SpectraLaser Elemental Analyser

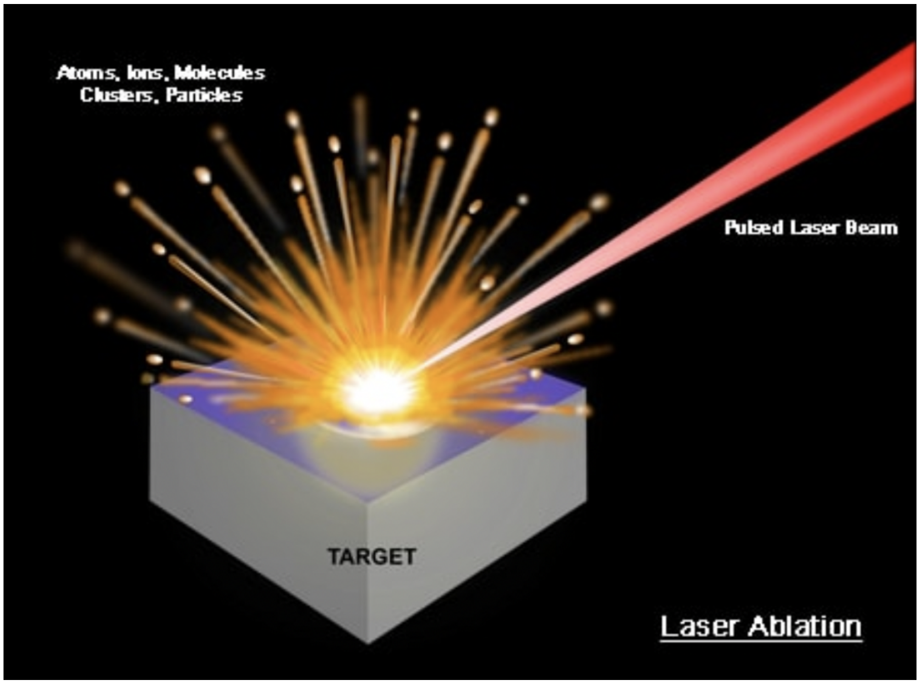

Fig 1.

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1. Executive Summary

The SpectraLaser Elemental Analyser prototype is a LIBS system used for the analysis of non-organic samples. The focus of the project is to create a LIBS system that can have applications in hazardous environments, extraterrestrial exploration, or educational institutions. The SpectraLaser Elemental Analyser provides a lower cost alternative to the highly expensive LIBS systems currently on the market. This system is designed, tested, and built by a four person team which is composed of ECE and PSE undergraduate students. LIBS systems provide a way to analyze samples in a remote or educational setting, without having to transport any materials. The basic goals of the project are as follows. Create a system that consistently generates plasma. Measurement results have less than 10% variance over 5 samples. Identify a known alloy or object to within 70% accuracy of its expected spectral emission. The LIBS system is controlled digitally. Convert analog spectrometer data into digital form. Output results in under a minute. The work distribution between the team members for the project is as follows. Benjamin Logan is responsible for the laser and its optical systems. Faisal Abdallah Salim Al-Quaiti is responsible for the power systems, excluding powering the laser due to the safety concerns. Liam Collins is responsible for the digital control, sensors and data output of the system. Stephen Styrk is responsible for the spectroscopy systems and the sample emission optical guidance system. The proposed system uses an Nd:YAG laser, which is focused through an optical system to strike a sample, generating plasma. The light emission from the sample is guided into a Czerny-Turner spectrometer for diffraction and spectral analysis. The plasma bloom is detected by an IR sensor, which triggers the MCU to activate the CCD. The diffracted light is directed to the CCD and the spectral data from the CCD is converted to digital form by an ADC. The spectral data is then displayed or transferred to an external device. A market investigation revealed some common features that most LIBS systems shared, and will be implemented in the proposed system. A technology comparison was performed to determine the appropriate technologies to use for each subsystem. From the technologies selected, components were compared and selected for the system. The constraints for the LIBS system were considered and included safety, supplier limitations, cost, time, and detailed LIBS information. Standards that are relevant to the project were listed. These included safety, optical standards, and electrical standards. The use of large language models in the project were addressed and compared. The electrical subsystems were designed. This included block diagrams and circuit schematics. The software diagrams for the MCU and the external machine were presented. The optical subsystems were designed. The design of the PCB and aspects of PCB fabrication were outlined. Electrical and optical component testing began. The overall system integration plan was presented, describing how the various individual systems are expected to be connected. An overall budget projection is presented for the project. The academic, production and testing milestones are listed for both senior design one and senior design two. The project has

progressed through the research and initial design phases. All but a few components were ordered and have arrived. Testing and specific hardware implementation has begun. Subsystem testing and integration, full PCB design, and system integration along with testing for those specific areas are expected to begin in senior design two.

2. Project Description

The motivation and specific goals for this project are listed as well as how the team aims to achieve them. The diagrams used will assist understanding of the design and objectives of the SpectraLaser Elemental Analyser. The history of LIBS systems is also addressed. A Hardware block diagram is presented, along with a software block diagram. The proposed system design schematic is all included in this section. The specifications and requirements are also listed. The House of Quality diagram for the system is also presented which relates the hardware realities with market needs.

