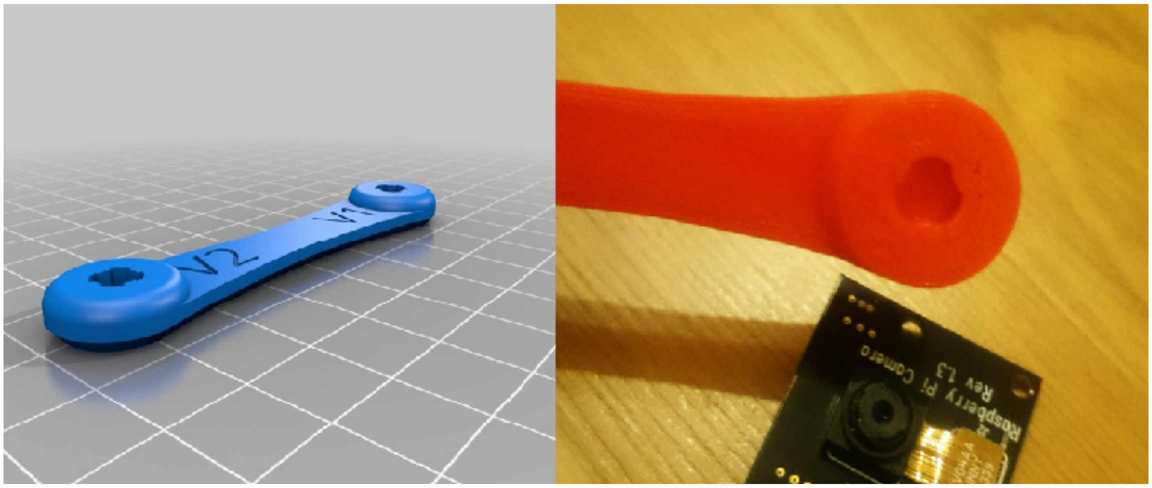


Figure 46: Custom Wrench for Focal Adjustments

3. The instructions for this procedure recommend that the following formula be used to calculate the magnitude of rotation θ necessary to achieve a specific focal length of *f*.

$$\theta = \frac{360^{o} \times 3.5cm}{f}$$

This suggests that we will need to rotate the threaded lens holder approximately 165° to change the focus from infinity to 3 inches.

4. The validity of this formula will be checked in-lab on an optical rail to ensure a proper focal length is obtained.

Once the proper tools are obtained and the focusing procedure is finished, the in-situ testing of the current beam width's effectiveness will be properly conducted.

5.1.3.2 Camera Resolution: 2D and 3D Performance

The USAF resolution test target has been widely used within the field of optics for many decades, and it remains a highly reliable measure of an imaging device's 2D resolution. The test has remained in use due to its simplicity: image the USAF target with the device in question, and identify the smallest spatial frequency grouping for which the lines don't appear to "blend together." In more technical terms, this is a measure of the minimum spatial frequency for which the dark pixels of neighboring lines don't spread to fill in the white space between them.

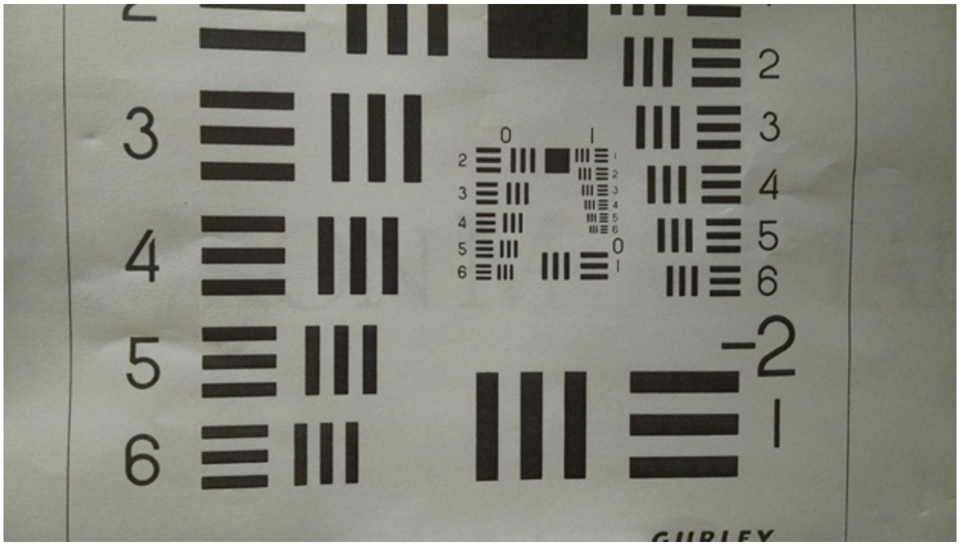


Figure 47: USAF 1951 Resolution Test Target

The "improfile" function of MATLAB will be used to determine the minimum resolvable spatial frequency. It can generally be observed that a "resolvable" grouping of lines will have a contrast, defined by

$$\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}},$$

such that a profile taken across those lines appears as a step function (however noisy) similar to that shown in figure 50.

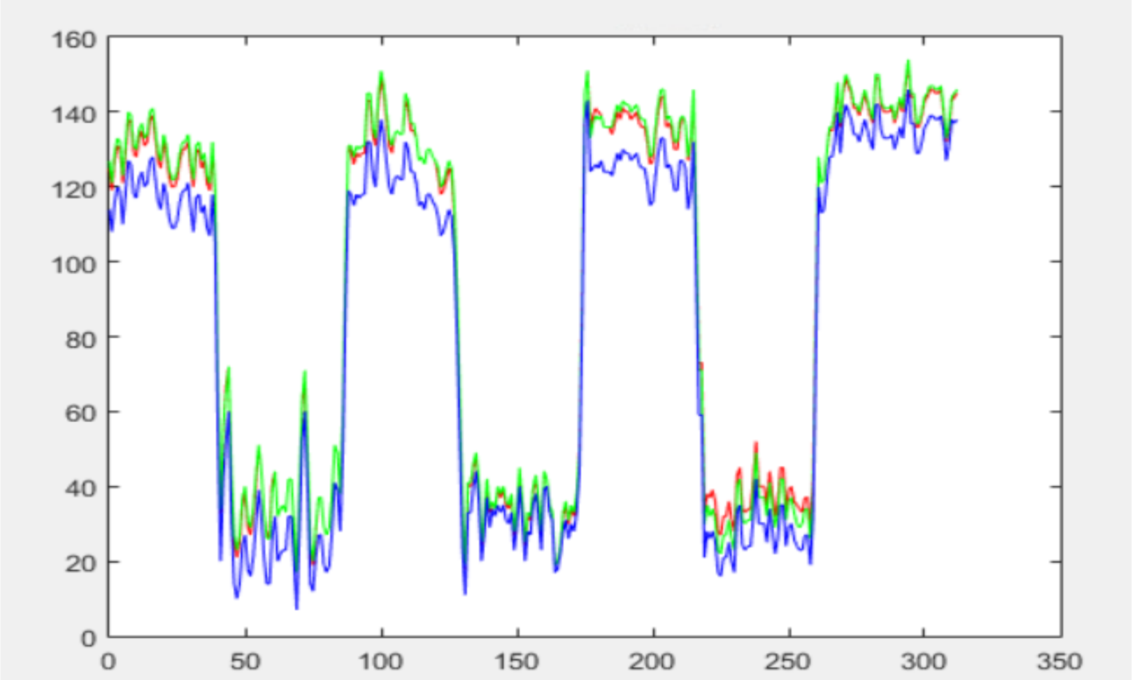


Figure 48: High Contrast Line Profile

As the resolution limit is approached, the distance between intensity maxima and minima will shrink and neighboring lines will start blending together such that the profile becomes sinusoidal in nature. Once a set of lines is found for which the contrast between the sinusoid's peaks is very small, the resolution is defined as the thickness of one period of that sinusoid. .

To gauge the scanner's 3D performance, the test target shown in figure 51 be printed and subjected to test scans. This test target was found as an STL file at the Thingiverse open source database, just as the specialized wrench was in the focus-adjustment section. It will not only test spatial resolution with periodic grooves, but it will additionally test for occlusion using the concave dome structure, among other metrics of interest to 3D scanning.

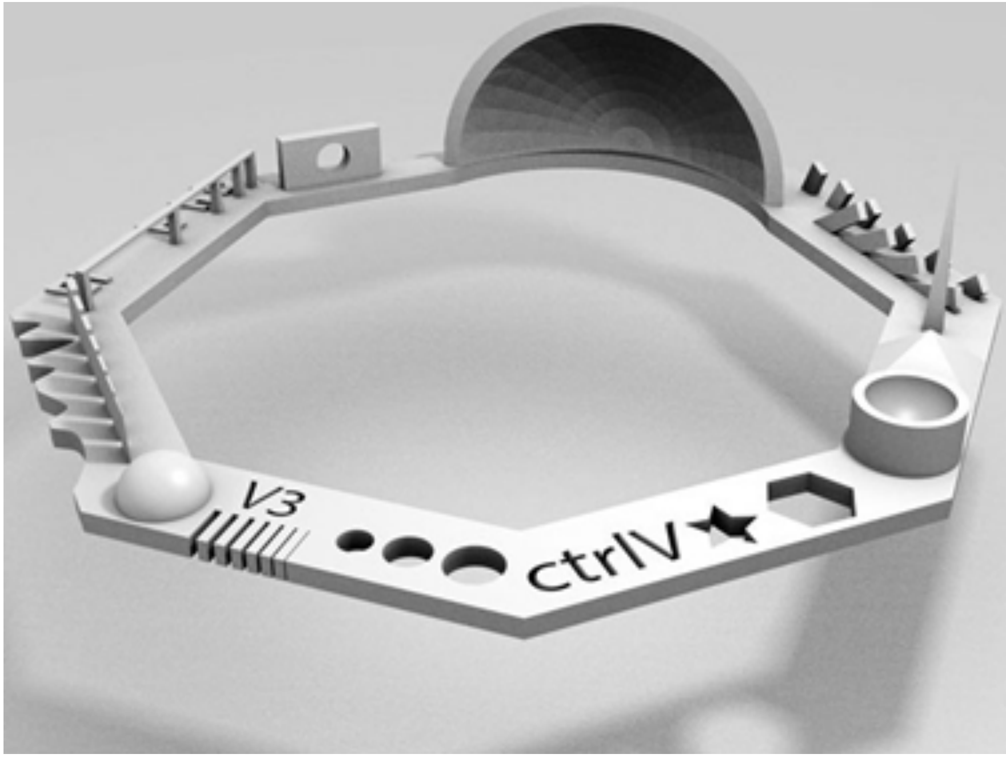


Figure 49: 3D Performance Test Target

5.1.3.3 Camera OpenCV Intrinsic Calibration Testing

To test the camera’s intrinsic properties a series of 20 images were captured and passed through an OpenCV script run on the Raspberry Pi 3.0. Analyzing the images at various angles for all 20 images allows the program to locate the intersections of the black and white squares as seen below in figure 52.

The spacing between the squares can be used to calculate a 2-D matrix, which characterizes the spatial aberrations present in the imaging device [15]. That matrix can then be used to correct spatial distortions in future images. For future tests of this nature, once the camera foci are finalized, a more rigid checkerboard will be used. It will also be mounted on an optical railing with finer control over checkerboard orientation.

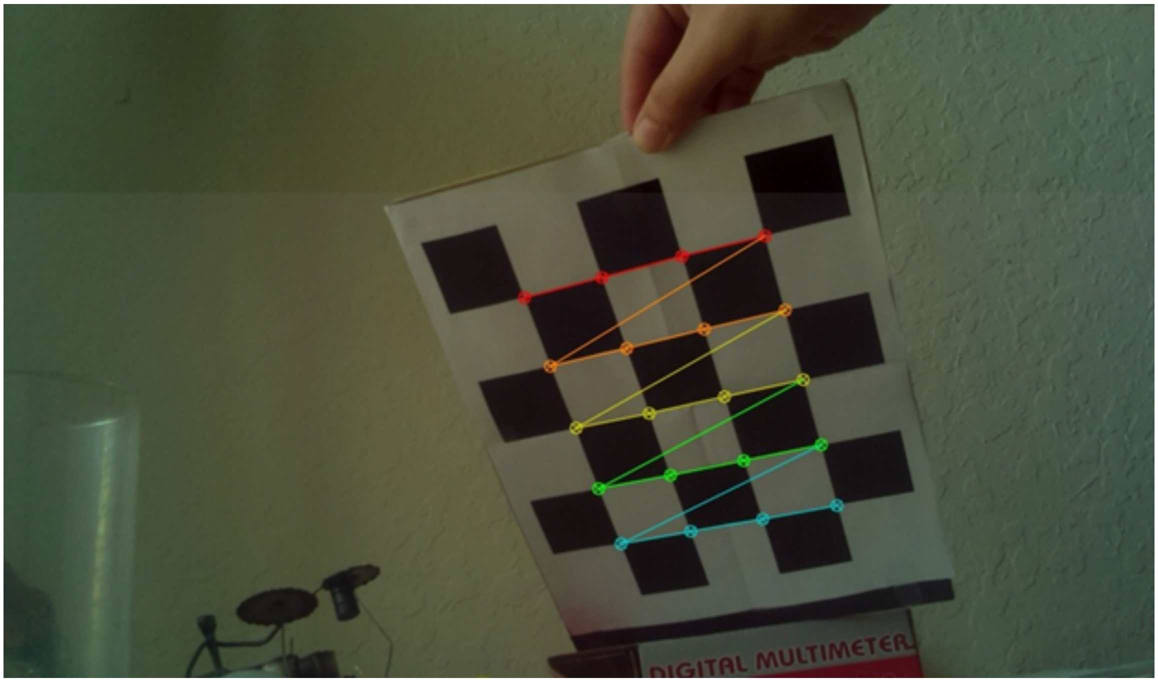


Figure 50: Intrinsic Calibration Test of the Camera

5.1.4 Container

Due to the primary function of the acrylic container being to house the all the electronic components most the testing for this part of the project is simple stress testing and physical materials testing. While the housing of the electronic components is essential the major criteria for this design is to have stability. It is paramount that the when the stepper motor turns the platform inside the container that the object not shift or bounce around too much as it will severely distort the laser profile of the object. In turn, this will make it more difficult to process and render the objects properly to a user. Therefore, through experimental observations the test procedures for determining the stability will be measure empirically by allowing various positions, locations, and tension on the platform to allow rotation with any unwanted movements. Ideally, for this it is expected to be minimal or the noise created should be small enough that it can be filtered out from the data through data processing techniques after the scan because the centerpiece of the platform will have an adhesive material to prevent excessive movement. Furthermore, a light source will be placed inside the containment unit where the object, laser, and camera are in order test how much light leaks through the container. The inside of the containment unit will contain a black acrylic stained layer to prevent ambient light from entering and escaping the unit. In addition, the unit will be sealed and the camera left recording to see how much ambient light is entering the chamber where the platform and object are housed. The expected results are that the ambient light entering should be minimal such that it does not affect the intensity of the laser profile being recorded by the camera.

The laser will require an overall stable platform so the camera can clearly capture the profile of the laser on an object. As the stepper motor rotates the platform there will be some excess vibrations applied to object, camera, and laser. The vibrations will cause some distortion the captured laser profile, which will reduce the quality of the image. To reduce the distortions, there are two sections where there must be a focus on dampening the vibrations: the under section of the stepper motor and the arm which holds the laser and camera pair. For the arm, once the optimal angle between the laser and camera is calculated this will allow the size and shape of the arm to be properly measured. As such, a dampener like dense foam will need to be placed at base connection of the arm against the platform or along the under section of the stepper motor mount.

