University of Central Florida
Department of Electrical Engineering and Computer Engineering

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Final Project Documentation

Semi-Automated Diffraction Grating Efficiency Measurement Station

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1.0 Executive Summary

Diffraction gratings play an integral role in a variety of applications relating to the field of optics. In particular reflection gratings are particularly useful as they provide a better resolution in the use of dispersion. Despite this, measuring the efficiency by which the grating can output is often hard to determine. When collecting measurements such as in the field of spectroscopy it is important to maintain a consistent efficiency for a variety of wavelengths and across different gratings. Knowing this, we aim to design a system that can semi-automatically determine the output efficiency of a reflection-based diffraction grating. This will be used specifically to be integrated into a spectrometer which depends on a diffraction grating.

Our system will utilize a variety of light wavelengths to ensure that the efficiency data can confidently be considered to make a decision on the quality of a particular diffraction grating. Through a computer software, the user will be able to enter the characteristics of the grating (lines per millimeter) and the system will adjust accordingly and use the appropriate light sources to collect the efficiency data. Currently, there is very little in the way of automation as it relates to measuring the efficiency of diffraction gratings.

Automation will greatly cut down on the time necessary to test for quality in a commercial setting and will greatly improve productivity. The automation will consist of a motorized rotation stage and photodetector to collect the light depending on the wavelength of the incident light. Additionally the efficiency will be calculated using a computer software and will be relayed to the user. From this information, the user can make the decision as to whether or not the diffraction grating will be suitable for use in the optical design in question.

With applications for spectroscopy growing constantly it is important that when using diffraction gratings, quality is held to a high standard. In both research and commercial settings for accurate measurements we want to maintain that the efficiency of a particular grating is above the predetermined threshold that is acceptable for the measurements. Through this project we aim to design a thorough and novel system that can be used to greatly optimize the measurement of diffraction grating efficiency as it will prove beneficial to the field of spectroscopy.

The user can feel comfortable knowing that the grating they have chosen for a particular optical system is up to the quality with which the user needs for the system to function at an adequate potential. The driving motivation was to have semi-automation and NIR compatibility whilst still being relatively low cost in nature. This satisfies a need in the field of spectroscopy and provides an incredibly useful tool that can be used with little to no hassle. We believe that our system satisfies a tool that is not yet available or optimized to measure diffraction gratings. This idea was brought about through personal experience working with spectrometers which are heavily centered around the efficiency of the diffraction grating inside the spectrometer. In observing spectrometers with lower than expected output, more often than not it is a result of the grating not performing up to spec. With a system to automatically measure the efficiency we can check diffraction gratings beforehand to ensure that they will not be an issue in emission peak height in our system.

2.0 Project Description

This section will outline the specs and functionality requirements for our proposed project design. We will also list any constraints and standards associated with aspects for both the hardware and software design when applicable.

2.1 Goals and Objectives

The end result of this project should be a quick and seamless method of measuring the efficiency of reflection-based diffraction gratings. To achieve this we will first consider the optical design that best suits our needs to carry out this task. Additionally ensuring that the electrical components provide automated focusing and placement through computer software are incredibly important to the fundamental idea of the efficiency station. With this automation it becomes significantly easier to measure the efficiency of gratings in a short period of time. Within the scope of the project we would like to have a wide range of wavelengths usable for diffraction grating measurements spanning from 200 - 1100 nm.

As a stretch feature, including an even wider range of wavelengths would be greatly beneficial as it would be applicable for infrared light applications and deeper ultraviolet light measurements. We aim to eliminate the need for unnecessary manual replacement of parts and adjustments depending on wavelength and focal length and design a system which will eliminate the need for manual intervention. Additionally, the system should maintain a lifetime for several years as a useful tool for measurements.

2.2 Project Functionality

The optical system for this project contains a wide combination of elements which ensure that the measurements for the efficiency of the grating are both consistent and accurate. Additionally the input variable for this system will be the light source of monochromatic LEDs at various wavelengths. Before the light is input into the system, the user will determine the characteristics of the particular grating they want to measure the efficiency of. This will determine the corresponding wavelengths and positions of both the angular rotation stage as well as the position of the photodetector for the system.

Once the information is input into the system the lowest wavelength light source will enter the system. From this point, the light is then passed through a slit, an appropriate cutoff filter and collimating lens to ensure that the light is fully collimated with no outside interference. The light passes through a linear polarizer and then a 50/50 beam splitter to collect the incident light power to compare later. The light is then passed onto a blazed reflection grating on a rotation stage which collects the 1st order light. Grating and photodetector are positioned in such a way through automation that no matter the wavelength of light, the measurement can be taken. The incident and reflected powers are compared and we are left with an efficiency at a particular wavelength.

2.3 Specifications

The measurements taken by our system and the parts used are incredibly important to the functionality of the project as a whole. Through part selection and design choices we must ensure that our project can function at the desired accuracy. Shown in the table is a set of parameters describing the parts used for our particular design. These were chosen through calculations which are elaborated on later in the report. Any optical design using lenses must make adjustments based on the focal lengths and requirements for the design.

Feature	Spec
Power Supply	~5 V
Collimating Lens	1.5mm Focus, AR Coating 600-1100 nm
Rotation Stage	Accurate within a ± 0.5mm margin of error
Collimating Lens Adjustment	Adjustment along 8 cm long rail, accurate within a ± 0.5mm margin of error
Graphical Display of Measurements	X-axis: wavelength (nm) Y-axis: lines/mm

Table 1: Engineering Requirements (Highlighted Features are Demonstrable)

2.4 Requirements

- Incorporates Accurate Semi-Automated calibration to ± 0.5mm
- Will not require the use of mirrors
- Will operate with a variety of light sources
- Power usage will be under 50 W
- Simple GUI
- Minimal setup requirements
- Measures light wavelengths within the visible light range (~740 nm to ~380 nm)
- External Power Supply between 5V and 12V
- Ability to receive user input needed for Semi-Automated functionality

2.5 Project Diagrams

In this section, we will go more into detail for the Hardware and Software aspects of the project. There will be visuals for the block diagrams and other related items for each side of the design process.

Each team member's part responsibility in the hardware and software design will be divided as shown with the color scheme of the table below. With that being the case, there will likely be some overlay between the parts as some of them will consist of both electrical and computer or photonic systems.

The hardware and software block diagrams are arranged in a way that somewhat reflects what the physical build may look like for the project, but are not the exact representation of their positions. The prototype graphic will provide a better model of the part arrangement overall. The design is still subject to change but the parts outlined in the research themselves will not differ much from what is currently present. We aim to allocate an equal portion of the workload to each member in order to have an efficiency and productive design schedule. Each member will show their respective knowledge on the subject and ensure that the respective components are constructed in a responsible and efficient manner.

This is important as our project relies on several disciplines working synchronously to achieve a particular goal. If any single portion of the design falls short of what is expected we can not utilize the measurements or the project to its fullest potential. We aim to use interdisciplinary knowledge to ensure that the work is cross-examined by each member based on their knowledge of other fields inside the project.

Teams Responsibilities	
Ryan Goff	
Christopher Robertson	
Carlos Irizarry	
Ecclezias Senat	

Table 2: Teams Responsibilities for Block Diagram

- The block status of both the Hardware and Software Block Diagrams is currently being researched.

2.5.1 Hardware Diagram

As modeled by the block diagram, the arrows model how the flow of light in the project is meant to travel through each of the systems present in our project design. When the Beam Splitter is reached, that is where the first break in the flow of light should occur. Both photodetectors are meant to capture the light at different stages in the project which will then be transferred to the MCU for the software to handle.

The power supply lines represent the electrical connections for the project part that need external power and movement. The rotation and translation stage are directly connected to the parts that they will be in control of moving in the project. Their positioning will be important in order for the photodetectors to collect the light properly. Most of the electrical and the display will also be connected to the MCU in order to handle the collected data and output both the semi-automated functions and display the measured data for the user.

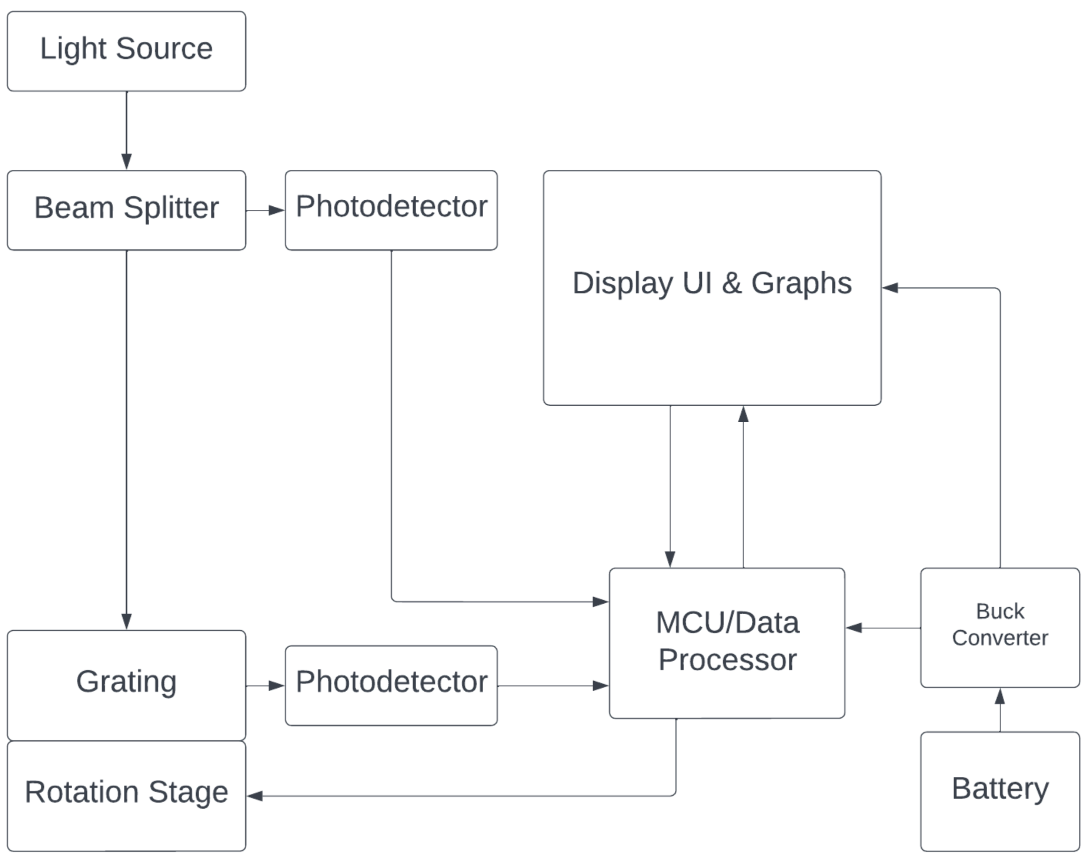


Figure 1: Hardware Block Diagram

2.5.2 Software Diagram

This software diagram shows how we expect the system functions to interact with each other before proceeding to the next operation. The adjustments will occur prior to any actual measurements being taken, as the parts will need to be positioned before we can receive the measurements from the photodetectors.

Both photodetector readings will then be used to determine the efficiency rating for the diffraction grating. The rating for each associated wavelength of light will then be individually displayed to the display allowing the user to start the process over if necessary, or adjust the system manually before making a new reading.

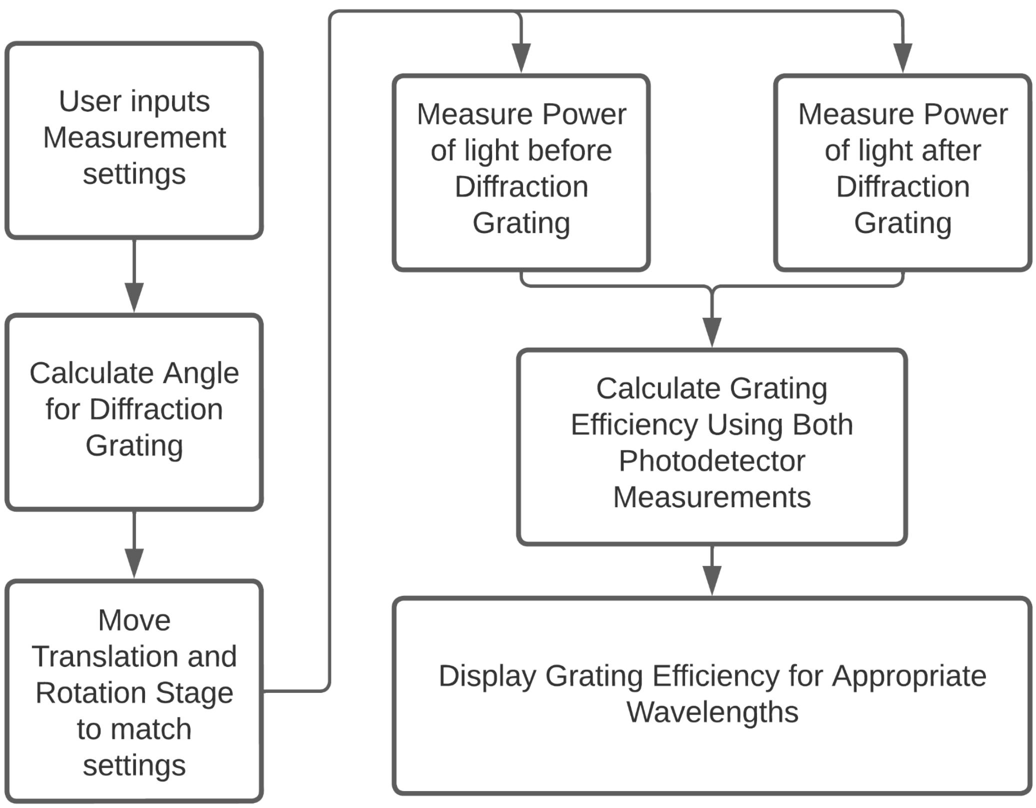


Figure 2: Software Block Diagram

2.5.3 Prototype Illustration

This prototype illustration will serve as a general outline of how the system will operate together. While it is not exactly to scale, the arrangement of the parts and their relative positions to each other is meant to be accurate to some degree. For the light source a broadband light source will be used at the primary light source.. The graphic shows the light passing through the polarizer before reaching a beam splitter which will separate the light before reaching the diffraction grating station.

The diffraction grating station will be positioned on top of our rotation stage in order to adjust the angle at which the light hits the grating as it is diffracted into one of two photodetectors present in the design. The other photodetector will collect the light directly from the beam splitter to be used in a different calculation. All the collected data will be handled by our MCU and then displayed onto the LCD Display to show the desired measurements. The display will also function as the system's GUI to input the data required to adjust the lens and diffraction grating into their proper locations.

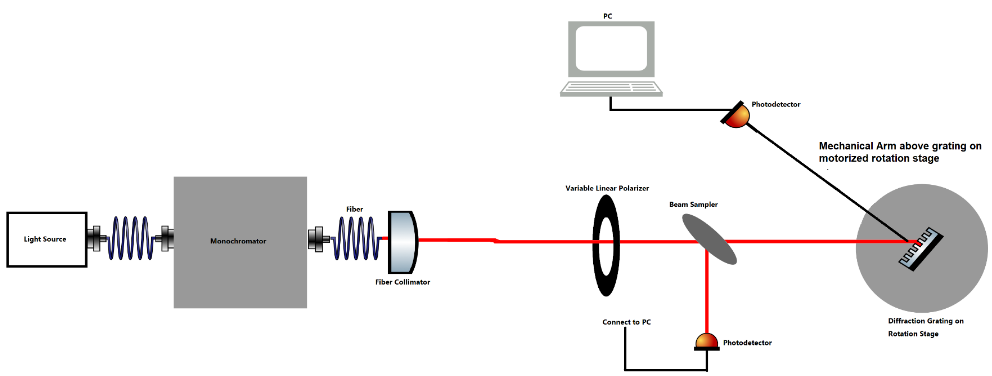


Figure 3: Project Graphic

2.5.4 House of Quality Diagram

The house of quality diagram is meant to illustrate how different project features affect and/or influence the other part choices or performance. It also displays the correlation between engineering and market requirements present in the design.

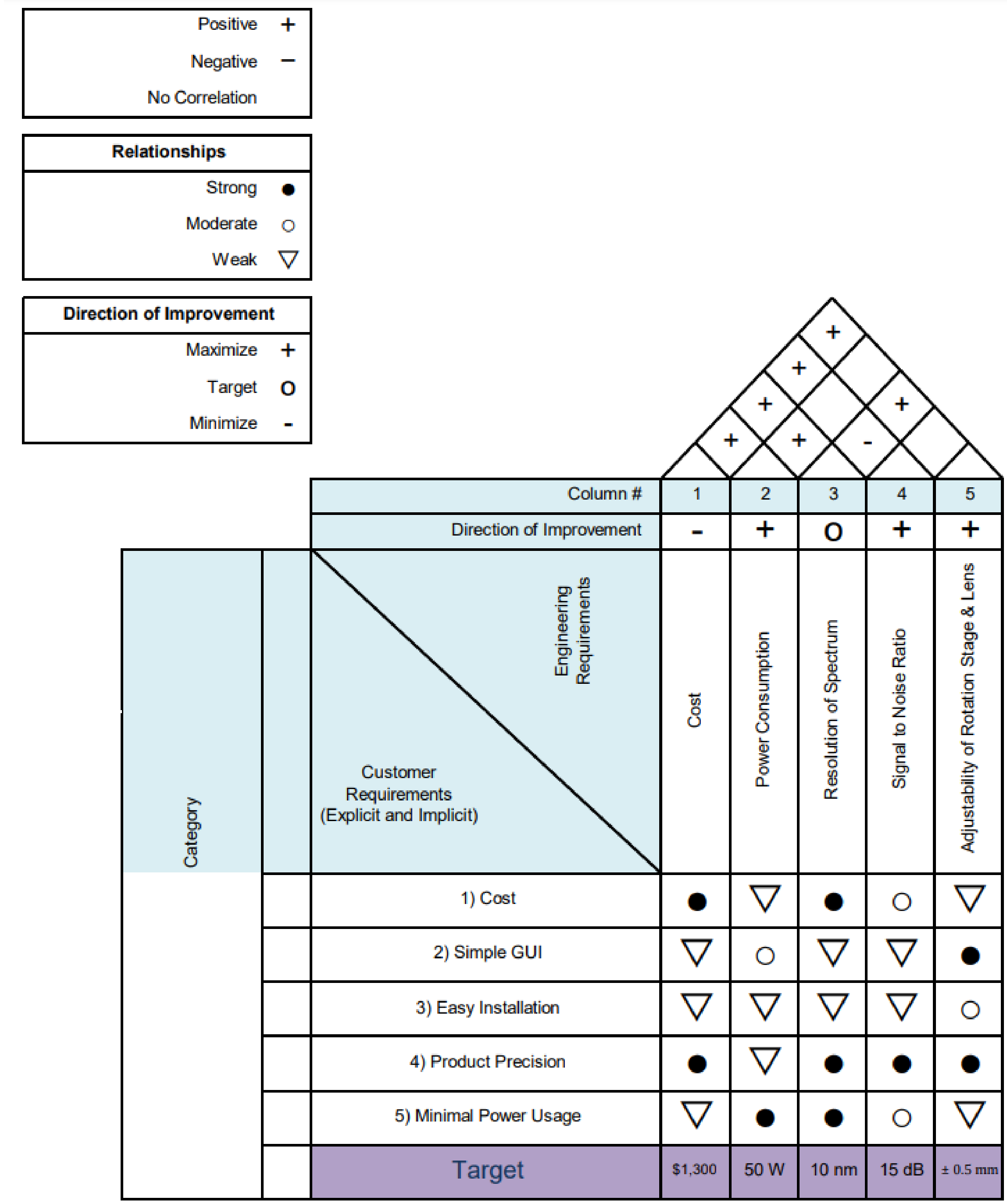


Figure 4: House of Quality Diagram

With respect to the cost, the relation between the Engineering and Marketing requirements is very cohesive as the product's capabilities and performance will increase if we use more expensive parts. It will however also increase the price of the product if it were to be sold on the market, which is why we wish to minimize this relationship as much as possible where we can.

The cost and the GUI have a rather weak relation as the graphics are more dependent on the code itself rather than the price of the product. That's not to say price will have no relation, as it is possible to acquire a higher quality display at higher prices, but that is less of a factor in simplifying the GUI.

The Installation process also has a weaker relation with the cost as it is more dependent on the design itself and not how expensive the parts in the design are. The same can be said about the power usage as the price will play a large role in altering this requirement in comparison to the design itself.

The product precision will have a strong relation with cost as more expensive parts will offer a smaller margin of error in measurements as a wider range in which they can make those measurements. In dealing with the wavelengths of light we want our spectrometer to measure, a larger range would be more beneficial but it would also be costlier.

The power consumption and GUI would have a moderate relation with each other as the display will need to be powered. In terms of its simplicity though, this will still be reliant on the code itself. A simpler GUI would likely lessen the power consumption as the display wouldn't need to draw as much power given a smaller range of information that we need to give to the user.

The power and easy installation would have a weak relation since the design does not require the project to be powered through a wall outlet. If the device were to be powered this way, then the relationship would be stronger as you'd need to account for a location with access to the correct type of power source.

The spectrum resolution and cost will have a very strong relationship as higher powered light sources with wider ranges of wavelength variability along with the equipment needed to then measure these wavelengths are expensive on an individual level, which doesn't even take into consideration the costs of the accompanying parts in the project design. This will be the main target we aim to design around as we were aiming for a less expensive product with a similar range of accuracy in terms of measurement. Balancing these two points will be a determining factor in the project design.

The installation and GUI have little to no relation with the spectrum resolution as these two aspects don't play a role in calculating the range or the accuracy of the measurements we are making in the project. The physical layout of the parts will affect the measurements but not the ease of the part arrangement.

The product precision is directly tied to the spectrum resolution as the higher resolution of light wavelength that we can accurately measure will determine how precise we can be with said measurements. If the spectrum resolution is limited, we can still be precise but only on a smaller scale. The power usage can also factor into the resolution as higher powered light sources may demand a higher current draw. Working around these requirements will be the other focal point of our design.

The adjust requirement will have a weak relation to the cost as the parts needed to make the semi-automated adjustments aren't expensive in relation to the total predicted cost for the project parts. They also don't require much alteration to the original design so we don't have to go out of our way to add these features.

The simple GUI will be directly related to the adjustability of the rotation and translation stage as they will be operated through this feature. Ensuring that their operating procedures are user friendly will be the main goal for these requirements in the project. To go along with this, the precision will also factor into the accuracy of these adjustments since working with lenses and light is dependent on the positioning and angling of the apparatus that are involved in the measuring process.

3.0 Research

To develop a better understanding for our project design, our group members conducted individual research on the respective parts we were responsible for in this project. The sections below will dive into more detail on the parts we looked into and how or why we decided to use the parts we ended up choosing for the design.

3.1 Light Sources

As our goal is to measure efficiency from the range of 200 - 1100 nm we must have light sources that cover that range whilst not being excessive as to keep costs low. For this reason we believe that a set of relatively inexpensive LEDs will be able to carry out the necessary task. These wavelengths include 405 nm, 532nm, 633 nm and 980 nm. In the event that it is possible to obtain a supercontinuum white light laser, a monochromator would be added to the system in order to have more points to measure efficiency within the visible light spectrum.

The light sources for the system will be translated from left to right in order to record values for the efficiency of the grating. The light sources must be securely mounted in order to maintain consistency across measurements for different gratings. Additionally, we must ensure that the monochromatic laser sources are indeed in line with the wavelength which is assigned to the particular light source. This will be measured using a spectrometer which can accurately present the wavelength of the incident light source. This is an important distinction to make as it ensures that the efficiency at a particular wavelength is accurate to what is described. The final design of the project utilized a broadband light source due to enhanced wavelength choices.

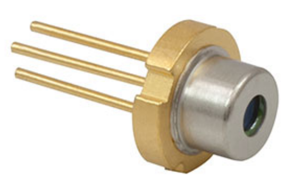


Figure 5: Laser Diode Component from Thorlabs

3.2 How an LED Works

LEDs are a household object that almost any person is familiar with. The everyday applications for LEDs are numerous and they are an incredibly useful tool. They also prove to be useful in many optical designs. In the event of using an LED over a laser diode in our design we have to understand the principles of how an LED functions. Light-emitting diodes produce light when a current is passed through. Photons are emitted at the wavelength of the semiconductor material's emission wavelength. Depending on the material inside the diode, we are left with a different color of light. This is the working principle behind LEDs. Using this information we can have a wide variety of colors for measurements at a relatively low cost. However, due to the shape of the LED we are left with incoherent light which, depending on the application, may not be suitable. LEDs are encapsulated with a hemispherical casing to limit total internal reflection.

3.3 How a Laser Diode Works

Laser diodes are incredibly useful tools that can produce coherent light with a small footprint. There are several components which make the laser diode possible. Similar to the laser diode, we utilize the mechanism of diodes in that of a p-n junction. However, unlike the LED a laser diode can excite the photons which are present within the p-n junction. Through this process more and more photons are created with the same phase, polarization and wavelength. Once the junction is filled with laser light, some will exit through the rear of the laser diode and pass through a collimating lens leaving us with a coherent and collimated light source. There are problems that arise with using laser diodes. Laser diodes require more space for use and thus in situations where there may be more than one light source present they may not be the best option. Another issue that arises is that of temperature dependence in voltage regulation. This can be an undesirable aspect to handle if wavelength dependence is not important for the individual's design.

3.4 Alternate Light Sources

Despite the current model using monochromatic light sources, there is the potential to use either a supercontinuum white light laser, or a white light halogen source to achieve similar results. The reason we opted for the current design is that the current light sources in use are cheaper and avoid the use of a monochromator. A monochromator is a device which allows the user to select a particular wavelength from a white light source and emits that wavelength on the other side. This is only possible for visible light usage and eliminates the possibility of NIR light. NIR is an important portion of the electromagnetic spectrum which we would like to observe the efficiency of.

The supercontinuum white light laser avoids this problem but is much more expensive and additionally does not have compatibility for NIR light. There are a wide variety of light sources with different spectrums, these include argon, mercury, cadmium and other light sources. However, for the purpose of reading power we are only interested in particular wavelengths and not the entire spectrum so these light sources would not necessarily be the best choice. In the final iteration of the design, the broadband light source was used instead of the laser diodes.

3.5 Mechanical Optics

The following sections will cover the mechanical optics which do not involve alterations to light in the form of optical properties outside of beam spot size. These are important for the functionality of automation as well as the limiting of light entering the system. However, they are not wavelength dependent, or affect the phase of the light that is traveling through the system.

3.5.1 Translation Stage

Our project will utilize four individual light sources placed on a translation stage. It is important that the translation stage in use can stop in a precise location as it heavily influences the overall alignment in the system and thus can affect the efficiency reading of the grating. For this reason, through predetermined parameters set in a software, our stepper motor will allow for the light sources to almost perfectly line up in the same position every time when that particular wavelength is required. This enhances the automated design and removes the need for manual adjustments on a monochromator. Having the light sources mounted on a motorized translation stage improves the efficiency of the design and speeds up the process by which an individual will be able to measure the efficiency of a diffraction grating. The translation stage was changed in place of a monochromator and broadband light source combination with a fiber collimator.

Figure 6: Optical Translation Stage from Optics Focus

3.5.2 Aperture

To ensure consistency across light sources there will be an aperture of 1mm in diameter placed in front of the LED. The purpose of this slit is to have a consistent shape and transmission across all four LEDs. As previously stated, in the case of measurements in a commercial and research setting, consistency is an incredibly important characteristic as the diffraction grating could potentially be an integral part of the optical system which is being observed. The aperture will be circularly shaped to shape the beam traveling through the optical system. The choice of 1 mm is chosen as to have a limiting factor for the amount of light passing through the system whilst not eliminating too large of a portion of light. Ultimately the iris was not implemented in the design in the final build, despite being considered originally.

Figure 7:Optical Iris from Newport

3.5.3 Rotation Stage

For the rotation stage of the Semi-Automated Diffraction Grating Efficiency Measurement Station, the part that will be rotating is the diffraction grating. Since the angle of reflection from the diffraction grating varies with wavelength the system needs to be able to adjust accordingly. To do this the rotation stage will consist of a platform of sorts that the diffraction grating is attached to. The platform will be able to rotate due to a motor, whether that be a DC brushed motor, DC brushless motor, or a stepper motor. With the use of the motor the platform will be able to rotate to the optimal angle and thus collect the light at the ideal angle and produce the proper results.

The placement of the diffraction grating will be dependent on the user's inputted characteristics, since the idea is that the motor will turn the diffraction grating relatively precisely and to user selected points the process must be repeatable. To get the user's input some sort of screen will be used which will then be attached to some sort of microcontroller, whether that be an Arduino board, Texas Instruments MSP board, or Raspberry Pi. Either way the motor that will be used inside the rotation stage must be compatible with these microcontrollers. Ideally the motor used in this rotation stage will be 5V or less, since the size of the motor does not need to be too big since the rotation stage will be relatively light.

3.5.4 Rotation Stage Motor Options

As discussed before, the grating efficiency team has chosen to create a rotation stage that will be able to rotate a platform that carries a diffraction grating. The angle of this diffraction grating is necessary and important to the system since the team plans on using all types of wavelengths and with varying wavelengths the light will reflect differently through the diffraction grating. As discussed before, the stage itself must be accurate within 0.5 mm of the intended mark. For example, if the user inputs a value that will cause the rotation stage to move 7 millimeters, when activated the motor should rotate the platform with the diffraction grating anywhere from 6.5 millimeters to 7.5 millimeters.

In addition, the group plans on using motors that are about 5V as this will make the PCB design easier and will also allow the group to use a power storage system that uses less volts and thus will ideally be continued across the rest of the components. Lastly, the motor used on the rotation stage must be compatible with the microcontroller we will be using, which will most likely be a Texas Instruments MSP board, an Arduino, or a Raspberry Pi. In order for the motor to be used by the microcontroller, either an ESC (electronic speed control) or a transistor will be used to translate the microcontroller's power outputs to the motor. The 4 types of motors that will be looked at are DC brushed, DC brushless, servo, and stepper motors.

3.5.5 Antrader DC Motor Mini

The Antrader DC Motor Mini is a 5-volt DC brushed motor that can run up to 6000 RPM. The dimensions of the motor are 24 x 12 millimeters with a shaft size of 7 x 2 millimeters. The power consumption of this DC motor is 50 watts, with a DC motor cost of $2.66 per unit.

This unit was chosen as it was a low cost and small size motor that could be used in the rotation stage; however, an ESC or diode would be needed to vary the rotation speed, and with such a high RPM a system of gears would be needed to reach the small and precise adjustments the group is looking for.