2.1 Introduction

Identifying and classifying substances is an integral part of understanding the world around us. However in hazardous or non-terrestrial environments the task of identifying and classifying substances becomes extremely challenging. In hazardous environments additional safety measures must be taken to protect the researchers who are gathering samples. To ensure the researchers are not injured, things like safety equipment and protective gear need to be supplied. The scientific equipment used for sample extraction and the samples themselves must also be protected. This requires protective carrying cases, and other specialized equipment to ensure the integrity of the extraction equipment and the extracted samples. All of this extra equipment increases both the cost and effort needed to extract samples from hazardous locations. For extraterrestrial scientific expeditions the cost of acquiring and returning samples to earth is an order of magnitude more expensive compared to acquiring samples on earth. This increased cost is a function of the energy requirements needed to escape a gravity well. In extraterrestrial sample acquisition because space travel is often a rough process, the costs associated with sample protection are also incurred. Laser-Induced Breakdown Spectroscopy is a method of localized sample analysis, which can be used to significantly reduce costs and increase throughput of sample analysis in hazardous or extraterrestrial environments. There are many applications of this technology here on earth that will also be addressed throughout this paper.

2.2 Motivation

The team endeavors to make a system to assist scientists in the exploration and understanding of space as well as industrial and educational purposes for those here on Earth. By using a Laser-Induced Breakdown Spectroscopy system, the process of sample identification can occur on site and the resultant data is then returned. This significantly reduces costs as samples do not need to be physically collected and returned. Additionally since the sensor data can be returned much faster, analysis can occur almost immediately. Meaning that during a single mission, for example to the Moon or Mars, areas of interest can be found, and more thoroughly explored. However it should be noted that the process of Laser-Induced Breakdown Spectroscopy is inherently damaging to the sample, therefore with some samples it is preferable to use alternative techniques for analysis. With an increase in the international community's interest in space exploration, the need for low cost rapid sample analysis continues to grow. The Laser-Induced Breakdown Spectroscopy system being created will also provide a more affordable option to smaller educational institutions. The cost of traditional LIBS systems is generally prohibitive for smaller educational institutions. The proposed system would provide a low cost option to these institutions. This would provide students an additional tool to use in their studies and help them to better understand the elemental composition of many non-organic samples. This will also increase the awareness of this technology. The team will build a Laser-Induced Breakdown Spectroscopy system that will show proof of concept for these applications by analyzing a sample of an element using Laser-Induced Breakdown Spectroscopy.

2.3 Background

Laser-Induced Breakdown Spectroscopy (LIBS), works by using a process called atomic emission spectroscopy. To better understand how LIBS works, it is necessary to look at how this process functions. When a material is heated the atoms absorb the energy. If the material is heated enough, the electrons in the atoms are excited, going from a low energy level to a high energy level. In this state the electrons are not stable, so they will fall back down to the lowest energy state when able. When they make this transition, they emit the energy that they had absorbed earlier. This energy leaves in the form of a photon, emitting light. The size of the transition determines the wavelength of light emitted. If the electron falls from a high state of energy, it will emit a short wavelength and if it falls from a low state of energy, it will emit a longer wavelength. Each element will have a different transitional level, and this will help to identify and determine each sample with a unique spectrum using a LIBS system. A laser is used to vaporize a very small portion of the sample's surface into a cloud of plasma. As the plasma is cooling the electrons and atoms recombine, while this happens, they emit light. This is when the spectrum analyzer is used for the process of atomic emission spectroscopy to determine the element being vaporized. A fiber-optic cable can be used to guide the light viewed during these processes to a spectrometer.

Laser-Induced Breakdown Spectroscopy was introduced in the 1960’s as a method of analyzing and identifying samples [1]. During the 1970s and 1980s, Laser-Induced Breakdown Spectroscopy became far more widespread. One of the earlier commercial uses of Laser-Induced Breakdown Spectroscopy was to analyze and identify scrap metal, for sorting [2]. In 1999 a method of calibration free Laser-Induced Breakdown Spectroscopy was presented [3]. This LIBS method removed the need of control samples, and reduced the time needed for the overall LIBS process. The Mars Curiosity rover which landed on Mars in 2012 included a Laser-Induced Breakdown Spectroscopy system called the “Chemcam” [4]. Currently LIBS is widely used in science and space exploration as well as in many terrestrial applications. Handheld LIBS units are often used to verify material shipments in a variety of industries, to ensure quality standards are met for purposes of safety and quality. Laser-Induced Breakdown spectroscopy continues to be an important tool for object analysis and identification.

2.4 Goals and Objectives

Establishing goals for a project is important to ensure there is direction for the product to move towards. The goal of this project is to create a Laser-Induced Breakdown Spectroscopy system. This system should be in the low to medium cost range where there is a lack of LIBS systems commercially. The LIBS system should consist of a commercial sourced laser, which is capable of inducing breakdown plasma in basic non-organic specimens. The optical components used to focus the laser are designed to best create the plasma for the spectroscopy system. The optical components used for capturing and refracting the emission spectrum from the sample are comprised of an original custom design. When fired, the system consistently generates plasma which releases emission wavelengths. Within a reasonable margin of error the system should read spectral emissions that are consistent with known test materials. The LIBS system should use a form of digital control to detect the firing sequence of the laser. The digital control system is also used for the timing of the spectral data capture sequence. The digital control system will either process the data and display it or transmit the spectral data to an external machine for processing. The chosen digital control system and software used are required to be of sufficient speed to ensure that the timing requirements of the system are met to record spectral emissions. The displayed data is shown on an intensity plot to easily visualize the spectral data of a given sample. All components of the system, excluding the laser, are powered by a custom designed power path circuitry. The power path uses a standard 110V wall outlet, along with a standard AC-DC transformer. The transformer is used followed by high efficiency DC-DC converters to provide power to all non-laser based systems. Noise protection on DC power rails is applied as needed to ensure that interference to sub-systems is kept to a minimum.