5.1.5 Prototype and Integration of Designs

The next step for the hardware design phase is to implement all of the components together into a single unified design. Before doing so, a switch will be soldered to the battery leads in order to ensure safe operation for the user and the various components. For ease of integration, the appropriate headers and connectors will be applied to the battery leads and the stepper motor driver and various types of jumper cables will be used to connect all of the components. The entire project will be powered together by integrating the battery and the two voltage regulators into the single unified design. This will verify that the battery is sufficient for powering the project for an appropriate amount of time. Furthermore, it will verify that the design is solidified and a PCB is ready to be designed based on the prototype and integration of all components. For the initial implementation of all components, the purchases motor stepper driver breakout board will be use. However, as seen in previous sections, a design for a unique stepper motor driver for this specific project has been produced in Eagle Cad and this will be implemented onto the PCB for actual demo implementation and presentations. Initial testing and integration of all components can be seen in the figure below. Please note that the lighting is dimmed in order to verify that the power LEDs are on and the laser can be seen.

For prototyping purposes, the 7.2V, 5000mAh NiMH battery pack and compatible battery pack charger are used. This is a portable method that eliminates the necessity for an outlet if mains power were to be used. Plugging into an outlet for power will reduce the size and weight of the project as well as contribute to its aesthetics. For this method, the bulky battery pack will be eliminated and several common electrical components and circuits will be added to the printable circuit board in order to receive the appropriate power from the wall socket. An AC to DC converter will be necessary as well as a method of tremendously stepping down the voltage to an appropriate level for this project. Although the product will not be as portable, battery charging will not be a stressor in this case. The scanning process will have no time limit or boundaries in terms of power. However, this isn't a huge issue as the scans should be under 10mins.

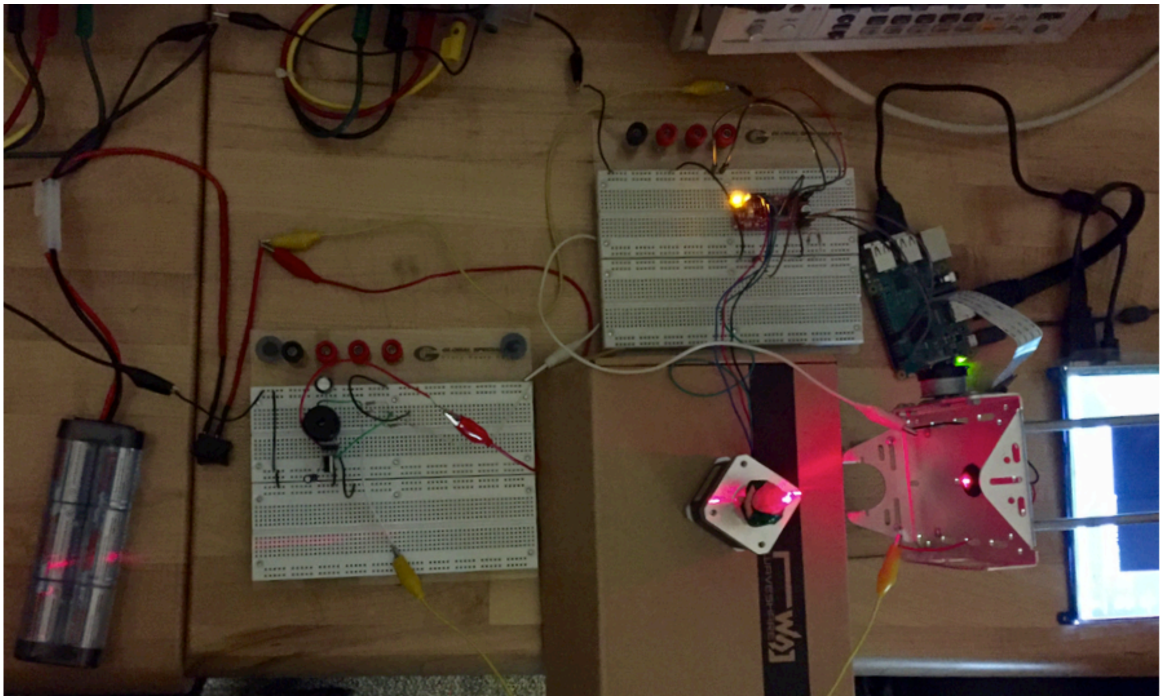


Figure 51: Initial Prototype Testing

The figure below is the full system schematic with all parts integrated. This is what will be produced on a printable circuit board in the future. The schematic as of now does not incorporate any LED functionality; however, this will be considered greatly before the final designing and manufacturing of the printable circuit board. Furthermore, other power management components may be researched and implemented to further add electrical engineering complexity to this yearlong project.

With all components implemented, a script was ran on the Raspberry Pi to instruct the motor to rotate at 400 steps per revolution and to instruct the camera to capture a photo at each step. This was tested twice with very similar results. Any differences in results can be attributed to the reflex of the individual starting and stopping the stopwatch at the appropriate time. The results can be seen in the table below.

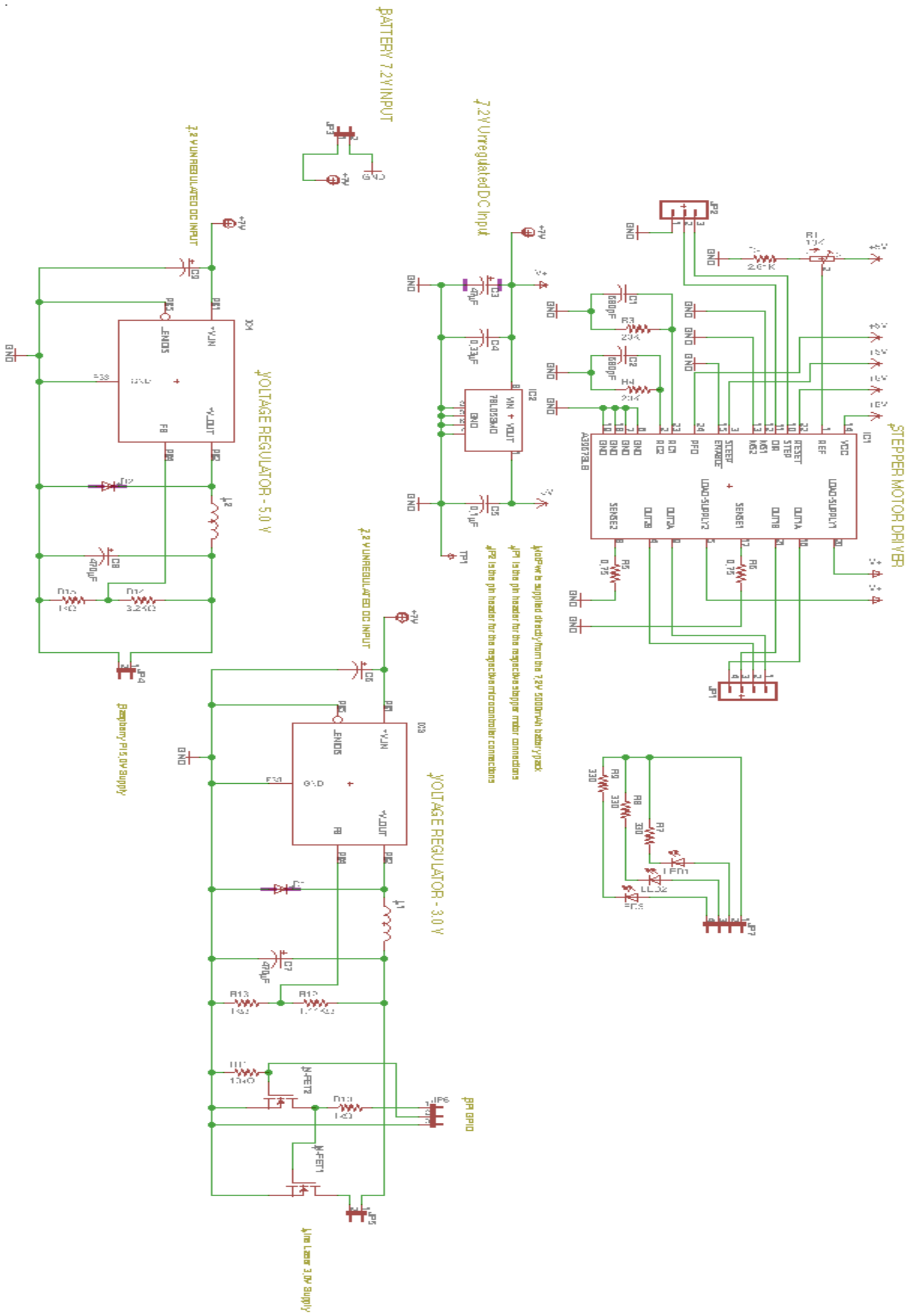


Figure 52: Full System Schematic

The PCB was designed using Eagle and AutoCAD software. It was manufactured through OSH Park. The PCB was revised to incorporate the switching circuit on the 3V regulator and the LED circuit for added functionality to the software team. The final PCB version can be seen in figure 55 below.

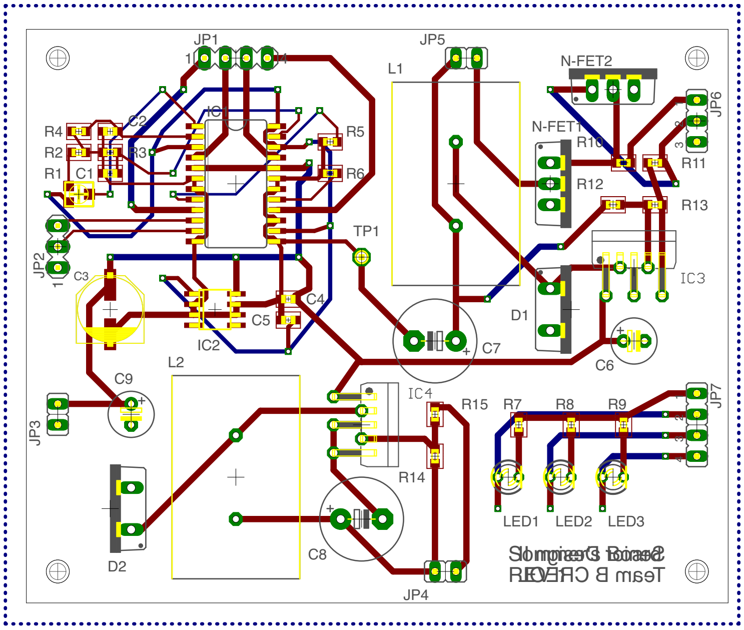


Figure 53: PCB Design

This table suggests that scanning any small object should take just about four minutes to complete. More time will be allotted for the collection and transformation of this data into a 3D image and 3D printer appropriated file. This is an important initial test helps gauge if the project is on track to meet the design specifications in regards to scanning time.

Table 14: Initial 3D Laser Scanner Time Tests

System Testing			
Test Number	**# of Steps/Rotation**	**# of photographs**	**Time (minutes)**
1	400	400	3:53:02
2	400	400	3:52:30

This table suggests that scanning any small object should take just about four minutes to complete. More time will be allotted for the collection and

transformation of this data into a 3D image and 3D printer appropriated file. This is an important initial test helps gauge if the project is on track to meet the design specifications in regards to scanning time.

5.2 Software Design

Being that the 3D Scanning System is so heavily dependent on software, the approach to the design of the software requires special attention. The following sections will offer an in depth assessment of the team's approach to the software demands of the system. These will range from an overview of the chosen design process to the individual methods chosen for each task.

5.2.1 Design Process

The software process model chosen for a project can significantly facilitate or hinder the project as a whole. For the 3D Scanning System, the team selected the agile model to follow for the development of the software side of the system. The agile method provides an emphasis on flexibility in producing software quickly without compromising quality. The agile model does so through the ideals presented in its manifesto. First of all, being by individuals and interactions over processes and tools. Being that this is a project, which requires the collaboration of a team, a focus on interpersonal relations is ideal. In addition to this, the manifesto also encourages dedicating time to producing functional software instead of comprehensive documentation. Lastly, the manifesto prefers responding to change as opposed to simply creating a plan then following it. This is extremely instrumental to the team due to the steep learning curve that is faced. During the development of the 3D Scanning System, the team will be working with several new technologies and libraries which none of the team members are experienced with. As a result, it is very likely many challenges may arise or perhaps better solutions may be introduced during the course of the development process. In addition to this, the team may need to solve problems that they did not know existed until actually trying to implement the system. Where traditional plans may encourage developers to abide by their current plan and avoid any deviation, the agile model encourages them to choose the new, more optimal solution and continue to build on this and any other changes along the way. As seen in figure 33, the key with this method is to continue developing functionality, early and often. When this is completed, developers should seek feedback from their respective clients, in this case the professor. Based on this feedback, developers can make the necessary changes to perfect the system. After testing the changes, the system is then ready to be delivered if all functionalities are complete.

As mentioned before, more traditional models were ruled out for this project due to the much more concrete approach. The Waterfall Model, for instance, was one of the first process development models created. This method is ideal for problems that are well understood, without much or any change in what is needed, essentially following a step-by-step approach. Though extensive research has been done, the team must still account for and prepare for any changes or problems that may arise. As a result, this is one of the major drawbacks of traditional project development models. The process does not outline any method to handling changes that may occur during development. As a result, any changes that may occur late in the development process may result in a large increase in the overall project cost since no prototypes are constructed and products are only seen towards the end. Being that the economic constraint on the project as a whole is one of the more significant constraints, any measures to reduce cost without compromising quality should be taken. As such, traditional software development models were avoided and the newer, more personal agile model was selected instead.

5.2.2 Development Tools

There are many software development tools available for streamlining the development process. The primary tools used to design the 3D Scanning System are the Integrated Development Environment (IDE) and Version Control System (VCS).

5.2.2.1 Integrated Development Environment

An Integrated Development Environment, more commonly referred to as an IDE, is an all-encompassing software suite that provides all the necessary tools to both write and test software. These environments typically come with a code editor as well as a compiler/debugger. All of this is contained within one interface, reducing any delays in the development process by removing the need to bounce around from one environment to another.

- **PyCharm** – PyCharm is a popular IDE developed by JetBrains, directed primarily for Python. PyCharm is extremely useful in streamlining the development process due to the extensive features that it offers. These range from smart code completion as well as advanced code inspections. These features will optimize the development process for the 3D Scanning Team as it will vastly reduce the amount of time spent debugging. In addition to this, the amount of time spent searching for syntax will significantly decrease, as well, resulting in a much more efficient software design. Offering two editions, Professional and Community, the Professional which provides additional features, however at an additional cost. The Community edition, however, is free to all users and is a suitable option for most projects and developers. Advantageous for the team is the discount offered to students, offering all JetBrains IDE Professional Editions for free with the provision that it is not for commercial use.

- **ReSharper C++** - In addition to the Python IDE, the JetBrains Student Package also offers a Professional IDE for C++. Similar to PyCharm, ReSharper C++ improves the development process by directly improving the coding experience. One of the methods used to accomplish this is their common code generator. This essentially prompts the user to complete common phrases, relieving them of the need to remember or search proper syntax. This significantly enhances the coding experience, as well as also increasing the efficiency of the development process as a whole by reducing the time spent searching for syntax. Also like PyCharm, ReSharper C++ alerts users of redundant code or code that is incapable of logically being reached. This ultimately improves the quality of the code through increasing its efficiency, as well as reducing the time the 3D Scanning System developers will need to spend analyzing their code.