Figure 8: Antrader DC Motor Mini

3.5.6 Greartisan DC 3V High Torque Speed Reduction Motor

The Greartisan DC 3V High Torque Speed Reduction Motor is a 3-volt DC brushed motor that runs up to 19 RPM. Unlike many other DC motors, this motor comes with a built-in gearbox which allows the motor to rotate much slower. The dimensions of the motor are 24.2 x 12 x 10 millimeters, with a D shaped output shaft measuring 2.5 x 9.2 millimeters. The unit cost of this motor is $11.99.

Figure 9: Greartisan DC 3V High Torque Speed Reduction Motor

This unit was chosen as it was a small and compact motor that could be used in the rotation stage, while also adding a gearing system which would reduce the RPM of the system which gives the group a higher level of precision which is vital, however the unit price of the motor is relatively high, and an ESC or diode will still need to be used to control the motor.

3.5.7 abcGoodefg 1000KV RC Brushless Motor

The abcGoodefg 1000KV RC Brushless Motor is a 5-volt DC brushless motor that runs up to 35000 RPM. Unlike the previous two motors, this brushless motor comes with a 30A ESC. The dimensions of the motor are 27.5 x 27 millimeters with a shaft size of 3.17 millimeters. The unit cost of this motor is $20.99.

This unit was chosen as an alternative to a brushed motor and met the general qualifications of the project being relatively small. Unfortunately, brushless motors generally have a much higher RPM range which is the exact opposite of what is needed as precision is the group’s main goal. With that being said this motor does come with an ESC which can be used on most microcontrollers.

Figure 10: 1000KV RC Brushless Motor

3.5.8 Kingroon Nema17 Stepper Motor

The Kingroon Nema17 Stepper Motor is a 4.1-volt stepper motor that has a step angle of 1.8 degrees. The dimensions of the motor are 42 x 23 millimeters with a shaft size of 18 x 4.5 millimeters. The unit cost of this motor is $7.99.

This unit was chosen as an alternative to either of the brushed or brushless motors since stepper motors are able to be much more precise than the brushed and brushless motors due to their design. Unfortunately for this unit in particular there is no driver board to connect to the selected microcontroller and thus a circuit design like the one below would have to be implemented to control this motor.

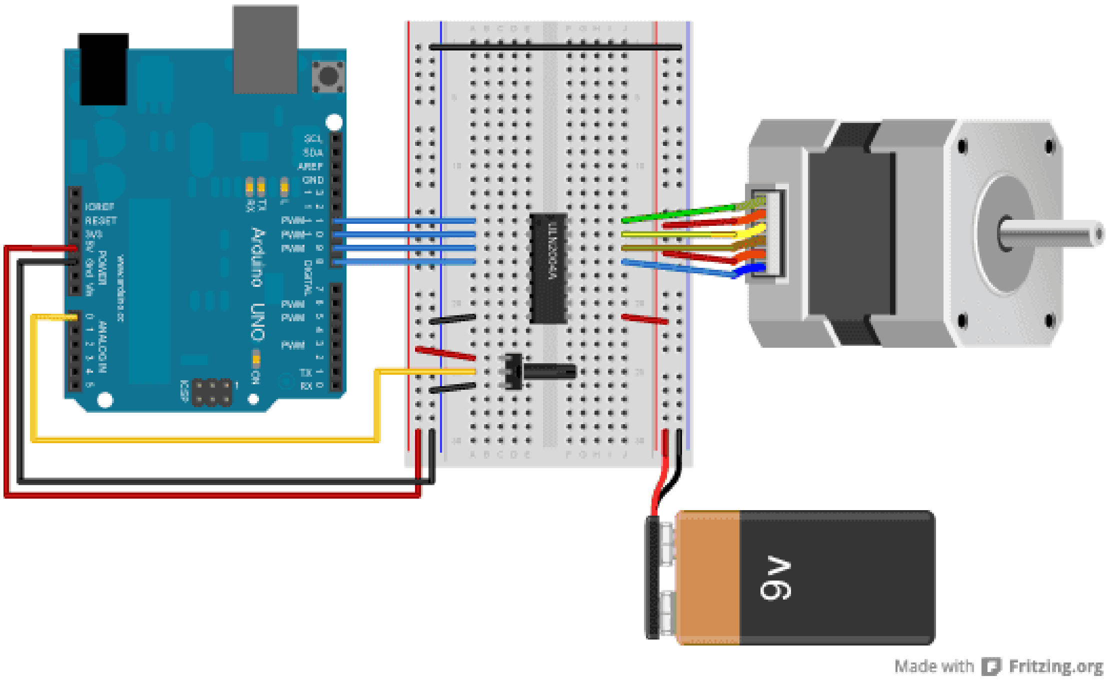


Figure 11: Nema17 Stepper Motor Integrated with Arduino

(Photo taken of https://docs.arduino.cc/learn/electronics/stepper-motors)

3.5.9 Twotrees Nema 17 Stepper Motor + Stepper Motor Driver

The Twotrees Nema 17 Stepper Motor and Stepper Motor Driver is identical to that of the Kingroon Nema17 Stepper Motor, except this package includes a driver which can be used rather than the implemented circuit design above. This set has a unit cost of $19.99, this stepper motor and driver combo were selected because it simplifies the circuit design and implementation.

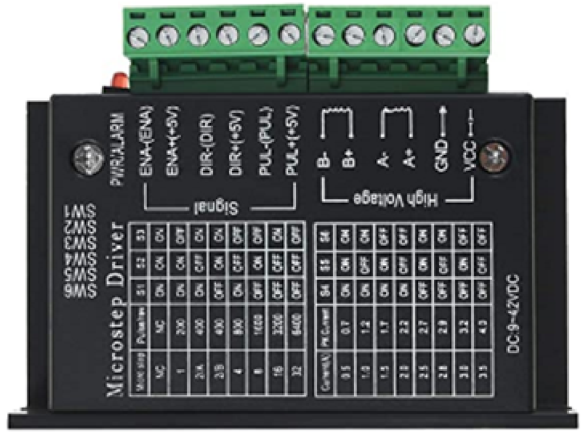


Figure 12: Stepper Motor Driver for Nema17 Stepper Motor

3.5.10 ELEGOO 28BYJ-48 ULN2003 Stepper Motor

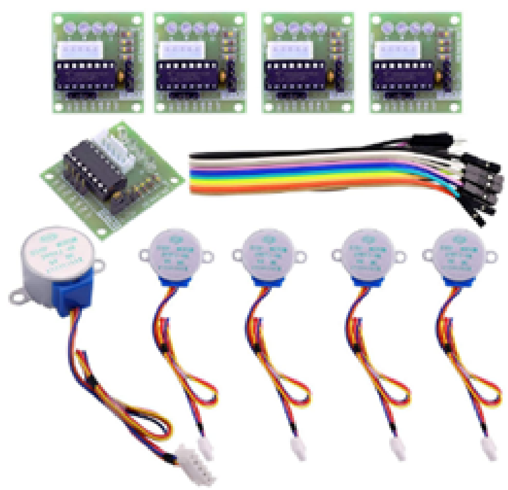


Figure 13: ULN2003 Stepper Motor + Driver Board

The ELEGOO 28BYJ-48 ULN2003 Stepper Motor + Driver Board is a 5-volt stepper motor that has a step angle of 5.625 degrees. The dimensions of the motor are 27 x 27 x 18 millimeters. This unit comes with a total of 5 stepper motors and 5 driver boards, with a unit cost of $2.80.

This unit was chosen for a few reasons, the first of which was the references made to Arduino which make setting up the motors very easy with Arduino, the second was the number of stepper motors and drivers in the case one breaks there are many more to replace it. Thirdly was the size, the driver board in particular was noticeably smaller than that of the Nema 17. The only bad thing about this unit is that the step angle is 5.625 degrees which will be way too large to reach our goal of +/- 0.5 millimeters.

3.5.11 Smraza SG90 9G Micro Servo

The Smraza SG90 Micro Servo is a servo motor with an operating voltage range of 4.8 to 6 volts. The dimensions of the servo are 12 x 32x 30 millimeters. This unit comes in a pack of 4 servos giving a unit cost of $2.50. Due to the nature of servos the “step” angle of the motor is 1 degree with the excessive play of this servo being <0.5 degrees with a total control angle of 200 degrees.

Figure 14: 9G Micro Servo Motor

This unit was chosen because of the small form factor, the relative ease of connecting servos to Arduino or Raspberry Pi since there is no need for a driver or ESC. In addition, servos are generally more precise than stepper motors and our group is looking for precision more than anything else. The only concern is that the servo is very small and the diffraction grating that will be rotated by the servo could exceed what the servo is capable of moving.

3.5.12 MG996R 55g Metal Gear Torque Digital Servo Motor

The MG996R 55g digital servo motor is a servo motor with an operating voltage range of 4.8 to 7.2 volts. The dimensions of the servo are 40 x 19 x 43 millimeters. This unit comes in a pack of 2 servos giving a unit cost of $6.50. Since this is a servo the “step” angle of the motor will be 1 degree with the excessive play of this servo being <0.5 degrees with a total control angle of 180 degrees.

This unit was chosen because of servos ease of use with microcontrollers such as Arduino and Raspberry Pi, in addition, this servo motor in particular has a higher torque rating than the previous servo which might be too much, but in this case, there is nothing wrong with more torque.

Figure 15: 55G Digital Servo Motor

3.5.13 Rotation Stage Motor Comparison

All of the rotation stage motor options listed could be used to achieve similar results, however the both the brushless and brushed DC motors do not give us nearly enough precision which is the main goal of the motor choice. Next all of the stepper motors would be great options since they are far more precise than normal DC motors, and they can return to selected positions repeatedly. However, the servos listed give us increased precision at a lower unit price, although the servos will only be able to rotate 180 degrees this is far more than what is required, and the increased precision is what ultimately made us choose servos.

The only difference between the two servos is the amount of torque each produced. We decided on the MG996R 55g Digital Servo since the servo will no doubt be able to rotate whatever we put on the rotation stage and the 9G servo lacked the quality that a larger more expensive servo offered.

	Step Angle (degrees)	Motor Type	Dimensions	Voltage (V)	Cost
Antrader DC Motor Mini	N/A	Brushed	24 x 12 x 7 mm	5	$2.66
Greartisan DC 3V High Torque Speed Reduction Motor	N/A	Brushed	24.2 x 12 x 10 mm	3	$11.99
abcGoodefg 1000KV RC Brushless Motor	N/A	Brushless	27.5 x 27 x 3.17 mm	5	$20.99
Kingroon Nema17 Stepper Motor	1.8	Stepper	42 x 23 x 18 mm	4.1	$7.99
Twotrees Nema 17 Stepper Motor + Stepper Motor Driver	1.8	Stepper	42 x 23 x 18 mm	4.1	$19.99
ELEGOO 28BYJ-48 ULN2003 Stepper Motor	5.625	Stepper	27 x 27 x 18 mm	5	$2.80
Smraza SG90 9G Micro Servo	1 +/- 0.5	Servo	12 x 32 x 30 mm	4.8 – 6	$2.50
MG996R 55g Digital Servo	1 +/- 0.5	Servo	40 x 19 x 43 mm	4.8 – 7.2	$6.50

Table 3: Rotation Stage Motor Comparison

3.5.14 PRMTZ8 - Motorized Precision Rotation Stage

The motorized rotation stage we ended up using for our final design and implementation was the PRMTZ8, which is a precision motorized rotation stage developed by ThorLabs. The reason for the change in rotation stage was that our sponsor, Ocean Insight, wanted a rotation stage that offered more precision than our previously selected digital servo. In addition, our new design only uses one motorized rotation stage, while the diffraction grating now rests on top of a manual rotation stage where the angle of incidence can be chosen. The Thorlabs PRMTZ8 uses a special motor controller called the KDC101 or K-Cube for short. With this motor controller we are able to rotate our stage to any specific angle with an accuracy of 0.1 degrees, which is well within our goal of 0.5 degrees. The K-Cube can also be programmed with MATLAB to incorporate our wavelength from our monochromator and the angle from the rotation stage.

3.6 Optical Elements

The following sections will cover optical elements which efficiently travel through collimating, polarization, beam splitting and diffraction. These elements ensure that the light hitting the diffraction grating is consistent and of the same spot size and polarization every single time.

3.6.1 Collimating Lens

Following the slit in our optical system a collimating lens will be placed with a focal length of 1.5mm. Despite using a laser diode which would maintain a particular level of collimation, the placement of a collimation lens improves the accuracy of the system when considering the light received by the photodetector. In combining the collimating lens, the slit, and the coherent light source, we can ensure that there will be a consistent and steady path of travel for the light on the grating. The lens will be an achromatic doublet to minimize chromatic aberrations in the design of our system. This lens will also be designed in zemax to be perfect for the optical system in use. This lens will also be diffraction-limited to minimize chromatic aberrations due to the wavelength of light. This implies that the wavelength of light will not have an effect on the path or power that travels through the lens and will be consistent throughout the glass.

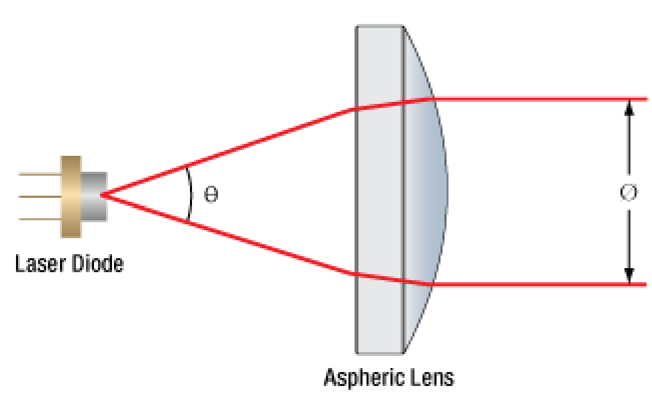


Figure 16: Ray tracing of a collimating lens

3.6.2 Design Of Collimating Lens

The collimating lens in our optical design is crucial to ensure that light travels in a straight and coherent path down the optical axis. The lens in use will have a focal length which is quite short to minimize the travel and collect a higher portion of light from the LED. A collimating lens typically consists of one planar side and a convex side to have all rays traveling parallel to each other through the concave side of the lens. The characteristics of the collimating lens are dictated by several factors. We first want to determine the divergence angle of our beam as well as the beam diameter we want to establish. With this information we can determine the focus of the collimating lens and verify that the lens is in the proper position for the optical system.

3.6.3 Linear Polarizer

The purpose of a linear polarizer is to take light which may have different polarization components, an example of unpolarized light would be sunlight. In the case of a LED, it is possible to be linearly polarized without the use of an external linear polarizer. However, we can not guarantee that the LEDs purchased from the supplier are necessarily perfectly linearly polarized. For this reason, we must make sure that we are maintaining a linear polarization for all four LEDs in the design.

A linear polarizer is essential in the consistency component of our optical design. The linear polarizer will function to ensure that the light traveling through the system will not be affected by polarization dependent losses. This will remain constant to ensure that the only driving factor for efficiency is the grating itself. The polarizer will operate such that in the event that the LED is not perfectly polarized we can ensure that the same linear polarization is incident on the diffraction grating.

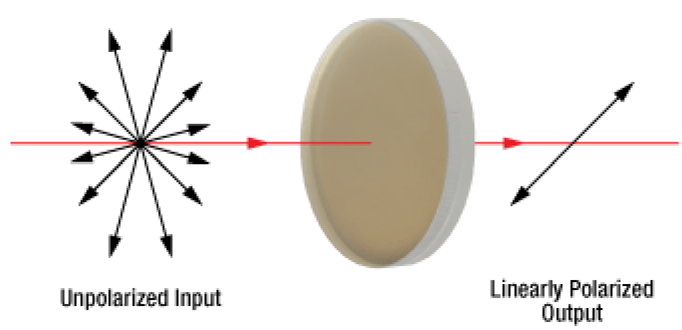


Figure 17: Mechanism of a linear polarizer

3.6.4 Different Types Of Polarizers

The polarizer used in our system will be a linear polarizer which will take our LED light and filter out other polarizations that are undesirable. Similarly there are different types of polarization which were not suitable for our design. The other main type of polarizer is that of a circular polarizer. Circular polarizers are typically used to control reflection from surfaces which is not necessary for the goal we are aiming to achieve.

A similar technology whilst not a polarizer in itself, is a wave plate. This device shifts the electromagnetic wave's phase in such a way that we can achieve different polarization states depending on the amount that is shifted. Similar to the circular polarizer this is not applicable to the scope of our project. Wave plates will simply shift the phase of the wave but not guarantee that all beams are linearly polarized in the same fashion. Quarter and half waveplates do have a variety of other useful applications but do not have a place in our project.

3.6.5 50/50 Beam Splitter

The purpose of the beam splitter is to divide an incident beam into a particular ratio designated by the construction of the beam splitter. For our design, we plan to utilize a 50/50 beam splitter in order to accurately compare the incident beam to that of the beam which reflects from the diffraction grating. Due to the beam splitter's wavelength dependence it is important to have a diffraction grating which is appropriate for the particular range being measured. In our case, we will be using a beam splitter which is apt for 300 - 1100 nm. The beam splitter will additionally be non-polarizing as the beam traveling through the beam splitter will be polarized already so we do not want to affect the polarization of the beam further as this could potentially present issues.

An important aspect of the beam splitter is proper calibration of the listed ratio for the element. Before operation, the ratio must be tested to ensure that there is a 50/50 split between the reflected and transmitted beams as this is crucial to comparing the powers. Comparing the reflected and transmitted power is the foundation of the efficiency measurement. Discrepancies in the ratio could result in either a higher or lower efficiency than what is actually present for the diffraction grating. For this reason, the beam splitter must be calibrated at regular intervals to ensure that the system is delivering accurate results to the user.

An alternative design is possible for the grating system where there is no beam splitter and instead the diffraction grating can be replaced with a mirror. A singular photodetector could collect two individual power measurements, one with the diffracted order as well as one for the mirror. This design was not chosen and the beam splitter took priority as it would require the user to manually replace the mirror or a mechanical system would replace the grating. This would ultimately add to the total cost of the system or add to the amount of manual replacement needed for the grating system to operate. Despite this, a mirror-based design could prove to be more efficient long term as it would require less calibration for the beam splitter but this was not a shortcoming that we felt was necessary to change.

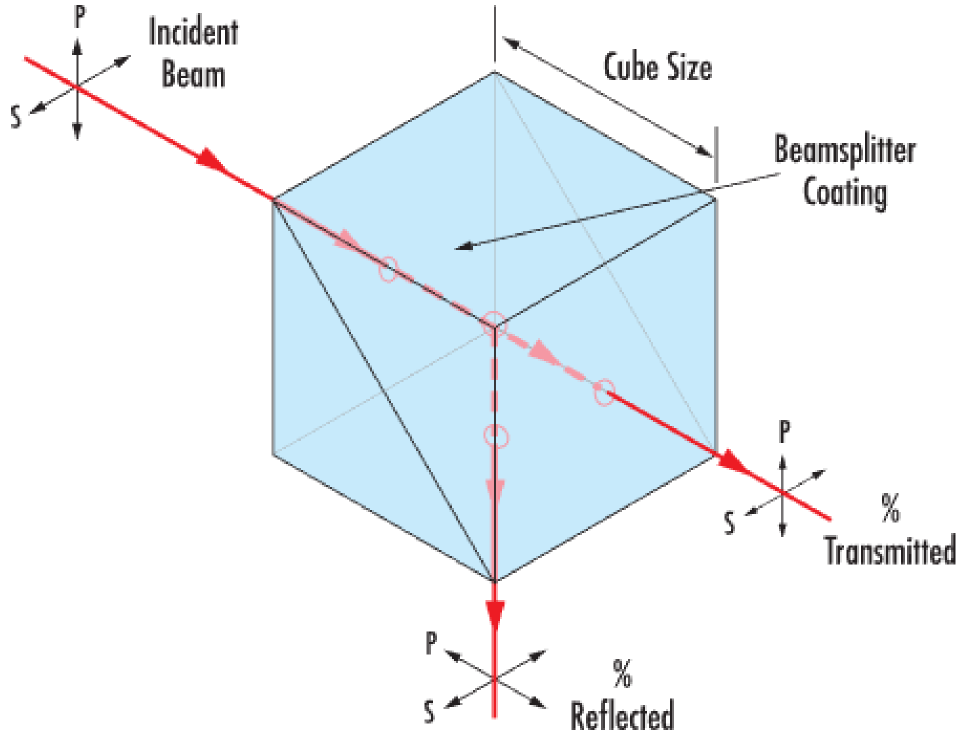


Figure 18: Beam splitter schematic ray tracing

3.6.6 Diffraction Grating

A diffraction grating is an optical element which can separate light into dispersed wavelengths depending on the angle emerging from the grating. The diffraction gratings used in this project will be reflection-based diffraction gratings. This is unlike diffraction gratings which rely on transmission through a series of slits. A reflection-based diffraction grating has many grooves which are coated in a reflective material. The number of grooves in the gratings will determine the amount of diffraction and the wavelength dependency of the element. Additionally, there is a blaze wavelength which is the point at which there is the highest efficiency.

Due to the nature of the element it can be expected that a portion of light will be lost to transmission and reflection after hitting the surface. For this reason, we can define efficiency of the diffraction grating as the fraction of output light diffracted compared to the incident light as a function of wavelength. Diffraction gratings are wavelength dependent so it is incredibly important to take the efficiency measurements at different wavelengths to account for this variability.

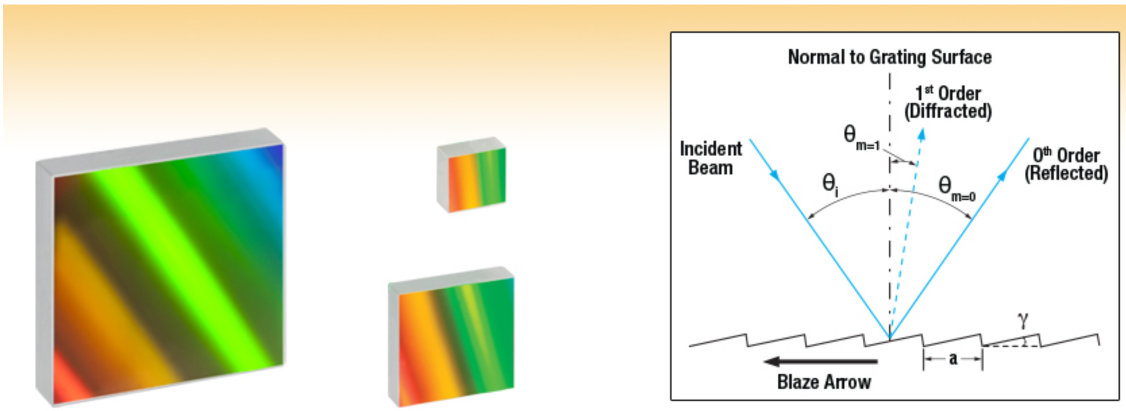


Figure 19: Diffraction grating mechanism for reflection-based gratings

3.6.7 Different Types of Gratings

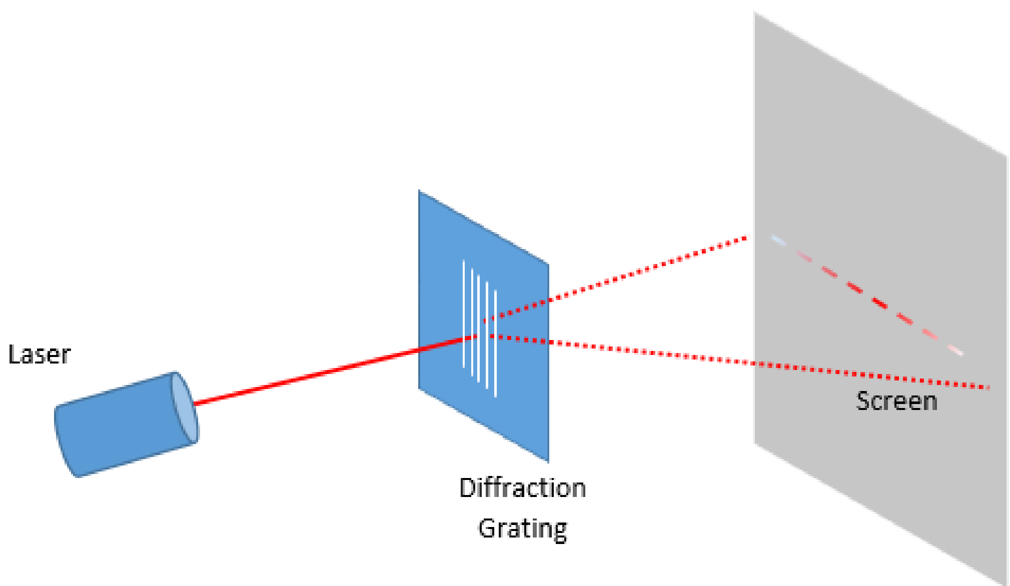


Figure 20: Transmission Grating Schematic

There are several types of diffraction gratings used in optical systems. Because the purpose of our project is to measure the efficiency of gratings used in spectrometers, reflection based gratings will be the focus of our project. Transmission gratings and holographic gratings would not be applicable as they require a much larger distance to travel to observe the first order diffraction, and also do not yield as high of a resolution for spectroscopy applications. Transmission gratings have repeated light and dark lines which cause diffraction through constructive and destructive interference. This results in reflection-based gratings being the primary type of gratings used in spectrometers. Transmission gratings are useful for other applications and still prove to be useful in spectroscopy applications but they require more space to be beneficial in different settings. Our project may be extended to accommodate transmission gratings in the form of a stretch goal. However, the scope of our project will be limited to reflection gratings as it proves difficult on its own to automate for one type of grating. I believe there is a need for transmission grating compatibility that may be expanded upon in the future if we wish to continue further on the design of our project.

3.6.8 Diffraction Grating Efficiency

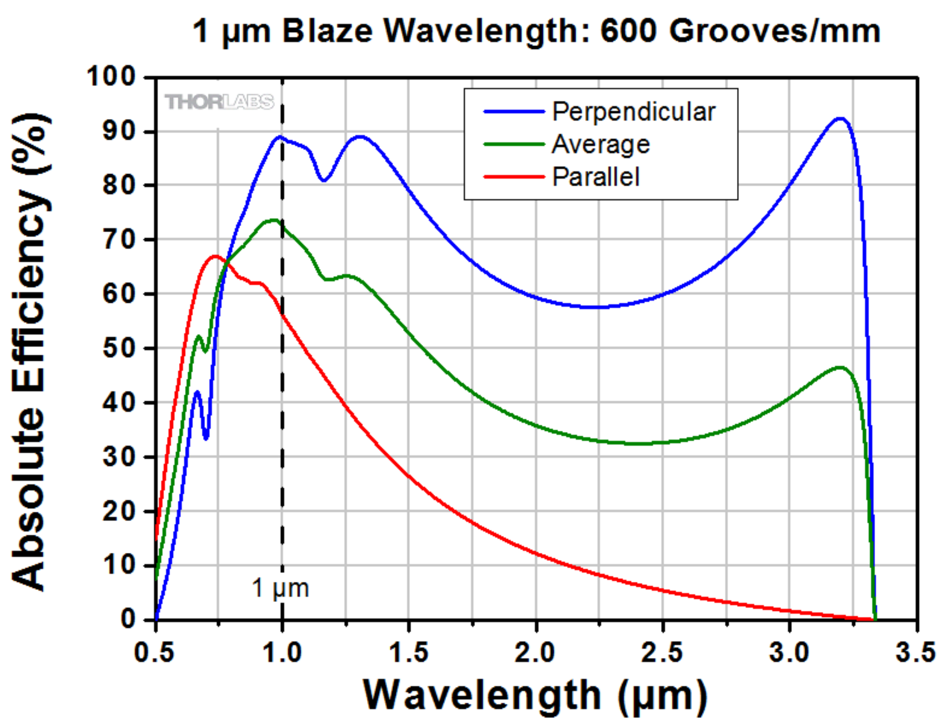


Figure 21: Wavelength vs. Efficiency Graph for Reflection-Based Grating

Diffraction grating efficiency is typically measured through 1nm increments over a particular wavelength range. However, due to price constraints we will not be able to graph nearly as many points as a traditional system. Despite this, we will have an overall idea of the pattern that the grating follows for the efficiency at four different wavelengths. This will provide the user with enough information to make a decision about the general efficiency of the grating. The typical efficiency of a diffraction grating varies from roughly 60-80%. This can change depending on the manufacturing process or the wavelength of interest. Wavelengths which are much longer are more often associated with lower efficiency which is not always true. Depending on the blaze wavelength and construction of the grating, higher wavelengths can also achieve high levels of efficiency. As shown in the figure there is a peak in the efficiency at the blaze wavelength, showing that the blaze wavelength is the point at where the grating shows the highest amount of efficiency. This is important in deciding the grating to use for a spectrometer as it determines what value will be able to output the most power for measurements.

3.6.9 Similar Technologies

Currently there are very few existing technologies that aim to solve the same problem that our project does. However, there are several designs that exist that measure the efficiency of a diffraction grating. These technologies share several things in common, firstly they all rely on the presence of a monochromator which greatly increases the price of the system. Secondly, they use a white light source which only measures efficiency at visible wavelengths. These two differences separate our project immediately from existing designs because our design operates at a larger spectrum as well as being lower in cost. We believe that makes our design the most efficient of the current grating efficiency stations that exist.

Lastly, the semi-automation aspect of our design is novel and incredibly important in the overall design of our system. This allows for quick and easy measurements which allow the user to continue on the work of which the grating is necessary. We believe the ease of access for the semi-automation will ensure that our technology can outlive the competition of existing technologies for an extended period of time to come. Automation for diffraction grating measurement technologies are incredibly hard to come by. A variation of the grating measurement system uses an integrating sphere which can be impractical depending on the application or the budget in question.

Technical Data	
Laser Spot Size	1mm
Input Power	0.1mW
Diffraction Grating	300lines/mm Blazed at 600 nm
Beam Splitter	300-1100nm 50/50 Split
Collimating Lens	AR Coating 600-1100 nm, 1.5mm Focal length
Total System Size	1m x 0.5m x 0.25m

Table 4: Component Specifications

Product Performance	
FWHM of Monochromatic Source	<8nm
Photodetector Accuracy	0.1μW
Photodetector Light Pickup	100%

Table 5: Product Performance Specifications

3.7 LCD Display

For the display of the Semi-Automated Diffraction Grating Efficiency Measurement Station, the display itself has to be easily legible with the ability to fit a graph onto. In addition, the display needs to have a way of displaying user inputs, this could be done via touch screen with buttons on the screen or have a non-touchscreen display and use other tools such as potentiometers to adjust user inputs. The main constraints for the display are that it can effectively display a wide variety of data and can be flexible enough so that if changes to the UI need to occur the display can easily accompany them. The display also needs to be compatible with microcontrollers such as Arduino, Raspberry Pi and Texas Instruments MSP boards.