2.4.1 Basic Goals

Create a laser system that will consistently generate a plasma plume. The plasma generated by the laser affects the output spectral emission and is determined by the sample make-up. An evenly distributed plasma plume results in spectral emissions that are easier to read. To accomplish this, the laser system emits a uniform beam through a focusing lens system on to a designated sample. The laser that the team picked is a Q-switched Nd YAG laser system with a dual operating mode of 532 and 1064 nm. This laser will be strong enough to create the plasma needed for a spectral scan to be taken for sample characteristic determination.

Create a LIBS system that produces measurement results with less than 10% variance over 5 samples. LIBS systems are unique in terms of the wavelength result, no two systems will produce the exact same spectral emissions. Even several samples taken from the object, using the same machine can have spectral differences in intensities and wavelengths. This is a function of how the laser in the LIBS system interacts with the sample creating minor changes, in addition to component differences and environmental factors. However internal consistency of results from a LIBS system are achievable within a margin of 10%.

Use the LIBS system to identify a known alloy or object to within 90% accuracy of its expected spectral emission. Due to the differences in results that are produced by LIBS systems, these results are often normalized to match expected values for elements in a LIBS database. The created LIBS system produces results for a known alloy or to within 90% accuracy of that alloy or items expected spectral data.

The LIBS system is controlled digitally. The LIBS system uses a form of digital control: microcontroller, FPGA, CPLD, etc. This digital control is used to detect the laser blast and control timings to produce accurate sample readings. The digital control system handles displaying or transmitting the results.

Convert analog spectrometer data into digital form. The analog data output from the spectrometer is converted into a high resolution digital form for data processing or transmission.

Output LIBS sample results in under a minute. The results of the spectral analysis of the sample are recorded by an FPGA or MCU. The sample data is then analyzed and stored, the results of the analysis are displayed. The LIBS system presents these results in under 1 minute.

The non-laser systems are powered by a standard 110 volt wall outlet. There will be an AC-DC convertor as the laser uses DC current. The AC-DC converter is connected to a voltage regulation system. The voltage regulation system reduces the output voltage to a level that is tolerable based on the sub-systems input power specifications. Due to the sensitivity of the sub-systems to electrical noise, the power circuitry is designed to ensure that any noise on the power line of the sub-systems is significantly reduced. The output of the voltage regulator may have additional circuitry to provide an additional level of noise protection. The additional protection is warranted due to the sensitivity of the sub-systems

2.4.2 Advanced Goals

Sample alignment system. The LIBS system has a system to detect the position of the sample relative to the laser and spectrogram. This alignment system uses sensors in conjunction with the FPGA or MCU to provide a method of ensuring that the sample is properly aligned. The system will indicate the sample alignment to the user.

Achieve less than 5% sample variation over 10 samples. The addition of sensors or the implementation of an algorithm are used in conjunction with refinements made to the laser design and spectrogram design to reduce sample to sample variation significantly. This provides more consistent readings per specimen.

Use the LIBS system to identify a known alloy or object to within 80% accuracy of its expected spectral emission. Improvements in the LIBS system are made to produce specimen results for a known alloy to within 80% accuracy of that species expected spectral results.

Output LIBS sample results in under 30 seconds. The results of the spectral analysis of the sample are recorded by the digital control system. Changes to the algorithm and or physical hardware allow for a faster analysis of the results, which are then displayed more quickly.

System display. The libs system has a small display mounted on it. This display could be used to display various forms of data such as temperature, sample distance measurements, and spectral emission results.

Additional laser noise protection circuitry. Additional custom noise circuitry is added to provide an additional level of noise protection to the laser. This ensures that laser output is extremely stable.

Digital control implements rastering. The firing sequence is modified to average the results of several laser blasts, to create a more consistent spectral data set for a given material.

2.4.3 Stretch Goals

Achieve less than 1% variation over 50 measurements. The addition of sensors or the implementation of an algorithm are used in conjunction with refinements made to the laser design and spectrogram design to reduce sample to sample variation significantly. This provides more consistent readings per specimen.

LIBS system motion control. The LIBS system is controlled remotely by the user. This involves including a transmitter and receiver to control the system. In addition to motors and motor drivers, potentially commercial RC modules in conjunction with pulse widths of the throttle and steering are detected. Based on the pulse widths, the MCU or FPGA controls the motor drivers to move the vehicle based on the instructions of the transmitter.

Use the LIBS system to identify a known alloy or object to within 90% accuracy of its expected spectral emission. Implement machine learning in conjunction with a database to more accurate predict the spectral data of the alloy or object

Argon gas deployment system. The digital control system is used to saturate the sample in argon gas. This intensifies the emission spectrum of the sample when using Laser Induced breakdown. A small cylinder of Argon gas is controlled to permeate the area around the sample.

Op amp Noise Filter. Implement a series of op amp circuits to protect the laser. The normal use of the op amp is to regulate the voltage to the desired voltage. The op amp provides a low pass filter that can reduce the frequency input to the laser, which can reduce the noise to a lower level and increase the level of safety in the system. The main benefit of this operation is to prevent the high frequency load on the output voltage. The team will use the amplifier as protection from noise. The op amp is additional protection to the laser to ensure that the voltage does not fluctuate. The system will have more stability and more precise control over the voltage.

Read and digitize sample temperature. Use an external temperature sensor to read the sample temperature. Process the temperature data and display the results in celsius, fahrenheit, or kelvin.

Buttons to switch between temperature units. such as, celsius, fahrenheit, or kelvin.

Have the *laser focusing* system decrease the focal point by one quarter to increase the power and intensity.