- **Atom -** An extension of IDEs is another useful tool the team will be using, an advanced text editor. Atom is an extremely advanced text editor developed by the people at GitHub. It completely transcends the likes of NotePad, for instance, and completely transforms the coding experience. Atom allows developers to install various packages for the coding language of their choice. This creates an all in one development environment, capable of supporting all of your required programming languages. These packages offer similar prompts and code suggestions as the individual IDEs, ranging in quality dependent on the package chosen. Therefore, the team will be able to write the necessary code for Python and C++ within Atom, the only downfall being the lack of debugger and necessity to run code from the command line or separate IDE. Being that the team will spend less time bouncing from IDE to IDE, more time will be spent actually coding and developing software, thus resulting in a higher quality code and project as a whole.

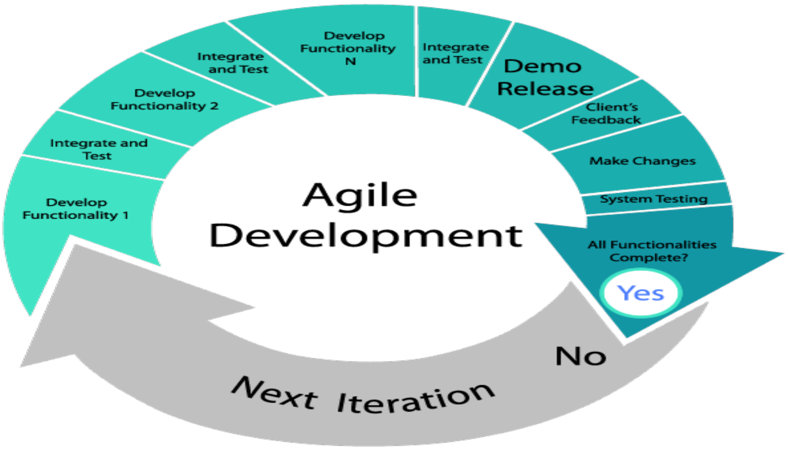


Figure 54: Agile Devolopment Model (used with permisison from TechTARGET)

5.2.2.2 Version Control System

Version control systems are a type of software that essentially regulates the software development process by keeping track of any changes to the source code at any time. In addition to this, version control systems allow you to reverse the hands of time and revert your code back to any stage in the development process. Therefore, if one team member makes a mistake, version control systems allow users to theoretically erase this mistake and return the point at which the software was working.

Along with tracking all changes, through branching and merging, version control eases the process of collaborating on software. A repository is essentially the foundation of version control and most software projects. This is where all of the source code is stored, both past and present versions. Developers are able to make a copy of this repository, typically stored in a cloud, and ‘clone’ it onto the personal computer into what is now called their local repository. This local repository, or local repo as it is often referred, can only seen by the user. That is, until they have pushed their changes from their local repository, to the global repository stored in the cloud. In addition to this, users are able to create their own branches. With branches, different developers are able to work on different parts of the source code without interfering or being interfered by changes made by other developers. When the time comes to combine the different parts of code, this can be easily be done by what is known as ‘merging’ the two branches. Once prompted, the version control software will combine the two source codes automatically, alerting developers of any conflicts if they arise. As a result, multiple developers are able to work concurrently on a single project, without running the risk of ruining someone else's code, or even worse, the project as a whole. In the event that the two branches are incapable of being merged due to conflicts that can't be resolved, the source code can always be reverted back to a previous working version.

Version control is more or less necessary in modern day software development, whether it be individual or with a team. Especially in a project such as the 3D Scanning System where the overall quality of the product is heavily dependent on that of the software, every measure must be taken to remove as many risks as possible. Developers that have not used version control systems before typically have attempted to implement their own variation of it. For instance, many developers will save different copies of their work, ending one file with the tag latest, and then later updating it final, etc. This is okay until a bug is found and then the developer has to have a new final, then another, until it is no longer clear which file is which and the code is now hard to keep track of. As a result of situations like this, it is unpractical and unheard of to not use version control in modern day software development.

Choosing a version control system was probably the easiest part of the process. Being that GitHub is the most widely adopted system by developers; most of the team already had exposure to it, thus reducing the learning curve among the team as a whole. The only worry with GitHub was having a public repository, which could become a problem in regards to both intellectual property, as well as the university's honor code. However, under further inspection, it was discovered that students are eligible for private repositories therefore the team chose GitHub as the version control system for the project.

- **Slack** - Slack is an extremely useful communication tool used among developers in the industry. One of the major advantages of Slack is their easy to use API, as well as the large community for developers. Being that interpersonal communication is one of the concepts emphasized in the Agile Model Manifesto, Slack's messaging system will be instrumental in implementing this. Expanding on its easy to use API, Slack offers a seamless integration with GitHub, the team's selected Version Control System. This integration allows for real time updates when commits are pushed to the GitHub Repository, allowing for developers to constantly stay up to date with any changes that are made in the code. Another useful feature of Slack is the ability to not only send text messages, but files of any type as well. This will be extremely useful as it allows the team to use one channel to communicate regardless of the content of the message or nature of the conversation. If there is a portion of someone's code that a developer is uncertain about, Slack makes it easy to send this code, alerting a teammate of any questions or concerns that you have. This enhancement of interpersonal communication, especially among the team’s software developers, will result in a higher quality 3D Scanning System, due to the higher quality code behind it.

5.2.3 The Environment

Setting up the operating system environment is the first step in the overall design process, but before this can be done an SD Card must be selected. The Raspberry Pi does not come with any onboard storage. Instead, a Micro SD is used as the Raspberry Pi’s hard drive.

When selecting the Micro SD, there are two major factors to take into consideration. First of all, the size of the Micro SD in terms of memory is extremely significant. The selected card must have sufficient space to install and run Raspbian, as well as the additional software and libraries that will be used such as the Point Cloud Library. In addition to this, both Python and C++ interpreters must be installed as well as these are the primary programming languages for the system, therefore the Micro SD Card must have sufficient memory to store this as well. The other important factor, perhaps even more important than the other, is the speed of the selected Micro SD Card. The speed at which an SD card can transfer and process data is rated on a scale of 2 to 10, with 10 being the fastest and 2 the slowest. Those with ratings of 2 are typically used for taking and storing pictures since there isn’t a need for quick data transfers. Those on the other end of the spectrum, however, are used primarily in video equipment due to the dependency on quick data transfers without delay. Therefore, in order to optimize the speed of all memory read and write operations and minimize any latency in these operations, a class 10 MIcro SD Card should be used.

Now that a Micro SD Card has been selected, the Raspbian Operating System can be installed. With use of an image writer, the Raspbian Operating System can be written to the SD card and ready for use. Following a similar process the Python interpreter, C++ interpreter, Point Cloud Library and the remaining dependencies for the 3D Scanning System.

5.2.4 Raspbian

One of the major benefits of the Raspberry Pi series is their ability to run an operating system. This both makes the overall software design more simple and my complex, as there are several libraries and software available built directly for things that the 3D Scanning System needs to do. The drawback, however, is that the chosen operating system has to be compatible with the desired libraries.

As a result of this, Raspbian will be installed, as the operating system of the Raspberry P 3 Model B. Raspbian is essentially a distribution of Linux that has been optimized for the Raspberry Pi microcontroller. The operating system is actually a variation of Debian, an extremely popular distribution of Linux that has high reputation due to its extremely high quality and reliability. Debian is backed by a large community, which is ideal for the team as there is support for virtually any problem. This will be vital in the development process in regards to minimizing the amount of time spent troubleshooting the device or software. This should also help with the steep learning curve the team faces due to the lack of experience with Raspberry Pi microcontrollers.

The largest benefit of Raspbian's optimization for the Raspberry Pi is their adjustment in the handling of floating point operations. The original Debian operating system issued for the Raspberry Pi operated by using "soft float" ABI, application binary interface. This essentially means that the Raspberry Pi's floating point hardware was not used for floating point operations, thus vastly decreasing performance for applications that were heavily dependent on them. Raspbian, however, utilizes the hardware floating point unit and the "hard float ABI." As a result, any applications requiring floating point operations will see a significant increase in performance. This will be vital for the 3D Scanning System as accurate outputs are a direct correlation to the amount of points generated. With strong floating point performance, the system will be capable of gathering thousands of points while still staying within a reasonable overall scan time exceeding this time constraint.

5.2.5 Communication

As the center of the 3D Scanning System, the microcontroller holds the responsibility of controlling several of the other parts. This includes managing the motion of the stepper motor, the input voltage to the laser and the camera. Therefore, the following sections will expand on how the microcontroller will interface with the stepper motor and the camera.

5.2.5.1 Stepper Communication

The stepper motor will control the rotation of the platform that will be supporting the object to be scanned. The stepper motor will provide a rotational motion along the x-axis, allowing for a full scan from each angle of the object. These results in a more comprehensive final scan, achieving a true 3 dimensional object as opposed to simply a 2 dimensional profile. The primary method of controlling the stepper motor will be through use of a Python script. This will be accomplished through use of the library, RPi.GPIO. RPi.GPIO is a Python library that is provided with the Raspbian Operating System download. This library grants users with control of each of the 40 GPIO (General-Purpose Input/output) Pins on the Raspberry Pi.

The python script begins by first initializing the direction of the GPIO pins that will be used. Being that the Raspberry Pi will be sending a signal to the stepper motor, the direction of those GPIO pins will be set as output. Since the GPIO pins are defined as output, the Raspberry Pi will know that it is sending a signal to the pin as opposed to waiting for a signal if it was defined as input. Now that the directions of the pins have been initialized, the next step is defining the delay for the steps, which controls the speed of the rotation. With this now set, the portion of the code that handles the heavy workload is next. The easy driver has a rising edge clock associative; therefore the driver knows to take to a step when the signal toggles from 0 to 1. As a result, the python script will set the GPIO pin to on, then off, simulating the rising edge clock signal. When this occurs, the stepper motor will take a step, before pausing in the python script for the selected delay duration. With a minimal delay set, the script will continue sending rising edge clock signals to the easy driver, resulting in the motor continuously rotating. This is impractical as there must be enough time allotted for the camera to capture an image of the surface of the object, as well as for the Raspberry Pi to process these points. Therefore, this delay will be optimized to both minimize latency after the points have finished processing and maintain accuracy by allotting sufficient time for the microcontroller to process every point. After the rotation is complete, the GPIO pins will be cleared by the python script, and released for use by another system or project.

5.2.5.2 Camera Communication

Similar to communicating with the stepper motor, the Raspbian Operating System provides several tools to streamline the communication process between the PiCamera and the Raspberry Pi. Also similar to the stepper motor communication process, is that this method is also based on a python library, specifically PiCamera. PiCamera is a python module built to control the Raspberry Pi Camera. Unlike the stepper motor, the camera is connected to the Raspberry Pi directly to its camera port. The script will begin by initializing a PiCamera object, followed by then starting a preview. When a preview is started, the display of the Raspberry Pi is filled with what the camera sees, similar to the likes of a typical smartphone. With its built in capture function, the PiCamera module simplifies the process of taking a picture, simply requiring the user to specify the path and name of the file they would like to save.

Being that this script is also built in Python, this will be combined with the aforementioned stepper communication script to streamline the process in which the Raspberry Pi communicates with external devices. This will also reduce the workload of the Raspberry Pi as it will not need to run multiple scripts at once, allowing for more availability of the microcontroller’s 1 GB of RAM. The following diagram offers an overview of how the communication process will work.

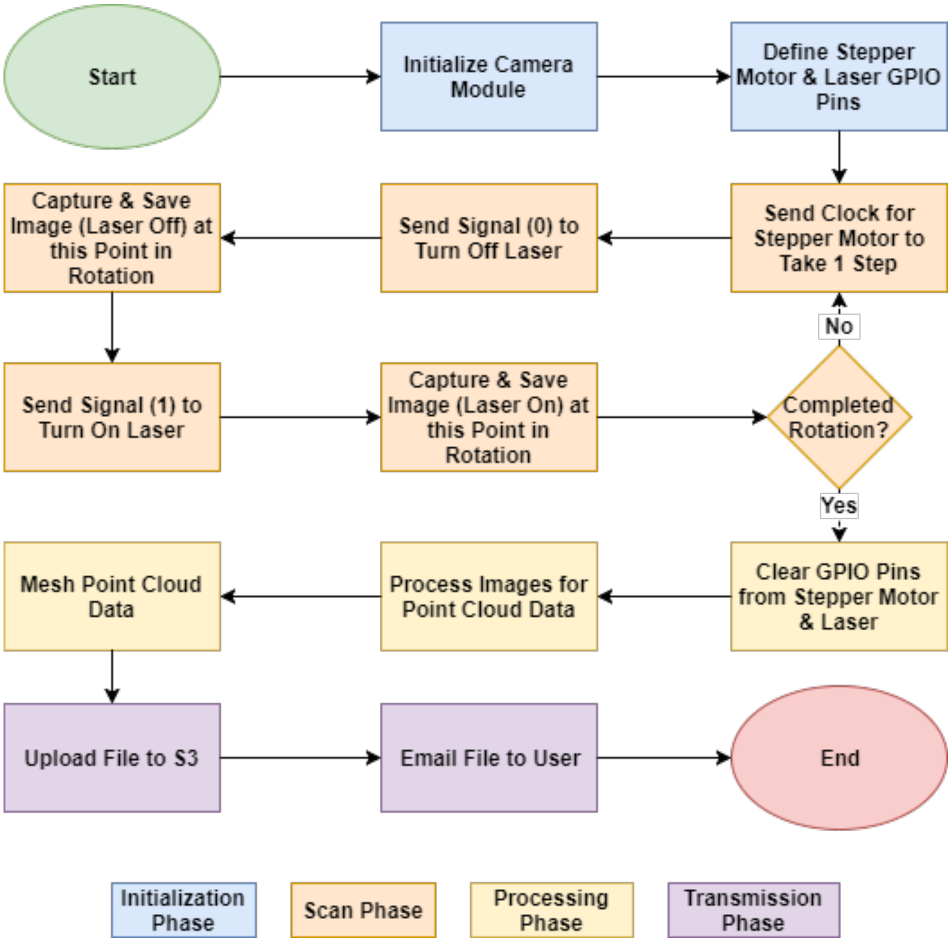


Figure 55: Device Communications Flowchart

5.2.6 Point Cloud Extraction

Moving from a raw RGB image to a set of well-defined coordinates requires image processing. Before any actual distances can be determined within the scanner's global coordinate system, points must be isolated from the raw images in terms of where they fall on the camera's pixel array. Before this can happen, steps are taken to isolate the laser line to minimize the likelihood of our code identifying false points.

Laser line isolation in our system is based around the principle of image subtraction. For each static position of the turntable, two images are captured in quick succession. The first image contains the object with the laser light incident on it, and the second image is of the same scene with no laser light present.