3.7.1 LCD Display Options

The LCD options we are looking at are 20x4 LCD display, 3.5” LCD display, and 7” LCD display with touchscreen. The 20x4 LCD display will most likely be far too simple and small for use in this project since we would be unable to display something like a graph, or even multiple points of data at a single time. The 3.5” display will likely be sufficient for use but too small to easily read data. The 7” touchscreen display option is looking like the best fit for what our project requires.

3.7.2 WayinTop 20x4 LCD Display Module w/ Serial Display Adapter

The WayinTop 20x4 LCD Display Module comes with a serial interface adapter for microcontrollers such as Raspberry Pi and Arduino. With the use of the included serial interface adapter the display is able to utilize IIC, I2C or TWI. The display size is 20 columns by 4 rows, allowing for a maximum of 80 characters. The working voltage of the display is 5-volts, and the display includes a potentiometer to change the contrast of the display. The display is limited to only displaying characters, letters, and numbers with a unit cost of $11.99. This unit was chosen to display one of the simplest LCD displays which could be

utilized by the group, in addition to its relatively low cost and ease of use.

Figure 22: 20x4 LCD Display Module

3.7.3 HiLetgo TFT 3.5” LCD Display

The HiLetgo TFT LCD display is a 3.5” 480x320 LCD display that is compatible with the Arduino Mega2560. The display itself allows for more complex imaging than the 20x4 LCD previously described, the display operates with a voltage level of 5-volts. The unit cost of this LCD display is $19.99. This unit was chosen since it offers a middle ground between the 7” touchscreen displays and the standard 20x4 LCD displays. This display allows us the ability to display much more data, as well as make it look nicer, but other buttons and potentiometers would need to be set up to change user inputted data.

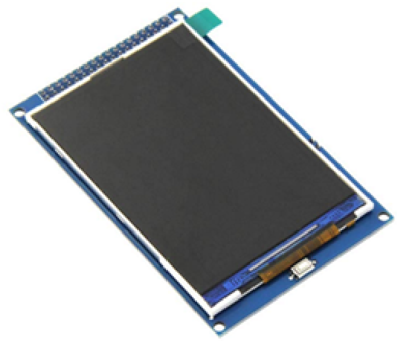


Figure 23: HiLetgo TFT 3.5” LCD Display

3.7.4 Nextion Display 7-inch NX8048T070 Resistive Touch Screen

Figure 24: 7” NX8048T070 Resistive Touch LCD Display

The Nextion NX8048T070 LCD Display Module is a 7” LCD with a resolution of 800x480. This display is compatible with both Arduino and Raspberry Pi making it a flexible option for whichever microcontroller we decide to use. The LCD display operates with a voltage level of 5-volts. The unit cost of this LCD display is $94.98. This unit was chosen since it is larger than the 3.5” display which allows the team to further increase the amount of data and graphics available at a time. In addition, the display is compatible with both Arduino and Raspberry Pi making this a flexible 7” LCD option. Lastly, the touchscreen capabilities will allow the user to easily input necessary data which will be necessary to the project, and much easier and cleaner to implement when compared to extra buttons and potentiometers.

3.7.5 7"Arduino Touch Screen Shield w/SSD1963

The 7” Arduino Touch Screen Shield is a 7” LCD with a resolution of 800x480. This display is only compatible with Arduino and can connect to Arduino Mega, Due and Uno boards. The display operates with a voltage level of 5-volts, with a unit cost of $57.35. This unit was chosen since it was larger than 3.5” which allows the team to increase the amount of data and graphics available to the user at any given time. In addition, if our microcontroller choice was to be Arduino this display would be much easier to set up when compared to the other 7” display. With the addition of a touch screen this display would be the go-to LCD display choice for Arduino.

Figure 25: 7” LCD Touchscreen Display with Arduino Shield

3.7.6 LCD Display Comparison

The display that our group ended up choosing was the 7” Arduino Touch Screen Shield w/ SSD1963. We chose this display over the other 3 due to its compatibility with our microcontroller of choice, the Arduino Mega. In addition the LCD came with a capacitive or resistive touch version, the resistive touch only allows one input to be taken in at a time. For example, if you were to tap the screen with two fingers only one of those fingers touch inputs would register, but with capacitive touch both of those fingers touch inputs would register.

The biggest reason for moving away from the 2004 LCD display module and the 3.5” HiLetgo LCD display was the small screen size. The group was worried that the limited real estate on the screens would make the data and user inputs difficult to read and interpret. The 2004 LCD display also lacked the ability of displaying a large variety of data since the display only consisted of 4 rows. Also the built in touch screen means that we can use this function of the display to input user data whereas if we were to use a different display without the touch screen capabilities we would need to use buttons or potentiometers.

	Display Size	Voltage	Cost	Bonus
WayinTop 20x4 2004 LCD Display Module with Serial Display Adapter	20 columns x 4 rows (80 characters total)	5V	$11.99	Easy to use, compatible with a majority of microcontrollers
3.5” HiLetgo TFT LCD Display	3.5” 480x320 pixels	5V	$19.99	Display a wider range of data and graphics, directly attaches to Arduino Mega2560 board for easy use
Nextion Display 7-inch NX8048T070 Resistive Touch Screen	7” 800 x 480 pixels	5V	$94.98	Display more data and graphics than the 3.5” display, compatible with both Arduino and Raspberry Pi, and has full touchscreen capabilities

7"Arduino Touch Screen Shield w/SSD1963	7” 800 x 480 pixels	5V	$57.35	Display more data and graphics than the 3.5” display, connects directly to Arduino Mega or Due board, and has full touchscreen capabilities

Table 6: LCD Display Comparison

3.8 Lens Adjustments

The lens adjustment of the project will essentially slide the collimating lens forward and backward on a motorized translation stage. This stage allows us to adjust the collimating lens into the right position so that the light is correctly focused.

3.8.1 Collimating Lens Translation Stage

The collimating lens translation stage of the Semi-Automated Diffraction Grating Efficiency Measurement Station will be in charge of sliding a collimating lens backward and forward along a path. For this to work properly we need there to be no side-to-side movement in the platform the collimating lens will be on, the goal is to only have one dimension change on this stage. To do this we will need to use a linear translation stage, and since we want everything to be automated, we need the stage to be motorized. Ideally the collimating lens will be able to be adjusted by 10 centimeters, 5 one way and 5 the other, so at a minimum our travel length will need to be 100mm, but ideally a larger length would be preferred. In addition, the group wants the positioning of the collimating lens to be precise to within +/- 0.5 mm of the target location.

3.8.2 Befenybay 100mm Linear Stage Actuator

The Befenybay 100mm Linear Stage Actuator is a linear motorized translation stage that is guided by a large screw that goes through the stage. The motor used to traverse the rail guide is a NEMA17 stepper motor which was looked at in the previous rotation stage. For the application of this portion of the project a stepper will be the best motor option since we will be turning a screw which can only be done with continuous rotation, and our pick for the rotation stage was a servo which only allows a limited turning radius. The key factors here are the repeat positioning accuracy and the length of the rail which are +/- 0.03mm and 100mm respectively, both of which meet our criteria for the translation stage. The unit cost of this motorized linear stage is $68.80.

Figure 26: 100mm Linear Stage Actuator

3.8.3 Befenybay 150mm Linear Stage Actuator

The Befenybay 150mm Linear Stage Actuator is an exact replica of the Befenybay 100mm Linear Stage Actuator except for the fact that the rail length is now 150mm rather than 100mm. This motorized translation stage was chosen because it gives the group a second option length in case the collimating lens needed to be adjusted by more than 10cm, in this case we could adjust the lens up to 15cm which would be more ideal because of the flexibility it gives the group. The only issue for both of these stages is that they do not come with a motor driver to connect to the microcontroller, so if either of these is purchased a separate stepper motor driver would need to be purchased. The unit cost of this motorized linear stage is $73.80.

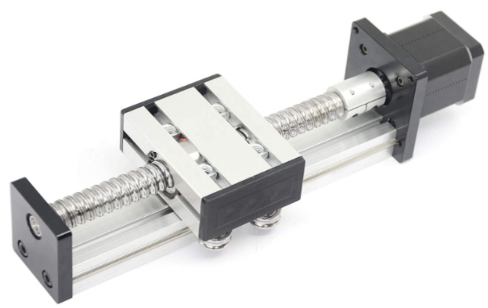


Figure 27: 150mm Linear Stage Actuator

3.8.4 Newport ILS150BPP

The Newport ILS150BPP is a motorized linear stage that is 150 mm long which uses a stepper motor to control the platform on the rail. This motorized linear stage also uses a stepper motor to accurately guide the stage up and down the screw, but this product has something called micro-stepping, which allows the users to further divide the normal steps of the motor into much smaller steps which will create an even higher level of accuracy. Rather than the standard stepper motor being about 64 steps per revolution the 'rotary encoder' used in this product allows us to go up to 4000 steps per revolution. This of course means that our accuracy margin is much better and thus the accuracy of this stage is about +/- 2.5μm, which is over 10 times more accurate than the other options we have looked at. The power consumption of this unit is 40 watts with a unit cost of $4,905.

3.8.5 Translation Stage Comparison

	Rail Length	Motor Type	Positioning Accuracy	Cost
Befenybay 100mm Linear Stage Actuator	100 mm	Stepper	+/- 0.03 mm	$68.80
Befenybay 150mm Linear Stage Actuator	150 mm	Stepper	+/- 0.03 mm	$73.80
Newport ILS150BPP	150 mm	Stepper	+/- 0.0025 mm	$4,905

Table 7: Translation Stage Comparison

The Newport ILS150BPP is a fantastic motorized linear stage, but due to its quality the product is over-qualified for what we need from it. In addition, the price of the Newport ILS150BPP is way outside of our price range and would only need to be used in a setting that needs more precision and repeatability.

Since all of these linear stages use a stepper motor to control their stage's positioning, a motor driver will be needed to fully incorporate these motors with the Arduino board of choice. Since these motors take more voltage than the Arduino can supply an external power source will also need to be implemented to power the motors.

Since the only difference between the two Befenybay linear stages is simply the rail length and everything else matches the project perfectly, the group has decided to choose the 150mm length variant. The reason for this is the added flexibility that a larger rail will give us, while also retaining the same precision needed, the price increase is not a huge factor as $5.00 for extra security is a necessary trade off.

3.8.6 Translation Stage Design Decision

In the updated design of our project the need for a motorized translation stage was no longer needed. Instead of a motorized rotation stage a fixed position beam splitter was put in place so that our beam of light was split between our first photodiode and the rest of our system.

3.9 Photodetector

Figure 28: Photodiodes

To begin with, a photodetector is essential to measuring wavelengths produced by a light source. As a result, we are going to use two photodetectors for the grating station. Two photodetectors will measure the wavelengths produced by the light source of our system. The photodetectors can be placed at any desired angle, as long as it is in contact with the grating system. The photodetectors will be able to measure the intensity of the input power and the power of the diffracted signal. We are using the photodetectors to compare these measure values.For our research work, we are investigating four types of photodetectors, and the noise effect.

Photodetector can be defined as a device that transforms optical signal into electrical signal. In the field of optic, a detector or a photodetector is the first stage communication of a system. Most modern photodetectors are operating with electrical response by converting photons into a charge carrier and producing a change in voltage or current in electrical circuits. Photodetectors have a wide range of applications in both industry and our daily lives. Including environmental monitoring, machine vision, cell phone camera or convenient devices that we use typically. Another aspect of photodetectors is that it converts an optical signal into a signal of another form. In the field of optic, the electric signal produced by the optical signal can be a photocurrent or a photovoltage which is proportional to the power source carrier by the optical cable. According to research, there are many types of photodetector out there but we are focusing on two classes of photodetector which we might use base on our project desires, and we also want to elaborate on four other photodetector we might possibly use one of base on type, speed, efficiency and also price. Moreover, we will discuss what they are and how they practice, and similarly the noise effect.

In the same fashion, as we mention, there are two classes of photodetectors which are Photon detector and Thermal detectors. The difference between these two are speed, type, efficiency, noise arising and response time. In addition, because of the photoelectric effect, a photon detector can be known as a quantum detector because it can convert a photon into an emitted electron or an electron hole pair. On the other hand, thermal detectors are based on photothermal effect, meaning it can convert optical energy into heat. According to research, the response of a photon detector is a function of the optical wavelength.

3.9.1 Noise

Photodetectors also produce various kinds of electronic noise that can attenuate the output signal. In addition, the noise can be generated externally or internally by fluctuations in voltage or current due to various statistical processes. Second, the noise current determines the minimum or the maximum optical power level that can be detected which defines sensitivity of a photodetector.

When it comes to noise, there are three different types of noise that play a major part in photodetectors. The three main types of noise due to spontaneous fluctuations in optical fiber communication systems. The noise can be defined as thermal noise, shot noise, and dark current noise. Moreover, due to the nature of the noise and the best way to specify them is to use statistical value. Below we are going to look at how the configuration of the noise and how are they different.

3.9.2 Thermal noise

In every electrical circuit, thermal noise is always present due to vibration of the charge carrier within an electrical conductor and is also proportional to the temperature no matter what type of source voltage or current that it is being fed. Because of that, it is nearly impossible to get rid of thermal noise, however it can be reduced by lowering the temperature of operation or reducing the value of the resistance in such a design or circuit. Thermal noise can also be categorized as white noise, figure 25 below demonstrates some of the characteristics that are expressed in time domain.

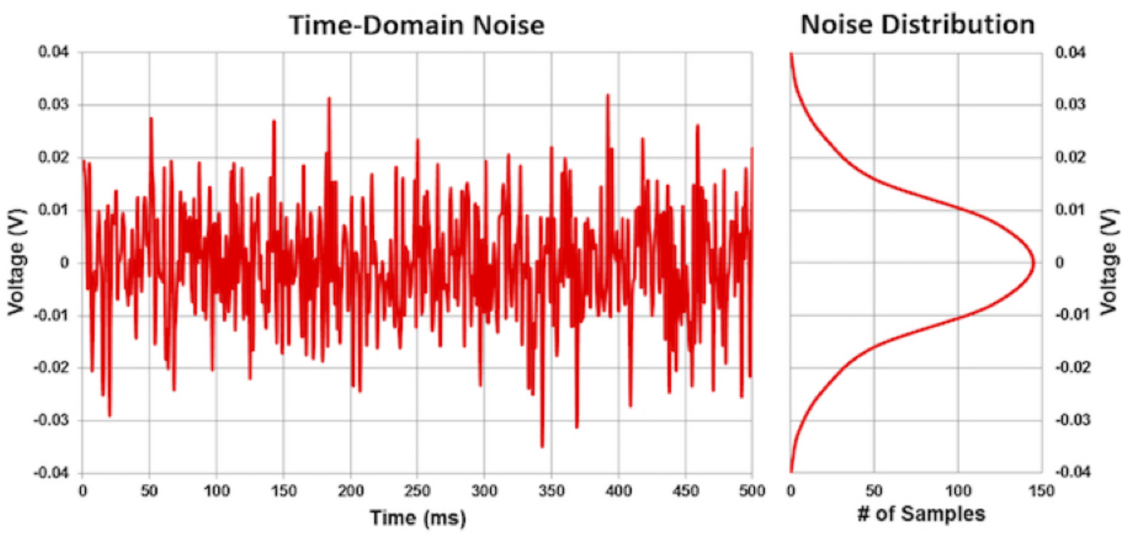


Figure 29: Thermal Noise Measurement

3.9.3 Shot Noise

Shot noise was discovered 100 years ago in vacuum tubes. Shot noise is dependent on a number of factors.These factors can include sensor size and gain. In a fiber communication system, the shot noise can vary based on input system power.

3.9.4 Dark Current Noise

Dark current noise is when there is no optical power incident on the photodetector, a small reverse leakage current still flows from the device design system terminal.

3.9.5 Types of Photodetectors

When it comes to photodetectors, there are many types out there in the market, but each of them is working over the same basic principles; in order words, they provide the same technique but in a different way depending on how they practice. Below we are demonstrating the type four most commonly used in modern technology or in the field of optics also infrared.

1. P-N Photodiodes
2. PIN photodiodes
3. Avalanche Photodiode
4. Schottky photodiode

3.9.5.1 P-N Photodiodes

This device is a form of light sensor that converts light energy into electrical energy (voltage or current).

Structure of P-N photodiode:

P-N Photodiode is a type of semiconductor device with PN junction which has positive (p) and negative (n) layers. The gap in the middle is called the depletion regions which consist of holes or protons.

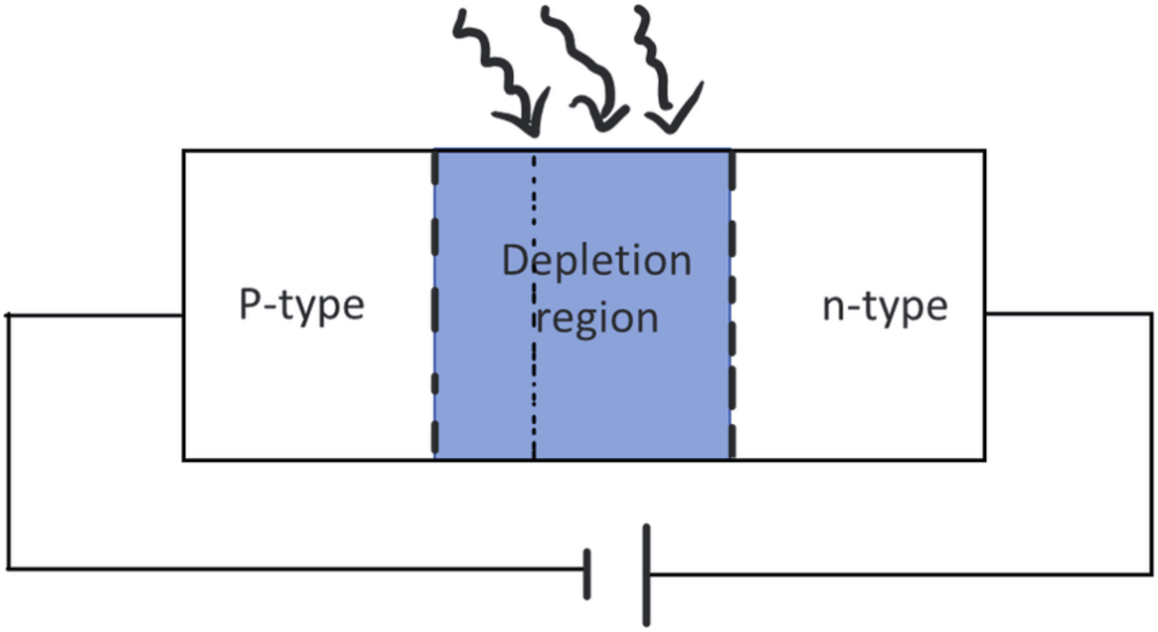


Figure 30: P-N Photodiode

Working conditions:

This photodiode is sometimes called photodetector, light sensor, due to it consuming light energy to produce electric current. Moreover, it is designed to work only in reverse bias condition. Figure 26 shows a basic prototype of PN photodiodes which display that the P side is connected with the negative terminal of the battery and the N side is connected with the positive terminal of the battery.

3.9.5.2 PIN photodiodes

This photodiode can be found in many modern applications nowadays. It is basically collecting the light photons more efficiently than the PN photodiodes.

Structure of PIN photodiode:

As the name indicates, this diode has an intrinsic layer that is sandwiched between two highly doped p type and n type layers. In addition, it give performance improvement compare to p n diode, and the layer has higher resistivity ranges from 10 to 100 kh/cm

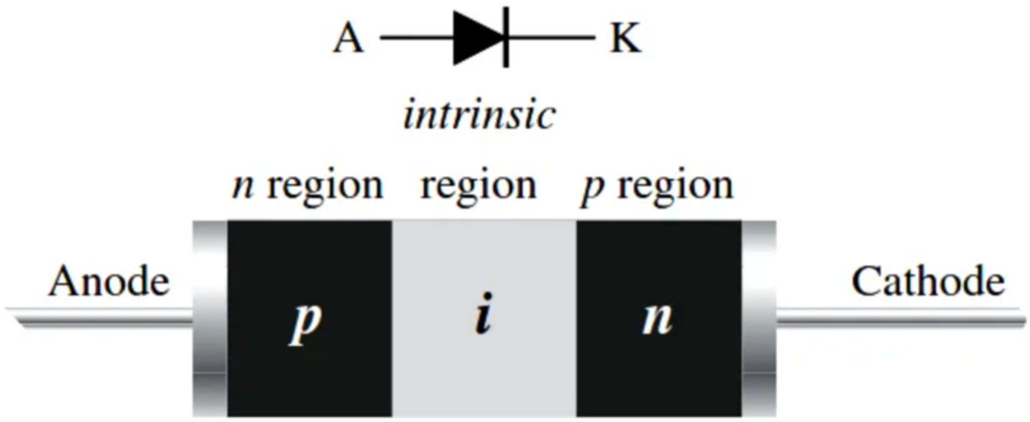


Figure 31: PIN Photodiode

Working conditions:

Figure 31 illustrates the Pin diodes that are separated by the intrinsic region. However, this device works both forward and reverse bias; in forward bias mode, the pin region acts like a resistor and in reverse bias mode the pin region acts like a capacitor.

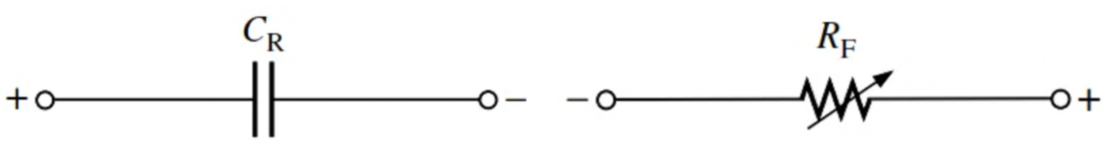


Figure 32: PIN Diode in Reverse (left) and Forward (right) Biased Mode

3.9.5.3 Avalanche Photodiode (APD)

PIN	APD

Between the two highly dope regions, there is an undoped intrinsic layer	Layer is placed between p and n regions
Does not have high intensity electric field	Has high intensity electric field region
Photocurrent generated less	Photocurrent generated is more as compared to PIN
Responsivity of PIN is limited	Responsivity of APD can have much higher values
Good temperature stability	Poor temperature stability
Response time of PIN is half of the APD	Response time of APD is almost double than PIN
Low reverse bias required	Higher reverse bias is required at all time
Sensitivity is less	Higher sensitivity

Table 8: PIN vs APD Photodetector

This device provides extreme performance, it is similar to both PN and PIN devices. The difference is that it works in a higher reverse bias condition that is enabling many holes and electrons. Avalanche photodiodes (APDs) are most commonly used for single photon detection, "because they are simple robust semiconductor devices with high detection efficiencies and low dark count noise". Kardynal (14). Another key aspect of APD is that it can detect low levels of light and have very fast response times. Moreover, APD are available from a few hundred um to 16 mm in active diameter. Below, we are going to look at the comparisons of photodetectors of PIN vs APDs.

3.10 Power Supply

To begin with, the electronics chips in our design have some sensitive parts that include photodiodes, microcontrollers, and rotation stage motors. For this reason, the components require constant voltage for their operation. If the supply voltage is not stable our system will not operate and we will end up with component failure. In addition, for the spectrometer grating station, we are going to use a voltage regulator so that our component doesn't burn out due to voltage fluctuations. In the world of electronic circuit design, selection of the right voltage regulator is one of the most important decisions. Every product that runs on Dc power employs voltage regulation, so what is a voltage regulator?

3.10.1 Voltage regulator

VLR	Input Voltage (Max)	Input Voltage (Min)	Output (Voltage)	Input Current (Max)
LM2937(-3.3-2.5)	26	4.8	3.3-2.5	1A
LM7805/LM2673T-5	20	7	5	1-2A
LM7806	21	8	6	1-2A
LM7808	23	10.5	8	1-2A
LM7809	24	11.5	9	1-2A
LM7810	25	12.5	10	1-2A
LM7812	27	14.5	12	1-2A
LM7815	30	17.5	15	1-2A

Table 9: Voltage Regulator Comparison

As the name indicates, a voltage regulator takes variable or unstable input voltages and converts them to higher or lower constant output that matches the voltage and current needs of an electronic circuit. In modern electronics devices, the most commonly used voltage regulators are LM7805, 7806, LM7808, LM7809, LM7810 LM7812, LM2X and LM78X. The difference between these regulators is that they provide different output desired voltage. In addition, we are going to use the LM7805 to provide power to our "Semi-Automated Diffraction Grating Efficiency Measurement Station".

We choose the LM7805 Linear regulator because it will provide our desired output voltage which is 5V Max. When using the LM7805, during operation, it is dissipating a lot of heat which sometimes causes the chip to burn out. The only way to fix this is to reduce the input voltage or use a proper heat sink to lower the temperature. For our system, we will use a less than 13 volts input battery. After testing we might not need a heatsink to lower the temperature due to our input voltage being low. Table 8 above demonstrates the voltage linear regulator used based on output voltage needed. The last digit of the voltage regulator number indicates the output voltage. […

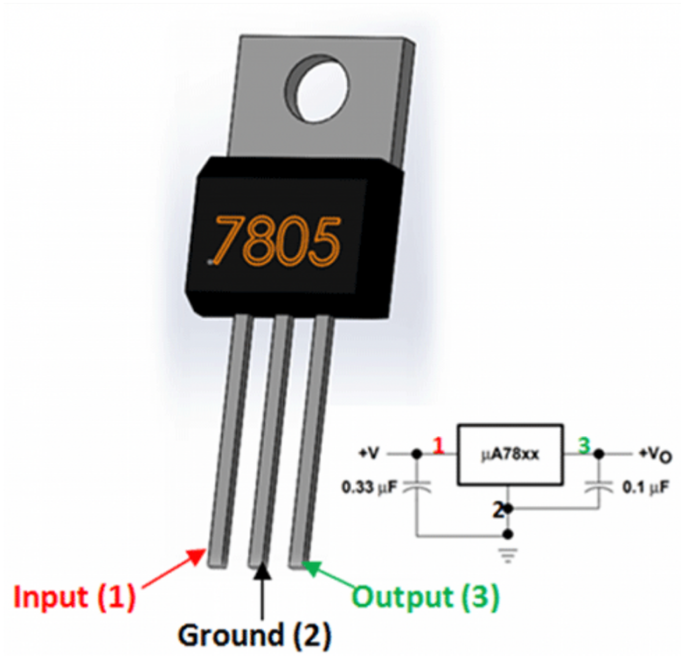


Figure 33: Voltage Regulator (VLR)

Initial design:

To start off, we are going to focus on the LM7805, and define the working condition of how it works, and also elaborate on different types out outhere in the market. Figure 31 displays an LM7805 voltage regulator consisting of 3 pins. Pins 1 provides input unregulated voltage, pin 2 provides the reference ground and pin 3 provides the output regulated voltage. For best results, a capacitor is required in both input and output. The input capacitor is required if the regulator is far from the filter supply. The capacitor helps to smooth out interruptions to the supply and also low frequency distortions.

Final Design:

Due to parts that are unavailable, we could not come up with the linear regulator design, instead we end up designing a buck switching converter that will deregulate the 12 volts battery to 5 volts to power the PCB. The buck switching converter is more complex to design and it is more efficient and it also does not require a heat sink. Below is the final schematic of the buck Switching converter. To design the Buck Switching converter, we referred to ti.com. In the schematic below, we added a switch that will turn the power on and off. This final schematic will be added to the overall schematic.

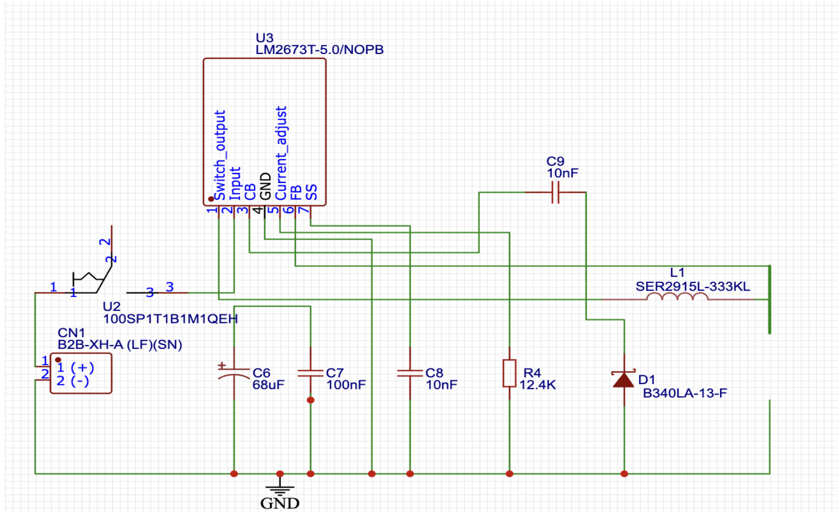


Figure 34: Buck Convertor Schematic

3.10.2 Types of Voltage Regulators

There are two types of voltage regulator. Each working over the same basic principles but in a different way.

1. Linear regulator
2. Switching regulator

3.10.2.1 Linear Regulators

Linear regular is much simpler to design than switching regulators and it's easier to mount on a breadboard; it also dissipates a lot of heat.The power supply has a closed negative feedback loop. This feedback loop holds the output voltage at a constant value. Engineers often used the linear regulator because it is simple and low cost compared to switching regulators that are extremely difficult to design and super expensive nevertheless the linear regulator is not efficient.

Linear regulators are sometimes called step down regulators due to the input voltage source must be higher compared to the desired output voltage. In addition, there are two types of linear regulator. The shunt regulator and the series pass regulator. The shunt regulator is placed in parallel with the load. Moreover, the series pass regulator uses an active semiconductor as the series pass unit between the input source and the load, therefore; it is more efficient.

How a linear voltage regulator works:

As can be seen in Figure 33 below, the applied voltage goes on one side and a desired smaller voltage comes the other. The circuit has two coupling capacitors due for low frequency distortions, and to smooth out interruptions. For example, if we use a 12V+ battery base on the regulator calculation, we will end up with 5V+ constant output voltage.