2.4.4 Objectives

- Laser
    - To make a lens system which will focus the beam to induce plasma
    - To create a measurable amount of plasma.
    - To incorporate a dichroic mirror to measure the heat from the sample area.
    - Determine the cost of the lens needed for the focusing system and the dichroic mirror.
    - Design the system so it will measure the heat of the area.
    - Design the system so it can be operated in a safe manner.
- Spectroscopy System
    - Determine the spectral range of the system.
    - Choose a gradient that suits the spectral range and resolution needs (groove density, blaze angle, size) of the system
    - Create an optimal system for spectroscopy: Design a slit entrance, collimating mirror, and focusing mirror
    - Determine location in system for light to enter a fiber-optic cable to connect to the spectrometer
    - Select the correct detector array based on the needs for the system (size of detector, pixel size, quantum efficiency, read-out noise)
- Digital Controller
    - Determine controllable aspects of the system
    - Determine appropriate hardware controller type
    - Compare hardware controllers
    - Purchases hardware controller
    - Design hardware control system
    - Test Appropriate controller systems
- Analog data conversions
    - Determine if ADC is internal or external to controller
    - Ensure ADC has sufficient speed to capture required events
    - Ensure purchases match speed requirements
    - Design data capture subsystem
    - Test data capture subsystem
- Output data
    - Compare data transfer protocols
    - Determine expected volume of data to transfer
    - Select hardware with sufficient storage
    - Design data transfer subsystem
    - Test data transfer subsystem
- Powered systems
    - Determine power requirements
    - Compare DC power source technologies
    - Determine subsystem power requirements
    - Compare Tradeoffs of voltage regulator technologies
    - Design power converters for subsystems

2.5 Requirements and Specifications

This section discusses the specifications of each component selected to achieve the desired result of acquiring a spectral scan for elemental characteristic identification with the LIBS system; these can be seen in table 2.1. Each component selection contributes to the overall goal of achieving a high resolution spectral system. In later sections the choices made and the reasoning behind each component selected is discussed.

Table 2.1 Requirements and Specifications

Laser Strength	1000 - 1200 Watt laser (Peak power-pulsed output)
Creation of plasma	Pulse width 6-8 ns, Spot area 1-5 mm
Identify object	To within 90% accurate of its expected spectral emission
Emission measurement results	Results are with less than 10% variance over 5 samples
Results output	LIBS sample results in under a minute
Diffraction grating	600-1200 lines/mm
Q-switch for Laser	1 - 10 Hz pulse rate
Sensor Wavelength detection	300 nm - 1200 nm
Analog to digital resolution	12-bit
communication protocols	USART, SPI, I2C
Linear CCD Resolution	2048 pixel
Laser excitation sensor detection range	750 - 1100 nm
Digital Power Regulation Type	Linear DC-DC converter
Digital controller Speed	64 MHz
Total System cost	≥ $4,000
Number of sample data sets stored	>5
Laser excitation detection time	<1.6 us

2.6 Project Diagrams

This section contains the block diagrams of the project's subsystems, this includes both the hardware and the software. The block diagram helps provide a simplified visual representation of a complex system. The block diagram breaks down the system into discrete “blocks" that help conceptualize the system and the overall intent of the project. It is critical to provide a clear and concise way to communicate how the key components function and are connected. These diagrams can be used to communicate how the system and its components function to team members, stakeholders, and reviewers. It also helps team members of cross disciplines to see where they are affecting the project and how their contribution is affected by others. Early design planning is also aided by the use of block diagrams, as it identifies the major components of a system and lays out the architecture for development. A block diagram can also assist in troubleshooting, identifying problems that arise and isolating it to specific components or systems. Figure 2.1. is the overall block diagram for the system. Both electrical and optical components are included. The responsibilities of individual team members are listed by color.

Figure 2.1 Hardware Block diagram

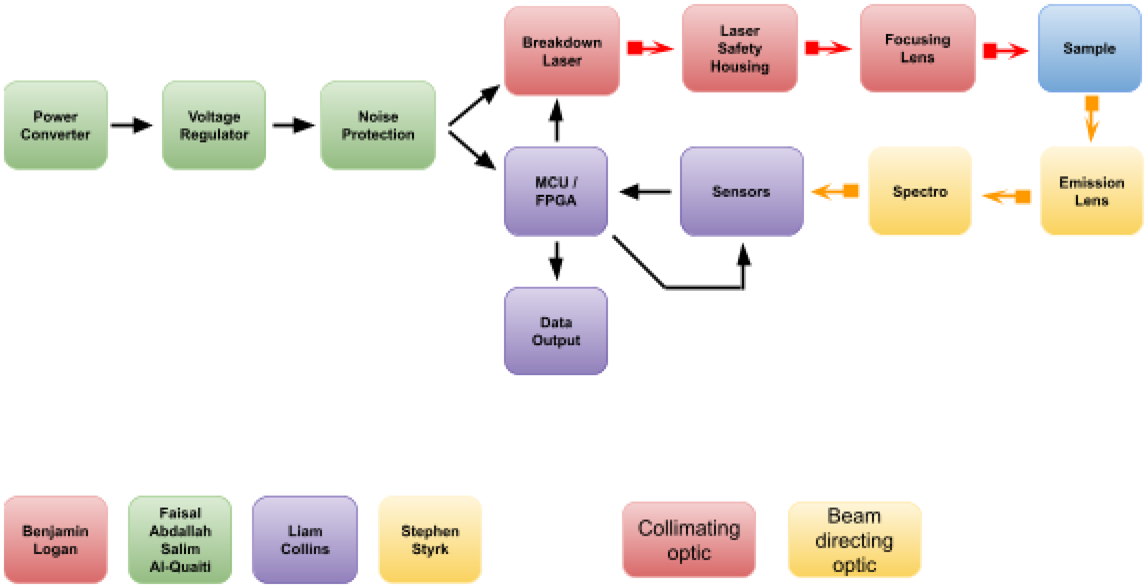


Figure 2.2 is the software block diagram for the entire system. It is an overview of the expected software control for the system. This includes both the firmware for the digital controller and any software for independent applications that may be located on external devices. This is subject to change based on the realities of testing and hardware implementation.