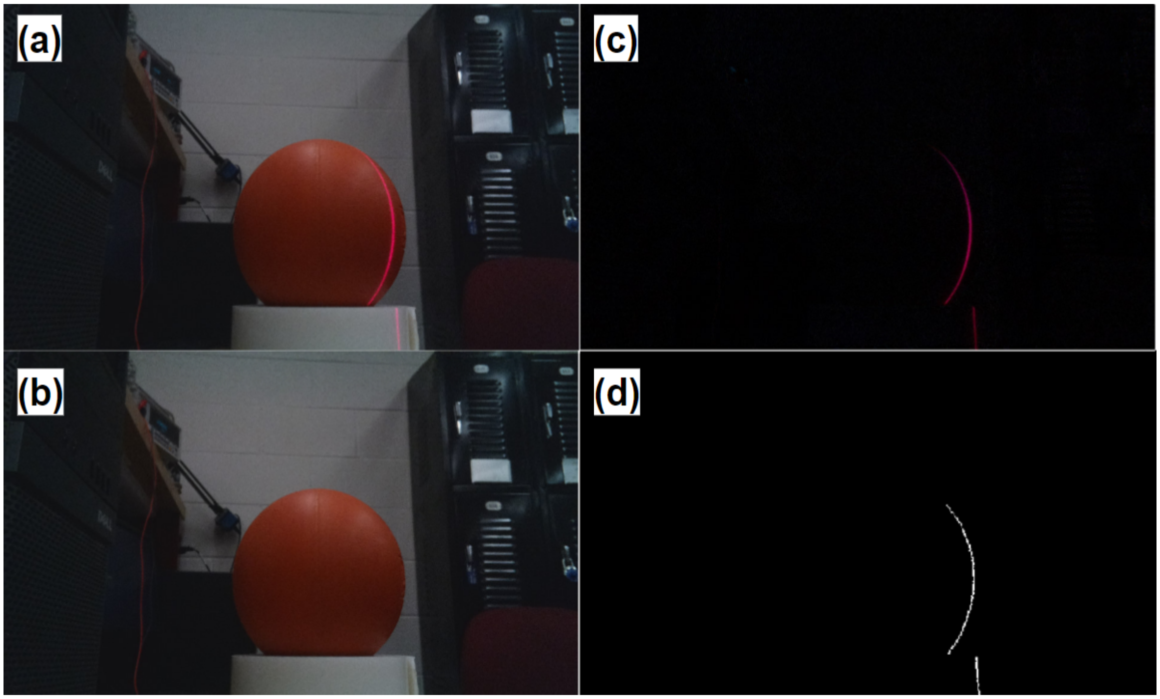


Figure 56: Laser Line Isolation

Assuming ambient lighting conditions and the background scene have not significantly changed in the dozen milliseconds separating the two images, all pixel values aside from the laser contour can be brought effectively to zero by subtracting the second image from the first, which are shown as figures 57a.b and 7a.a, respectively. The resulting image is of a completely isolated red Gaussian line laser profile, which is shown in figure 7a.c.

In anticipation of the occasional quickly changing background, an additional filter used is that of color channel subtraction. This filtering mechanism adds the RGB image's green and blue channels together, divides the sum by 2, and subtracts the resulting image from the red channel. This removes remaining pixels, which are not prominently red.

Preliminary testing has indicated that under ideal lighting conditions, the simplest possible search algorithm for segmenting the laser line is the quite effective. The figure below is a compilation of three images compiled from testing the laser. Figure 57b.a is a raw image of the 1" tall Buddha test figurine under profile scanning illumination conditions. Figure 57b.b is the result of applying a MATLAB script, which determines each row's FWHM and places the point at the FWHM midpoint. Finally, figure 57b.c is the result from a much simpler MATLAB script, which searches for each pixel row's absolute maximum.

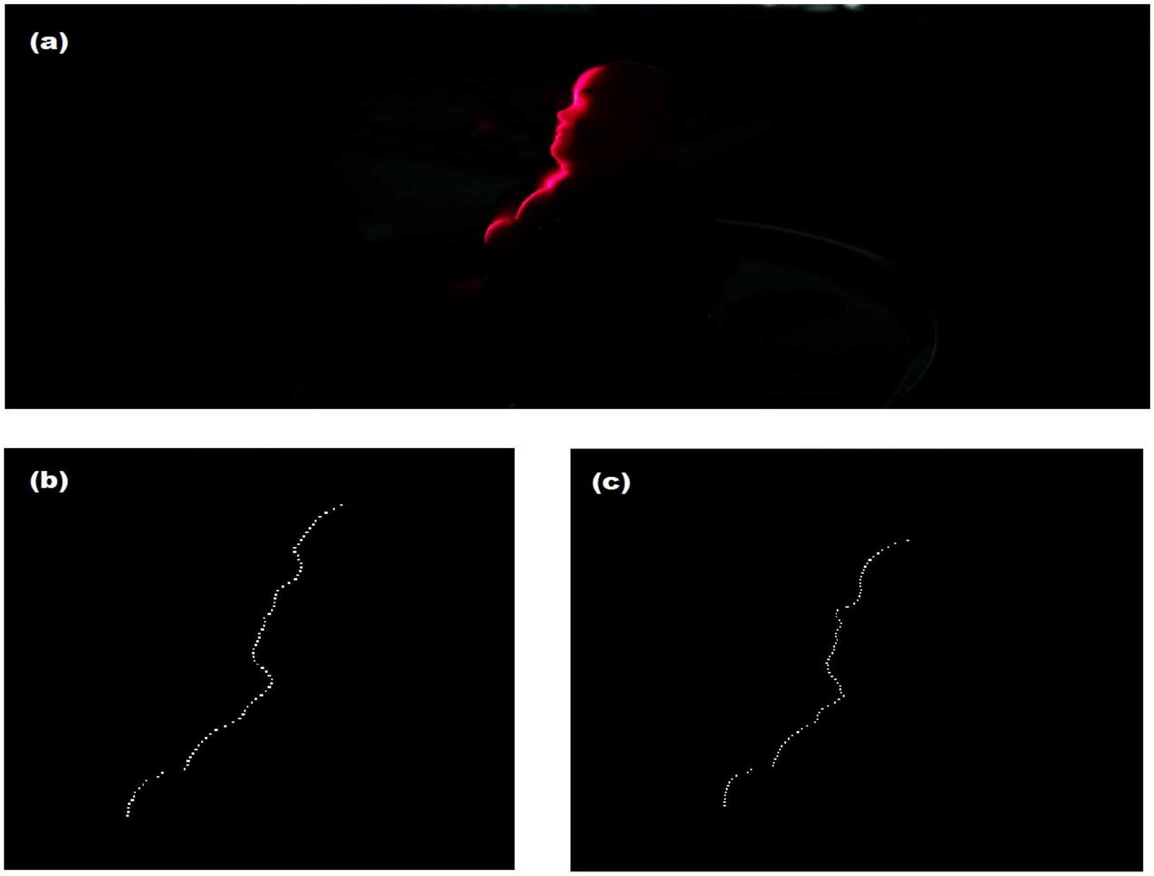


Figure 57: Image Segmentation (W/ MATLAB)

Assuming the object's reflectivity is roughly uniform across the narrow region illuminated by the beam, the FWHM scan effectively estimates the pixel address of the beam profile's true center by taking advantage of the Gaussian distribution's known symmetry. Alternatively, a neutral density filter could be used to attenuate the image until no saturation occurs, but the software solution is preferable due to budget constraints.

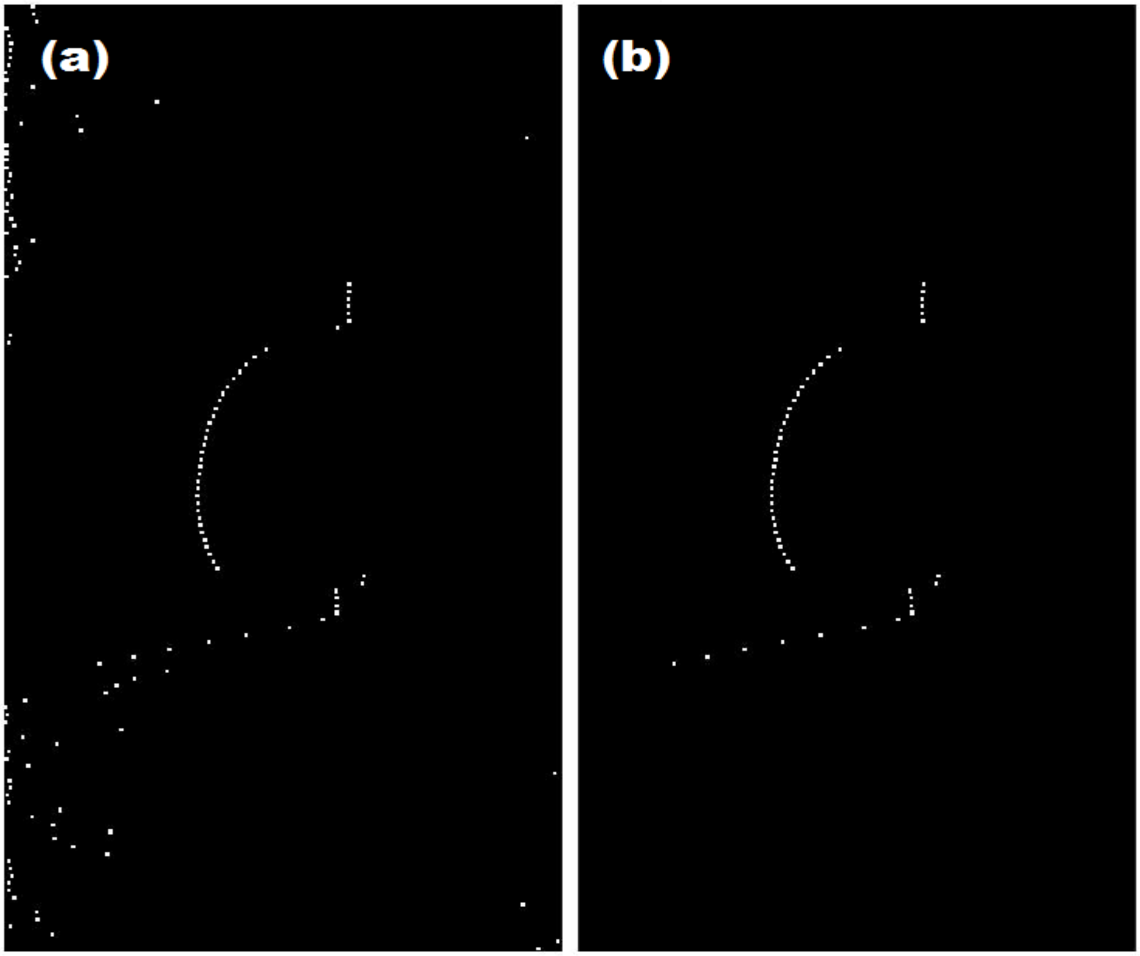


Figure 58: Excluding Background Maxima with an Intensity Threshold Filter

Two point search algorithms were tested for their ability to accurately capture fine details on a small test figure. Both algorithms scan only every 4th row because the image's dimensions (1080 x 1080) are large and the camera's comparatively low optical resolution limits the usefulness of information contained in adjacent rows.

The most basic script (used in figure 57b.c) simply uses MATLAB's max() function every 4 pixel rows and returns its associated pixel address to be added to the point cloud. In the case of this particular image, it worked exceedingly well compared to the alternative FWHM scanning script found in figure 57b.b.

The second algorithm defines a Full Width at Half Max (FWHM) found in figure b of the beam profile in terms of pixels address. It searches for the maximum intensity of the laser's profile in a given row, then finds the address of the nearest pixels on each side of the maximum corresponding to half its intensity. The pixel address located midway between the two FWHM boundary points is then extracted and written as point cloud data. This approach to point extraction was developed to account for the not uncommon case in which clipping will occur in the beam profile as seen in the figure below, resulting in dozens of redundant intensity maxima over a continuous span of adjacent pixel addresses. A simple maximum search is inadequate for this case because it returns the value of the first maximum encountered, extracting a coordinate that may be as many as several dozen pixels away from the beam's true center. In the figure below, a highly reflective Gaussian surface saturates the CMOS detector within the region of interest, hindering the ability to locate the beam center's pixel address using a basic maximum search.

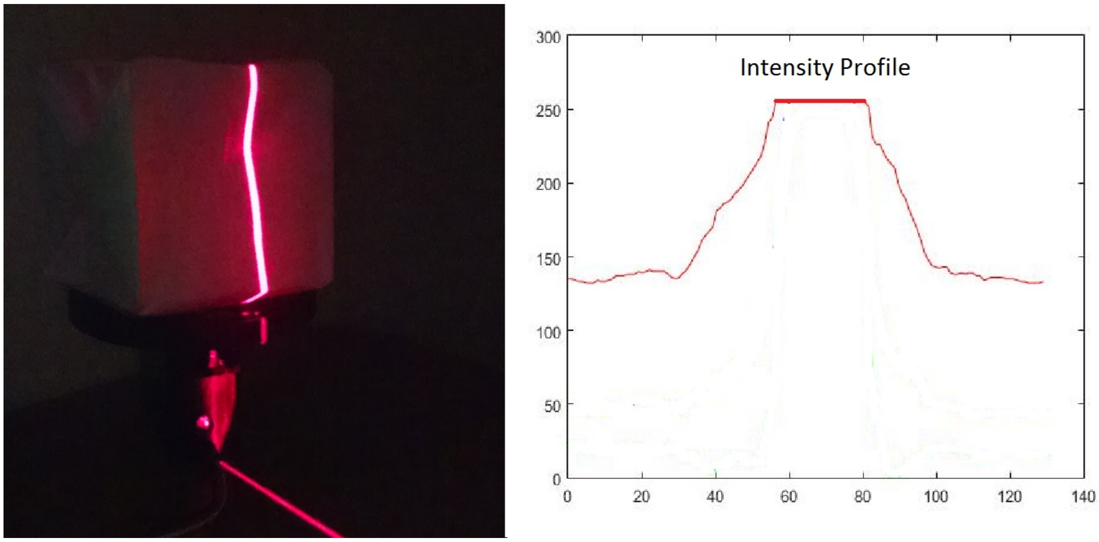


Figure 59: Clipping in Beam Profile

5.2.7 3D Image Reconstruction

Representing the object in units of millimeters takes a few mathematical transformations of the points collected from the segmented laser line. Originally, these points are expressed in two dimensions and in terms of their pixel address. The proportions of the contour are compressed in the horizontal direction because the camera is at shallow 40° angle with respect to the laser and the center of rotation. Fortunately, the contour can be stretched out to its true proportions by multiplying all point x-values by a stretching constant.