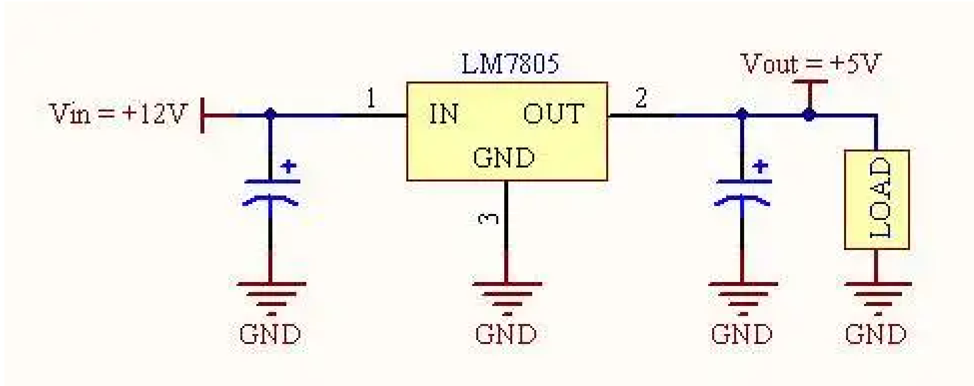


Figure 35: Linear Regulator Circuit

3.10.2.2 Switching Regulator

In the same fashion, the switching regulator can be built with a Bipolar Junction Transistor (BJT) or a Metal Oxide Semiconductor Field Transistor (MOSFET) transistor which then operates as a switch. As we mention in the previous section, switching regulators is more efficient, expensive, and complex to design. Moreover, during operation, the switch produces voltage change which generates ringing that causes a noise in the output voltage, that is one of many reasons why engineers use the Linear Voltage Regulator more often.

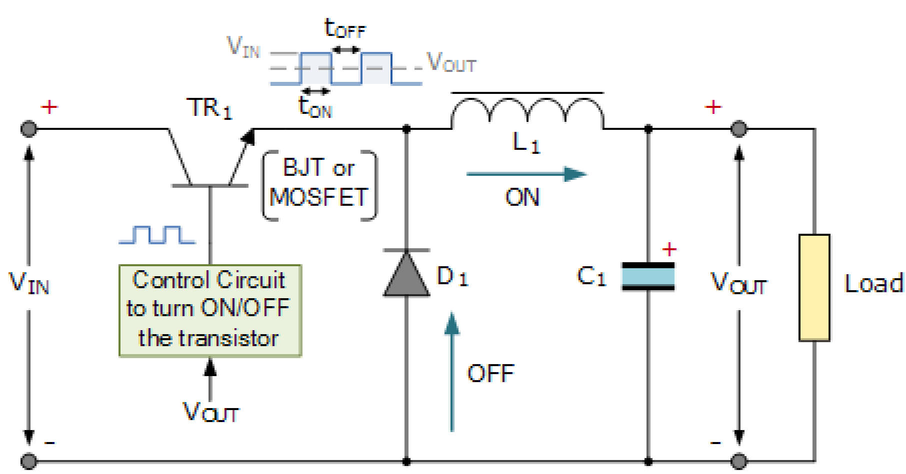


Figure 36: Switching Regulator Circuit

Linear Voltage regulator	Switching regulator
Simpler/ design flexibility	Complex
50%	100%
($40-50$)	($300-500)
1-2dB	10dB

Table 10: Linear Regulator vs Switching Regulator

3.10.3 Battery

Battery is one of the most essential pieces used in modern electrical devices, imagine the world of portable electronics today without a battery. The mobile world depends on batteries every day. “Last year consumers brought five billion li-ion cells to supply power hungry laptops, cameras, mobile phones, and electric cars”.[8] The battery is so important to electronics devices, it is like people who cannot live without water. To put this in another way, let’s follow along and see how a battery works.

How does a battery work?

A battery consists of five components Anode, cathode, separator, electrolyte and collector.The anode always places on the negative side of the battery whereas the cathode is placed on the positive side. The electrolyte is a liquid that reacts with the anode and cathode, when connecting a circuit into the battery, a chemical reaction occurs between the anode and electrolyte. This reaction produces electrons in a process known as oxidations. At the same time another process occurs between the cathode and electrolyte and this reaction requires extra electrons and is known as reductions. In order for the reactions to happen, electrons from oxidation need to move to the reductions. The chemical in the battery ultimately will reach a state equilibrium, and will not react between the cathode and the anode. When that happens, the battery is considered dead.

3.10.4 Types of battery

There are two types of battery which are primary and secondary. The difference between these two is that primary batteries are not rechargeable whereas secondary batteries are rechargeable. According to research, each of these two batteries have their own pros and cons. Therefore, in the next

sections, we are going to look at the distinction between these batteries, and see how they work.
Primary Battery:

There are many types of primary battery out there in the market, some of the most used are Alkaline and dry cell. These batteries are one time use and cannot be recharged, therefore, they need to be thrown away. Alkaline and dry cell batteries are extremely important to today's electronics devices around the world.

Secondary battery:

As we mention in the previous section, secondary batteries are rechargeable, this type of batteries are in mostly use in modern electronics devices that include cell phones, laptops, iPads, cars, and etc.
Type of secondary batteries:
According to research, there are four types of secondary batteries, the list are

1. Lithium ion batteries
2. Lead acid batteries
3. Cadmium batteries
4. Nickel Metal Hydride

3.10.4.1 Lithium Ion Batteries

Rechargeable lithium batteries have developed into the dominant energy source for portable electronic devices because of their high energy density. As we know energy storage is more important today than ever, due to portable devices that are more evolving. According to research "Lithium ion batteries have aided the revolution in microelectronics and have become the choice of power source for portable electronic devices.". [25]. Let's take a look at how Lithium batteries work.

Lithium ion batteries consist of four components which include cathode, anode, electrolyte, and separator. The difference between the anode and cathode is that cathode is made with metal oxides phosphate whereas anode is made with graphic materials. According to research, the cathode and anode have different chemical potentials separated by a separator. The electrons flow from the anode to the cathode during discharging. Now we are going to look at the advantages vs disadvantages of Lithium Ion Batteries. When it comes to lithium ion batteries, there are some advantages that make them more phenomenal. Below is the list of type 5 of reasons.

- Lithium ion batteries have higher energy density compared to other rechargeable battery systems such as Liad Acid, NICD, and NIMH. Moreover, it has long cycle life and extended shelf-life maintenance free.

- The most important aspect of a Lithium ion battery is that it has a simple charge algorithm and a reasonably short charge time.
- When it comes to the Lithium ion battery, it is smaller and lighter, it has no Lithium metal exit.
- Lithium ion battery have low self-discharge (less than half that of NICD and NIMH)
- Another advantage of a Lithium ion battery is that when it is used correctly, it has a long lifespan.

Now let's take a look at some of the most disadvantages of Lithium batteries.

- The most sensitive part about this battery is that it requires a constant protection circuit to prevent thermal runaway if stressed or overcharge.
- Lithium ion batteries cannot store at a high temperature, if that happens then it will degrade.
- When it comes to disadvantage lithium batteries are far more expensive than lead Acid counterparts per average.
- Safety concerns are a big problem, because lithium batteries can overheat, leak, burst, and even explode which can cause serious injuries.
- The last disadvantage of LIB is that transportation regulation is required when shipping in larger quantities.

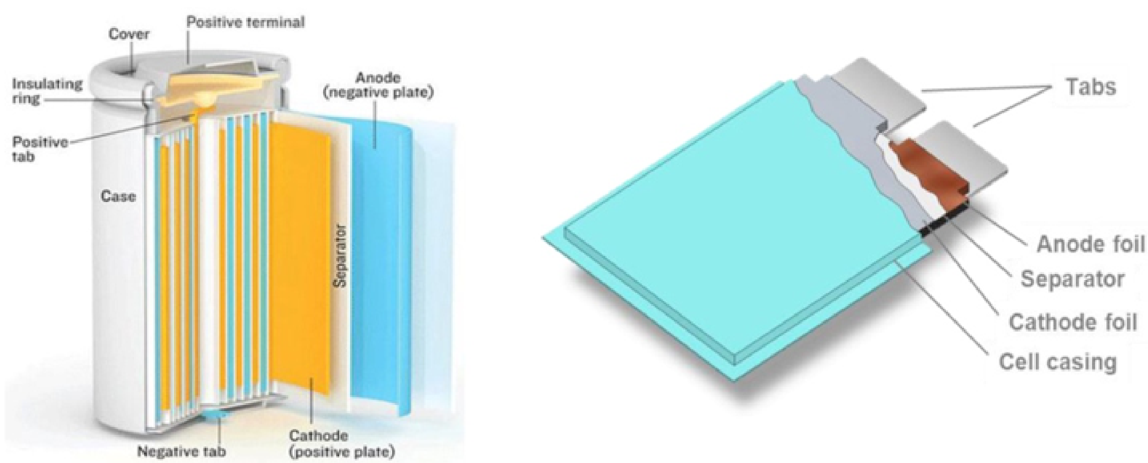


Figure 37: Lithium Battery Composition

3.10.4.2 Lead Acid battery

Lead Acid batteries are low cost secondary electrical power sources invented 118 years ago. Despite new batteries emerging as competitions, it has still not been dethroned as the most single use battery system in the world.

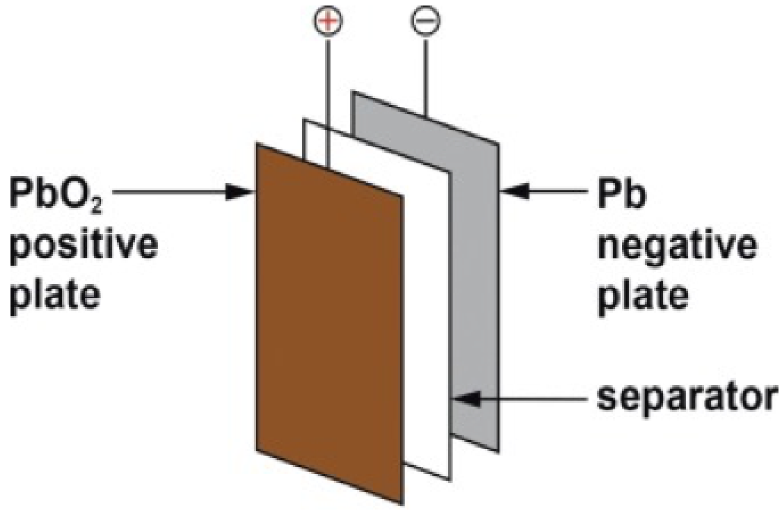
“Today, hundreds of millions of lead-acid cells are in use for starting automobiles, to power electric fork-lift trucks, for delivering emergency electric power, for transmitting and signaling operations in telephone central offices, for railway car lighting, for starting diesel engines, to name a few of the more important applications” [16]. Below we are going to look at some advantages vs disadvantages of Lead Acid battery.

Advantages of Lead Acid Battery.

- One of the major advantages of Lead Acid batteries is the low cost.   It is low cost per watt hour
- Low internal resistance
- When it comes to size, it has wide range of size and capacities are available
- The most important aspect of Lead Acid battery is that it performs well in low temperatures.

Disadvantages:

- Lead Acid battery is slow charge, takes up to 17 hours to fully charge. Moreover, if having greater size, it would take 2x 17 hours to fully charge up.
- Lead Acid batteries must be stored in charge state once electrolyte has been introduced to avoid deterioration of active chemicals.
- Lead Acid batteries need constant attention in high temperatures to avoid thermal runaway.
- When it comes to lead Acid battery it is very bulky, heavy and does not last long. In addition, it needs to be replaced every 3-5 years depending on type.
- Another aspect of lead Acid battery is that it contains toxic material which is a major challenge for the environment.



$$Pb + PbO_2 + 2H_2SO_4 \rightleftharpoons 2PbSO_4 + 2H_2O$$

Figure 38: Lead Acid Battery Composition

3.10.4.3 Cadmium Battery

As we mentioned above, Cadmium battery is another secondary battery that is widely used in modern electronics devices. Nickel Battery is workable despite what weather you're in. It functions properly, saves consumers a lot of money, and is easy to store. These batteries have a lot of benefits but let's take a look at below some benefit such as top five advantage vs disadvantage

Advantages:

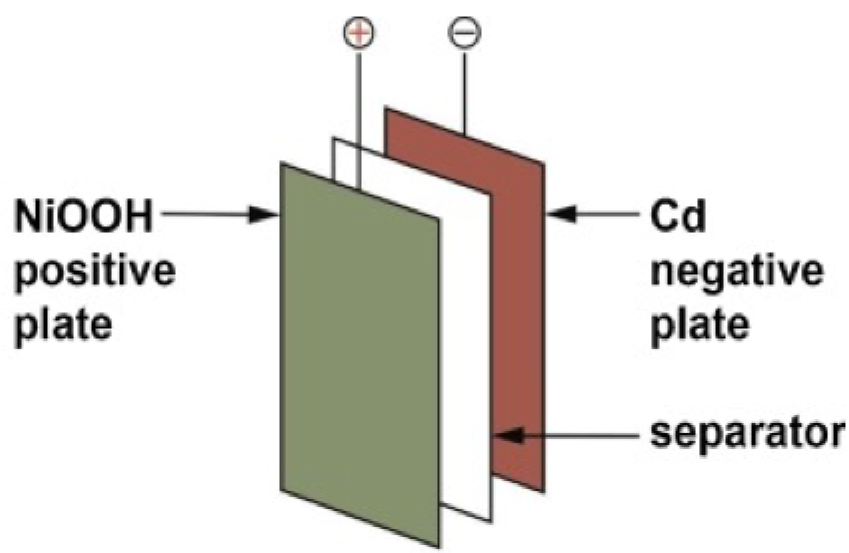
- When it comes to advantage Nickel cadmium battery, these batteries can withstand inner pressure and are inert to external damage.
- When these batteries store, then they stay as it is and undergo no deterioration. Even in discharged condition, no loss occurs and their physical composition does not change. Moreover, these batteries will be harmed if they completely discharge.
- As we mentioned above, Lead Acid batteries need a lot of care when deep discharge is taking place; however, that is not the case with Nickel-cadmium batteries. This is because the metals that this battery contains in the electrolyte are inert.
- Another aspect of Nickel cadmium battery is that it is capable of high rate charge and rate discharge.

- Last point of advantage, when Nickel cadmium batteries charge, they do not omit oxygen and hydrogen. Anyone can charge them many times, approximately for around 500 times.

Disadvantages:

When it comes to disadvantages there are many factors, which is very significant when comparing to other batteries such as the list that we have mentioned above. Therefore, below is the list of disadvantages.

- According to research, when it comes to Nickel Cadmium batteries, however, it has its limitations. For instance, the batteries need to be completely discharged often so that they work to their full potential. Plus, cadmium waste is hazardous, and these batteries can therefore not be thrown in landfills or with garbage waste. Their environmental impact is a challenge and very bad.
- One of the major disadvantages is that these batteries cannot be left in storage, if it happens then it will get completely discharged and need to be charged again from the beginning.
- At high temperature, it provides poor performance
- These batteries are unfriendly environment and problematic
- Last point of disadvantage is that these batteries are toxics and restricted in European Union Country



$$Cd + 2NiOOH + 2H_2O \rightleftharpoons Cd(OH)_2 + 2Ni(OH)_2$$

Figure 39: Nickel Cadmium Battery Composition

3.10.4.4 Nickel Metal Hydride (NiMH)

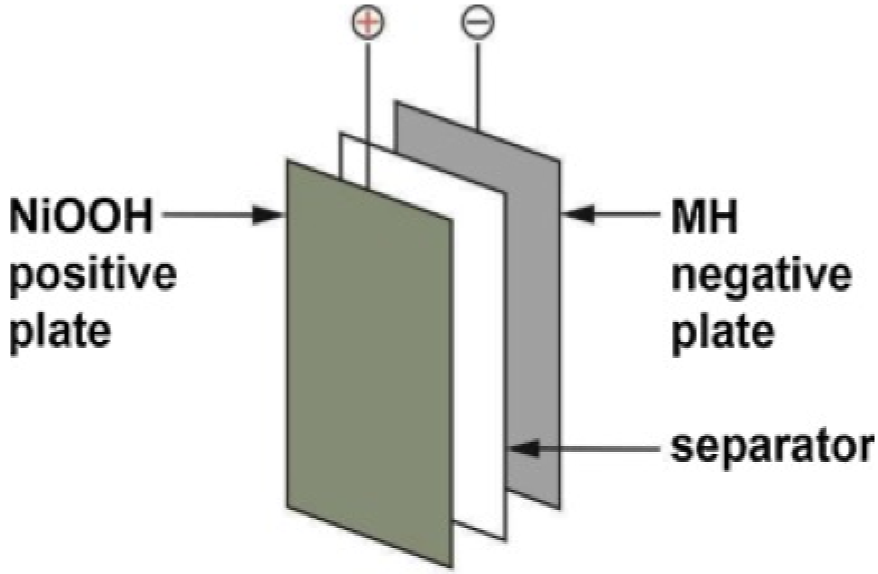
As we have mentioned above NiMH is a secondary battery, meaning it is rechargeable. According to research, NiMH batteries can substitute for nickel cadmium (Ni-Cd) batteries cell for cell with almost indistinguishable voltage characteristics but provide 25-40 percent more energy and are free of environmentally undesirable cadmium. NiMH batteries offer excellent cycle life of more than 500 cycles. Now let’s take a look of the NiMH advantage vs Disadvantage

Advantages of NiMH:

- NiMH have high cycle life, no pollution resistance to overcharge and over discharge, and high recovery value.
- When it comes to NiMH, it is Environmentally friendly, low internal resistance and higher energy density (wh/kg)
- NiMH performs well in low temperature, the inorganic electrolyte system is used, and the low temperature is better than lithium batteries.

Disadvantages of NiMH::

- NiMH material costs are high, a large number of relatively precious metals such as nickel and cobalt are used in nickel-hydrogen batteries which makes the cost of the battery raw materials relatively high.
- At high temperature, the charging efficiency decreases and the decrease in reaction efficiency pushes the battery temperature to rise further. Eventually runaways may occur and also safety issues may arise.
- NiMH energy batteries are generally lower in the range of 50~ 70Wh/kg. Although it is 2 to 3 times that of lead acid batteries, compared with lithium batteries it is significant.



$$MH + NiOOH \rightleftharpoons M + Ni(OH)_2$$

Figure 40: Nickel Metal Hydride (NiMH)

After consideration, we choose to use NiMH as the battery that will power our semi-automated distraction grading efficiency system. With all the positive and negative aspects, we mentioned above, we conclude NiMH is our best option.

Charging:

When it comes to charging, charging a battery is one of the most important aspects of any design. Correspondingly; in our design, we want our battery to power efficiently. Our NiMH battery will have a charger. The charger is needed when the battery is low. Below is a picture of a 12v NIMH.

Figure 41: NiMH 12 Volt Battery

For figure 38,

- Tenergy's 12 volt made of features a 2000mAh capacity rating
- This Battery is compatible with most hobby units such as lightweight RC planes (Wattage, Higher, JR and Futaba) and RC cars. Dimensions 50x29x72mm with bare leads.
- No memory effect which helps retain its max energy capacity despite recharges and discharge
- This 12 Volt battery NiMH features rapid charging, long life.

Table list of needed components to build the circuit.
To fill in this table below, we are using the UltraLibrain to find the parts that are needed.

Component	Description	Qty	Part Number
J1	Switchcraft 722A Straight DC Power Jack - 0.080Inch (2.0mm) pin -	1	722A
SW1	Switch SPD/Toggle	1	2-1825138-8
D1	TBD	1	TBD

D2	Diode, Schottky Barrier, Vr 40V, If 1A, Pkg CASE	1	1N5819G
C1	Capacitor, Ceramic, .1uF, 50V, Radial Leads	1	TBD
C2	Aluminum Electrolytic Capacitor, 100 uF,	1	EEU-FC1H100L
C3	TBD, "size might change due to testing"	1	TBD
C4	TBD	1	EEUFR1E101B
R1& R2	TBD	1	TBD
7805	Voltage Regulator, Linear, TO-200 Package	1	MC7805ACTG
LED	LED; Red; 70mcd; 5mmDia.; T-1-3/4; 50mA If; 1.8V Vf;	1	TLDR5400

Table 11: Part list

Parts:

Since we did not use the linear voltage regulator for our final design. Below is a different list of parts for the Buck Switching Converter that we use for our final design. These part, we refrred to Ti.com

Bill of materials for the Buck Converter.

Parts	**Manufacture**	**Part number**	**Quantity**
Rilim	Vishay-Dale	CRCW040212K4	1

		FKED	
Css	TDK	CGA4C2C0G1H103J060AA	1
Cin	Panasonic	EEHZA1V680XP	1
L1	Coilcraft	SER2915L-333KL	1
Cb	TDK	CGA4C2C0G1H103J060AA	1
Cout	Panasonic	10SVPC120M	1
Cinx	Kemet	C0805C104M5RACTU	1
U1	Texas Instruments	LM2673T-5.0/NOPB	1
D1	Diodes Inc.	B340B-13-F	1

Table 12: Final Part List

3.11 Microcontrollers

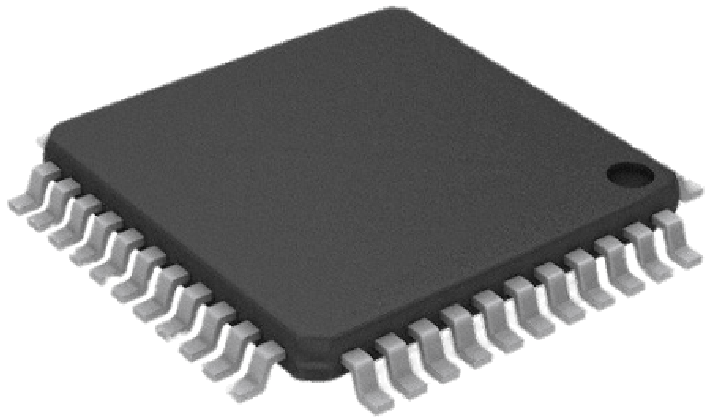


Figure 42: Microcontroller Chip

Microcontrollers are miniature computers used to control devices that require programmable features to operate. Once the controller is programmed with a specific task, it can operate this function on its own until it is otherwise reprogrammed which makes it very useful in products that need to run the same set of functions without constant live monitoring to keep it going. Known as embedded systems, the products that use these controllers range from household items like the Air Conditioning Units, refrigerators, or smoke detectors, to the parts inside of vehicles, common office devices, and many other electrical devices. The “micro” part of the name also insinuates that the size of the device can be on the smaller scale if necessary so that space to place the controller is easier to allocate without altering the product’s overall design.

In choosing a microcontroller, the range of choices is quite broad in terms of features so finding the right controller for a given project isn’t the difficult part when looking for an appropriate board. Price is usually the deciding factor. As different boards will typically have more features than each project may require, making sure you don’t spend more on the board than what your project needs is important when budgeting. I/O Pin count, Memory size, Memory Type, clock speed, and power consumption are some of the typical baseline features that may make or break a part choice. Other features such as Ethernet connectivity, Bluetooth/Wifi capabilities, UART, SPI, and I^2C pins are some other useful features but may not be required in every project.

The clock speed on the microcontroller determines how many instructions can be completed per second. This plays directly into the performance of the MCU as a higher clock rate allows for a faster execution of the program that will be running. It also affects, both directly and indirectly, the data transfer and communication protocols, namely SPI and I^2C as they utilize the clock when performing their functions.

The memory size factors into the size of code the microcontroller can store on its own. Since the program will have to run independent of any other devices, this is a vital point to consider. While the program meant to be run on a microcontroller in most situations will not be more than what most modern day devices can handle, it is important to consider the project scope to determine how big the program will likely be. A project that may be heavier on the computational side will need more memory to handle more complex programmers.

Pin Count is a feature that can be easily overlooked as most if not all pins serve multiple functions that are determined by the program itself. Since the pins are multifunctional, smaller MCUs may have a limited pin count, but make up for it by having similar functionality that can be found on “bigger” MCU devices. This feature can henceforth be left up to what we require of the device in the project overall. Since there will be multiple connections that will be controlled that will utilize the data communication protocols, we are looking for a board that needs to have either multiple I^2C pins or SPI pins in order to give us the ability to connect them on the same lines.

A new current day concern when choosing a board is part availability. As the Covid pandemic has yet to come to a close, the production of some of the required components used in microcontrollers and many other electrical products is still catching up, so this leads to a new problem when planning to find a product. Knowing what is required of your controller is even more important now since there is a chance the device you want may be limited or unavailable in some cases. Planning ahead and knowing which boards are still easily accessible is something else that requires more consideration outside of just budgeting.

3.11.1 MSP430FR6989 Launch-Pad

The MSP430 boards are pretty high up as an option as familiarity and availability are two aspects to consider when making a decision. The board in particular that we are considering in this family is the MSP430FR6989. They are produced by Texas Instruments and are commonly used in Embedded Systems courses as well as Junior Design at UCF, making it likely that we already have one on hand due to previous course history. The chip itself is a 16-Bit RISC Architecture with up to a 16 MHz Clock rate. It has 128 KB of Non-volatile memory and 2 KB of Random Access Memory (RAM) with 83 General Purpose I/O (GPIO) pins. It features DMA (Direct Memory Access), 2 UART, 2 I^2C, and 4 SPI. It also features a LCD display, Real-time clock, Advanced sensing, and 16 Comparator channels.

The Supply Voltage can range from 3.6 V to 1.8 V which helps support the low power consumption. Along with this, there are 3 additional Ultra-Low Power Modes that can be used to further reduce power consumption. In standby mode, the typical power is 0.4 μA. With the Real-Time Clock (RTC), the typical power is 0.35 μA, and in shutdown mode the typical power is 0.02 μA. The FRAM also utilizes Ultra- Low Power Writes along with Fast Writes, with a speed of 125 ns per Word. This board comes with a variety of useful features and can be optimized for very small power consumption making it easier to use a smaller power supply for the other parts that would be in our project. It also has the necessary features we'd need to interface to a LCD display with the required information. To package all this together, the chip itself is currently around a price of approximately $4.164, with the entire Launch Pad being $20.00 at Texas Instrument's website. As stated earlier there are still part shortages in the electrical industry, so already having access to this product makes it a high ranking option when deciding on a board to pick.

Figure 43: MSP430FR6989 Launch-Pad

When it comes to programming the board, Code Composer Studio is tailored to support the MSP430 Family of boards. It includes the libraries, debuggers, many header files needed to operate the microcontroller and also has links to different user guides and manuals pertaining to the different boards. It uses a C/C++ compiler so familiarity with the coding language won't be an issue in our case, but it is something to consider when choosing a board to use. We aim to establish consistency in both part selection as well as coding languages. This ensures that our project will have a longevity component that is acceptable for extended use. Due to the nature of measurement devices, consistent measurements and calibration are incredibly important as they are both the foundation and purpose of the project as a whole.

3.11.2 Arduino Mega 2560 Rev3

Arduino microcontrollers are generally a well recommended board for DIY projects and is a good competitor to any of the boards on this list. The Mega R3 in particular is equipped with an ATmega2560 which is an 8-Bit 16KB Flash Memory Type Architecture. There are 54 Digital I/O Pins , 15 Pulse Width Modulation (PWM) pins, 16 Analog Inputs, 256 KB Flash memory, and a 16 MHz Clock Speed. It features UART, I^2C, and SPI and also has another 8 KB of Static RAM (SRAM), and 4 KB of Electrical Erasable Programmable Read Only Memory (EEPROM).

The operating supply Voltage is 5 Volts but something to consider is that the Input Voltage ranges from 6 V to 20 V. The recommended input voltage however is between 7V and 12V. This means that we could support a larger input voltage supply if we desired for the rest of the project design, but it also means that we're forced to have a slightly larger voltage supply than we may potentially need for the other parts. That said, there is still a 3.3 V pin and a 5 V pin available on the board to circumvent this problem if necessary. The maximum current draw on the board is 200 mA. This board has a lot of similar features to the MSP430FR6989, so it can also be used as a good option for what we need to do in our project. The wider but higher base power supply range will influence the resulting parts needed in the other parts of the project. The price of the ATmega2560 chip is around $17.79 and the Arduino Uno R3 board is around $35 on Amazon, although Arduino's store website lists the board at $48.40.

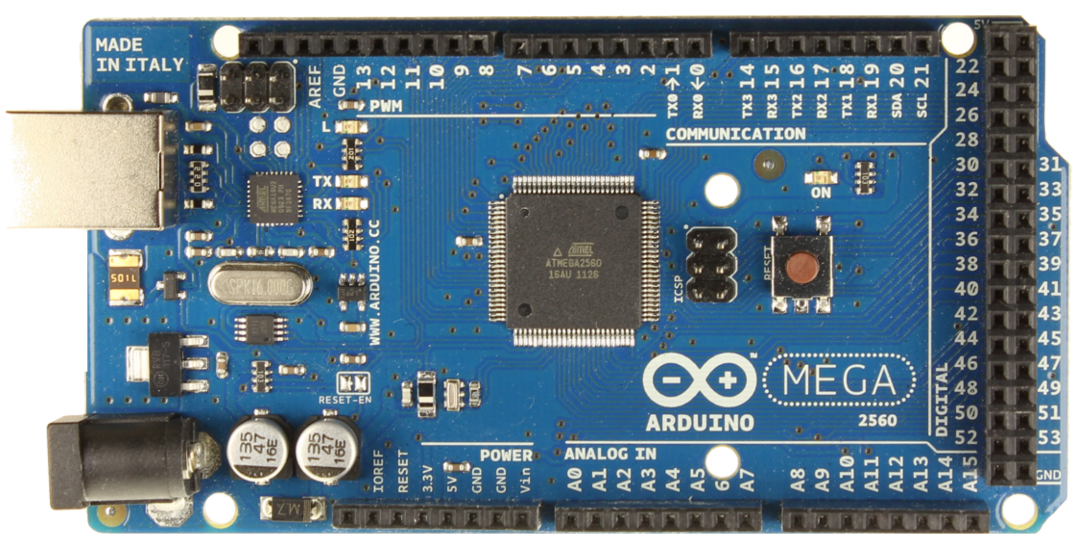


Figure 44: Arduino Mega 2560 Rev 3

Arduino has its own IDE and is an open-source software. This makes it easy to write and upload the code to the board. It also uses the C/C++ coding language, but it uses its own set of functions and variables making the programming a little simple for users who may be unfamiliar with using higher level programming languages.

3.11.3 Teensy 4.1

The Teensy 4.1 is another popular board choice which features a 32-Bit ARM Cortex-M7 processor at 600 MHz and a NXP iMXRT1062 chip. This board is typically supplied power through USB, so the input voltage about 5 V. In terms of features, there are 55 digital I/O pins, 35 PWM pins, 18 analog pins, 3 SPI, 3 I^2C, 8 MB of Flash memory, 1024 KB of RAM, digital audio support, 32 general purpose DMA channels, and some other features that probably won't be needed for our project in particular. The Cortex-M7 allows for executing 2 instructions simultaneously per clock cycle which means the execution speed of a program could be exceptionally fast, but isn't required. The large Flash and RAM memory also means we can support quite large program files if need be.