Figure 2.2 Software Diagram

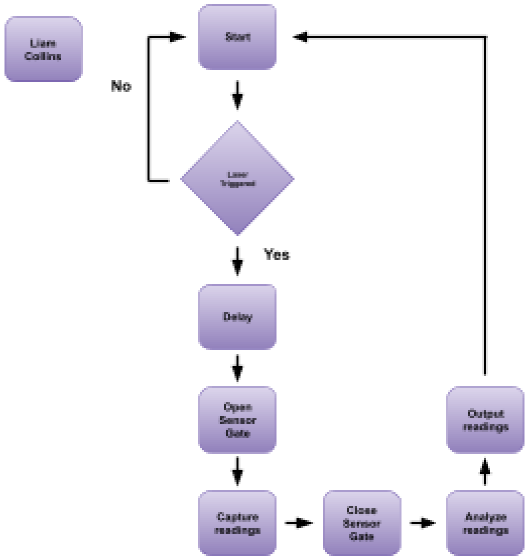
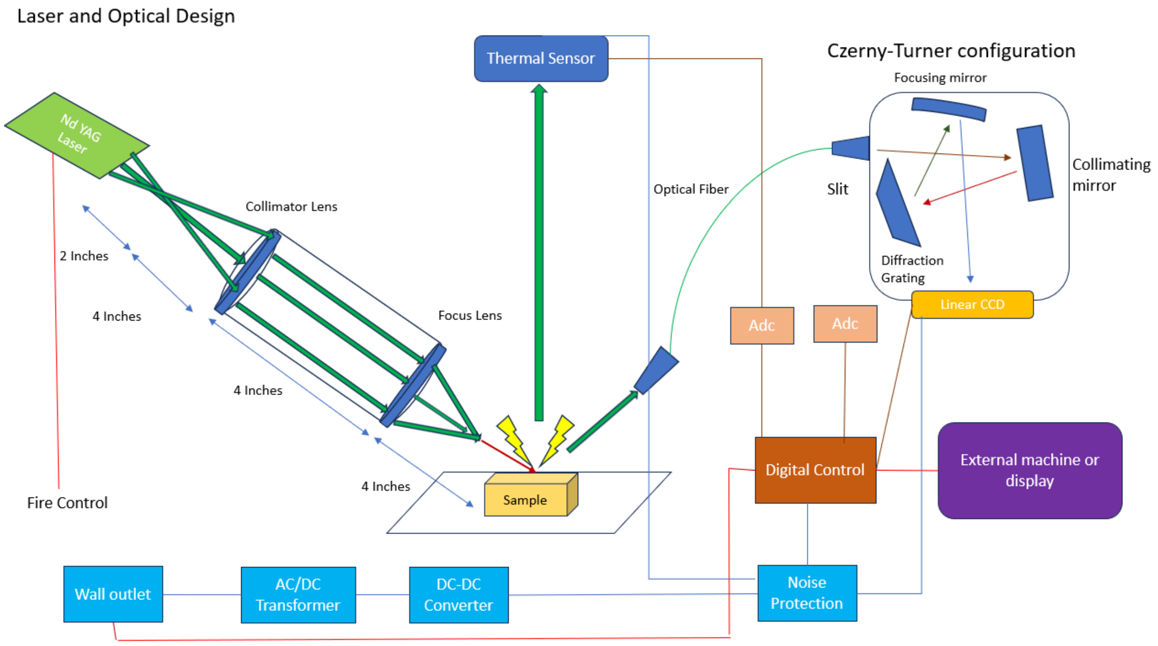


Figure 2.3. Shows the schematic for the hardware prototype of the system. The design is subject to change based testing and hardware implementation.