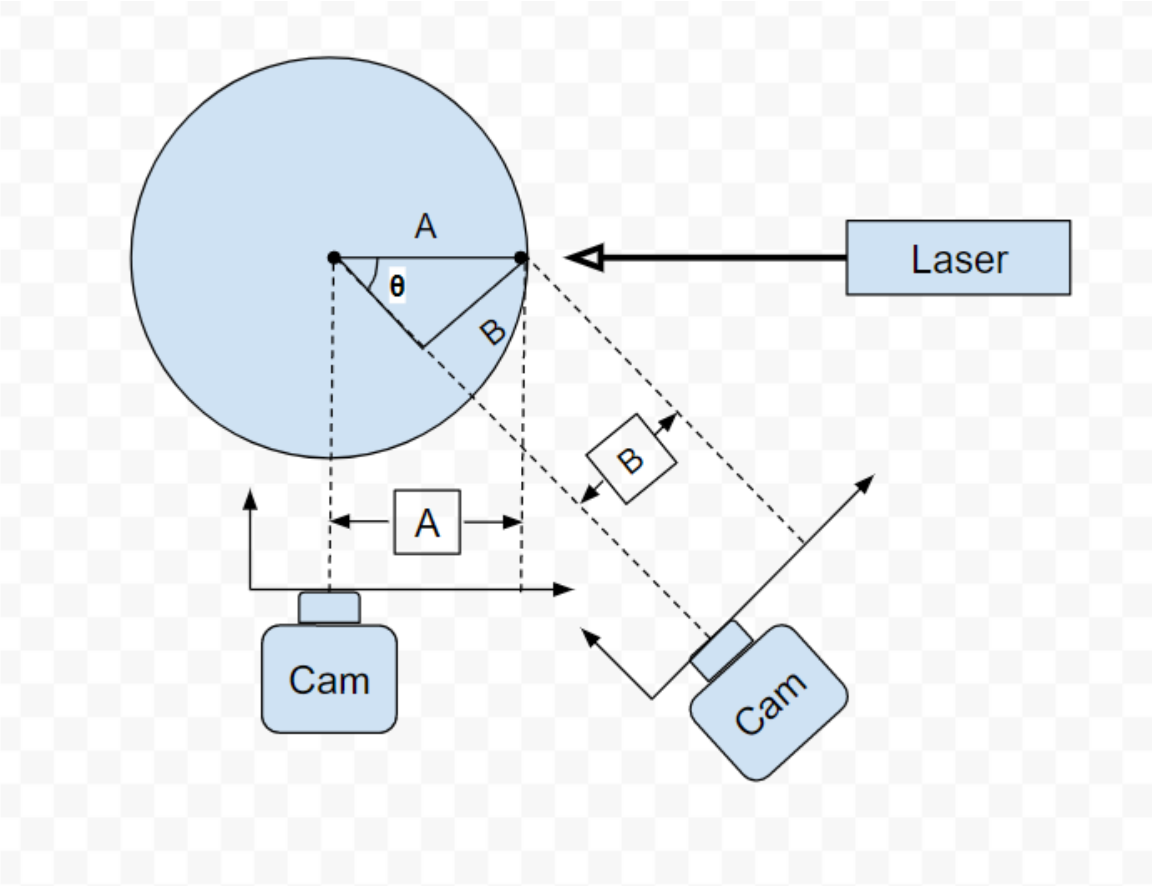


Figure 60: Deriving the Stretch Multiplier Constant

From figure 60, we get

$$A = (B/\sin\theta) = S_t{*}B$$

$$S_t = (1/\sin\theta)$$

Where S_t is the stretching constant. Next, the stretched contour is translated in the x direction by finding the x-value of the turntable's center in terms of pixels and subtracting that from all x-values in the coordinate array. This only purpose of this translation is to position the contour such that it can be rotated around the z-axis at x=0. This rotation is achieved through a rotation matrix about the Z-axis,

$$R_z = \begin{pmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (6)$$

Once rotated into place and proportionally accurate, the contour is converted from units of pixels to millimeters. The scaling factor, $S_c = 0.088$, was determined through much trial and error.

After these transformations are applied to all 400 contours, the point cloud is ready to be meshed.

5.2.7.1 Point Cloud Meshing

The Point Cloud Library will be used to handle the majority of the 3D image rendering, specifically the Surface library. The Surface library focuses on the reconstruction of surfaces based on information gathered from 3D scans. In this process, the point cloud data would be first loaded into the C++ file. The surface will then be meshed from these points using one of two methods. The first method considered that could potentially be used is triangulation. With triangulation, PCL uses a greedy algorithm to generate a triangle mesh of the surface as shown in figure 54. The triangles help form the shape of the image by providing somewhat accurate measurements and a general idea of the volume of the object being scanned. Using this method, an image can then begin to be reconstructed with a fair amount of accuracy to the original object being scanned. This however is not the more accurate of the two available methods.

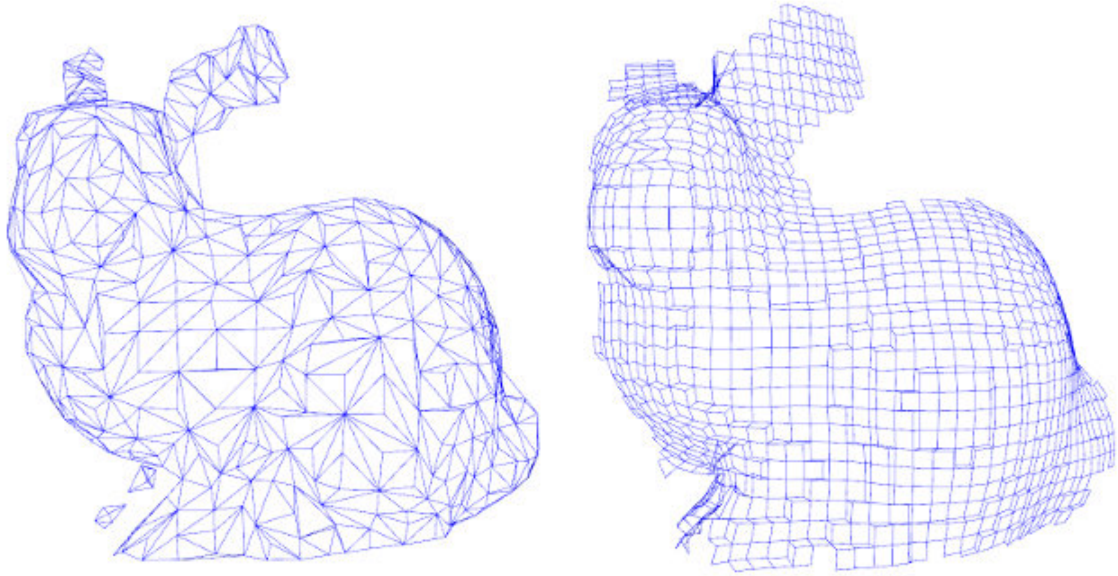


Figure 61: Triangulation Method (used with permisison from PCL)

The higher quality alternative, however, is the slower meshing which handles hole filling along with smoothing through use of a more complex B-spline algorithm. The B-spline algorithm handles the duty of obtaining the smooth surface representation. This is accomplished by first initializing the B-spline surface, which is then refined and further the fitted to the point cloud. Now that the B-spline surface is fitted to the point cloud, the next step is remove the any overlapping regions. This is achieved through an initialization and fitting of the B-spline curve, a process similar to the one previously defined for the B-spline surface. This surface then goes through a triangulation process before being ready to be saved. The end result of this is a VTK file which can be viewed using the Point Cloud Library or converted to another format, including PLY. Both of these options will be useful for the 3D Scanning System. The VTK file will be viewed and displayed with the Point Cloud Library via the LCD screen connected to the Raspberry Pi. While this occurs, a copy of the image and VTK file will be transmitted to the user via Bluetooth, making use of the BLE module provided by the Raspberry Pi 3 Model B.

The built in option to convert from VTK to PLY will be instrumental in eventually 3D printing the meshed image. After the file is converted from VTK to PLY, the PLY file will also be transmitted to the user via Bluetooth where users will then have the option of processing it for 3D Printing. This would be accomplished with Mesh Importer for AutoCAD, which is capable of importing 3D meshes from PLY files. From here, the AutoCAD software would be used for printing the 3 dimensional images, which could then be compared to the original object scan.

Alternatively, there exists an open source application, Meshlab, which can be used to clean and process point clouds. Similar to PCL, it offers a variety of implemented algorithms for pre and post processing data within a point cloud and meshing algorithms to reconstruct the surfaces. In addition, Meshlab provides an command line instance, or headless-meshlab instance, to do batch processing without the overhead the full gui.

5.3 Software Testing

The software testing must take place on two different platforms – a personal computer and the raspberry pi. Since all development takes place on personal computers it is necessary for all the programs to execute or compile once on them to develop the software models at faster pace, more agile pace. Due to possible differences in the compiler tool chain and operating systems, once a method or piece of code is finished it must be ported to the Raspberry Pi. Ideally, it should work but the test suite for the software must cover both platforms equally to ensure a working system. In addition, it is important to test basic input/output operations to ensure that the hardware and software are fully integrated and communicating properly with each other. This is also including the tracking of keeping track how data is flowing and piped through each step of the software to ensure minimal uncaught errors during testing and compilation.

5.3.1 Point Cloud Software Testing

As described in the research and design sections, the point cloud software is a collection of software packages written in C++, which perform mathematical transformations on coordinate data to be rendered and visualized. Several steps must be taken to ensure that each part of the software flow diagram works as expected. The first steps taken to test the software was to implement basic parts of the visualizing process to make sure the raspberry was working as expected with the point cloud library function calls.

Next, the data points extracted from the laser profile would be computed and processed so that I could it can be passed to the point cloud implementation. This point cloud data would be used to first visualize simple two-dimensional shapes, which is extracted from the object profile extraction package that will be implemented. The expected results of this test are that it will render the object, which roughly resembles a square. It is expected for the initial tests there will be some distortion happening around the bottom portion of the rendering due to where the laser profile meets the edge of the square plane and the surface plane. This will ideally be fixed through filtering methods that shall be tested as the software process and packages mature.

5.3.2 Object Profile Extraction Software Testing

This functionality of the scanner is implemented after a laser profile is achieved from the laser scan, which should produce a series of images at slow turning increments for the objects. The primary function of this portion of software process is to take these images and deconstruct the line profile to discrete values. There should be a large amount of incremental line profiles that are taken as the object is rotated or moved on the platform. Each line profile will be turned to discrete points along the line. To test this several stationary profiles were taken to ensure that it was possible to create a discrete profile from an image. In addition, to a single straight profile several other objects of varying shapes and contours were profiled to see how the variations in the discrete profile varied. For this test, the expected results would be that the more regular and flat an object or surface is the better the profile will have captured and extracted from an image. Also, it will be more accurate due to less extreme surface perturbations.

5.3.3 Communication Testing

Communication between the Raspberry Pi and other devices constitute a major role in the functionality of the 3D Scanning System as a whole. As a result, testing of these communication methods constitute a major portion of the testing of the 3D Scanning System as a whole. The following section explores the methods that will be used to test the communication between the Raspberry Pi and the stepper motor and the Picamera.

Before this can be done however, the GPIO pins of the Raspberry Pi must be tested. The GPIO pins allow developers to interface with external devices, in this case, the stepper motor and the Picamera. Output devices are relatively simple as they generally have two options available for the developer, setting them on or off. Setting this GPIO pin to on should result in a voltage of approximately 3.3 V, while setting it to off should result in one of 0 V. This is significant as devices such as the stepper motor are right clock associative. They depend on the toggling of the clock signal from on to off (voltage from 0 V to 3.3 V). Because of this dependency, a test must first be conducted to verify that the GPIO Python module and GPIO pins are functioning correctly. This test simply attempted to verify that when turned off in the Python module, the voltage measured for that GPIO pin was 0, and when turned on the voltage measured for the GPIO pin was 3.3 V. The figure below is a waveform to help demonstrate this communicative aspect of the Raspberry Pi.

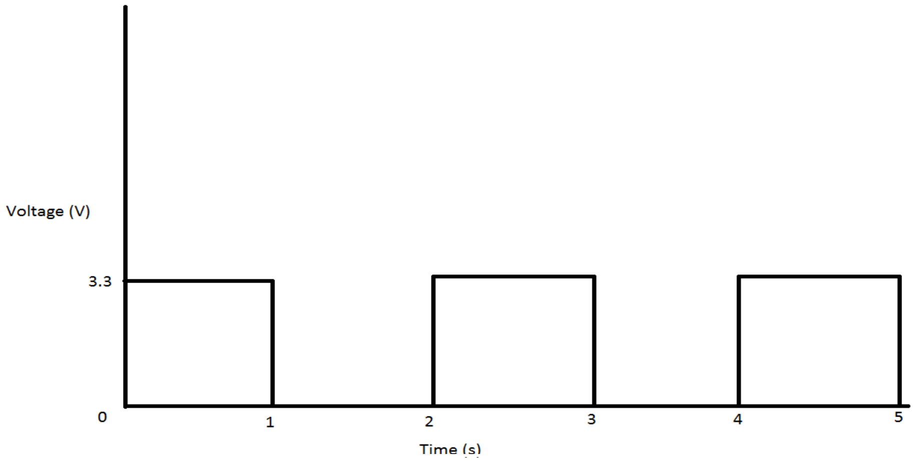


Figure 62: Raspberry Pi GPIO Waveform

The results for this test were as expected. When turned on, the voltage measured was approximately 3.3 V and when turned off it was approximately 0 V. The Python script used for testing, executed a toggle or clock signal 5 times before terminating. As such, the waveform was as the one seen in the figure below.

5.3.3.1 Stepper Motor Communication

As previously discussed, the stepper motor and the easy driver, which controls it, serve as the primary tool used to support the rotational motion needed for the platform. The major. The software written for the Raspberry Pi must allow it to interface with the easy driver through use of its GPIO pins, essentially telling the stepper motor (via the easy driver) when and when not to step. The main attributes to be analyzed in this process are verifying that the stepper motor does in fact move and assessing the latency between when the signal is sent to step and when the stepper motor actually takes a step. Any significant latency discovered in these tests would greatly influence the constraints on the remaining processes in the system in hopes of meeting the overall time constraint of the system. Therefore, it is better to discover this during early testing as opposed to late in the development when other processes have already been developed and may need to be adjusted. This subsystem of the overall 3D Scanning System's software will be written in Python, therefore the tests for these requirements will be done through a Python script as well.

The Python script used will make use of the RPi.GPIO module provided in the Raspbian Operating System. This module gives developers access to the the Raspberry Pi's GPIO pins from within the Python environment. Although it comes preinstalled with Raspbian, RPi.GPIO can be installed on desktops or laptops as well, as long as the required dependencies for the module are also installed. This allows for development of the tests to extend from being restricted solely to the Raspberry Pi to being accessible for any of the team's developers on the personal computers. In addition to the GPIO module, the Winsound module will also be used in the Python testing script. This essentially allows devices to make a sound from within the script. This will be used to alert developers when the clock signal for the stepper motor has been sent so that the latency between the sent signal and the motor's response can be recorded.

The steps taken to test the interfacing with the stepper motor were as follows:

1. Start both devices and make the required connections.
2. Start the Python script.
3. Verify that the motor has moved.
4. Record the delay (if any) between signal being sent and motion of motor.
5. Record the time it takes for the motor to move.

6. Repeat steps 2-5 for various amounts of steps.

The results of the tests were as expected. There was an insignificant delay between the time that the signal was sent and the time that there was motion detected from the motor. Verifying motion of the motor was not initially sensible by sight, instead feeling the motor for what felt like a pulse was required. Upon this recognition, a small toy was placed toy was placed on the motor to allow for visible motion. With the standard configuration of the motor and driver, the motor required 400 steps complete full, 360-degree revolution. The time required to complete a revolution was dependent on the delay between each step, however with a minimal delay of 0.00005 seconds, the motor was able to complete a full revolution in approximately 2.5 seconds.

5.3.3.2 Camera Communication

Now that communication with the motor has been solidified, communication with the camera can be tested and integrated into the design. This process begins with use of the previously mentioned PiCamera Python module, which offers developers the ability to interface with the PiCamera (the camera selected by the team). To test this module, a small script was written to start a preview and simply capture an image. Upon verifying the expected result of the preview starting and the picture being saved to the specified destination, this functionality was added to the previous stepper motor script.

Therefore, the complete script follows the following steps:

1. Start camera preview.
2. Send signal to take step.
3. Capture and save image.
4. Repeat steps 2 and 3 400 times for a full revolution.
5. End camera preview.

Upon running the test module, the system crashed shortly after the camera preview began, becoming completely unresponsive. Being that the camera preview is extremely demanding on the resources of the Raspberry Pi, the initial solution was to remove steps 1 and 5 from the previous process. This was expected to relieve the system of some of the heavy duty processing and prevent crashing. If functioning correctly, the software should meet the following requirements:

1. Execution shall be completed with 10 minutes.
2. Image shall be captured and saved in the specified directory.
3. Each image shall be captured at different angles.
4. 400 images shall be visible upon completion.
5. When given clock signal, stepper motor shall take a step.
6. After 400 steps, the system shall have completed a full revolution and shall end execution.