Figure 45: Teensy 4.1

The power is approximately 100 mA at the 600 MHz clock speed, so the power consumption is also relatively low. Taking the power supply into account again, 5 V is a relatively easy to implement power supply in the overall project design and there is still a 3.3 V on the board if we need to use a lower voltage externally somewhere. The price of the chip on this board is $4.84, and the board itself is $31.50 with Ethernet or $28.60 without it. Availability may be an issue again due to part shortages, but the Teensy board appears to be a competitive option in comparison to the other boards. The main issue is there are a lot of features that are not needed for our project that are on this board.

Teensy also uses the Arduino IDE which means implementing the program itself will be relatively easy for beginner level programmers. The code language is a combination of C/C++ and some self-made functions and variables.

3.11.4 BeagleBone Black Rev C

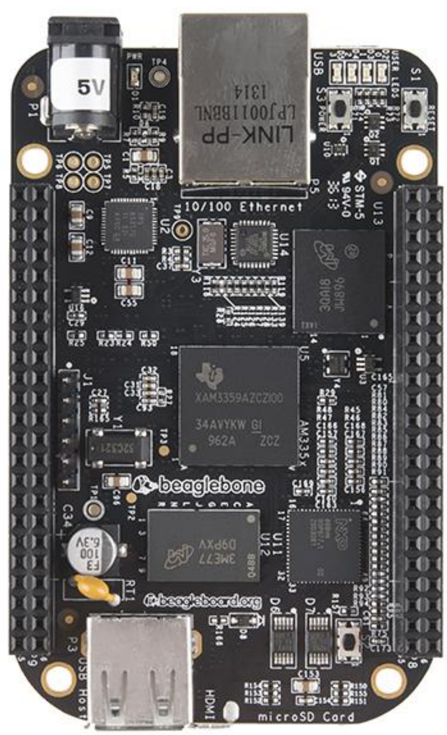


Figure 46: BeagleBone Black Rev C

The BeagleBone Black Rev C is a microcontroller that's on the higher end of the price spectrum compared to the other options but not without reason. Similar to the Teensy 4.1, the BeagleBone is equipped with an AM3358 1GHz ARM Cortex-A8 Processor, 4 GB 8-Bit eMMC onboard Flash memory, 512 MB DDR3L 800 MHz Dynamic Random Access Memory (DRAM), a 3D Graphics Accelerator, and 2 32-Bit 200 MHz Programmable Real-Time Units (PRU Microcontroller). There are 69 GPIO pins, SPI, I^2C, UART, USB Ethernet, and HDMI connectivity.

Additionally, there are 3 options for powering the board available upon receiving the board. This includes a DC Barrel Plug recommended at 5 V with up to a 2 A current draw, a Mini USB Port also listed at 5 V but limited to a 500 mA current draw, and finally an option to power it through the use of batteries via its Battery Pins. While it rivals, and in a lot of areas out-performs, the other boards in terms of features, similar to the Teensy 4.1 there are a lot of additional features that aren't necessary to fulfill our project goal. These features also cause the BeagleBone Black to have a price of $73.50.

The reason this board was included even though the price is much more expensive compared to the others is its software compatibility. It is compatible with Debian, Ubuntu, Android, Cloud9 IDE and a few other software programs. This gives the BeagleBone Black a more options when it comes to programming as the coding languages available along with the BeagleBone libraries lets the user code in a language they are more familiar with which is good for user's who may not be that experienced or comfortable with a specific coding language.

3.11.5 Deciding Factors

Both the MSP430 and the Arduino Uno boards have similar capabilities when it comes down to their chips. They are in a similar price range as well in comparison to the Teensy 4.1 and the BeagleBone Black. When it comes to overall specs, the BeagleBone outdoes all the other boards almost to a fault. It does more than what would be necessary in most applications for our project. While it does add some interesting features that could be used for the display interfacing, they may not be worth the tradeoff when it comes down to price. The Teensy 4.1 also falls into this category where it almost does more than what would be needed of it. It however, has a price closer to that of the arduino, so it can still remain an option if need be.

This leaves the MSP430 and the Arduino Uno as the most likely choices for our MCU element in the project. The choice will most likely come down to their compatibility with the display options and their ease of use when it comes to Programming Software. While Arduino is proposed to have an IDE that can be easily picked up by programmers with different levels of experience, familiarity with the Software is still something to consider. Whether we have an easier time with C/C++ or Java will factor in as well since CCS (Code Composer Studio) is only in C, Arduino IDE is in Java, but can also run C/C++.

3.11.6 Comparisons

Board	MSP430FR6989	Arduino Mega	Teensy 4.1	BeagleBone Black Rev C
MCU	MSP430FR6989	ATmega2560	MXRT1062	AM3358
Architecture	16-Bit	8-Bit	32-Bit	32-Bit
Clock Rate	16 MHz	16 MHz	600 MHz	1GHz
RAM	2 KB	8 KB	1024 KB	512 MB
Flash	128 KB	256 KB	8 MB	4 GB
GPIO Pins	83	54	55	69
UART	2	4	8	4
SPI	2	Yes	3	2
I^2C	4	Yes	3	2
Supply Voltage	1.8 V – 3.6 V	6 V – 12 V (7 V – 12 V recommended)	5 V	5 V
Power Consumption	~100 μA/MHz	~200 mA	~100 mA	~1300 mA
Chip Price	$4.164	$17.79	$4.84	$5.617
Board Price	$20.00	$35.22 - 48.40	$31.50	$73.50

Table 12: Microcontroller Comparisons

3.11.7 UART Communication

A Universal Asynchronous Receiver-Transmitter, or UART is a hardware device used to transfer data between devices. Data bits are sent one at a time, from least significant bit to most significant bit, framed by start and stop bits before and after each transmission. This data transfer process requires a UART for both the device sending the data, and the device receiving the data. On the sender’s side, the bytes of info are broken down into bits sequentially and sent while the receiving side re-assembles the bits into bytes of info again. For the information to be sent and received correctly, both devices need to have the same settings for the Baud Rate, Parity/Check Bit, Data Bits size, Stop Bits size, and Flow Control.

The Baud Rate is the measurement for the speed at which the communication is taking place. The Parity/Check Bit is used to check the correctness of the data being sent. If they don’t match up, then it signifies that the data received doesn’t match the data that was sent. The Data Bits size lets both sides know how many bits will be sent during each data transfer that occurs. The Stop Bits size lets both sides know how many stop bits are being used, which signifies the end of each data transmission.

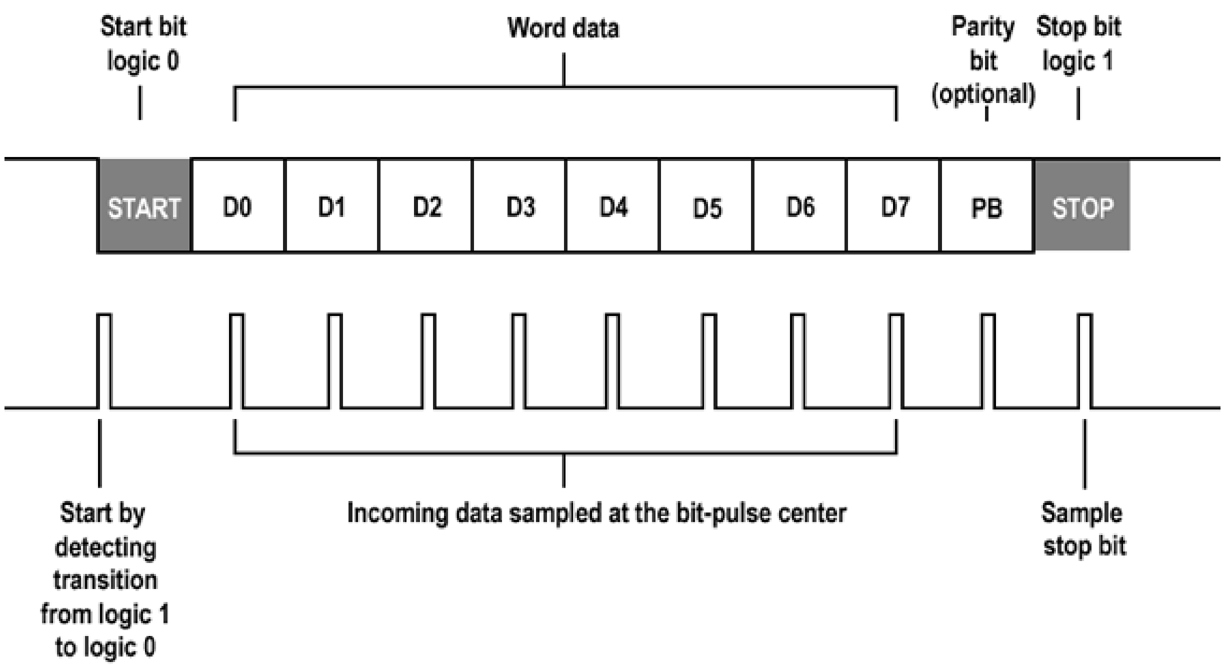


Figure 47: Example of UART Transmission

This UART functionality is part of what will be used for the data transfer between our moving parts in the project as well as the display. Since these are all external devices, they will require data to be sent to and from the Microcontrollers in order to operate since they can't be programmed individually.

3.11.8 SPI Communication

Serial Peripheral Interface, SPI, is a synchronous serial communication unlike UART which is Asynchronous and it is used for short-distance communication. It is a full duplex protocol, which means communication can take place in both directions. It uses a master-slave architecture which means there is one controller (master) that functions as the central device and processes the information and sends signals to the connected device(s) (slave). This protocol is better for higher speed data transfers, but becomes more costly when you want to add more slave devices to the same bus. This is because each slave device needs its own select line which means that as you add more devices you'll need more wires.

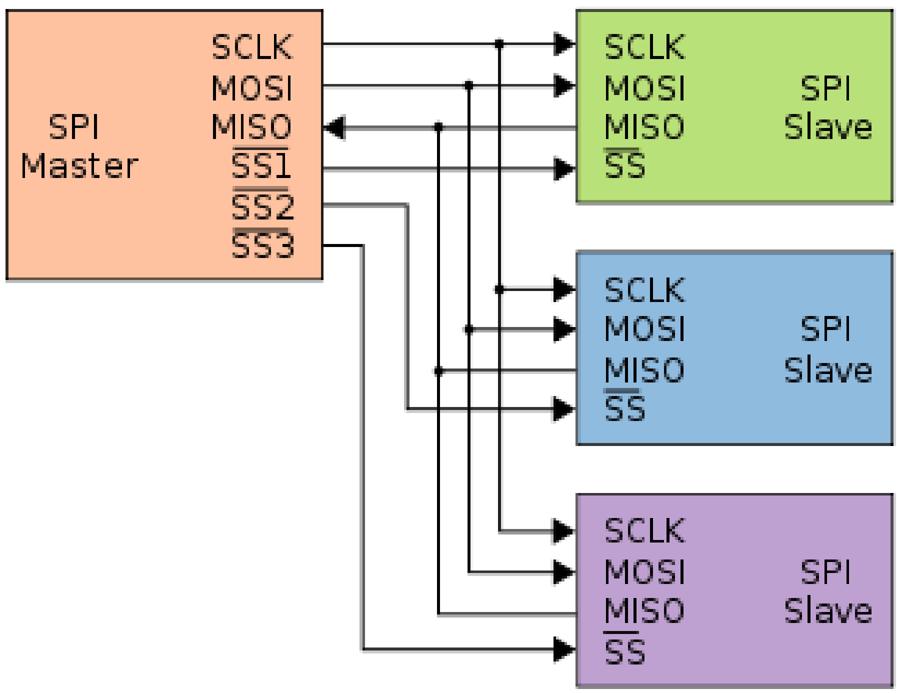


Figure 48: Example of SPI Master/Slave Connection

Similar to UART, SPI can be used to communicate with devices such as the display or light detector in this project, but connecting to multiple devices may be more difficult to implement. Correctness is preferred over speed with certain parts of the project such as the motors controlling the rotation stage and lens, so SPI may not be the most suitable for these parts of the project.

3.11.9 I²C Communication

Inter-Integrated Circuit, I²C, is also a synchronous multi-controller/multi-target, single-ended, serial communication bus. This means that unlike SPI, which has a duplex (2-way) communication style) I²C only communicates in one direction. This makes the overall protocol simpler to implement and means it’s easier to add multiple devices to the architecture. While speed is limited on the High end in comparison to SPI which isn’t limited, since I²C includes flow control and error handling which makes it more reliable. It also has the ability to be run in a multi-masters setup while SPI can only have a single master.

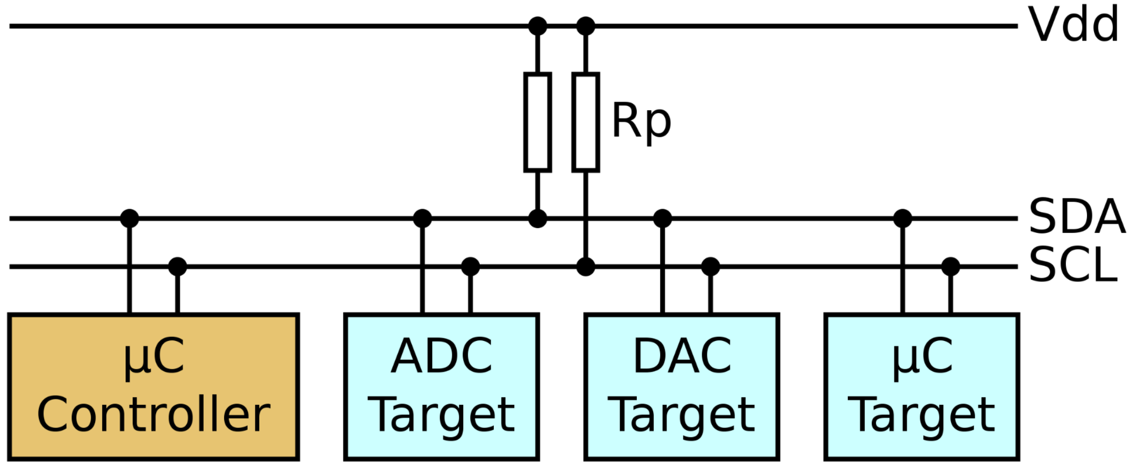


Figure 49: Example of I²C Connection

In terms of functionality in the project, I²C is similar to SPI in which it will allow for short distance communication between some of the moving parts in the project as well as the detector. It is also less complex to set up and more reliable than SPI, so certain parts like the motors controlling the rotation stage which need to be accurate may be well suited for this protocol.

3.11.10 Communication Protocol Comparisons

As a summary of the 3 communication methods, both I²C and SPI protocols use Synchronous clocking to transfer information. UART is an Asynchronous method that can only be used by two devices connected to each other. In terms of transfer speed, SPI does not have an upper limit for how fast the data can be transferred. It is only limited by the hardware being used, while I²C is limited but more reliable as it has built in exception handling. I²C protocol also only requires two wires to add a new device to the architecture. The devices will share the same wires which serial data line (SDA) and serial clock line (SCL) as the other devices on the bus making the protocol fairly simple. SPI however, will require more pins in order to add new devices making this protocol more complex. UART is limited to 2 devices in any configuration so it is not ideal for connecting multiple parts in our project.

The table below summarizes the comparisons of the 3 communication protocols based on their key differences. In a project where the MCU will need to be connected to multiple parts and have a reliable data transfer, I^2C Protocol stands out as the best option. It is the least complex to implement and a Full-Duplex system is not something that will be required for our project scope.

Communication Protocol	UART	SPI	I^2C
Modularity	Full-Duplex	Full-Duplex	Half-Duplex
Architecture	2 Wires	4-Wire Protocol	2-Wire Protocol
Communication Type	Asynchronous	Synchronous	Synchronous
Connectivity	Up to 2 Devices	Many Devices (More Complex)	Many Devices

Table 13: Communication Protocol Comparisons

3.11.10 C Programming Language

Figure 50: C Programming Language

The C programming language is a general-purpose computer programming language that is widely used by most programs. It is available on virtually all modern computers and operating systems and is one of the languages we used to program a few of the Microcontrollers. While C is not the very first programming language, many of the other programming languages used today draw from the structure of C and share similar syntax. This is why C is generally learned before many other programming languages, as they usually share many features and coding practices that can be found in the C language. The other languages will however have a lot of built in functions or have less low-level modifiability than C which will make life easier for programmers, but may not allow for some dynamic programming that can be done with C.

While the libraries that specifically apply to the MCUs are not inherent to the C libraries and headers, they still utilize the syntax and other rules of the C language. Since C doesn't inherently support features that can typically be found in embedded C like fixed-point arithmetic, multiple distinct memory banks, and basic I/O operations, a common standard for these features were added in order to allow said implementations to be added.

3.11.11 C++ Programming Language

Figure 51: C Programming Language

C++ is an extension of the C programming language that uses object-oriented programming (OOP). OOP is a programming type that revolves its code around objects (data) rather than the logic and functions we see in C for example. This allows programmers to focus solely on the function of said objects rather than the logic and functions needed to implement them on top of basic functionality. Essentially, the complexity level for the code is reduced which is important, as manipulating the objects themselves can still be quite complex when you start working with larger programs.

Neither C or C++ are platform independent, meaning they will need to be compiled by each system using the code. This can limit its overall usability but since the languages are very commonly used, many systems will have a way to compile these codes built in. If not, there are also downloadable software programs available online which will allow for users to test code through those programs.

The goal of C++ when it was being developed was to focus on efficiency, performance, and flexibility of use with its design. C++ similar to C in terms of syntax but the code from one program can't always be used interchangeably. Them being similar however, does make it relatively easier for someone who is experienced with the C language to learn C++ Embedded C++ lacks some of the features found in C++, but it aims to keep the useful aspects of it while still being simpler to use.

3.11.12 Java Language

Figure 52: Java

Java is another object-oriented programming language that was first implemented in 1996. It is a general-purpose programming language that was created with the idea to allow programmers to write once, run anywhere (WORA) programs. This means that once the code was compiled, it shouldn't need to be recompiled on another machine to run on any platform that supports Java. Since the Java compiler converts its source code into bytecode, it can be used on any Operating System by using Java Virtual Machine (JVM).

Since it is an OOP, it shares many of the underlying principles seen in C++, with the syntax being slightly different in some cases. Unlike C++, Java uses a singly rooted hierarchy which means all the classes inherit from a single root or Object. Inheritance in a coding sense means that any objects inheriting another object will be able to be implemented in a similar fashion and use all of the properties associated with the inherited object. Embedded Java doesn't differ much from standard Java anymore, so there aren't too many differences when coding for embedded systems.

3.11.13 Code Composer Studio IDE

Figure 53: Code Composer Studio

Code Composer Studio is an Integrated Development Environment (IDE) used specifically by Texas Instruments (TI) embedded processors. It is mainly used for embedded project design and bare-metal Joint Test Action Group (JTAG) debugging, and can more recently be used to support and debug OS level applications. In relation to our project, it would be used as the IDE software to program the MSP430 Microcontroller if we were to use it. It uses the C programming language as its base.

Since the C programming language doesn't inherently support all aspects of embedded programming, there are header files and libraries provided by Texas Instruments to support and develop programs on any given microcontroller they have available. These files include functions that can ease the development process so that the user doesn't have to make every program from scratch, along with header files that assist in identifying the functions of different pins available on the board and how to interact with their functionality.

During the testing phase, there is also access to important debugging information which helps the user see how the values of different electrical parts are affected during live tests of the program. Information about the memory, resistor values, and other electrical aspects of the microcontroller can be viewed to help the user identify potential issues or mistakes in the program code.

Being able to see the values for these different parts on the board will also allow for accurate measurements for the power usage of the components of the board since we would be able to see which parts are active during specified code executions.

3.11.14 Arduino IDE

Arduino IDE is a software application used by many devices outside of just Arduino to program microcontrollers. It is supported on Microsoft Windows, macOS, and Linux and it is written in Java. Similar to C++ Java is also an object-oriented program, but it has less of the low-level or machine code capabilities that the C and C++ languages offer.

While it was stated that the Arduino IDE is written in Java, on the programmer's side the C++ language is used. Arduino gives user's a software library from the Wiring project, an open-source electronic prototyping platform, giving user's access to common I/O features that can be used in their program development. The code editor tries to make the coding easier by providing users with many additional features like text cutting and pasting, automatic indenting, syntax highlighting, and one-click tools to compile and upload programs to the user's project board.

Figure 54: Arduino IDE

In the upcoming 2.0 version of the IDE, Arduino looks to add more features to further enhance the coding process for programmers using their software. Some of these features include Git integration, Dark Mode, a Board List and Manager, a Library manager and autocompletion support for Arm products. Having a wider variety of tools available allows for greater potential when considering system designs.

4.0 Design Constraints and Standards

In these sections we will discuss the design constraints that will be applied to our project and how we plan to deal with them. The constraints may affect certain design choices or part selections as they may limit the freedom we have when it comes to part choice. The types of constraints we will be considering are:

- Safety
- Economic
- Time
- Equipment
- Environment
- Manufacturer
- Ethical
- Sustainability

To go along with these constraints, we will also look at some industry standards that we will need to abide in order to make our design be more accessible to the common market. Our project shouldn't be designed in a way that makes it unusable with the parts that similar products use, so we aim to identify any standards that can be applied to our design.

4.1 Constraints

For the constraints section, we will consider many of the factors that can either limit or influence both our part usage and design approaches. Some of the constraints may be self imposed based on the design of the project, while others may be dependent on factors outside of our direct control. Constraints directly result in design changes and considerations which may not be utilized under alternate circumstances.

4.1.1 Safety Constraints

When working with electronics, especially optics that are coherent, safety is incredibly important. For this design, we want to ensure that there are no stray beams traveling in the air that could potentially damage a person's eye. Low power lasers and LEDs still have the potential to cause systemic damage to eyes so proper usage of the machine is imperative. All optics must be properly mounted onto an optical breadboard and the entire system should be closed when powered on. An additional safety concern that comes in the form of care for the machine is that of ESD. ESD is electrostatic discharge and refers to the release of static electricity when contact occurs between two objects. When coming into contact with electronics we want to make sure that we are grounded to ensure that no parts are severely damaged as ESD is more potent than many people believe.

4.1.2 Economic Constraints

An important aspect of the project is the relatively low cost of the system. Because similar projects utilize monochromators, integrating spheres, and other expensive optical tools. Our project aims to eliminate expensive components at the cost of intermediate data points. Despite this, we aim to have as high of an accuracy as possible in our power measurements. An additional problem that arises in relation to economic constraints is the availability of parts. This can cause an increase in prices due to the limited number of part options available on the market. Because of this, it is possible we may have to cut corners on certain parts in an effort to lower costs as much as possible.

4.1.3 Time Constraints

With the pandemic still underway supply chain issues are an ongoing issue in the world. As mentioned previously, limited part availability is a potential issue. With this in mind, if a part is difficult to obtain this can result in delays in the build process and thus slow down the overall timeline of the assembly and testing period of the course. An additional time constraint includes ease of access when getting in contact with certain individuals. Oftentimes, reaching a particular person is not as easy as it seems. Many forms of communication go unnoticed due to the sheer influx of emails, calls and text-messages someone may receive. Delays in response can directly result in delays in production, assembly, testing and other factors. An additional time constraint comes in the form of time to take measurements. Our system aims to eliminate the time that it takes to take manual measurements for the efficiency of a diffraction grating. With this information, there would be largely no function for our project if it operates slower than a manual measurement as the driving factor for the system is quick and efficient measurements.

4.1.4 Equipment Constraints

We are certainly limited in the equipment we can use. As we are only undergrad students, we do not have access to the most high-end equipment available on the market. For this reason we have to make sure we find the highest quality parts within the price range we have set for ourselves. This means ensuring that products are quality and can achieve the desired result for our particular project.

As we become more established engineers we would be able to improve upon this design in using parts that result in higher levels of accuracy and sustainability. Given our experience however, we believe that this provides us with a better sense of creativity in making the best results with the equipment at our disposal. This is additionally beneficial as it allows us to operate under the constraint of a relatively low budget.

4.1.5 Environmental Constraints

Environmental constraints are not relevant to this project as it uses a low amount of power and will be operated inside. Under normal circumstances the environment will have little to no effect on either the design or the manufacturing of our project.

There aren't many parts of this project that can't be recycled or reused present in the project either and the scale of the project is small so there aren't additional facilities or special locations needed in order to use the product. Barring incorrect usage or other unnatural occurrences, the lifetime for the parts aren't short, so they won't require a large amount of resources in order to use the spectrometer over long periods of time.

4.1.6 Manufacturability Constraints

As mentioned, in other sections the biggest hurdle to overcome in terms of feasibility for manufacturing. There is another issue in relation to manufacturing that could arise. Because of the nature of optical designs the requirement for an optical table is necessary. These are not tools that can be easily moved and transported around. For this reason, an optical breadboard is necessary and these can also be very expensive.

There are ways to navigate around this that can be explored. One such option is drilling holes exactly where the parts will be mounted. This is a viable option however, it limits the amount of freedom in the event that parts must be moved due to an adjustment in the system. Another manufacturability constraint comes in the form of PCB production, if a PCB can not be made to the exact specifications for the design it will not be suitable for real-world applications.

4.1.7 Ethical Constraints

Ethical constraints can be difficult to determine at times due to the nature of the issue. We must ensure that we are able to accurately and responsibly create a project which is our work and only our work. The appropriate owners of any given intellectual property are entitled to that property and it is our responsibility to not infringe on said property.

4.1.8 Sustainability Constraints

Due to the low number of moving parts in our project sustainability should be consistent over a long period of time. However, this is still a factor that is incredibly important for the longevity of our project. The intensity of the light sources may diminish over time and may pose an issue for the reading on the photodetector. If the light is not bright enough to be picked up by the photodetector then the entire reading is useless and we can not achieve an accurate measurement for the efficiency of the grating. Periodically, it will be important to check the power output of the light sources to make sure they are of a reasonable value. We are currently not sure of what that appropriate threshold value should be to make measurements and will require further testing to determine.

4.2 Related Standards

This section will cover the standards pertaining to the diffraction grating efficiency measurement system and their role in the design of our project. It will also consider standards that may relate to the hardware and software systems that will be present in the project design.

4.2.1 Related Standards cont.

Standards aim to solve the problem of lack of uniformity and consistency across different technologies in the field of engineering. There are a wide variety of standards which affect our project as a whole as well as the individual parts supplied by the manufacturers. The standards discussed in the following sections will be taken from a variety of organizations including, but not limited to, the American National Standards Institute (ANSI), Institute of Electrical and Electronics Engineers (IEEE) and the Universal Licensing System (ULS). These organizations aim to establish conformity and requirements to ensure a better quality of life for individuals which may use certain technologies. There are many more organizations than the ones listed in this section yet we only aim to mention those which pertain to our project.

Standards also aim to ensure safety as an important goal for users interested in the usage of technologies of which the standards are created.

4.3 LED Standards

IEEE Std 1789™-2015 explains the safety measures and power regulations relating to LED usage. Through this standard we gain an understanding of the concept of flicker and the adverse effects that it can play on an individual's health. Flicker can be defined as "variations of luminance in time". With this standard we can minimize the risk of distraction as well as biological effects that may come with the presence of flicker in LED lighting. The findings of this standard indicate the frequency at which we observe flicker should be higher than 90Hz to minimize the risk associated with distraction and adverse biological effects. This means the manufacturer should ensure that the frequency of the LED is above the threshold outlined by the IEEE. Risk of seizures increases with lower frequency ranges from 1Hz to 65Hz.

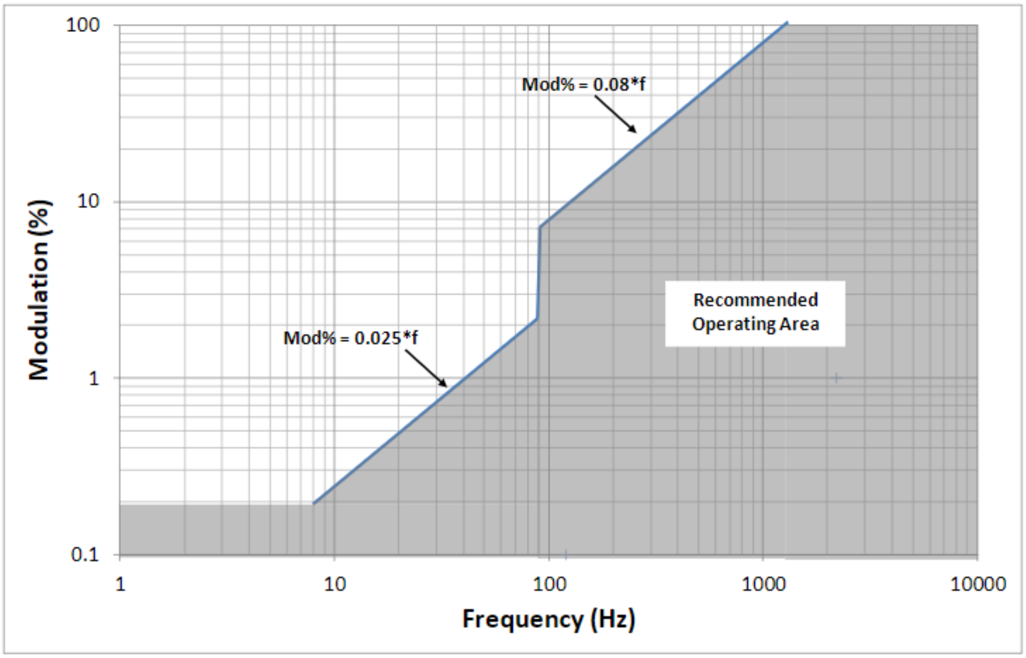


Figure 55: LED Modulation vs Frequency

Similarly, the percent flicker or modulation depth should be below 5%. Figure (pending) shows the area in which an ideal LED should operate to minimize the effects of flicker on the user. Flicker is the main concern when designing and using LEDs as LEDs are incoherent light sources and typically do not run the risk of severe eye damage in the case that the user looks into it. However, this does not mean that there are no dangers associated with the user of LEDs. The gray region limits the risks associated with seizures and headaches for users observing LEDs.Modulation depth is related to the maximum and minimum levels of luminance displayed by the LED. So not only is the frequency important to the design of an LED but the overall luminance plays a crucial role in minimizing adverse biological effects. We aim to implement this LED standard to ensure that no users are harmed in operating our system regardless of sensitivity to flashing lights. In a professional setting it is incredibly important to take all safety considerations very seriously as it not only reflects the individual but the group designing the project as a whole.

4.4 Design Impact of LED Standards

Usage of this standard will impact the frequency of the LED and the specifications by which the LED operates such that it does not cause negative effects to those using it. This will not have a large impact on the limitations of the project and will instead be a consideration in LED usage and overall safety.