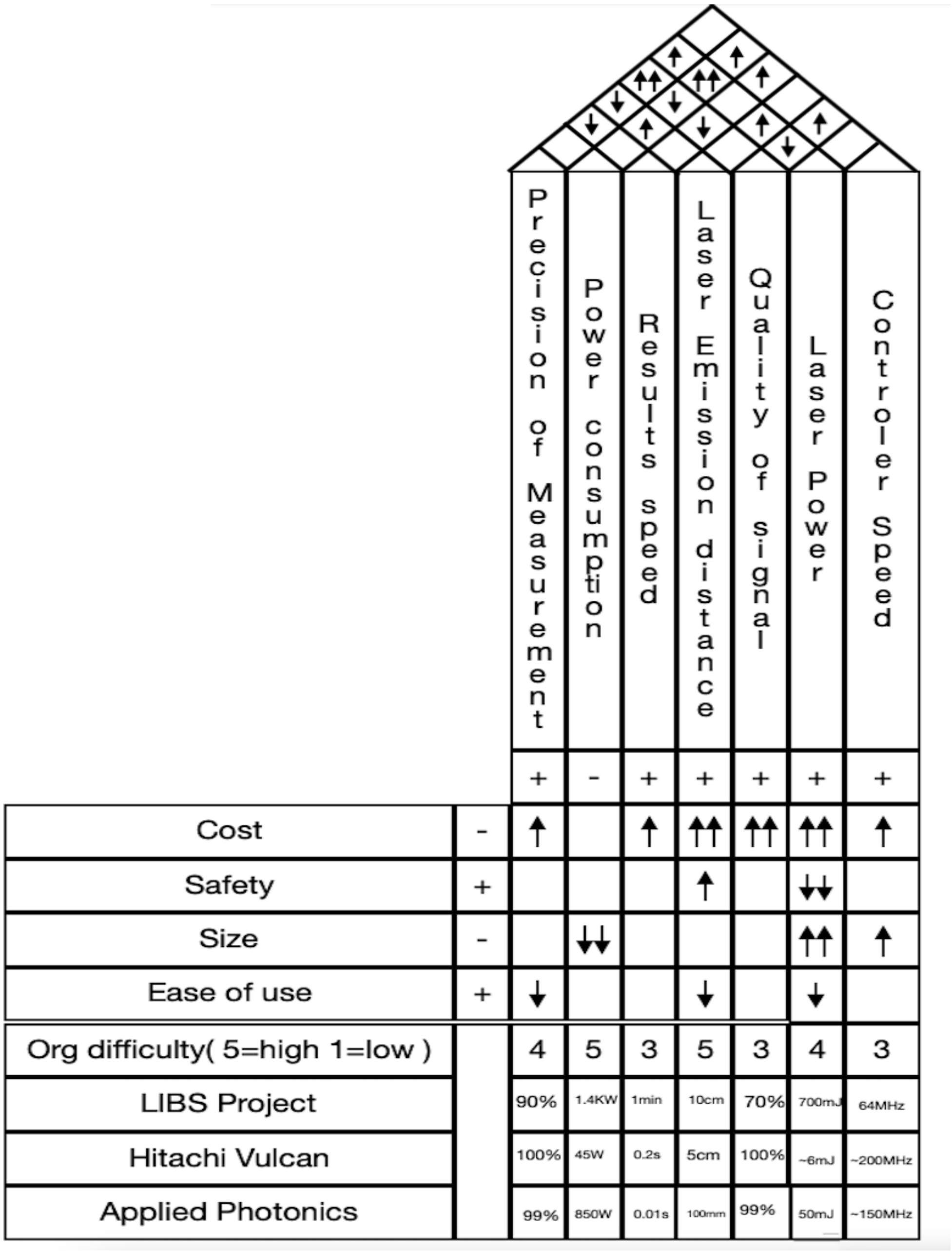
Figure 2.3 Block Prototype



2.6 House of Quality

House of quality is a comparison table which is used to understand the relationship between marketing and engineering factors of the project. The house of quality gives a visual representation of how changing different aspects of the project affect the other aspects, along with marketing factors. The house of quality for the proposed system can be seen in figure 2.3.

Figure 2.3 House of Quality Diagram



		Precision of Measurement	Power consumption	Results speed	Laser Emission distance	Quality of signal	Laser Power	Controler Speed
		+	-	+	+	+	+	+
Cost	-	↑		↑	↑↑	↑↑	↑↑	↑
Safety	+				↑		↓↓	
Size	-		↓↓				↑↑	↑
Ease of use	+	↓			↓		↓	
Org difficulty(5=high 1=low)		4	5	3	5	3	4	3
LIBS Project		90%	1.4KW	1min	10cm	70%	700mJ	64MHz
Hitachi Vulcan		100%	45W	0.2s	5cm	100%	~6mJ	~200MHz
Applied Photonics		99%	850W	0.01s	100mm	99%	50mJ	~150MHz

3. Technology Investigation

This section shows the technology comparisons conducted by the team throughout the project.

3.1 Technology Investigation process

With any product or technical system being designed and created, after the objectives, specifications, constraints, and standards have been decided on, or understood, the next step is always technology investigation. Different technologies need to be evaluated and compared to one another for the various subsystems of the product or system. This is an incredibly important step in the overall process of creating a product or technical system. The comparison of technologies needs to be of sufficient scope and depth to truly understand the technical avenues that are available to the team, when creating a product or system. Although, ultimately, only one technical path will be taken per subsystem design or section of the overall system. The initial paths chosen may need to be altered or abandoned, depending on issues discovered or obstacles encountered during the design and testing process. The process of creating a system or product is cyclical in nature, things are often discovered in the design and testing or production phase of the project. These discoveries can complicate or change the product. It then may be necessary or beneficial to return to the drawing board to redesign a subsystem or subsystems. Without a sufficient amount of technological investigation for the project, these technical setbacks or adjustments can bottleneck the project, if additional time is needed to find alternative technologies or solutions. Therefore it is more productive to frontload the investigation process with many or all potential technologies for a specific subsystem or portion of the product, thereby reducing or eliminating research bottlenecks in the product design process.

After technology choices for the subsystems have been decided on, specific components within that technology tree need to be selected to design the subsystems at a lower level of abstraction, for example when selecting an overall technology, or selecting specific components to make up or act as these subsystems. Comparisons between components need to be made.

In both the technology choice process and the component selection process, various criteria need to be considered. These criteria include: feasibility, cost, compatibility, maintainability, power, speed, along with numerous other aspects. In the technology choice process these aspects are compared at a higher and slightly more qualitative level of abstraction. In the process of component selection the above criteria are discussed at a lower and slightly more quantitative level of abstraction. The ultimate goal of this investigation process is to select the best technologies and components to achieve the goals and meet the specifications of the project while adhering to the constraints and standards of the project.

In the following sections several forms of investigation are presented. These include: Market Research, which is conducted to determine the current landscape for LIBS systems. This also provides a range of benchmarks for comparison with the proposed libs system. Investigation findings for technologies and components for the LIBS system are compared and contrasted. Decisions for specific technology choices and components selected are explained in detail.

3.2 LIBS Market Research

Systems to perform Laser-Induced Breakdown Spectroscopy cover a large range in the market. The simplest systems are open source individual or group passion projects. Typically these systems have relatively low engineering precision, and few features. Additionally they are produced at very low cost. Commercial or industrial systems are in stark contrast to open source systems. These industrial or commercial systems typically have very high engineering precision and many features. However, the costs to purchase these systems are also extremely high. The lowest cost commercial systems are typically priced in the $10,000 range.