7. System shall not crash.

As both expected and desired, the system met the test software requirements. All 400 images at different angles were captured and visible upon completion of execution. In addition to this, the system did not crash as with the previous test module, instead completing a full revolution in 3 minutes 52 seconds, 38.7% of the desired duration. Improved efficiency creates increased flexibility for the team and 3D Scanning System as a whole. The team can now offer lower scan times or increased accuracy, achieved by performing two scans and averaging the points generated at each step. These options will be assessed, and based on which is deemed more important, that route will be chosen in the design scheme of the system.

5.3.4 Occlusion Testing

One well-documented obstacle to obtaining quality 3D scans is the problem of occlusion. In triangulation, the necessary separation of the light source and the camera can be problematic when scanning certain surface topologies. Sharp corners, for instance, are quite common in real-world objects, and a user of our scanner will expect it to perform well regardless of the desired object's geometry. When a corner comes in between the camera and laser light reflected off the object as seen in figure 45, the camera would acquire no usable data until the occluded surface is rotated into view. The figure below shoes that the region of interest, although technically within the camera's FOV, is completely obstructed by the object's corners. A critically flawed point cloud will be generated unless the issue is addressed.

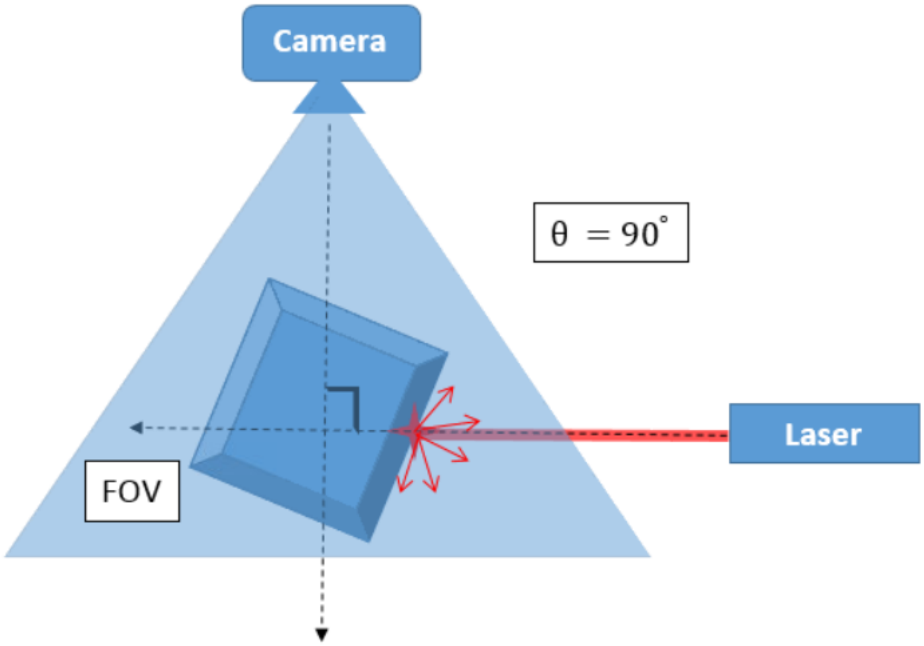


Figure 63: Corner Interfereing with Camera and Laser Functionality

This is unfortunate, because small details are easiest to discern when the camera’s FOV is centered orthogonally with respect to the light plane.

On the other hand, an extremely small angle will solve almost all occlusion problems, but to the detriment of point cloud resolution. As θ approaches zero as seen in figure 46, even the most prominent surface features will become indistinguishable from a flat line.

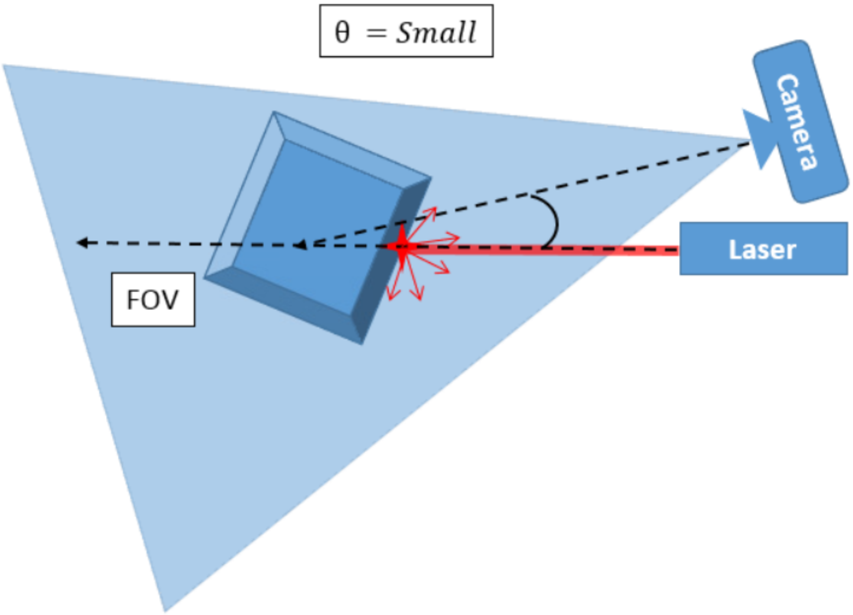


Figure 64: Small Angle Interfering with Final Resolution

The virtually infinite number of possible surface topologies that may end up inside our scanner makes this issue extremely difficult to tackle through mathematical analysis. Unless further research reveals a more elegant approach, we will mitigate the occlusion problem through iterative testing. Various highly symmetrical n-sided polygons will be subjected to full scans at a variety of camera angles such that 0 < θ < 90º, and the resulting point clouds will be measured for their accuracy. Additionally, a smooth, amorphous test object with locally concave features will be designed in AutoCad, 3D printed, and subjected to the same tests as the n-sided polygons. If tests indicate an optimal angle too detrimental to our goal of submillimeter resolution, a second camera will be incorporated into our system such that occlusion can be minimized without sacrificing point cloud resolution.

6.0 System Prototyping

Prototyping of the system is very important to the success of this project. In order to design a PCB, all components need to be tested individually. They then will need to be integrated together and tested as a unit. After this, the final designs for the PCB can be implemented with reassurance that the prototype design functions properly.

6.1 Integration and Testing

This section is an in-depth overview of how all the components of the project will come together and how each part was individually tested. It is essential that each component and part go through a series of rigorous testing and documentation to quantify the functionality of each part. In doing so, malfunctions or poor quality components can be replaced within a reasonable time. These tests provided that each component could work in conjunction with other components in the scanner and reveal what is and is not possible to perform.

A high-level overview of the entire scanner will be given and how the individual modules come together to provide a cohesive, functional unit. The integration will consist of the individual modules such as the power supply unit, hardware, PCB, and software programs. The most complex integration of the system comes with bringing together the software used in scanning the object and the software, which processes the laser profile of a scanned object due to the computational complexity involved in point-cloud computation.

There are many components for the scanner, which must be tested separately before putting components together. In addition, as individual components are put together they must be tested as a new unit to ensure that as the parts are assembled every module or unit is fully functional. The testing procedures are divided into three main categories broken into the hardware, software, and materials testing. A procedural overview for the tests and test procedures will be given which cover the expected and observable results of each section.

6.1.1 Final Product Testing

In the previous sections for the hardware and software design aspects, the individual components were designed and tested at a micro scale. It is paramount that each component be tested to make the design build more robust and easy to test. Individual quality and implementation testing allow the final tests to rule out any single individual piece from not working. This allows for quick debugging and checking, as it is easier to isolate where any problems may occur within the design.

Now that the initial demo has been built using the breadboard connections with the power supply, voltage regulators, and the connected raspberry pi the full build testing can be employed. The test to ensure that the scanner is at optimum capacity and is fully functional will follow a series of steps, which include basic feature checks and image calibration. The following steps delineate the testing procedures:

6.1.1.1 Final Design Scan Test Procedures

1. After powering the device on, the first step is to ensure that pressing the Bluetooth symbol at the upper right corner will establish a connection with the desired device.
2. Once the connection is successful, a terminal should be opened by clicking the terminal icon at the left hand side of the desktop environment within the home path.
3. In the home path there should be several python scripts which will test the individual software and hardware functionalities of the scanner start by executing the following command in the terminal window: *python3 blt-test.py*. If successful the script will display a message on the screen stating that a successful transfer has occurred and the target device should receive a test file with specified contents.
4. The next script, which should be executed, is to test the stepper motor and is executed as follows: *python3 step-test.py*. If successful this script should rotate the platform at several speeds for a short duration of time and in the terminal will show the necessary information until finished.
5. Now, run: *python3 calibrate.py* with an object on the platform and the laser off. This script ensures that camera is properly calibrated by picking up certain features of an object and testing them with calls to OpenCV. If successful a message will be display notifying of a properly or successful calibration in the terminal window.
6. The final scanning test ensures that the whole system can run all the functions at once to produce a scan of an object with a proper laser profile. In the terminal, invoke the following command: *python3 imagify.py*. On a successful executing the scanner will rotate the platform and initiate the camera to begin capturing images at several steps the motor takes and produce a final popup with the scan that was taken.

Once the aforementioned steps have been completed successfully, the scanner should be calibrated and fully functional. It is important to note that the scanner is separated into a two-step process that is: the image scan and the image processing. Therefore, the full design-testing phase is likewise separated to reflect this. The next set of steps will take the image produced by the python script *imagify.py* and utilize a combination of the Point Cloud Library and OpenCV. These final steps will produce a series of images at each step in the motors rotation and produce the actual rendering of the laser profile.

6.1.1.2 Final Design Image Process Test Procedures

1. Now that it has been verified that scanner can take images, it is now time to invoke the final test with: *python3 scan.py*. This script will run the whole system starting with the incremental scan and ending with the image-processing portion of the design.
2. Once the script has finished executing, there will be a popup message that confirms the process has taken place and is waiting for user input. Then, press the send button to transmit the final, processed image via Bluetooth to a properly connected device.
3. Once the image has been received, open the image and there should be a roughly processed image of the scanned object.

The image below depicts the sequence of the previously described testing procedures for those individuals that prefer to learn by pictures rather than reading extensive directions.

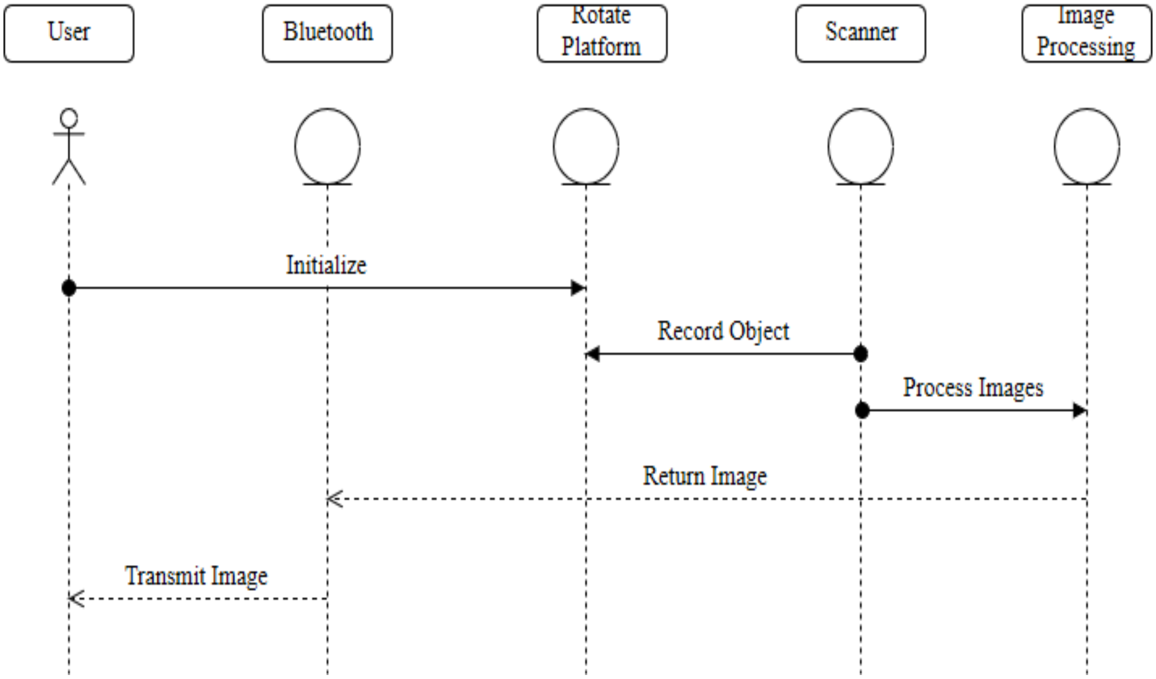


Figure 65: Sequence Diagram of Testing Procedures

After these procedures have been executed and have successfully passed all the tests, the scanner should be fully functional and ready for consistent use. In an effort to ease troubleshooting in the event that something goes wrong, a usage log will be generated. Each of these logs will contain information of a successful scan and the software will attempt to stop its process in the event that an error occurs, but will also attempt to log errors that may happen with a successful scan. Having these logs will allow a faster debugging and troubleshooting.

7.0 Administrative Contents

This section is a brief outline of the organization and management that goes into this project in order to ensure its success. The first section will address the budgeting of this project, while the next section will layout the schedule for the entire project.

7.1 Project Budget

The budget of this project is an important item to pay close attention to in order to design a high quality yet feasible 3D scanning device. A plethora of research is required in order to weigh the capabilities of each component with their prices and chose the overall best option. The budget table below represents an estimated total for the equipment and components our project requires. These values are subject to change as more research is conducted and project implementation is underway. The total cost of the project will be funded entirely by our group members, given there are no sponsors for our project at this time.

Table 15: Project Budget Breakdown

Description	Quantity	Price Per Unit	Item Total
PCB	1	$ 80.10	$ 80.10
Laser	1	$ 23.95	$ 23.95
Camera	1	$ 29.95	$ 29.95
Microcontroller	1	$ 34.99	$ 34.99
Battery Pack	1	$ 34.90	$ 34.90
Battery Charger	1	$ 17.99	$ 17.99
Stepper Motor	1	$ 16.95	$ 16.95
Mounting Device	1	$ 14.85	$ 14.85
Misc. Hardware	1	$ 20.00	$ 20.00
TOTAL			$ 274.68

7.2 Project Milestones

Proper management of this project is pertinent to completing it on schedule. The team will utilize the applications called Slack and Trello to coordinate communications and time management respectively. Slack is a viable asset to the success of our team thus far, as communication is of upmost importance to the success of any team. It is more compatible with group conversation, because everyone is using the same platform. Slack provides the confidence that any important information will surely reach every group member in a mater of moments. Trello offers a unique platform for visual organization of task breakdowns. It is helpful to see everything that needs to get down up front. The tables below are a brief breakdown of the major tasks that are required for the completion of this project by the end of Senior Design I and II.