4.5 Software Testing Standard

The standard for testing software (ISO/IEC/IEEE 29119) aims to establish a consistent and universal set of standards that can be used for software testing. Through this standard we can establish a testing process that is suitable for multiple designs and an overarching procedure for software testing. Testing of software can be an incredibly tedious and cumbersome task. This is why there are sets of testing standards which provide the user with certain qualities to meet. Through this, the user can be sure that the software in question meets the criteria of an appropriately tested software. There are several criteria to be met in this particular standard, these include concepts & definitions, test processes, test documentation, keyword-based, and techniques & strategies. All 5 of these categories cover a different aspect of software testing which must be considered when designing and testing any engineering software. The steps mentioned are in their respective order as it pertains to the software testing standards.

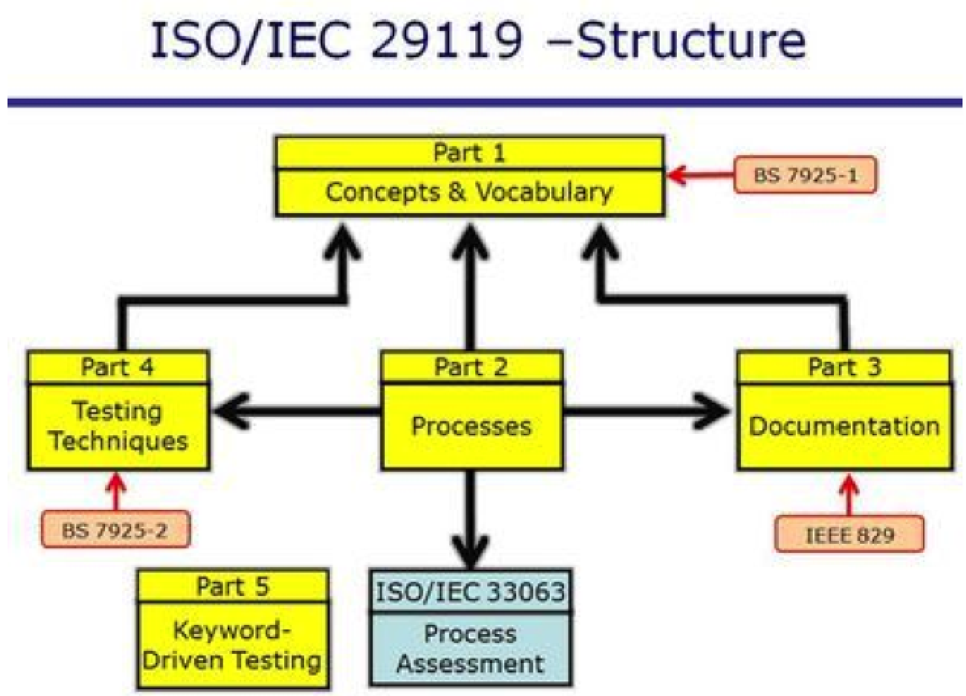


Figure 56: ISO/IEC 29119 Structure Diagram

4.6 Coding Standards

While there may not be a single style or template that is required when coding, when organizing a code and naming different variables and/or functions, it is important to maintain the overall readability of the code. This is useful for both the programmer and anyone else reading the file. For the programmer, having an easily readable program makes it easier to spot potential syntax errors or other mistakes and undesired errors that tend to occur when coding. For the reader, they need the file to be easy to read since they will most likely not know what the programmer is thinking when organizing the file. The less time they have to figure out what should be happening in different parts of the program, the easier it is to analyze what is actually happening in the overall code and how each part interacts with the others. There are a general set of rules for each part of the code that will typically be present in a program.

4.6.1 Naming

Naming variables, functions, objects, classes, or any other part of the program that can be named in the program, should always be intuitive. Neither the programmer or someone else reading the code should need to guess what each name in the program is being used for. The names should be self-explanatory while remaining short or even abbreviated if necessary. As an example, if you are writing a function that aims to calculate the average grade of a group of students in a class, then a name like "classAvg" or "avgGrade" would be easily understood. Ambiguous names like single letters and numbers should be avoided since they don't help the programmer or reader understand what each variable is being used for.

On top of using intuitive and concise naming techniques, the naming style should also be consistent throughout the program. When writing names for a program spaces aren't allowed, so either capital letters or underscores are used to show the separation between word for names with more than one word in them. Using only lowercase letters is avoided as that makes it hard to tell if there is more than one word in name. Starting a variable or function name with a capital letter is typically not done either, save for a few cases. Using the previous example, either "classAvg" or alternatively "class_average" would be 2 different styles one could use. Regardless of the style choice, all subsequent names with 2 or more words should be named using one style or the other. It's not detrimental to mix different naming styles, but keeping the code uniform makes it more readable as a whole.

4.6.2 Spacing/Indenting

Spacing in code is most often used to separate the code into sections for organization. Program codes can be formatted similarly to an essay when it comes to separating paragraphs. Simply using one or two empty lines between functions or classes is enough to make it clear where different code segments end and begin. Using more empty lines however can make a program too lengthy, so white space should be used sparingly and limited to 2 or 3 lines at most. This white space usage should again be consistent throughout the program.

Indenting in code, unlike spacing, is not used the same way as one would use them in normal writing. Indenting is used to show nesting, which is similar to saying the line that appears before the indentation either holds or will execute/perform all of the indented lines below it. When you indent, you should indent every line thereafter until the end of the intended function.

4.6.3 Framing Code

To go along with using indentation, the use of curly brackets, "{ }", is a way to frame the data, making it easier to read what class or function the indented code belongs to. If the programmer decides to frame the code this way, then any indented code should be framed the same way as well. This practice pertains to the curly brackets themselves, as nesting code can become difficult to read without the use of these brackets and the indentation.

Nested code works similar to parenthesis in math. Anything within the parenthesis, the nested code, must be done before you get back to the outside operations. This is where the importance of framing and proper indenting come into play. If the code is framed incorrectly or if the indenting is in the wrong position, the code may not execute correctly. It'll also make the code rather difficult to read properly which goes against the underlying principle of following these rules, readability.

4.6.4 Code Length

The length of the code is something to keep in mind as the longer a program is, the more chances there are for something to go wrong. Keeping the code as short as possible while still performing the task at hand should be the goal for a program. It should be stated that the code length only applies to the code that is being executed, so this does not apply to things like white space, framing, or the overall organization of the code.

One way to shorten code is to write function calls for any lengthy operation rather than rewriting multiple lines of code every time you have to perform said action. Using loops is another way to potentially shorten code in the situation that the code needs to perform repeated actions on multiple similar variable types. Using nested loops inside of a nested loop too often should however be avoided since the complexity level of the code then becomes higher than it needs to be. The line reduction goal should still allow the program to have as low of a complexity level as possible since it becomes more difficult to correct errors if the place where the error occurs isn't easily identifiable.

4.6.5 Program Headers

Header files are used to predefine and describe the contents that may be used in parts of the executable file. The "contents" can range from variable types and what they are used for, to initializing memory locations and byte usage for said variables. There shouldn't be any information put in the header file that can be placed somewhere else or that isn't being used in the program. It should be minimalized as much as possible while still being able to run the code properly.

4.6.6 Commenting

Comments are not a part of the executable code and only serve to act as readable notes for the person reading the code. They should be used to be brief summaries for the purpose of important lines of codes, functions, variables, classes, and why they are being used in the program. Remembering to keep them brief is important. The comments should not be entire paragraphs on the principles and logic behind how the code works. They serve the purpose to either clear any confusion that could arise if the person reading doesn't fully understand the name for certain sections, or as a physical reminder to the programmer in case they need to go back and modify a section of code. Using them in this manner helps improve the readability of the program when organization rules and intuitive naming aren't enough.

4.7 Battery Standard

Battery standards aim to establish a consistent and safe method of battery integration in electrical systems. IEC 61951-2:2017 establishes a set of standards concerning nickel-metal hydride batteries in engineering systems. This set of standards covers usage for portable applications which is relevant to our project as it will most likely be moving quite frequently due to the nature of the course. Through this standard we can observe the orientation and distinction of batteries and the importance of doing so for uniformity and consistency in using batteries.

An additional standard relevant to our project is that of IEEE 450-2020 which aims to set standards concerning the practice for maintenance, testing and replacement of batteries in a responsible manner. However, this standard is mainly focused at batteries used in stationary applications but it is still helpful to the scope of our project. It is incredibly important when handling any type of metal or chemical to be handling that item in a safe fashion as failure to do so could easily result in injury or damage to parts inside the system. As a result, we are going to take constant precautions with the battery we are using because of the IEEE code, and based on our project, the risk of being exposed to this standard is extremely rare, but as far as safety, we have to follow rules. The battery that we are going to use is safe, in terms of the way it is manufactured.

5.0 Hardware and Software Design

In this section, we will take a more detailed look at both the Hardware and Software design elements that will be present in the project. The Hardware will cover the lens, diffraction grating, and MCU integration as well as the different motor connections we could implement based on the types of motors discussed in the earlier sections.

The Software covered will be the semi-automated functionality, data handling, LCD User Interface, and the different iterations for the GUI. The testing plans for both the Hardware and Software designs will be elaborated upon in the section that follows. Since the design has not been finalized, some parts are still liable to change in terms of Hardware. Parts like the power supply and Software components will likely remain unchanged regardless.

5.1 Hardware Design Details

As shown in our prototype diagram, our project contains several optical, mechanical and electrical elements. We have four monochromatic LEDs on a sliding translation stage which moves left and right depending on the desired wavelength of measurement. Once the wavelength is picked the light then travels through an optical iris set at 1-2.5 mm. The light is then polarized to ensure that there is no polarization dependency of the grating and all measurements are consistent. The light is then collimated and given a straighter path of travel with a lower divergence angle. A plate beamsplitter transmits 50% of the incoming light and reflects the other 50% onto a photodetector which takes our incident light measurement. The transmitted light travels towards our diffraction grating and is then focused onto our photodetector where we take our second reading of the first order diffracted light. This is the extent of our hardware design which is incomplete without the use of software which will be elaborated on in a later section.

5.2 System Alignment

The majority of our alignment will take place across a straight axis. To ensure a straight alignment and little light leakage our system will be enclosed in a large tube all the way until the presence of the diffraction grating. We believe this is the most effective design as it ensures parts will be unmoving and aligned in a straight manner. Similarly this also ensures the same height across the entire system eliminating the need for excess optical posts and rails.

This tube will also aid in keeping the cost low as to improve upon our goal of being low-cost. Alignment for the grating and photodetector will take place using a mechanical arm which will have the photodetector moving as a function of the angle of incidence on the grating. The mechanical arm should not be longer than 6 inches to eliminate light losses and ambient light.

5.3 Lens Design

We have chosen to use a lens with an EFL of 20mm. This focal length allows us to place the lens quite close to the photodetector and obtain a spot size suitable for the photodetectors in our system. We can achieve a spot size of less than 1mm which is much smaller than the 3.6mm diameter of our photodiode giving us a total reading for the efficiency of the grating. The beam spot size being significantly smaller than the photodiode is imperative as it is the basis for the total efficiency of the grating as well as the incident light measurement.

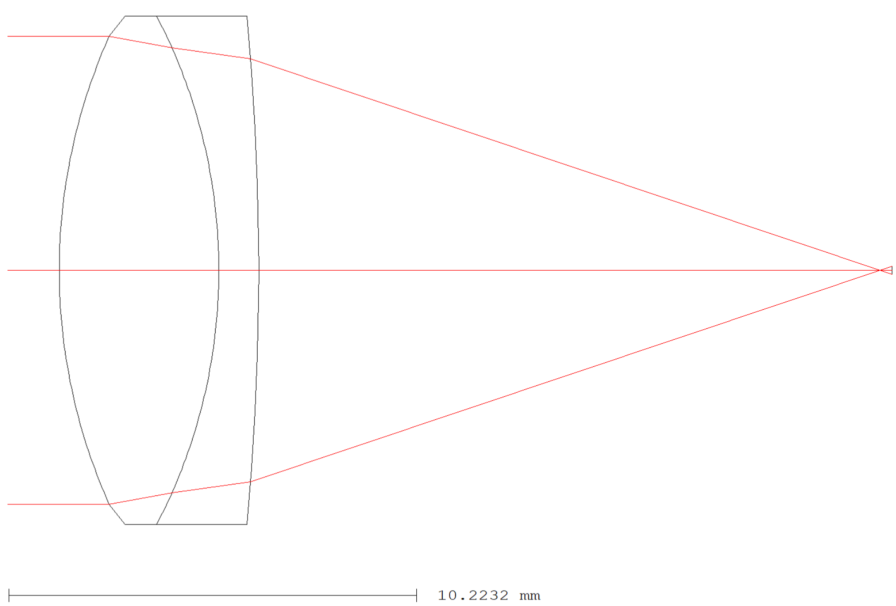


Figure 57: Focusing Lens Achromatic Doublet Ray Tracing

Our beam spot size is an important value to consider as we aim to collect all light traveling through the system. Similarly there should be the exact same amount of light independent of the diffraction grating that is incident on the photodetectors. This consideration is shown in the figure comparing wavelengths and spot sizes with a 0.5mm square scale. This shows that under ideal focus we should have more than enough space for the beam spot on the photodetector.

Figure 58: Spot Size of Focusing Lens at Various wavelengths

Our collimating lens must similarly achieve a particular spot size in order to be suitable for our project. We have chosen a collimating lens with a very short focal length and a collimated beam spot size which can be resolved much smaller than the total size of the photodetector. Several tests were done to determine what the most appropriate lens would be whilst keeping costs low and the collimating lens chosen was able to carry out the requirements necessary.

A collimating lens is imperative for our design due to LEDs having a high divergence angle compared to coherent light sources. We can combat this by choosing a collimating lens with a small spot size causing the divergence angle to decrease. To determine the desired spot size of our collimating lens we also have to consider the divergence angle as mentioned previously. This factor in conjunction with the focal length determines the possible spot size achievable by the collimating lens.

In an ideal scenario, a collimating lens would be unnecessary as we would be able to use a coherent light source, however due to budget constraints we must aid in the incoherent and divergent nature of the LED by supplementing the system with a collimating lens. Additionally, the collimating lens should have an anti-reflection coating to avoid stray light and back reflections in the system. These are important factors to consider as they may interfere with measurements in the system and result in unwanted efficiency values.

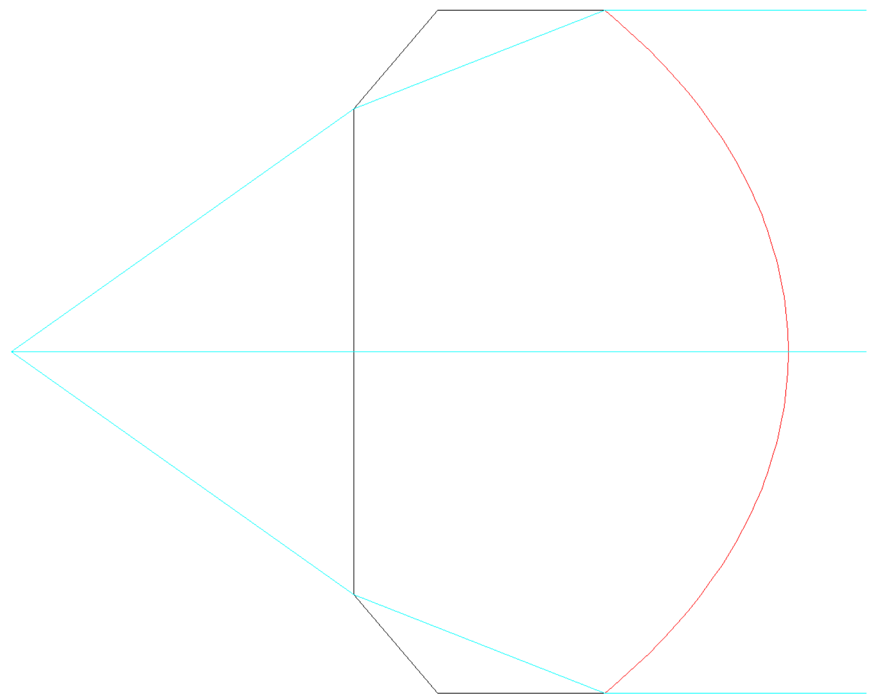


Figure 59: Collimating Lens Ray Tracing Lens Drawing

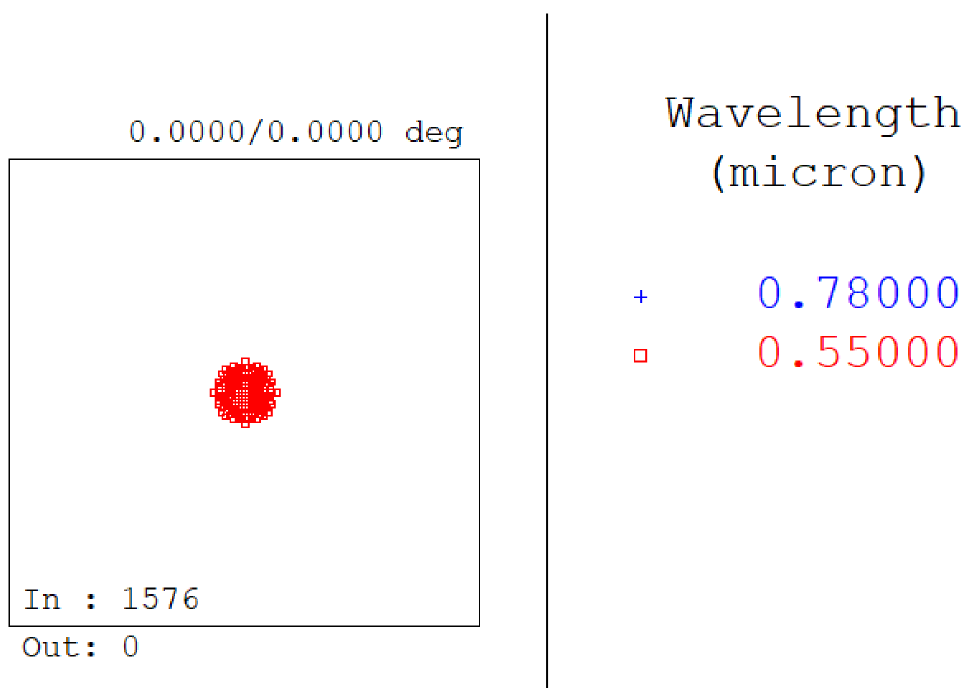


Figure 60: Spot Size of collimating lens at different wavelengths

5.4 Diffraction Grating Design

Our diffraction grating will be automatically set up in a littrow configuration to achieve the highest efficiency. This will be dependent on the blaze wavelength as well as the groove density. Our software will run the calculations and rotate the grating such that the incident light and the grating create an angle equal to the blaze angle for the chosen diffraction grating. Using this information, we can calculate the resulting diffracted angle to have the photodetector be in position to collect the diffracted light.

This will be a combination of two parts moving as a function of the angle of incident light. These measurements must be accurate as the nature of light can vary largely within a few millimeters. The equation used to obtain the diffracted angle for the following tables is the grating equation $n\lambda = d(\sin\theta' + \sin\theta)$ where d is the distance between slits, n is the diffracted order, λ is the wavelength being used in the system and θ and θ' are the incident and diffracted angles respectively. Using the blaze angle of our grating as the incident angle allows us to make consistent calculations concerning the input light in our system and eliminates the need to determine an arbitrary incident angle.

Blaze Angle = Incident Angle (Degrees)	Groove Density(lines/mm)	Blaze Wavelength(nm)	Diffracted Angle Violet Light (405nm) (Degrees)
2	300	300	4.96
5	600	300	8.96
10	1200	300	18.2
13	1200	400	15.132
4	300	500	2.96
8	600	500	5.96
17	1200	500	11.165
13	600	750	1.03
26	1200	750	2.73

Table 14: Diffracted Angle Comparison (Violet Light)

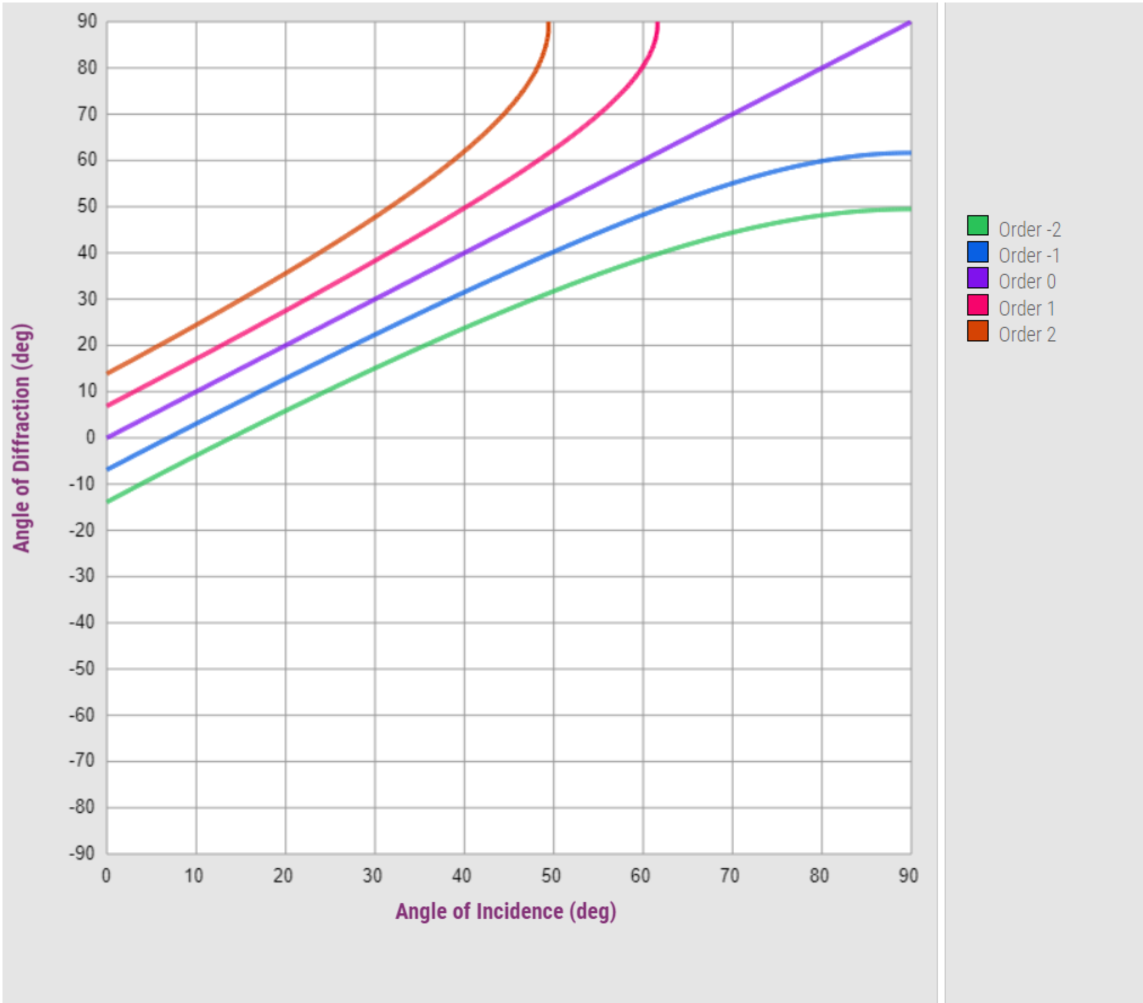


Figure 61: Angle of Incidence vs. Angle of Diffraction (300 lines/mm, 400nm Central Wavelength)

Using visible light we are able to obtain a diffraction angle value for all the tested grating configurations available to us. Because of this we can use this in a variety of testing and compare the efficiency to that of different wavelengths in our system. With UV light we are unlikely to observe high efficiencies using the gratings highlighted in red as their blaze wavelength is quite far away from the central wavelength of the LED being used. This means that our NIR light is more likely to outperform the UV light due to the design of the grating. We can utilize blaze wavelengths to achieve a high efficiency at a wavelength of interest and this is very important for various fields including spectroscopy and monochromators.

Blaze Angle = Incident Angle (Degrees)	Groove Density(lines/mm)	Blaze Wavelength(nm)	Diffracted Angle NIR Light (980 nm) (Degrees)
2	300	300	15.017
5	600	300	30.056
10	1200	300	N/A
13	1200	400	72
4	300	500	12.958
8	600	500	26.67
17	1200	500	62.08
13	600	750	21.288
26	1200	750	47.53

Table 15: Diffracted Angle Comparison (NIR Light)

These tools can be used to observe a particular wavelength of interest which is where efficiency can be incredibly important. The total output light is dependent on the grating so we may not observe emission peaks if our efficiency is not high enough. This is useful data as it provides a rough idea of the calculations necessary for the rotation stage to capture the highest efficiency of the grating. Similarly, we can also observe how the different characteristics of the grating greatly affect the diffracted angle for first order light. These calculations do not include second or third order light as it results in a lower efficiency for the greetings of interest.

Near infrared light has a lower success rate than that of UV light. We can also see much higher diffraction angles showing us how as wavelength increases we can observe an increase in the diffraction angle. However, we are likely to observe a higher efficiency using the gratings highlighted in red as they have closer blaze wavelengths to the near infrared light than the UV light used in the previous table.

Comparing this table to the previous one we can see how our system will be able to observe different frequencies depending on the characteristics of the grating being used. These characteristics can be measured using a variety of central wavelengths. Compatibility for a variety of gratings is a fundamental goal of our project so the algorithm being run through the board and rotation stage must ensure that we have accurate placement for the incident and diffracted light. Additionally we must be able to capture not only the zeroth order and first order but second order light is important as well. Our main focus is first order light as that is what is typically used for spectroscopy but additional orders are also important to consider as it relates to the total efficiency of the grating.

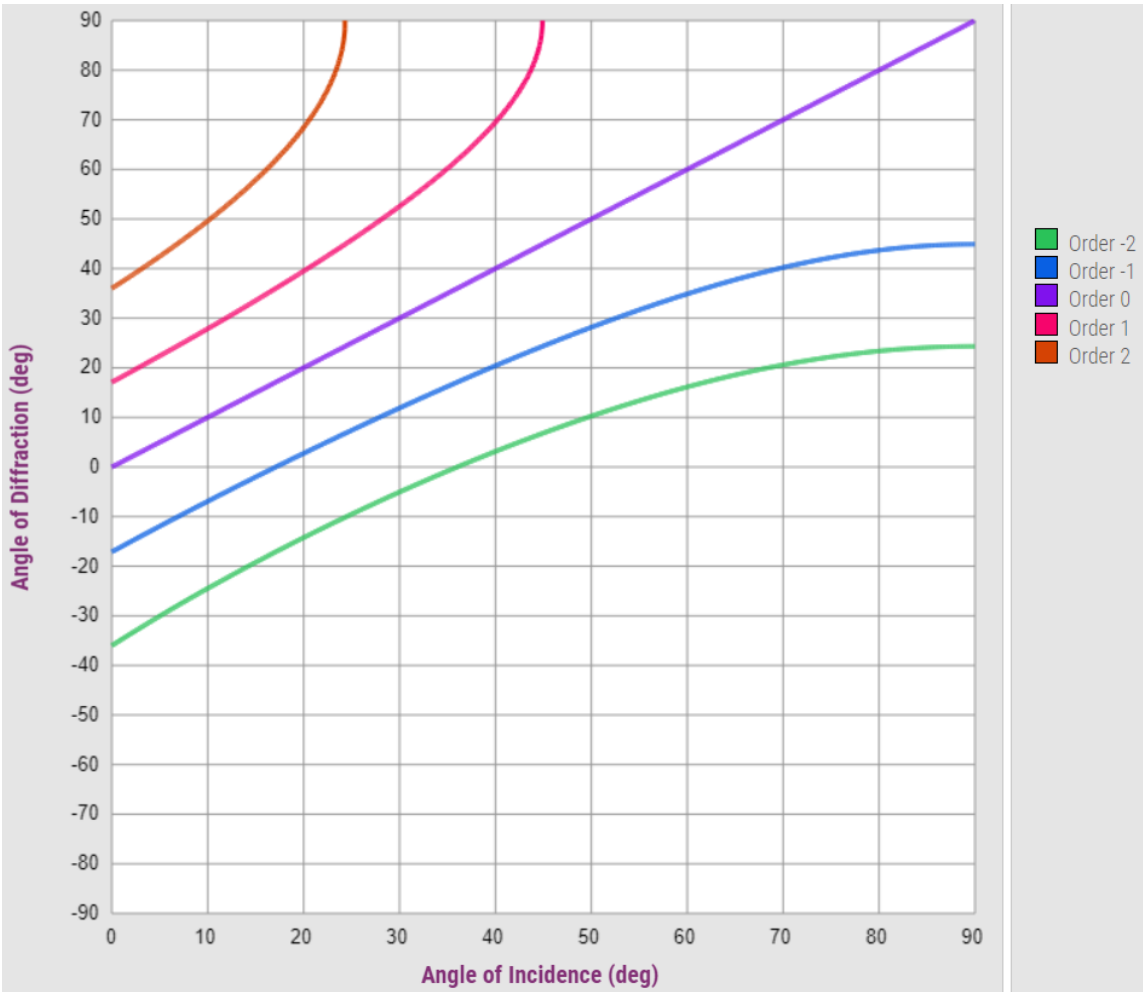


Figure 62: Angle of Incidence vs. Angle of Diffraction (300 lines/mm, 980nm Central Wavelength)

5.5 Arduino Integration Design

The microcontroller we chose to use was the Arduino Mega, there were a few reasons for this. The first reason was that the LCD we chose to use on this project came with an added shield which would allow us to further the capabilities of the processor. In addition this shield that came with the LCD is able to be fully mounted on top of the Arduino Mega making this extremely easy to set up. The second thing that the Arduino Mega board allows us to do is add multiple connection points, this will be useful when we need to add our stepper motor, LCD, and servo motor connections.