There are however very few low to medium cost systems for purchase on the market. With the continued trend towards privatization of space flight, which has emphasized slashing inflated budgets, a low to medium cost LIBS system would be an attractive addition to many low cost science payloads. The proposed system would also have potential customers in entry level scholastic arenas such as middle and high schools, science centers, planetariums, and museums.

Most LIBS systems are either handheld or desktop units. Depending on the expense of the system and the type, there are a variety of features available. However there are some common features found in most LIBS systems.

- Display data - either through a cable like USB to a computer, or on a dedicated display
- Pulsed laser - most systems use a pulsed laser
- Easy of use - place the sample and fire
- Mobile - all but the largest of LIBS system are transportable
- Under $10,000 - most LIBS systems exceed the $10,000 price point a few dip into the $3,000 to $5,000 range, but not many
- Rastering laser beam - Many of the LIBS units use a rastering technique
- Safety system - all LIBS systems must ensure that eyes and other parts of the body are protected during use.

3.3 Control Unit Technologies Overview

The continued decrease of the process node size of integrated circuits, has resulted in decreased costs and sizes of modern integrated circuits and chips. All but the simplest of products have some form of digital control system. Modern designers have a wide array of options to choose from when implementing system control. Many of the major components in the LIBS system pass through or are triggered by a digital control unit. The LIBS process begins with a user input to trigger the laser pulsing, followed by a small delay after which the emission spectrum from the sample is read, and processed or output. The controller needs to read and/or trigger these events, along with handling the timings between them. The time scale of the laser pulse and emissions from the plasma are very small, on the order of nanoseconds to microseconds. This necessitates that the control unit have adequate speed to handle these events. The primary firing sequence will likely consist of one or more laser pulses, which could be averaged to achieve a more accurate spectral result. In addition to the primary firing sequence, there are other data or control signals that need to be handled, therefore sufficient IO and ADC sources must be available. These signals include things such as sample temperature readings, or emergency stop signals. The inputs and outputs to the control unit can be handled via either temporally, or spatially computing. Temporal computing trades time for completing actions, this is typical of microcontrollers, and some SOC’s. Spatial computing trades areas for tasks that are run in parallel, this is typical of FPGAs, CPLDs. These different technologies each have their own advantages and drawbacks. How these advantages and drawbacks are expected to affect the LIBS system are covered in more detail in the following sections.

3.3.1 Microcontrollers

Microcontrollers are typically composed of a CPU, timers, GPIO pins, input-output devices like analog to digital converters, PWM, digital to analog converter and support various communication protocols. There are a huge range of choices for MCU’s. These range from extremely low power IoT controllers, to multi-core SoC devices. MCU’s are very popular for several reasons. Microcontrollers are easy to use, many MCU’s come ready on a PCB. All that is needed is programming knowledge, along with a development environment to begin controlling things. MCU’s excel at a variety of general tasks like reading analog signals, communicating with other peripherals or sensors, and precise timing applications. Microcontrollers are cheap, they range in price from cents to tens of dollars, depending on the level of performance required. Microcontrolers also have their weak points. Microcontrollers are general purpose, therefore when dealing with a specific task, a specific microcontroller may have more features than are required, or may not meet all of the requirements for the overall design. Some microcontrollers don't allow easy access to low level control of the chip, which can require using the manufacturer's API layer, which can sometimes complicate processing data. Another weakness of some microcontrollers is parallelism. Many microcontrollers have a priority order for timers and interrupts, for many applications this is sufficient. However, depending on the number of events and the speed at which those events occur, this can present an issue that leads to bottlenecking or missing events. To tackle these issues, some microcontrollers offer parallel sample and hold on GPIO pins or pin groups. Sample and hold is where sensor data can be read and stored in temporary registers in parallel, however processing that data still happens sequentially. Another feature sometimes offered is a Real Time Operating System(RTOS), this is where a small operating system running on the microcontroller is used to handle a large number of events like interrupts and timers more complex and efficiently manage to perform multitasking as would be seen on an operating system. Microcontrollers have a fixed number of timers to use.

3.3.2 FPGA

Field Programmable Gateway Arrays are spatial computing devices. The “digital fabric” of an FPGA consists of hundreds of thousands of logic blocks, registers, and digital signal processing cores. All of which can be configured and joined together to form any digital circuit. FPGAs are programmed using hardware description language(HDL) to describe the various logic gates, adders, and other digital subsystems. These descriptions of hardware can be done at a high or low level of abstraction. FPGAs have several key benefits. FPGAs offer a very large number of digital input and output pins to use. The FPGAs digital fabric can be molded to fit a specific task, this allows the FPGA to match the design criteria exactly. This can be particularly useful when dealing with uncommon bit width, or when very specific hardware circuitry is required. FPGAs provide a huge amount of flexibility, this is because they are reprogrammable. Which allows for easy bug fixes, and design updates and expansions. FPGAs excel at true parallelism, FPGAs are structured to transfer signals and data concurrently. This parallel nature allows FPGAs to provide a high level of performance. FPGAs can be very energy efficient under the right circumstance. FPGAs do have drawbacks, The cost of an FPGA is higher than a microcontroller. Usually costing tens of dollars. Programming an FPGA requires a fundamental understanding of digital circuits, and knowledge of a hardware description language such as Verilog or VHDL. Debugging an FPGA design is difficult as it is parallel programming. Significantly more time is spent debugging the design rather than designing it. FPGAs are slower than ASICs and microcontrollers at the same technology node. This is partially due to how the FPGA routes its signals and connects its logic elements together, along with some other factors. FPGAs generally don't have their own DAC or ADC units. The units that do have dedicated ADC/DAC capabilities tend to be far more expensive that standard FPGAs. Without internal ADC/DAC, the FPGA needs an additional external circuit to handle the DAC or ADC conversion. This can create additional points of failure to the design along with other complexities. Many FPGAs use volatile memory, and require some form of external non-volatile memory to hold the FPGAs configuration file between power cycles.