Table 16: Senior Design I Project Milestones Breakdown

Number	Task	Start	End	Status	Responsible
	Project Report				
3	Initial Document - Divide & Conquer	1/29/2017	2/3/2017	Completed	Group
4	Table of Contents	2/17/2017	3/24/2017	In Progress	Group
4	First Draft	2/20/2017	3/31/2017	Completed	Group
5	Final Document	4/1/2017	4/27/2017	In Progress	Group
	Research, Documentation & Design				
6	Laser Diode	2/4/2017	2/28/2017	In Progress	Sam
7	Bluetooth Module	2/4/2017	2/28/2017	In Progress	Cary
8	Microcontroller	2/4/2017	2/28/2017	In Progress	Cary, Isaias
9	LCD Display	2/4/2016	2/28/2016	In Progress	Isaias
10	PCB	2/4/2016	2/28/2016	Not Started	Sommer
11	Platform	2/4/2016	2/28/2016	Not Started	Isaias
12	Power Supply	2/4/2016	2/28/2016	In Progress	Sommer
13	Containment Unit	2/4/2016	2/28/2016	Not Started	Group

The table below is the subsequent project milestones breakdown for Senior Design II.

Table 17: Senior Design II Project Milestones Breakdown

Number	Task	Start	End	Status	Responsible
	Senior Design 2				
1	Build Prototype & Test	4/29/2017	8/22/2017	Completed	Group
2	Finalize Prototype	8/22/2017	8/22/2017	Completed	Group
3	CDR & Demo	10/6/2017	11/1/2017	Completed	Group
4	Final Presentation	11/28/2017	11/28/2017	Completed	Group
5	Final Report/Website	12/6/2017	12/6/2017	Completed	Group

8.0 Conclusion

All in all, the team has made significant progress in the overall development of the 3D Scanning System. From the initial conception of the idea, to the research and early design stages, each member has played an instrumental role in the advances that the team has made. The broad scope of the project has allowed members to focus on the areas for which they are most interested and proficient, while also getting exposed to areas where they lack much experience. Through this integration of efforts, the team has been able to implement what is believed to be effective subsystems, which will also function effectively with the other subsystems.

These subsystems are comprised of hardware and software components, which have been selected by members of the team after extensive research was conducted. The various components were assessed based on their individual performance, cost and compatibility with the rest of the system. Based on these parameters, the team has selected the most optimal solutions for each part. These selections will allow for a seamless integration, resulting in the best product possible. Members on the team have also constructed and conducted thorough tests for each of the various selections, verifying their functionality in their intended use in the system. Through a focus on the speed in which it conduct its scans, the quality of the image produced and the manufacturing cost of the system as a whole, the team is confident that the final product will be competitive among the other existing products on the market.

In addition to the testing and initial testing phase, once the constructions of the PCB and software have been officially employed (for the building phase next semester), the mounting process of the platform and container will be constructed. This phase of the project is left to the final stages due to the inability to predict how the final parts will be constructed without proper PCB and soldered connections. As such, it was necessary to test all the individual electronic components to ensure that the group could get each stage of the prototype working to continue onto the next part of the project build. Now that the proof of concept has been built and designed, the hardware and testing sections show that the demo build can indeed rotate and scan images. Moving forward, the next implementations are to write the software so that the image scans can be generated with the proper platform and container build.

During these initial stages, the team has run into and conquered several challenges. This was expected due to the many novel technologies that have been employed in the making of the 3D Scanning System. A major component of the design process, which was learned during and after the testing process, were the edge cases and unexpected behaviors. In response to this, the methodologies and standards which were adopted (specified in agile methodology section) the agile design process assisted in making changes while adhering to the original marketing and engineering specifications stated at the beginning of this report. It is fully expected that as the building and development process continues more unexpected or unpredicted changes will have to be made and established in the following semester when the heavy development begins and the depths of the various software are explored, especially those concerning computer vision and image processing such as the Point Cloud Library and OpenCV. Based on the research and foundation built in the spring semester, however, the team feels comfortable that the obstacles encountered in the fall will be overcome in a similar fashion to those that were overcome in the spring.

9.0 Appendices

The appendix includes all of the references used in this report. It will also include proof of request for permission to use the various images found in this report. For most cases the individual or entity that holds the rights of these photos has given permission for them to be included in this report. If a response has not been received, these particular images will be labeled with a permission pending alert.

9.1 Bibliography/References

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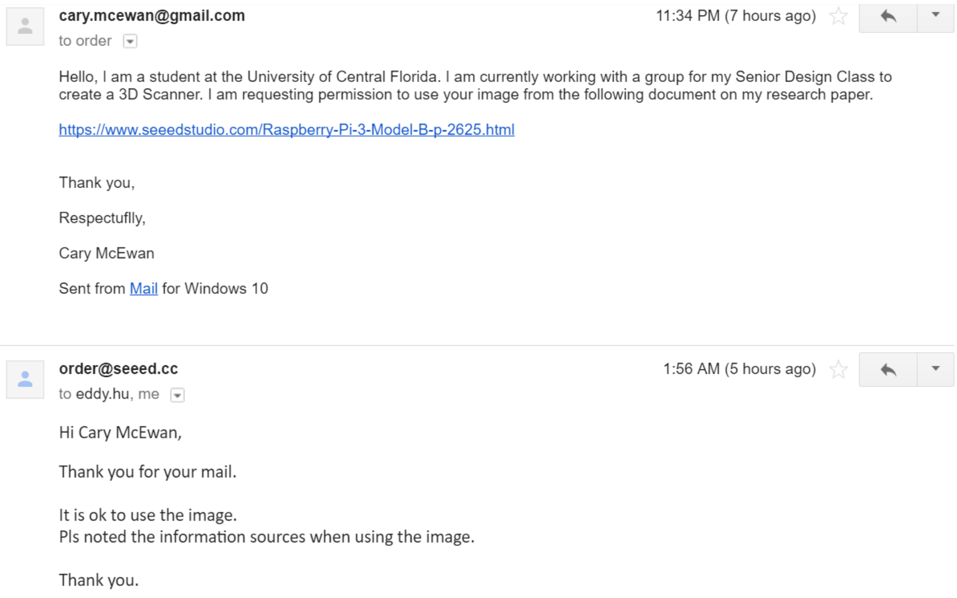
9.2 Permissions



cary.mcewan@gmail.com
to order
11:34 PM (7 hours ago)

Hello, I am a student at the University of Central Florida. I am currently working with a group for my Senior Design Class to create a 3D Scanner. I am requesting permission to use your image from the following document on my research paper.

https://www.seeedstudio.com/Raspberry-Pi-3-Model-B-p-2625.html

Thank you,

Respectuflly,

Cary McEwan

Sent from Mail for Windows 10

order@seeed.cc
to eddy.hu, me
1:56 AM (5 hours ago)

Hi Cary McEwan,

Thank you for your mail.

It is ok to use the image.
Pls noted the information sources when using the image.

Thank you.

Figure 66: Permission from DIYGADGET for Figure 14

Mike Wang <brisk2008@gmail.com>

3:29 AM (4 hours ago)

to me

Hi, Cary:

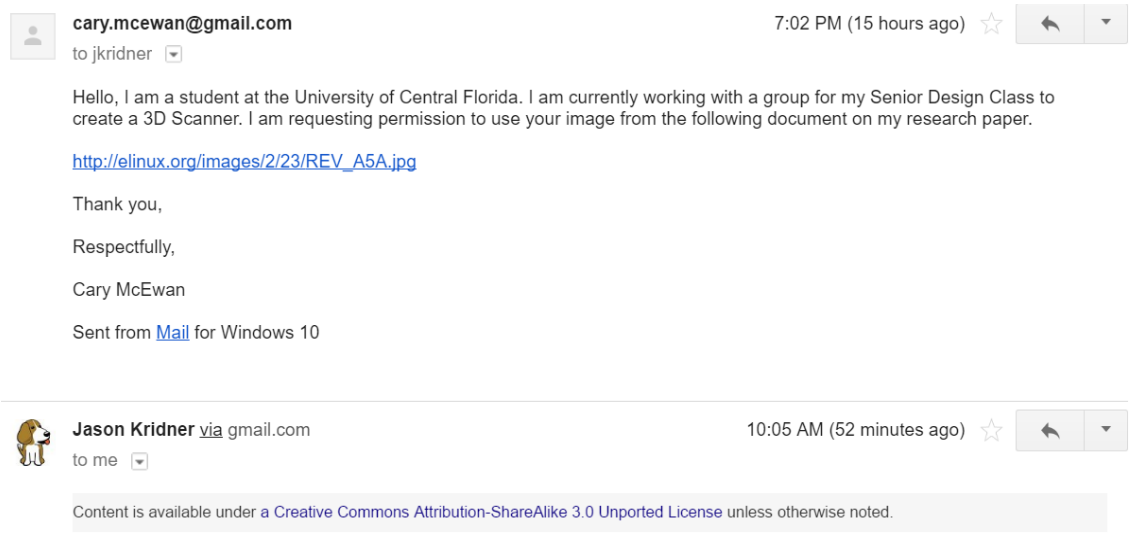
No problem, you can use it.

thanks

On Mon, Apr 24, 2017 at 11:28 PM, Sales <support@diygadget.com> wrote:

> Name: Cary McEwan
> E-mail: cary.mcewan@gmail.com
> Telephone: 9049554173
>
> Comment: Hello, I am a student at the University of Central Florida. I am currently working with a group for my Senior Design Class to create a 3D Scanner. I am requesting permission to use your image from the following document on my research paper.
>
> Thank you,
>
> Respectuflly,
>
> Cary McEwan
>
> http://www.diygadget.com/arduino/arduino-uno-r3-atmega328p-pu-usb-io-board-2012.html

Figure 67: Permission from SeeedStudio for Figure 15



cary.mcewan@gmail.com

7:02 PM (15 hours ago)

to jkridner

Hello, I am a student at the University of Central Florida. I am currently working with a group for my Senior Design Class to create a 3D Scanner. I am requesting permission to use your image from the following document on my research paper.

http://elinux.org/images/2/23/REV_A5A.jpg

Thank you,

Respectfully,

Cary McEwan

Sent from Mail for Windows 10

Jason Kridner via gmail.com

10:05 AM (52 minutes ago)

to me

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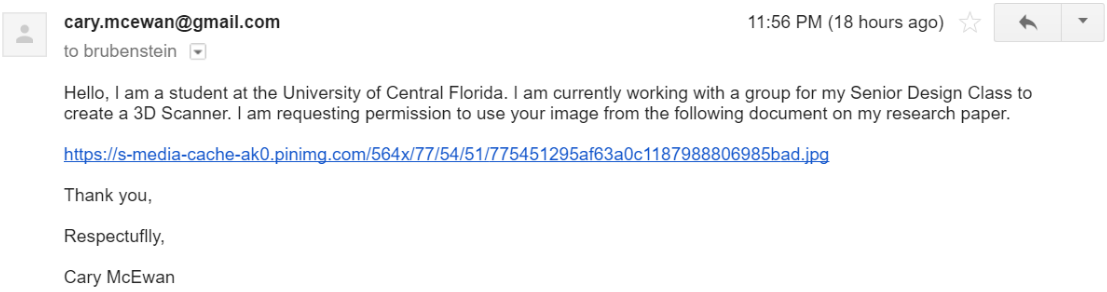
Figure 68: Permission Request from eLinux for Figure 16



Hello, I am a student at the University of Central Florida. I am currently working with a group for my Senior Design Class to create a 3D Scanner. I am requesting permission to use your image from the following document on my research paper.

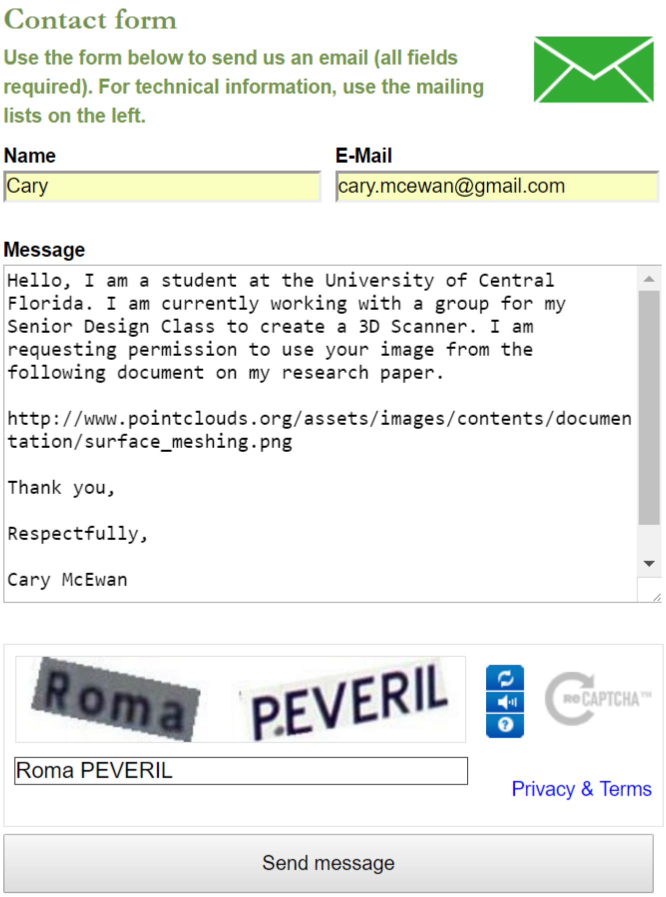
https://s-media-cache-ak0.pinimg.com/564x/77/54/51/775451295af63a0c1187988806985bad.jpg

Thank you,

Respectuflly,

Cary McEwan

Figure 69: Permission Request From TechTarget for Figure 48



Name: Cary

E-Mail: cary.mcewan@gmail.com

Message:

Hello, I am a student at the University of Central Florida. I am currently working with a group for my Senior Design Class to create a 3D Scanner. I am requesting permission to use your image from the following document on my research paper.

http://www.pointclouds.org/assets/images/contents/documentation/surface_meshing.png

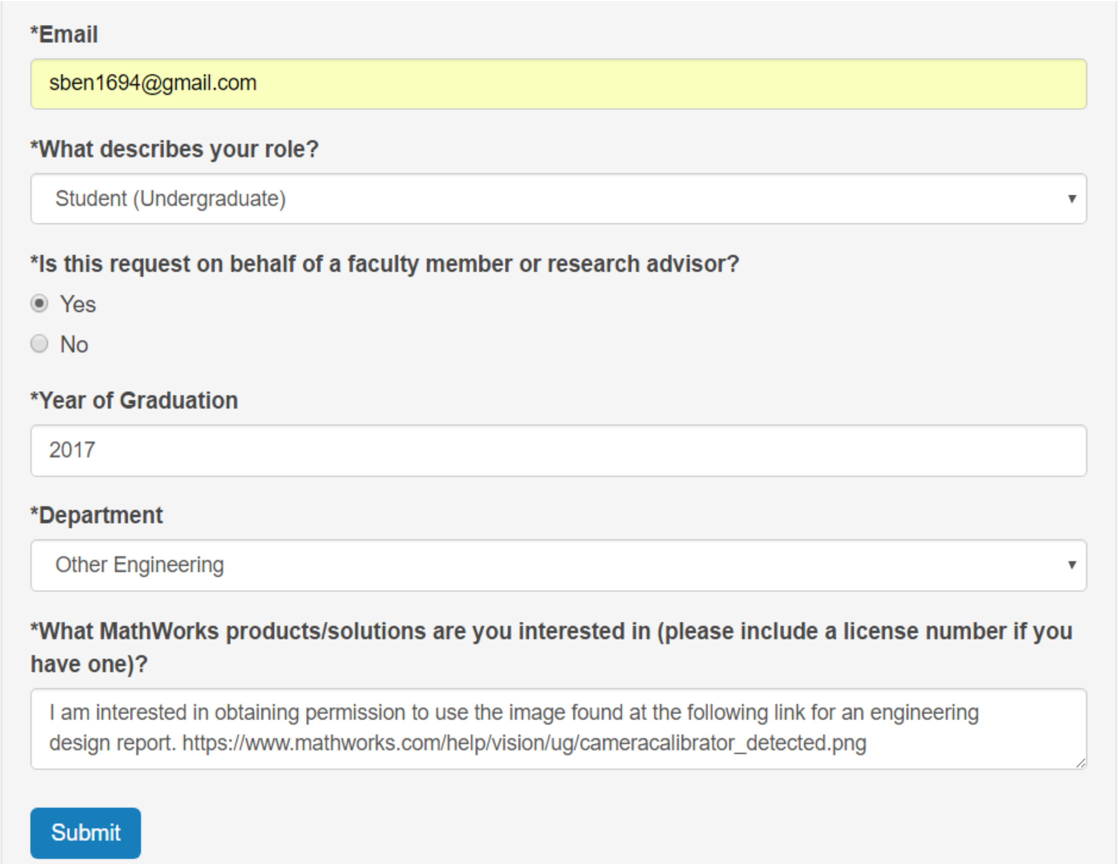
Thank you,

Respectfully,

Cary McEwan

Roma PEVERIL

Figure 70: Permission Request from PCL for Figure 54



*Email

sben1694@gmail.com

*What describes your role?