5.5.1 Stepper Motor Integration With Arduino

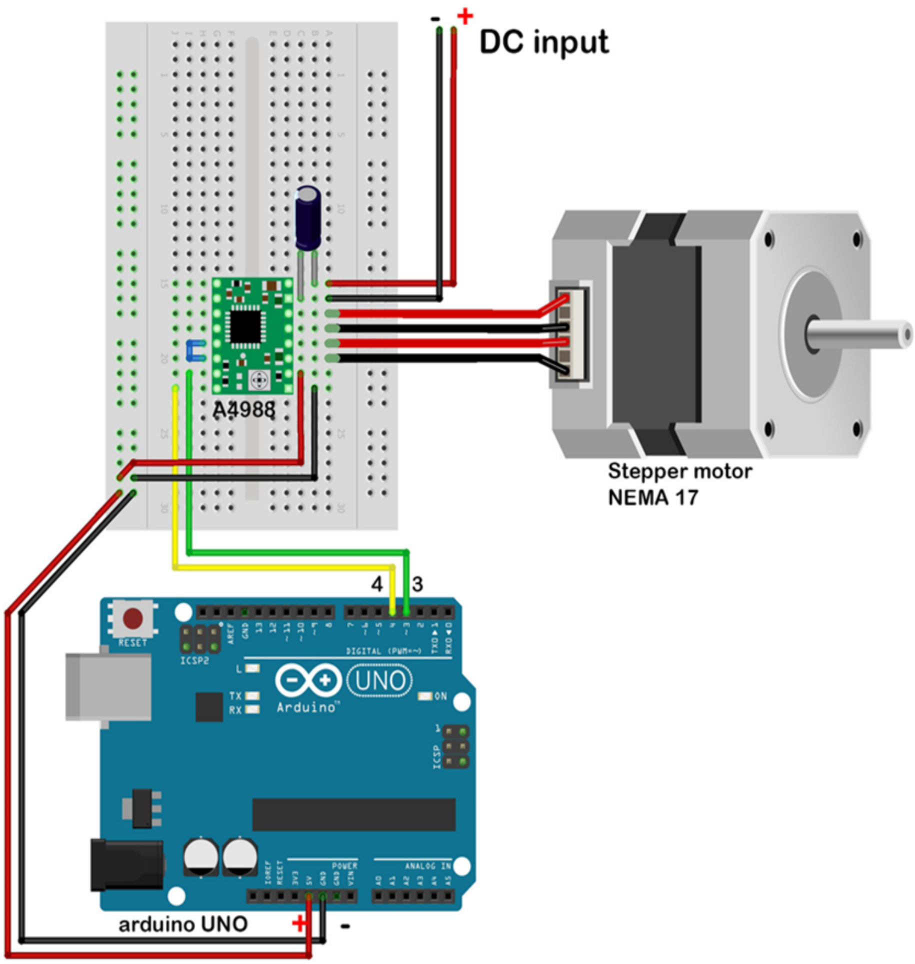


Figure 63: Breadboard Setup of Stepper Motor from Befenybay Linear Stage Actuator

Note: Superb Tech. (2018). Control Stepper Motor with Arduino - Tutorial. YouTube. https://www.youtube.com/watch?v=_jTYygbOTuI&ab_channel=SuperbTech.

The schematic in figure 74 is a setup that connects the stepper motor of the Befenybay Linear Stage Actuator to the Arduino microcontroller. In this schematic the stepper motor connects to an A4988 stepper motor controller, the Arduino microcontroller and an outside DC input. The DC input will be provided by our NiMH battery previously selected in the research portion of the report.

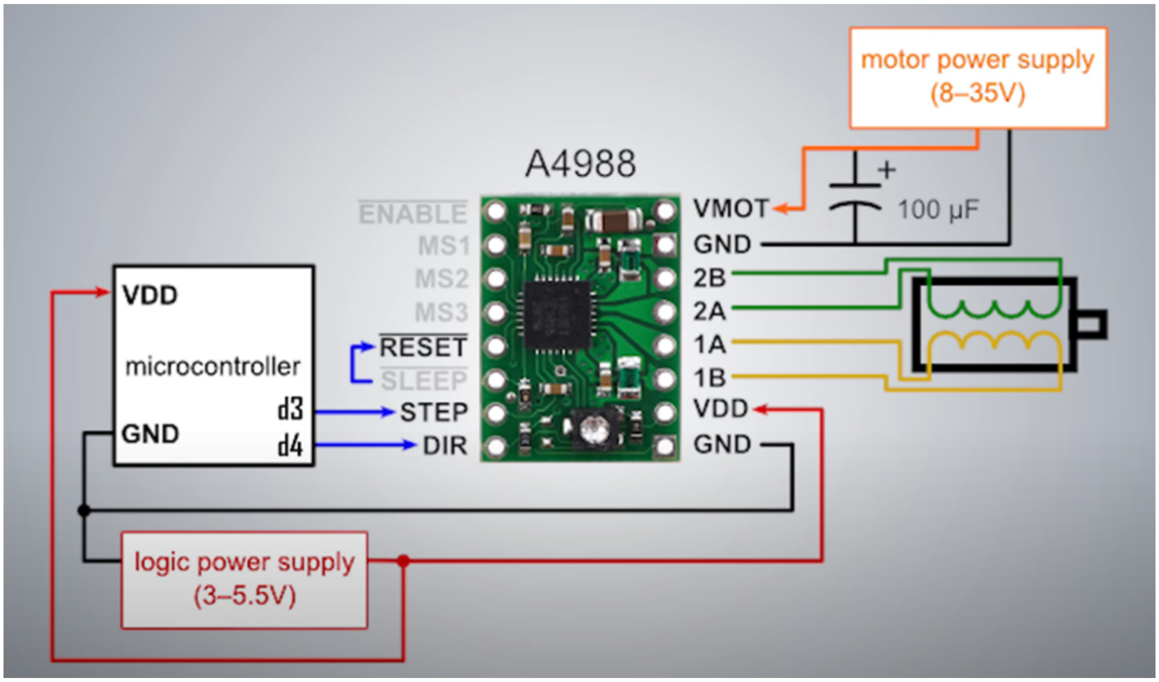


Figure 64: Schematic of A4988 Stepper Motor Controller to be Used With Befenybay Linear Stage Actuator

Note: Superb Tech. (2018). Control Stepper Motor with Arduino - Tutorial. YouTube. https://www.youtube.com/watch?v=_jTYygbOTuI&ab_channel=SuperbTech.

Figure 75 is the enhanced version of the specific connections to the A4988 board, in particular we want to look at how the stepper motor connects with the stepper motor controller. On the right side we see the 4 stepper motor connections labeled 1A, 1B, 2A, and 2B. In order for the stepper motor to work properly the stepper motor must be connected to the proper pins on the stepper motor controller.

In addition to this the stepper motor controller has two power inputs, one of which is for the controller itself which will be powered by our microcontroller, in our case that would be an Arduino Mega. The second power input will be from the external battery which will be powering the bigger components.

5.5.2 Servo Motor Integration With Arduino

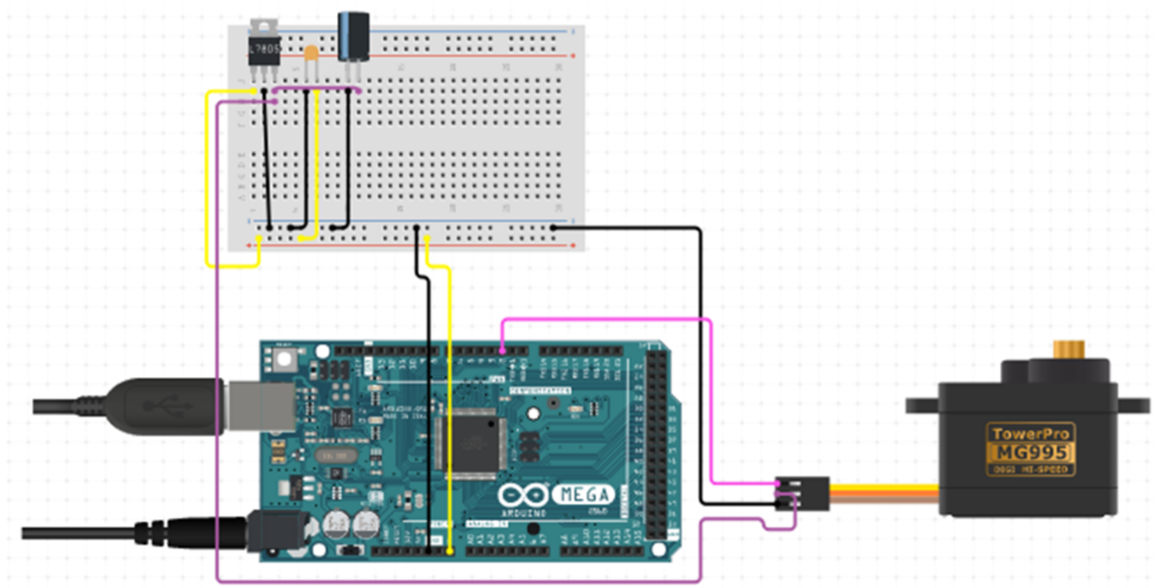


Figure 65: Schematic of Servo Integration into Arduino Board

Figure 76 shows the schematic that will be replicated in the final project where the servo that will be used to power the rotation stage will be powered by the Arduino Mega board. Normally a servo like this could be plugged into the Arduino Mega without the need for the voltage regulator and capacitors and breadboard, but since we want to maintain accuracy and maximum servo control, we will use a voltage regulator. This voltage regulator will take in the 5V power the Arduino Mega board outputs and will ensure that the voltage the servo receives is constant and unwavering which would result in inaccuracy on the rotation stage.

If we went a different route, we could also incorporate our power supply into the circuit as well to take some load off of the Arduino Mega. The angle of the rotation stage is a crucial component to the automation aspect of our project. Inconsistencies in angular measurements can result in lower than expected efficiencies in the grating resulting in gratings potentially falling short of what is expected. The arduino board chosen will ensure that the degree measurements are consistent and allow for consistent and accurate measurements for our diffraction grating. Since the servo motor has a built in controller we can directly connect it to one of the PWM slots on the Arduino Mega board and control the servo's rotation with the software we develop.

5.5.3 LCD Integration With Arduino

The 7" LCD display that was previously chosen to be incorporated into this project is a 7" capacitive touch LCD. The model we chose in particular comes with a separate board which the display connects to, this separate board then connects directly to the Arduino Mega. In our case we will not be directly mounting the display on top of the Arduino Mega, but rather have wires that will connect the two boards which will allow us to place both the Arduino Mega and the LCD wherever it is needed. In figure 77, the LCD shown is a smaller 3.5" display but the concept remains the same, the Arduino Mega will be wired to the LCD shield board which will then be attached to the LCD. All of these components will be powered by our power supply which although most likely won't be a 9V battery is represented by the 9V battery in the diagram. In reality the battery we will be using is a 12V 2000 mAh.

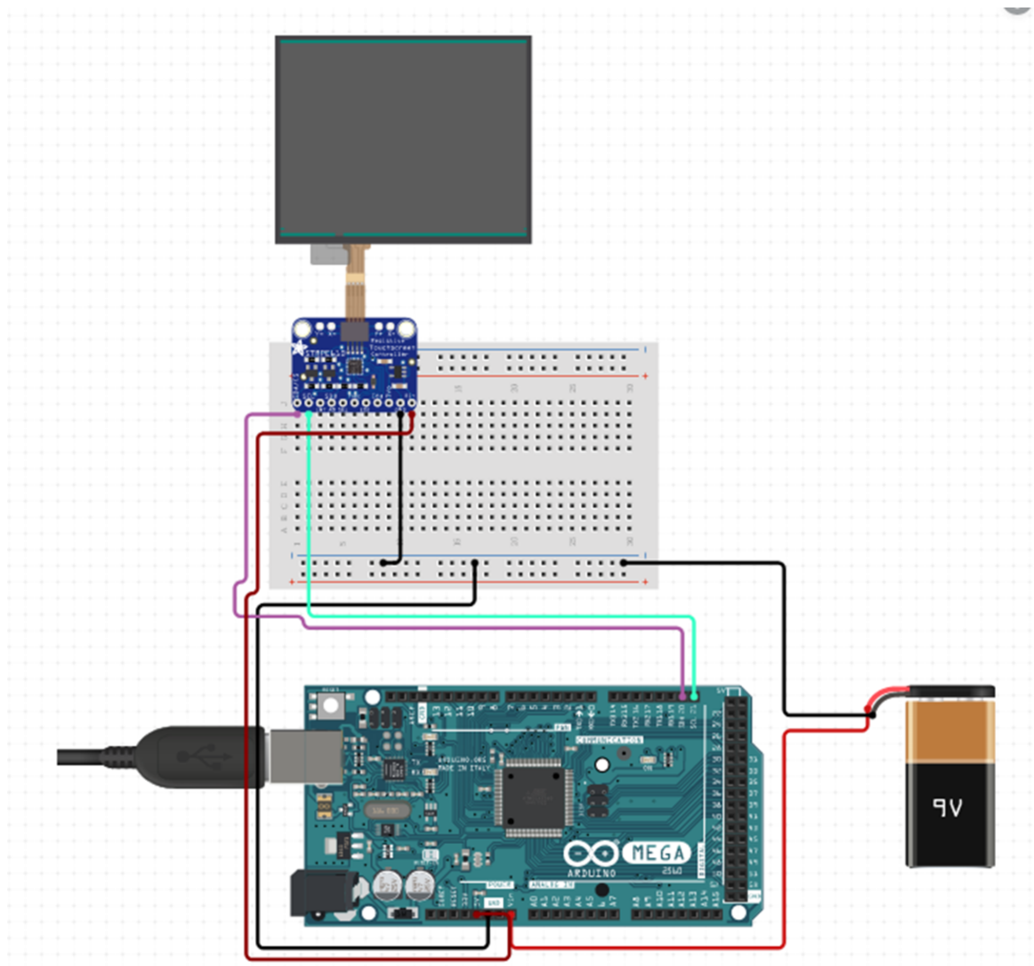


Figure 66: Schematic of LCD Implementation into the Arduino Mega Board

5.5.4 Fully Integrated Arduino Design With Components

The fully integrated design of the LCD display, stepper motor and servo motor with the Arduino Mega are seen in figure 78. In this display there will be two differences from the final project, the first of which is the power source for the Arduino and the accompanying components, in this schematic they are powered by 8 AA batteries which provide 12V of power, in our project this will be powered by the voltage regulator built by us which will use a 12V 2000 mAh NiMH battery as the power source.

Secondly the LCD in this schematic is the 3.5” touch screen LCD variant, whereas in our project we will be using the larger 7” LCD touch screen with capacitive touch. The stepper motor in use will be the same Nema17 except the stepper motor control may be different, but the connections will be the exact same no matter what controller is used since the 4 output wires from the stepper motor will always be the same.

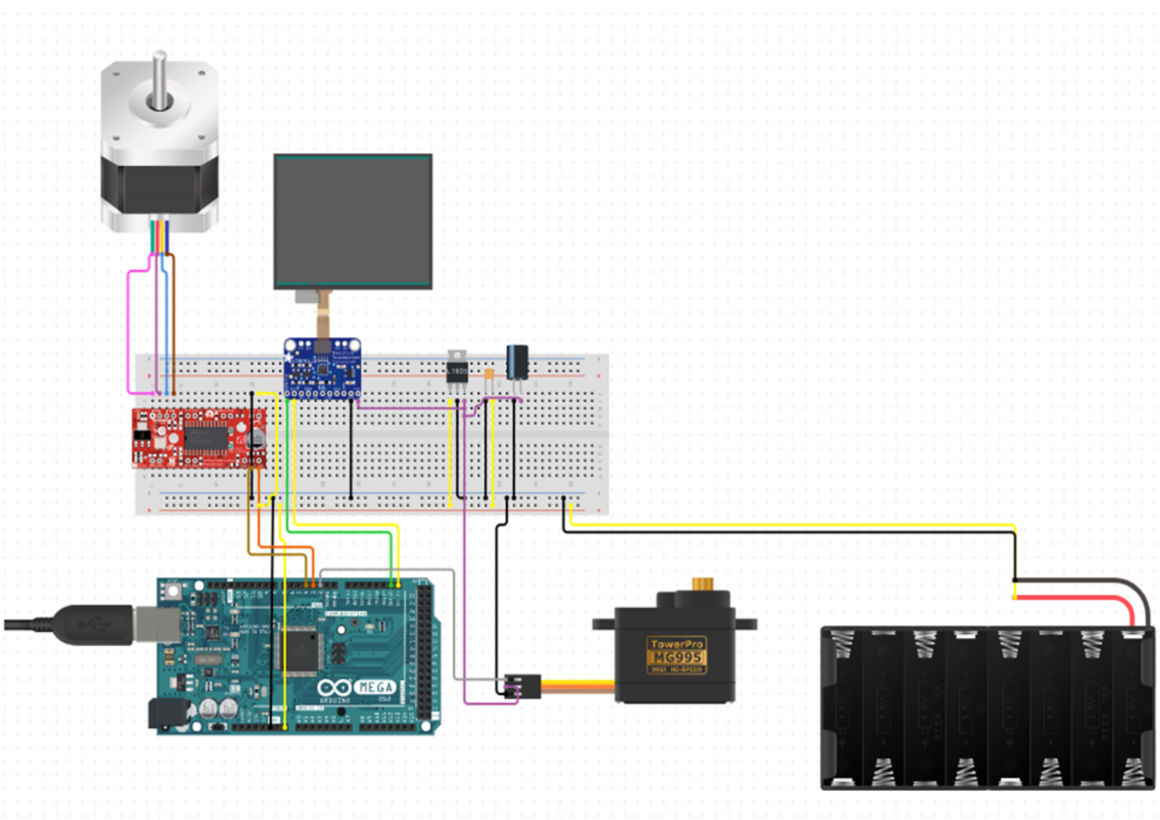


Figure 67: Schematic of All Components Attached to Arduino Mega

5.6 Building Facilities and Additional Materials

In terms of facilities needed in order to build and test a prototype, a standard laboratory with tabletop space will be enough to test our project. Ideally, an optical table would be used to mount the optical side of the project. That said, it isn't a requirement to have an optical table and is more of a convenience as it can assist with the accuracy of alignments and positions of the parts that will be used to make measurements on the light source.

For the MCU testing and its connections, a simple breadboard and wires can be used for prototype testing. It also doesn't need to be directly on the optical table, but it will need to be within wiring distance to the photodetectors present in the design. If the power source isn't being tested in conjunction with the other parts of the project, a dc voltage source will be needed to power the MCU, display, motors, and light source potentially.

To test the power supply prototype, we will need either a multimeter and oscilloscope which can be found in the laboratories on UCF's main campus, or we will use the test packs that we can sign out for the Senior Design I and II lab kits.

5.7 Alternative Design Considerations

We have considered multiple approaches for the spectrometer design as each one varies in terms of price, ease of implementation, time needed to create the parts, and the resulting accuracy of the design.

The current design makes use of multiple laser diodes with varying wavelengths of light we can use as the light source. This design choice was intended to take the place of a light source such as a monochromator, as we need a way to measure multiple wavelengths of light. The feasibility of this design isn't perfect as a laser diode doesn't cover as large of an area as we would prefer to have with the light source which means the beams would need to be both extremely accurate in terms of placement in order to measure correctly. If we wanted to have an easier time measuring the light, we would ideally need to use up to 100 individual laser diodes which just wouldn't be economically reasonable, nor would it be feasible with the amount of space or weight we intend to take up. Using this many diodes would make the spectrometer fairly large and require more structural integrity and while there isn't a specific weight limit for the project, there is a power consumption limit we want to maintain.

To account for this, we planned to use around 4 or 5 laser diodes with different wavelengths of light. This of course limits the range of light we can measure, but it does drop the costs of the project by a noticeable amount as a single laser diode isn't very expensive in comparison to a monochromator. The reason a monochromator is the ideal light source for the spectrometer is that it allows you to choose from a range of wavelengths of light with a single device. This would make implementing the light source into the design much simpler as there wouldn't be as much extraneous setup required to adapt the use of different light sources into the design.

The only issue in terms of feasibility would be both acquiring the monochromator along with the increased price of the product itself if you wished to put it on the market. Monochromators, of course, are available in a range of prices but in comparison to a laser diode which is well under a $100 even on the higher end side in most general use cases, monochromators that would work for our project design are typically in the $1000s in comparison. This isn't unobtainable but considering this is only a singular part of the project, this could present issues when it comes to budgeting/financing our project unless the part was provided by a sponsor/supplier.

Then there's the marketing of the product to consider. The market size that would be able to obtain this product would be more limited with the use of a monochromator as this part would increase the price of the overall product. The industries that need this type of product would have the budget for this product as they are aware of this and are prepared to account for that aspect. That said, the product would need to stand out in some way from what is already available on the market which was one of the underlying principles behind the project idea to begin with. While we knew that spectrometers were not going to be a type of product that you could spend $100 on if you wanted the capabilities that you'd expect from a $1500+ spectrometer, we were attempting to design a product that would have similar levels of accuracy and ranges of use to the more expensive products while being at a lower price relatively speaking. This plays into the design choices as a monochromator would help on the engineering side of things, but could potentially lead to negative effects to the marketability of our project.

Moving on from the light source, we also considered different ways to separate and/or diffract the light that differ from our current design choice. Those ideas included:

1. White light source using a prism to separate the light into the wavelengths we want to measure
2. Using different wavelengths laser diodes along with a beam splitter
3. Using a monochromator with a series of mirrors to refract the light accordingly

The design that incorporated the prism was an initial design choice since it could potentially cut down on the cost of the project without sacrificing too much when it came to the range of light wavelengths we could measure. It did come with its own set of difficulties though. One being we'd have to design the prism with both the materials we needed and the exact measurements we'd need for our product implementation. The measurements themselves wouldn't be difficult to determine, but in terms of time and manufacturability, we would be somewhat limited given the timeframe we have to design and build this project. If the measurements were wrong or if we changed the design a little later on, changing the prism wouldn't be as simple as just adjusting the position for a prism. There's a possibility we'd have to alter the prism's design altogether and order a new one. If this occurs more than once or twice, we could potentially run into financing issues on top of the already present time and manufacturability constraints present. The potential price savings that could be made would be thrown out the window if each and every spectrometer would need a different prism design for each product.

The accuracy of the measurements also differs when using a prism as the light is being refracted/bent through the prism rather than being deflected like it would be with a mirror. The choice of material used in the prism design as well as the angles at which the light is traveling through the prism could then play a factor in the resulting measurements. Whether that would be a positive or negative effect on the measurements would of course depend on the materials, but we don't want that result to be undetermined until measurement as those results will determine whether we need to alter the design or not. In terms of time, we'd rather not want to be too concerned with this if we can alternatively use a combination of mirrors and lenses to accomplish the same task with less variability.

With the design utilizing the laser diodes, a beam splitter was implemented in line with the lens that the light beam would be traveling through. This part would be used to allow for the measurement of the power of the light before and after it reached the diffraction grating station. This measurement would be needed in order to determine the grating efficiency. Since this design would be using multiple light sources with varying wavelengths, it would effectively replace the use of the prism while also giving us more room for modifiability without having to sacrifice the general project design. The degree of accuracy would be dependent on the effectiveness of the combination of a beam splitter and the diffraction station. In terms of potential project adjustments though, most changes that may be required could be fixed with positional changes rather than the redesigning of crucial parts in the design. This would cut back on the time needed to manufacture more products, but increase the total number of parts present in the design.

In a similar fashion, a design using a monochromator could be implemented in a similar manner to the current design. The difference would be that the beam splitter would be replaced with mirrors which would be used to get the light to the diffraction station. This design could potentially use more space than the current design, but make up for that by having the highest degree of project modifiability as we'd have the most potential range for the possible light wavelengths we could measure.

Each design has its pros and cons, but the current design gave us the most accessibility in terms of parts we could acquire that would satisfy our self-made project requirements, as well as our budget, time, and manufacturability constraints on top of all the others. The monochromator isn’t ruled out from the design either, assuming we could obtain one. At the moment though, we went with the design which will use laser diodes.

5.8 Software Design Details

The Software build for our project will have two main aspects: 1) Adjusting the apparatus to the correct positioning, and 2) Detecting the power reading of the light hitting the photodetector and outputting the efficiency of the power reading coming off the grating station for each associated wavelength. Furthermore, outputting these results in an easily readable way to a display for the user to read will also be a task handled by this part of the software.

5.9 Semi-Automated Adjustment Software Design

The 1st aspect, adjusting the apparatus will be split into two parts. The first part involves moving the lens to the appropriate position. The entire project will essentially revolve around the lens and whether it collects the light correctly before it hits the diffraction grating. The distance between the lens and the light source will be given by the user of the device in order to let the system move the lens to its position.

This will be given to the MCU and through the use of a motor, the lens will be moved either forwards or backwards on a translation stage. The accuracy of this movement is what’s important, which is why we want it to be semi-automated in the hopes of having a higher degree of correctness than doing this adjustment by hand. The next part will be to modify the angle at which the light hits the diffraction grating. The angle will be the input for this part and a rotation platform will be moved using a separate motor in order to get the diffraction station where the user needs it to be for the efficiency rating.

5.10 Data Handling Software Design

The 2nd aspect of the software will be to detect the light and display the collected data to our LCD Display. The light detection will be handled by the photodetectors which will give the data to our MCU. The data should be collected both before and after the diffraction grating station in order to determine the efficiency of the power reading we get from the light source. The reading should also be separated by the wavelength of the light that is being detected.

A continuation of the 2nd aspect of the software will be displaying the data to the user of the system. The LCD Display will be our user interface for the output (and input?) of the data. The information we choose to display will consist of the Grating Efficiency, and the power reading of the light coming from the diffraction station and its associated wavelength. The grating efficiency will be a percentage based on the power of the light before it hits the diffraction station, and the resulting power after it is diffracted.

5.11 LCD User Interface Design

The LCD we chose to use for this project was a 7” capacitive touch LCD screen, this means that we have a relatively large area of workspace. In addition, we also have capacitive touch capabilities which will allow us to use multiple points of touch at the same time. Whether this ends up being used we do not know but it will be leveraged as a tool by the user if they want to adjust multiple things at the same time.

The graphical user interface itself must accomplish two main goals, the first is to take user inputted data whether this be typed out by the user, or via touch buttons that allow users to adjust a number on screen. The second goal of this UI is to have an easy-to-read display that displays all necessary information easily and readily. This means that no colors are conflicting, the font sizing is right, the tabular output data is easy to read etc.

5.11.1 First Iteration of LCD User Interface Design

The display we plan to use is a 7” capacitive touch LCD display, which means that screen can be manipulated by more than one touch at a time. For example, if you wanted to zoom in or zoom out with two fingers this screen would allow you to do so, but if you were to use a resistive touch screen only one of those touches would register as an input.

For the mock up of the graphical UI, the parts that are manually adjustable for now are the groove density and the manual rotation. The groove density will be able to be adjusted via the plus and minus signs below the title. The plus and minus signs will be used as buttons which will either increase or decrease the value on the right. If the buttons are held down the input will increase much faster and if they are tapped slowly they will increment by 1.

For the manual rotation the plus and minus symbols act as buttons which will rotate the servo attached to the rotation stage. In the future this section might be adjusted to display which angle it corresponds to so that if you hit the reset button you know where you left off at.

The auto rotation button will cycle through all the possible positions of the servo and determine which position creates the greatest grating efficiency. The higher the efficiency means the position in which the rotation stage is, is optimal.

The reset button will simply be a button that will return the translation and rotation stages to a neutral position whether that be directly in the middle or on either one of the edges. This will give the group a baseline number in which we can always return to if needed.

The 4x4 grid on the right side of the example user interface is designated for the data we will receive from the photodiodes. As of right now the most likely way of displaying this information will be in a table rather than a graph.

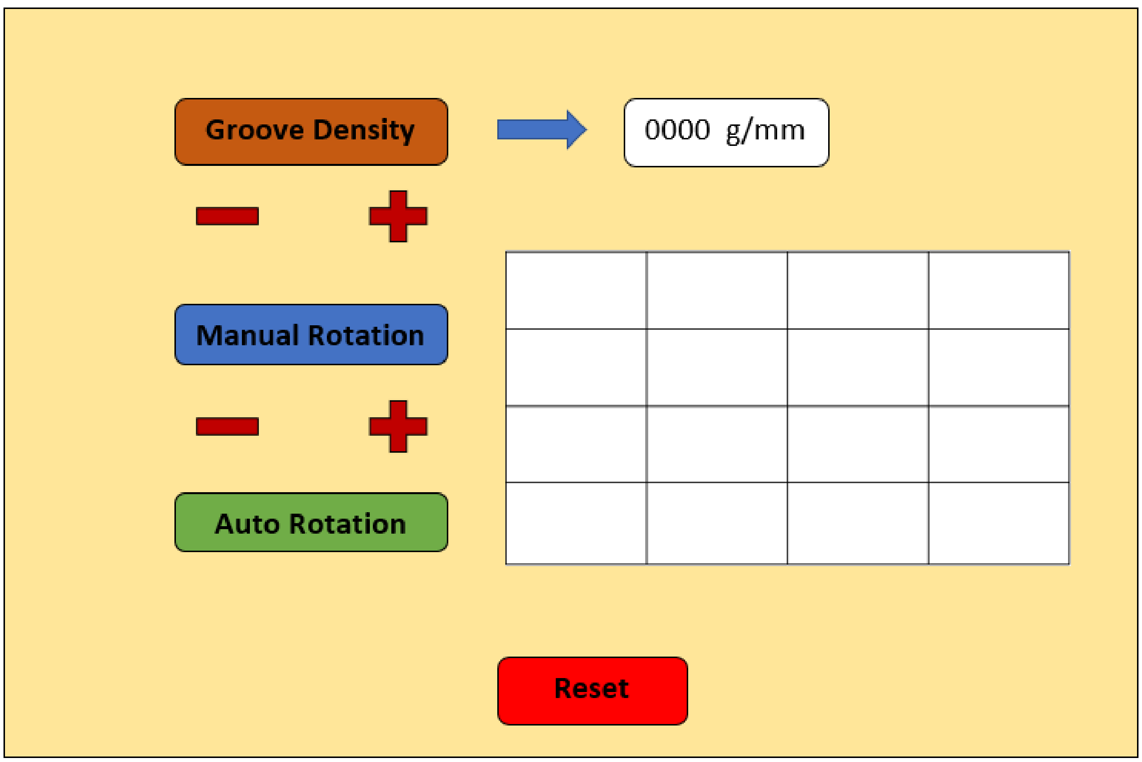


Figure 68: First Iteration of LCD User Interface Design

5.11.2 Second Iteration of LCD User Interface Design

The second iteration of our LCD User Interface carries over previous design elements such as the groove density adjustability, the reset button and auto rotation. Again the reset button will simply be a touch button that will return the translation stage and rotation stage to their corresponding neutral positions. The neutral position will either be positioned to either end of the rotation and translation stages or be placed in the middle of their axises.

The main change between the reset button in the first iteration and the second iteration is that the text on the reset button is outlined with white so that it is easier to read, while also keeping the red button to indicate that something will be deleted or in our case reset.

To further simplify the design the output data which will be represented in the 4x4 table has been put center stage to make it both bigger and easier to read. The manual rotation button has been removed because in reality the auto rotation would find the most optimal setting thus removing the need for manual rotation, this further simplifies the user interface with less buttons.

The biggest change overall is the white text boxes that will sit on top of the colored buttons so that the text on the buttons is easier to read. The gray background will provide a contrasting background while also being pleasing to the eye.

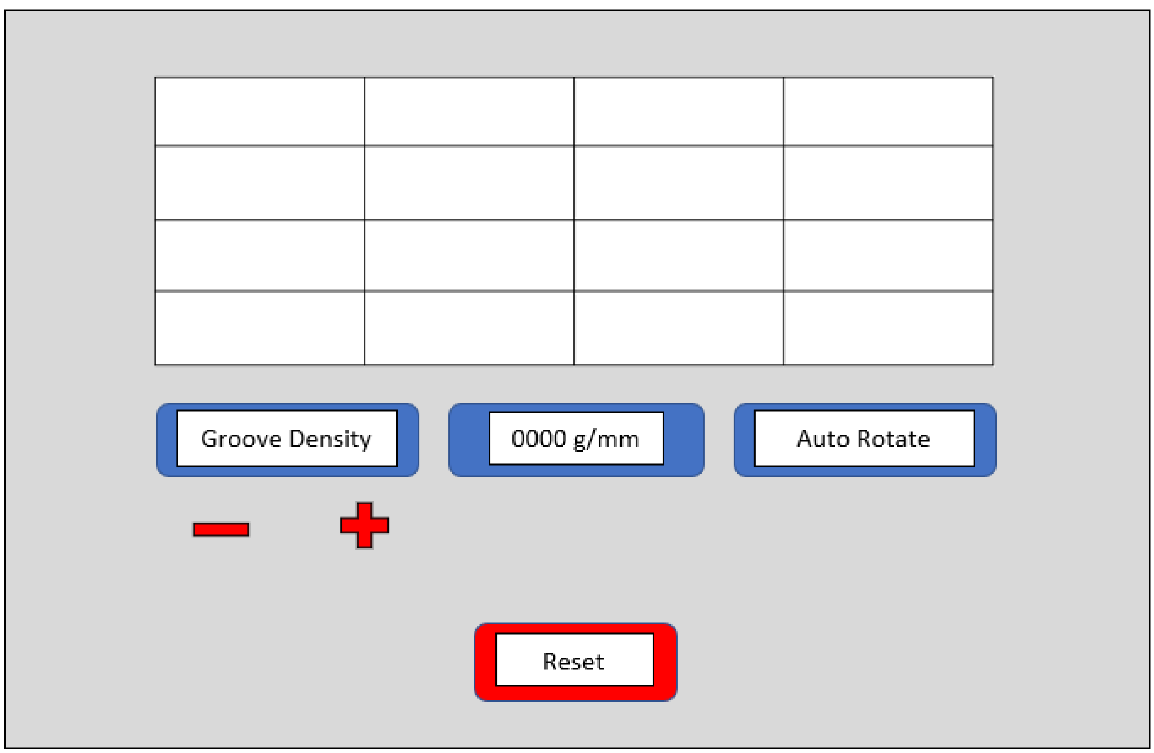


Figure 69: Second Iteration of User Interface Design

5.12 Software Flowchart

The software for this project will be in charge of taking in user input via a touchscreen display and converting these inputs into motor movements on the project. In addition the software will be displaying the user interface and all relevant data, this will include the output data which the microcontroller will compute. The software will need to collect data from two different photodetectors and then compare their data to create an efficiency value to be output to the LCD. The system will also need to be able to constantly update this information and use it quickly to fulfill the auto rotate function. Finally there will be a reset button on the LCD that when pressed will reset the groove density which will in turn reset the stepper motor to a neutral position that we will designate later. The same will be done to the servo motor operating the rotation stage, rotating the stage to a neutral position.

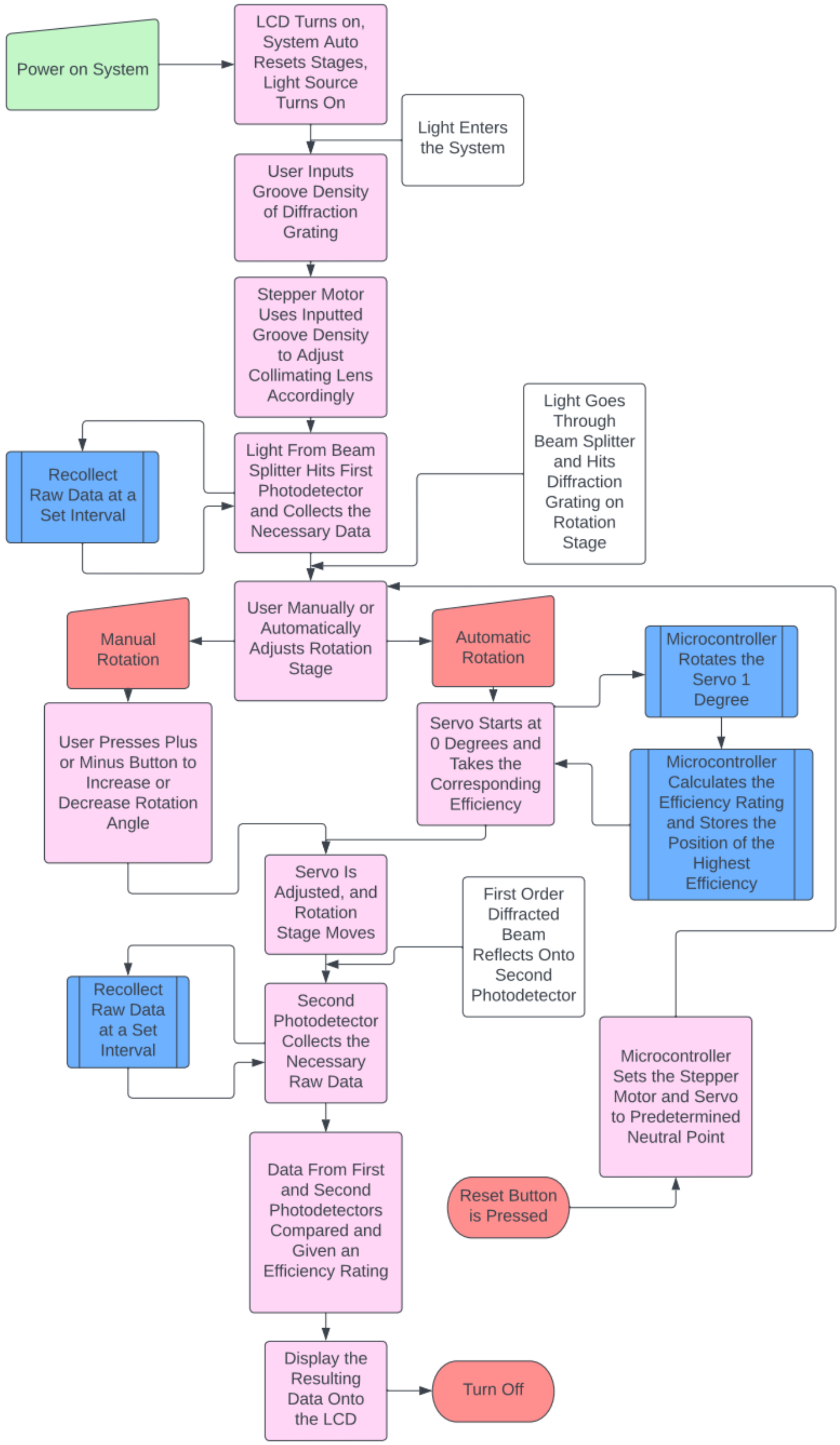


Figure 70: Software Design Flowchart

6.0 PCB Design and Testing

This section will cover the methods that will take place in order to ensure that parts and measurements are taken accurately. These steps will ensure that the project runs smoothly and consistently over a long period of usage. Thorough testing is a vital part of the manufacturing and design process that results in a successful project.

6.1 LED Testing

Several tests will be done to check and confirm the characteristics of the LEDs used in our project. This will include determining the divergence angle, characteristic wavelength, power output, and intensity. To measure the divergence angle we will observe the spread of the light from the LED. Because we are using an LED this will result in a relatively high divergence angle and incoherent light. However, this can be circumvented through the usage of the various lenses and optical iris. This will limit the amount of light in the system and the path the light will travel through the system. The divergence angle is particularly important as it determines the characteristics of the lens we would need to use and the beam spot size we can achieve on the photodetector as well as the resulting placement.

The characteristic wavelength is the next item of importance pertaining to the LEDs. This will be done using a broadband spectrometer to identify the peak wavelength of the led. Determining the characteristic wavelength is important as it determines the point at which we are measuring the efficiency of the grating. Because of the design of our system, we can only speak to the efficiency at the exact wavelengths we are measuring. This condition results in the wavelength of the light sources being incredibly important as it is the basis of the measurements we are taking for the project.

The power output and intensity are the final items to consider when testing the LEDs for their performance. We must ensure that the light output is enough such that there is sufficient light traveling through the system to be picked up by both photodetectors in the system. The light is being split in half so there must be a certain level of light to be discernible by the system. We will measure the light output using a power meter collecting a similar amount of light that the photodetectors would.

6.2 Lens Testing

Testing of the lenses is similarly a crucial process in the design of the project. Finding the real effective focal length of the lens is important as the listed focal length could vary in real-world application. Knowing this, we must trial several focal lengths to determine where power output and focus for the LED is the highest. We also have to test to ensure that collimation results in a small enough beam spot size to fully land on the photodetector. We aim to collect as much light as possible on the photodetectors. Similarly, the amount of light on each photodetector should be as similar as possible as it is the only way to ensure that the resulting efficiency measurement is accurate. Both focusing and collimating lenses must be thoroughly tested to eliminate potential inaccuracies in recording measurements and power output.

6.3 Beam Splitter Testing

Testing of the beam splitter should be simpler than the previously mentioned elements by comparison. The two main characteristics of concern are the reflection and transmission ratio as well as losses to diffraction. To do this, we must first measure the total light output of the LED. Afterwards we can set up the two photodetectors in a simple setup where the reflection and transmission can easily be measured. If the reading on both photodetectors is within 1-3% of one another we can determine that the beam splitter is valid for usage in our system. If we notice light scatter we can attempt to minimize the amount of loss due to diffraction by adjusting the angle of the beam splitter to accommodate for the losses.

6.4 Diffraction Grating Testing

The diffraction grating is the foundation of our system and the main focus of our project. For this reason, testing of the grating to predetermine the efficiency of the grating is vital. To do this, we will conduct a manual measurement for the efficiency of a variety of gratings. We will have the values for the efficiencies at the four designated wavelengths. These values will be used as references for the semi-automation component of our system. We can then compare the values obtained from the semi-automated test to the manual one and determine the closeness in value. We expect to see the same efficiency with both systems and a consistent measurement for the efficiency of the grating.

Another important characteristic to consider with the grating is the blaze wavelength and dispersion. For semi-automation in our system to work we must ensure that the grating has a consistent groove density such that the spread is the same throughout the length of the grating. An overarching goal for our project is ensuring consistent long-term results with the measurements we obtain.

6.5 Optical System Testing

Once accurately determining the characteristics and parameters for our individual parts we must assemble and begin to test the entire optical system with the parts. This will be the most time consuming portion on the optics front as it requires many moving parts and components that must work synergistically to ensure an accurate measurement for the efficiency of the grating. The testing will be to ensure that the calculations that are run through the system and components move in such a way that light is received by the photodetector after being focused, collimated and polarized. Three gratings will be tested with different groove densities and blaze wavelength, this will be done to ensure that the system is viable for a variety of gratings for the interchangeable nature of our system.

6.6 Software Testing

Testing the software can be done two ways. Since part of the software will involve physical adjustments to the positions of parts of the project, we can test this part of the system by either measuring the movements by hand, and/or electronically if we want to see the precision of the movements. The coding itself will have multiple testing phases. We can do tests with the connections initially just to check and see if the parts are all connected correctly. This may be needed since the programs will typically run as long as the code is correct in terms of syntax.

To check for any connection errors, we can run simple runs just to make sure the parts all function. Checking parts individually before we make the final build will also help identify any malfunctioning parts rather than doing everything together at once. Once we know the parts are working, we can write in the code for each part and test them individually first and then all together to check for any errors that may not be present when running simple tests. Some issues only occur after sustained use, so testing the system live after repeated use over a time period that is higher than what we'd expect the use time to be (Ex: 30 minutes of repeated use with different input values in a successive manner) will help test for sustainability and the integrity of the part structure.

For the data analysis, we will first test to see if we can collect data that appear to be correct based on the calculations used. If we see numbers that appear to make sense, then we can fine tune the system and compare our values to the actual expected values we'll have for reference. While getting them to match exactly will not be the requirement considering different testing equipment is likely to not get the exact same results, we want our measured results to be within at least a 10-15% margin of error at the highest. A smaller margin of error would be desired, so we can adjust the system's positioning either manually or using the software if we find our measurements to be too far out of the desired range and check to see if the issues are software related or hardware related.

6.7 Photodetector Testing

Due to the nature of design relying on relativistic measurements. The calibration for our photodetectors must be consistent with one another, the actual individual measurements are not necessarily as important. However, having an accurate light measurement for the incident and diffracted light still provides users with additional information pertaining to the efficiency of both the grating as well as the light source. A viable method for calibrating the photodetector would consist of using a light source with a known power output and shining the light directly onto the photodetector ensuring that all the light is captured on the active area. Additionally, using a surface such as a mirror with a known reflectivity could prove beneficial to the calibration of both the grating and the photodetector. A mirror with a silver coating can achieve reflectivity of over 99%. Photodetectors should be calibrated over regular intervals to ensure that measurements are accurate and the elements recording data are unwavering.

In this Circuit above, after we mount and solder every part, we will have a 12 volts battery connected to the input USB and as we mentioned in the previous section, then the output will provide 5 volts constant voltage as the 12 volt battery decreasing by fluctuate over time, our output will still be 5 volts. To sum up, this final printed circuit board layout of our VLR has been designed in eagle software using skills that we learned in our previous classes like Junior design. As can be seen, we model the same technique we did for previous assignments but in a different way.

6.8 Arduino Mega Connections PCB

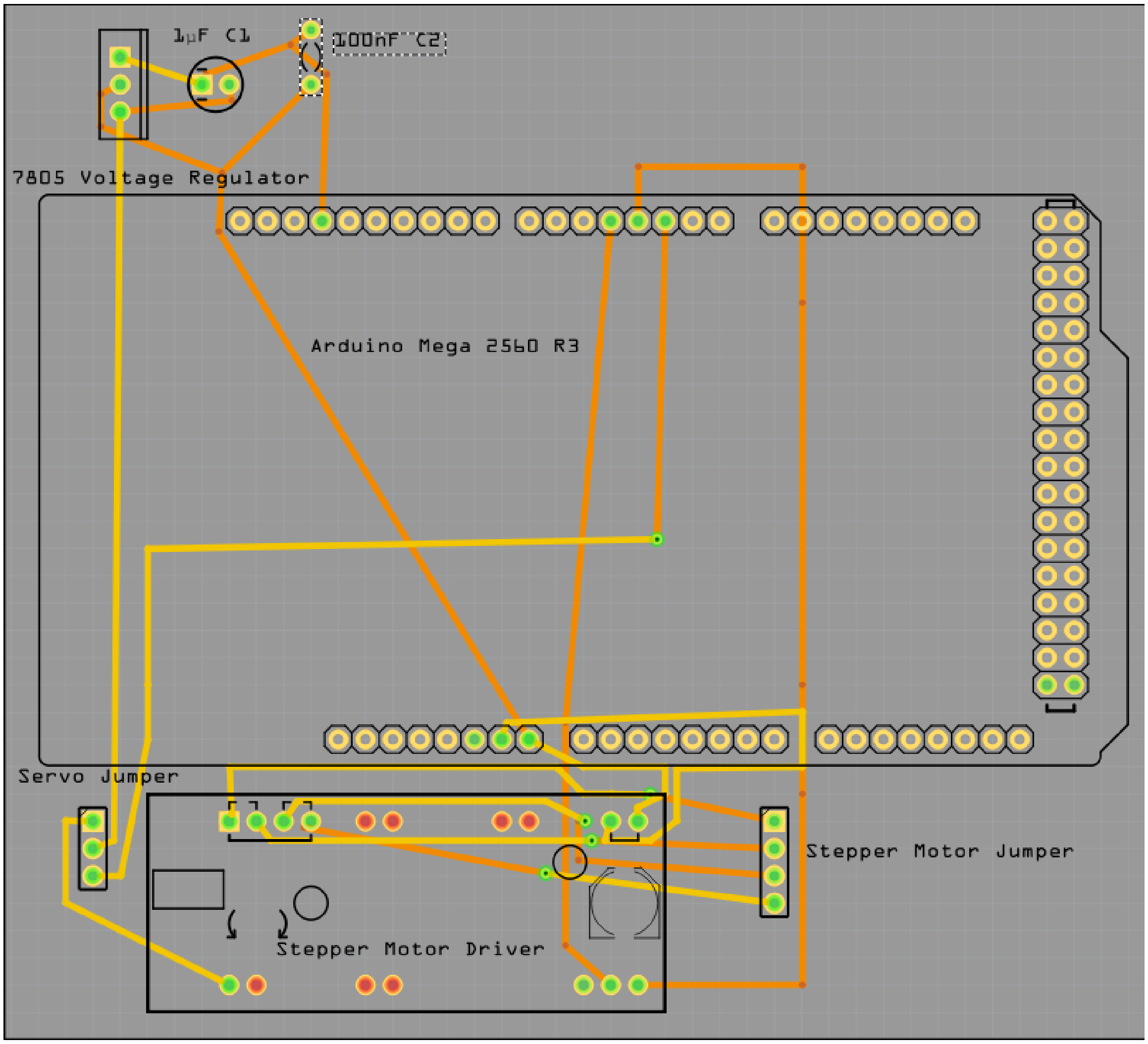


Figure 71: Arduino Mega Connections PCB Design

Above is the separate PCB design that will be associated with the Arduino Mega connections. These connections will include the Nema17 stepper motor from the translation stage, and the servo motor associated with the rotation stage.

The stepper motor will be attached to the Arduino Mega board via the accompanying stepper motor controller. The servo is able to be directly connected to the Arduino Mega board.

The testing of the schematic was done using the breadboard design from figure 78, although the LCD was not added to the PCB design since the touchscreen LCD and the shield associated with it will be placed directly on top.

6.9 Final Schematic

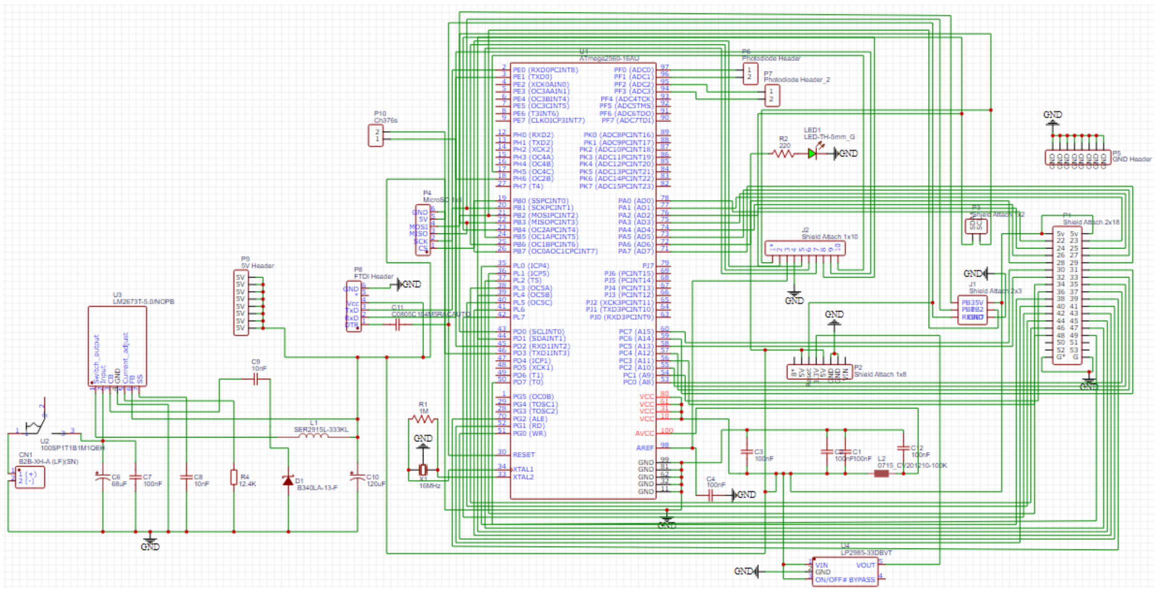


Figure 72: Final Design Schematic

Above is our final schematic design for our project. The chosen processor was an ATMega2560 since it was compatible with our LCD shield. Because we are using an outside shield the schematic needed to account for the headers the shield would use. Then the parts the LCD used from a standard Arduino Mega dev board were transferred over, such as the clock and the 3.3V regulator. The left side of the schematic consists of the buck converter which will deregulate our 12V battery down to a stable 5V for our microcontroller. In addition 5V and GND headers were added for external parts such as our CH376s, a separate header was added for our FTDI bootloader and two 2 pin headers were added for the wires to our photodiodes.

6.10 First PCB Iteration

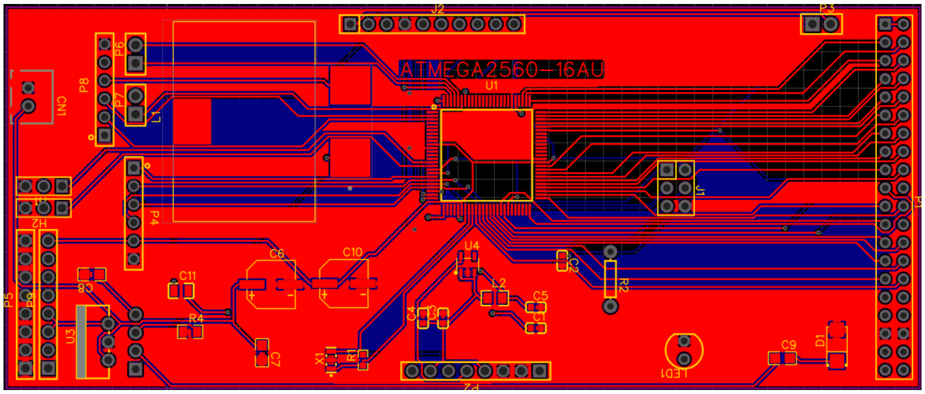


Figure 73: First PCB Design

The first PCB design we created mapped out the necessary headers so that our LCD shield could directly mount on top of it. The headers were placed in the correct position but some failures of this first design were that our inductor, L1, was too tall and was not allowing the shield to fully mount on the PCB. In addition the power components were spread out and causing noise, in addition our power trace widths were far too small for the current we were running through them.

6.11 Second PCB Iteration

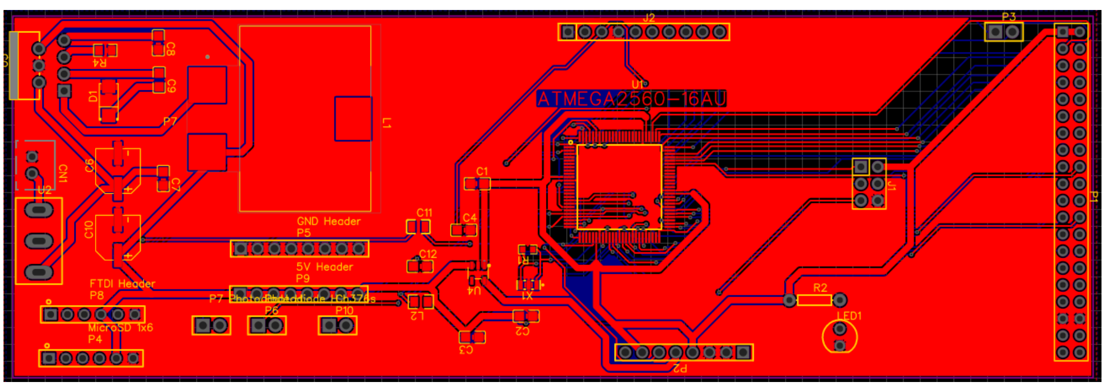


Figure 74: Final PCB Design

The second and final PCB design for our project fixed the three main issues of the first PCB; the thin power traces, the spread of power components, and the clearance issue with the inductor. With all of the previous issues solved the only thing left to add was a switch so that we could easily turn on and off our system without having to unplug the battery.

7.0 Administrative Section

In the administrative section, we will discuss project components such as the budget, how we plan on acquiring the parts needed, different milestones such as any hard and soft deadlines that we are currently aware of, and other plans we intend to have while we monitor and progress throughout both Senior Design I and II.

7.1 Budget & Financing

The budget for the parts needed to build the project isn't final for all the parts as some of the prices will vary depending on how prices change at the time they are ordered. A few of the parts that were already ordered have been included and reflect the prices at which said parts were ordered at. In terms of handling the budget, the price will be split between the members in the group in order to avoid having one person have the responsibility of ordering every part.

Senior Design Project - Semi Automated Diffraction Grating Efficiency Station		
Item	**Quantity**	**Cost**
HL-3P	1	$0
600µm VIS-NIR Fiber	2	$0
MonoScan 2000	1	$0
Variable Linear Polarizer	1	$269.06
1" Beam Sampler	1	$73.09
Achromatic Doublet	1	$53.88
30mm Cage Rod	4	$54.92
1/2" Optical Post	5	$26.52
1/2" Lens Mount 1/2"	1	$42.18
30mm Cage Mounting Bracket	2	$32.16
1/2" Post Component Clamp	1	$28.53
1/2" Post Holder	2	$17.90
Small Adjustable Clamping Arm	1	$21.43
Motorized Rotation Stage (DC Servo Motor)	1	$1,017.33
K-Cube Brushed DC Servo Motor Controller	1	$757.51
Mounted Photodiode	2	$79.36
Fiber Collimator	1	$177.45
Arduino Mega R3 Board	1	$35.12
SMA Male to BNC Female Cable	2	$17.98
BNC Male Connector (10 Pack)	1	$6.76

7" Arduino Touch Screen Display	1	$57.35
PCB 1st Iteration	1	$22.00
PCB Components	1	$18.00
PCB 2nd Iteration	1	$25.00
PCB Components	1	$21.00
Power Supply	1	$42.00
Ch376 USB Module	1	$6.99
Total		$2,903.52
Total (Self Bought)		$252.20

Table 16: Budget & Financing Breakdown

The parts that are highlighted in light green were purchased through our sponsor. The remaining parts were ordered by our group members out of pocket. We decided that we'd split the out of pocket cost amongst our group members at a later date. With that being the case, the total out of pocket expenses were much lower than the overall project cost so it was well within our means to handle.

7.2 Milestones

The milestones will lay out the predicted timeline for both the hard and soft deadlines for Senior Design I and Senior Design II that we are currently aware of at the time. Some of the soft deadlines may be subject to change if they are listed as TBD still.

7.2.1 Senior Design I

Due Date	Deliverable	Steps to complete
06/03/22	Divide and Conquer 1.0	Team meets to discuss the scope of the project
06/13/22	Meeting with Dr wei and Dr Kar	Team Meet with Dr Wei and Dr Kar to go over our initial 1.0
6/17/22	Divide and Conquer 2.0	Independent research and team meets to collaborate
07/08/22	60 Page Draft SD1 Doc	Continue Research on Project Parts

		Track Group Progress
07/22/22	100 Page Report	Continue any research needed to further our understanding of the skills and items we will need to use in our project. Begin to work on design schematics for power regulation and Arduino connections.
08/02/22	Final Document	Continue to add schematic details to report.

Table 17: Senior Design I Milestones

Table 15 describes the necessary milestones that need to be completed to successfully complete Senior Design I. Accompanying each milestone is the tangible deliverable which will allow us to track our progress, in addition the due date associated with that deliverable is mentioned. The table also describes the different steps needed to complete each of these tasks.

7.2.2 Senior Design II

Due Date	Deliverable	Steps to Complete
Early Aug. to Mid Sept.	Initial PCB design begin	Once the project design is nearing the testing stage, we should have a solid idea for what the PCB will need to include.
By the end of October	Finalize Design for PCB	Modify and finish any changes needed for the final prototype testing. The step after this will be to start testing the project as a whole.
Late Oct. - Mid Nov.	Testing project	Test and demo project to see if any parts need to be fixed or modified for final demo and

		presentation.
11/29/2022	Give final presentation	Finalize everything needed for the final prototype demo, organize review committee members and present the final project.

Table 18: Senior Design II Milestones

Table 16 describes the necessary milestones that need to be completed to successfully complete Senior Design II. At this time the milestones are only rough estimates of what will be needed. Along with these milestones are the due dates we associated with them which at this time are only rough estimates of the month in which they will be accomplished.

8.0 Conclusion

Our project aims to establish a consistent and accurate method for measuring the efficiency of reflection-based diffraction gratings. Our project aims to establish a novel technique for this concept by providing automation with a variety of gratings. Through testing and design there were a wide array of challenges to overcome. The diffraction efficiency measurement system was only possible through the intersection of computer, electrical and optical engineering knowledge. Collaboration is the only method by which a project such as this one would be possible. The work required of each member should be equivalently distributed and was beneficial to our work.

The diffraction efficiency measurement system should be applicable for a commercial setting such that it can accurately measure the efficiency of diffraction gratings over a variety of wavelengths. This project has a variety of applications and acts as a structure to ensure quality gratings are utilized in optical systems. The individual choice of both parts and design was decided collectively to limit the total size of the system as well as keep costs low. Testing was done such that the entire design is adequate and functional for the goals set by our team. We were able to arrive at the current design of our project through trial and error and considerations of what is needed for our system.

Future applications for our project and expand to different types of gratings as well as optimizations in measurement speed and accuracy. Using a larger number of wavelengths would allow for more accurate efficiency measurement and a graph that demonstrates a point-by-point analysis of the efficiency. Transmission grating efficiency can similarly be added to the design such that a user can input the characteristics of a transmission grating and measure the efficiency of the various orders. This was not possible for our project due to the scope of our project and main focus. Understanding the potential improvements to a particular project is important to think about what is still possible.

Design and testing of our project was ultimately successful and established a consistent and carefully considered to establish the best possible design to measure the efficiency of various reflection-based diffraction gratings. Our project aims to establish consistent measurements and maintain this capability with a fair degree of longevity. Creating a high-quality project that can be used for an extended period of time is important in the context of engineering as it limits costs and ensures that measurements are taken accurately. This is one of the main challenges faced in our design. Additionally, parts must be calibrated correctly such that they result in measurements that are suitable for efficiency measurements.

Development and the idea for our design came through personal work in the field of spectroscopy. Through running into issues concerning grating output we decided we wanted a quick and easy method to ensure that grating efficiencies are up to spec and allow for the expected output. We decided that automation would be the main focus of our design as to create a system that works quickly to deliver the results to the user in a timely manner. Given that only one member is a photonic engineering major, other members would have to gain a better understanding of the optics behind the design in order to create the optimal system given our goals. This is important as in the field of engineering we will not always be experts on the task we are working on so we must be able to adapt to the situation at hand to provide the best result.

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