Student (Undergraduate)

*Is this request on behalf of a faculty member or research advisor?

● Yes
○ No

*Year of Graduation

2017

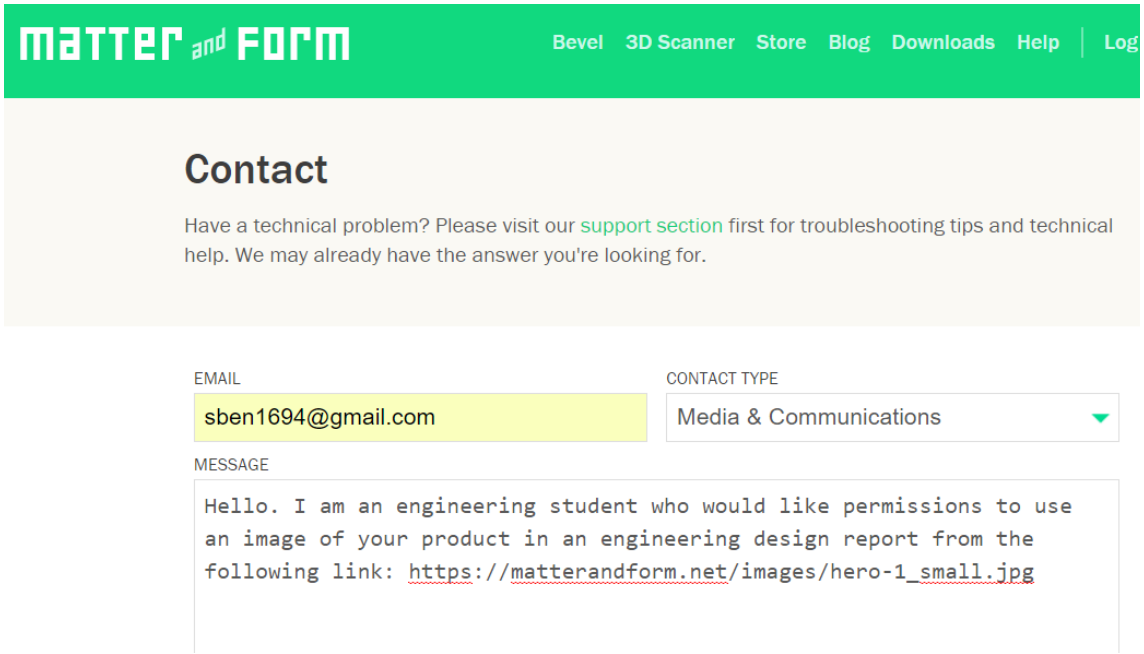
*Department

Other Engineering

*What MathWorks products/solutions are you interested in (please include a license number if you have one)?

I am interested in obtaining permission to use the image found at the following link for an engineering design report. https://www.mathworks.com/help/vision/ug/cameracalibrator_detected.png

Figure 71: Permission Request for Figures 17 & 18



Contact

Have a technical problem? Please visit our support section first for troubleshooting tips and technical help. We may already have the answer you're looking for.

EMAIL

sben1694@gmail.com

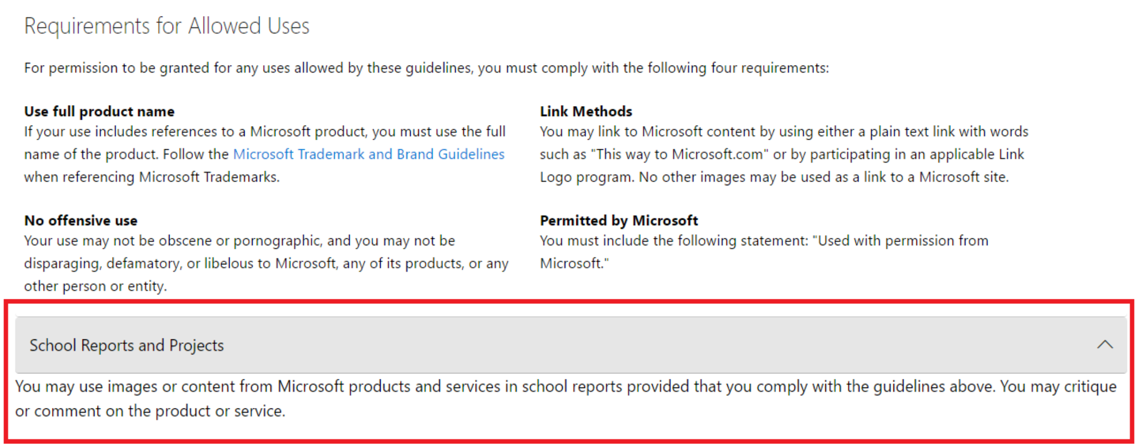
CONTACT TYPE

Media & Communications

MESSAGE

Hello. I am an engineering student who would like permissions to use an image of your product in an engineering design report from the following link: https://matterandform.net/images/hero-1_small.jpg

Figure 72: Permission Request from Matter and Form for Figure 10



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For permission to be granted for any uses allowed by these guidelines, you must comply with the following four requirements:

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If your use includes references to a Microsoft product, you must use the full name of the product. Follow the Microsoft Trademark and Brand Guidelines when referencing Microsoft Trademarks.

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Your use may not be obscene or pornographic, and you may not be disparaging, defamatory, or libelous to Microsoft, any of its products, or any other person or entity.

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You may link to Microsoft content by using either a plain text link with words such as "This way to Microsoft.com" or by participating in an applicable Link Logo program. No other images may be used as a link to a Microsoft site.

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You must include the following statement: "Used with permission from Microsoft."

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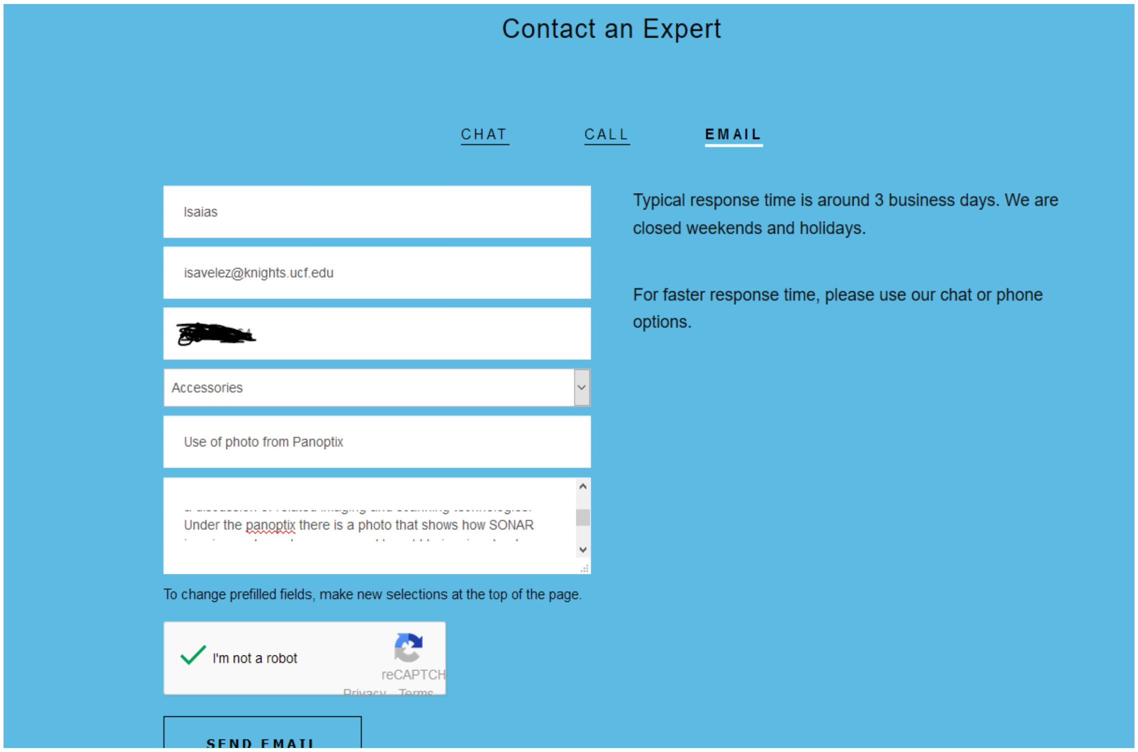
You may use images or content from Microsoft products and services in school reports provided that you comply with the guidelines above. You may critique or comment on the product or service.

Figure 73: Permission for Figures 8 & 9



Contact an Expert

Isaias

isavelez@knights.ucf.edu

[redacted]

Accessories

Use of photo from Panoptix

Under the panoptix there is a photo that shows how SONAR

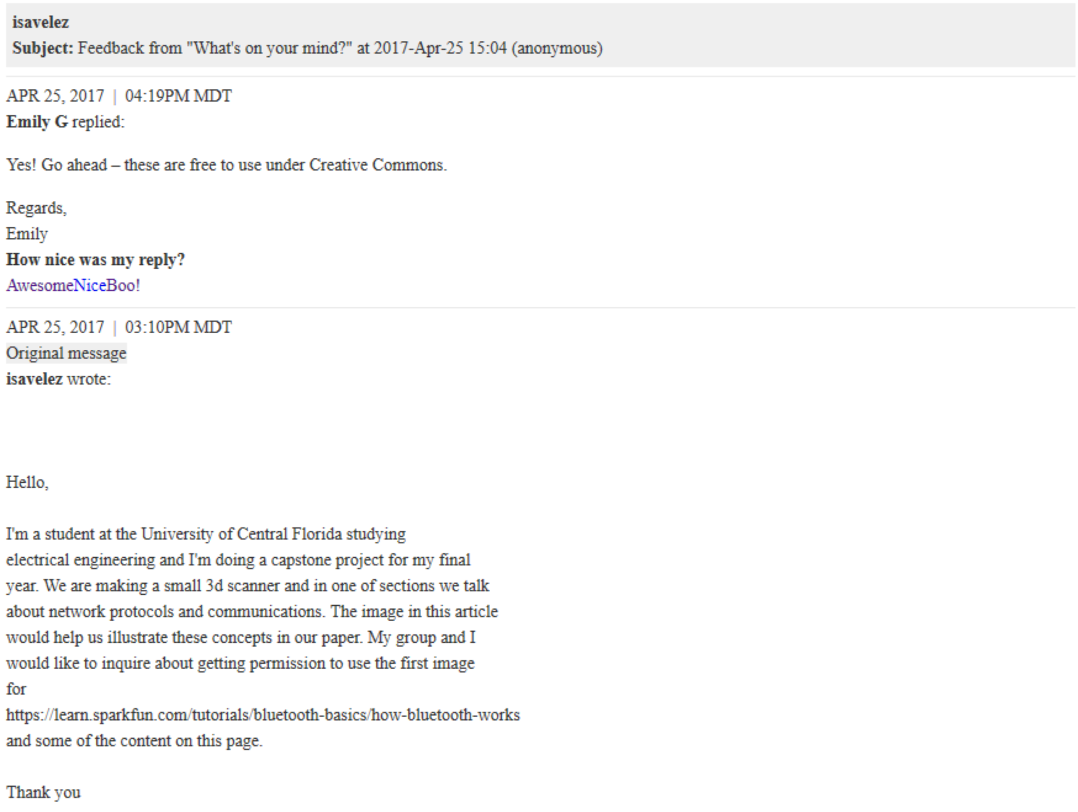
To change prefilled fields, make new selections at the top of the page.

☑ I'm not a robot

Typical response time is around 3 business days. We are closed weekends and holidays.

For faster response time, please use our chat or phone options.

Figure 74: Permission Pending from Garmin for Figure 5



isavelez
Subject: Feedback from "What's on your mind?" at 2017-Apr-25 15:04 (anonymous)

APR 25, 2017 | 04:19PM MDT
Emily G replied:

Yes! Go ahead – these are free to use under Creative Commons.

Regards,
Emily
How nice was my reply?
AwesomeNiceBoo!

APR 25, 2017 | 03:10PM MDT
Original message
isavelez wrote:

Hello,

I'm a student at the University of Central Florida studying electrical engineering and I'm doing a capstone project for my final year. We are making a small 3d scanner and in one of sections we talk about network protocols and communications. The image in this article would help us illustrate these concepts in our paper. My group and I would like to inquire about getting permission to use the first image for https://learn.sparkfun.com/tutorials/bluetooth-basics/how-bluetooth-works and some of the content on this page.

Thank you

Figure 75: Permission from Sparkfun for Figure 13

customercare@cwnp.com

Hello,

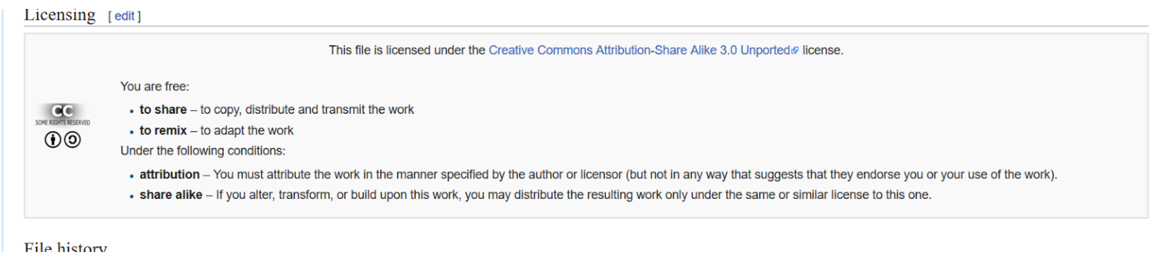
I'm a student at the University of Central Florida studying electrical engineering and I'm doing a capstone project for my final year. We are making a small 3d scanner and in one of sections we talk about network protocols and communications. The image in this article would help us illustrate these concepts in our paper. My group and I would like to inquire about getting permission to use the OSI image used in this article https://www.cwnp.com/cwnp-wifi-blog/whytheosimodelmatters/ .

Why Does the OSI Reference Model Matter? - cwnp.com
www.cwnp.com
Why Does the OSI Reference Model Matter? By CWNP On 04/29/2014 ...

Thank you,

Isaias

Figure 76: Permission Pending from CWNP for Figure 12



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- **attribution** – You must attribute the work in the manner specified by the author or licensor (but not in any way that suggests that they endorse you or your use of the work).
- **share alike** – If you alter, transform, or build upon this work, you may distribute the resulting work only under the same or similar license to this one.

File history

Figure 77: Permission form Creative Commons Licenses for Figure 3, 4, & 23