3.3.3 CPLD

Complex Programmable Logic Devices(CPLDs) are another form of spatial computing. Logic elements are connected together to form a variety of digital circuits. CPLDs are programmed using HDL to create circuits out of the logic elements. CPLDs have many benefits. CPLDs are cheaper than FPGAs typically costing dollars to tens of dollars. CPLDs can be tailored to very specific applications. CPLDs provide a moderate level of flexibility due to the number of logic elements available. CPLDs offer a high level of parallel performance. They can pass signals concurrently. CPLDs have very predictable response timings. This is due to the smaller number of logic elements and routing paths, timing analysis is very predictable. CPLDs use non-volatile memory, meaning no external memory is needed to store the configuration between power cycles. Many CPLDs have low power consumption, this can be on the order of micro amps for some CPLDs when they are idle. CPLDs have fewer logic blocks than FPGAs. This means that CPLDs cannot form very complex circuits like those formed by FPGAs. CPLDs are missing the more complex elements like DSP, PLL, etc. that are found in FPGAs. This can limit their applications to simpler designs. Like FPGAs CPLDs lack dedicated ADC or DAC capabilities, therefore external ADC or DAC solutions must be added to deal with or produce analog signals. Programming a CPLD is more complicated that programming a microcontroller as it is parallel programming. Although the designs are simpler than those found in an FPGA, due to the parallel nature of the programing the process of debugging can still take a significant amount of time. CPLDs are generally slower than high speed microcontrollers. This can be an issue when events happen at a very high rate. Although the parallel nature of the CPLD can sometimes counterbalance this.

3.3.4 Digital controller technology comparison categories

For the LIBS project, the primary constraints for the digital controller are speed, I/O, cost and complexity.

Speed is the most important factor of the digital controller for the LIBS system. The capability to accurately trigger or detect the laser pulse(s) from the LIBS system are required to maintain accurate timings between the heat bloom from the laser, and the emission spectra of the sample. Without precise timing, the intensity of emission spectra may be significantly reduced or missed entirely. Generally LIBS systems use a delay between laser excitation and sensor data capture. Most LIBS systems use a delay of between 40 nanoseconds to several microseconds [5]. Based on this the clock speed of the digital control system needs to be close to 25 to 50 MHz to be within the same time scale for capturing emission spectra. This is achievable for many micro controllers, as manufactures offer a variety of clock speeds in or above this range. FPGAs exist at various frequencies, which are typically differentiated by speed grades. The switching speed of the FPGA’s logic elements is determined by its speed grade. Determining speeds of an FPGA is more complicated than on a MCU. The type of design implemented on the FPGA, determines how the logic elements are connected together, which will affect the overall speed. Generally static timing analysis software is used to determine frequency requirements of a design. However certain metrics from an FPGA data sheet can be used to roughly estimate speed capabilities. For example, on the Xilinx Artix-7 FPGA family data sheet [6], looking at the maximum frequency metric “FMAX_BUFG”on page 36. The maximum clock speeds range from 394MHz to 628MHz. Now this metric simply governs top speeds of the clock tree. It does not account for delays in the I/O pads of the FPGA or critical path delays of the design. However if only 13% of these maximum speeds were achievable in the design, many devices in this FPGA family alone would still meet the minimum speed requirements. Based on this higher end FPGA Families would certainly meet the required minimum speeds. CPLDs also have speed grades to indicate speed capabilities. Like with FPGAs, estimating speeds of CPLDs typically use a static timing analysis software. This would be used to help determine accurate timing requirements of a design. However the data sheet of a CPLD family can be used to give a rough estimate of the speed capabilities. For example the datasheet for Lattice semiconductors ispMACH 4000 Family of CPLDs [7] indicates a maximum clock speed of 400MHz. Again this does not account for logic delays incurred due to the design, however if the implemented design could reach 13% of the maximum clock speed. Then this CPLD family of devices could be used. Therefore higher end CPLDs would easily satisfy the speed requirements of the project.

The number of I/O that the digital controller has is another important constraint that must be met. The digital controller is expected to read or trigger several signals which include the following. The 2 to 4 signals from the temperature sensor which are likely using either the SPI or I2C protocols. The 2 to 4 signals from the digital control to the display or external machine which will either require UART, SPI, or be a proprietary protocol. 4 to 9 signals will be required for the spectrometer sensor, one of which is an analog voltage for the spectral output. 1 to 2 signals will be needed to trigger or detect the laser pulses. This means a total of 10 to 19 I/O ports are required. The MCU will need the following features to support the above signals. 1 GPIO interrupt and 1 digital timer for detecting or firing the laser. 1 ADC and 3 to 6 digital timers for the spectrometers analog output, and digital inputs. 2 to 3 SPI/I2C interfaces and 1 UART interface for sensor and peripheral inputs. If a microcontroller is used, there are several manufacturers for different microcontrollers that offer these features and sufficient I/O resources. The number of I/O provided on the majority of FPGAs and CPLDs easily satisfies the minimum number of needed I/O for the LIBS project. However the majority to the entirety of the I/O provided on an FPGA or

CPLD will be digital. Therefore external ADC components will be required, in addition to any logic level shifters that are needed to interface with sensors. Another factor to consider is that any protocols used will need to be implemented in hardware of the FPGA or CPLD. Either the hardware needs to be written manually, or intellectual property blocks for those protocols may need to be licenced or bought.

Cost is another important factor on the LIBS project. The laser of the LIBS system requires a significant portion of the overall budget. Various optical components are also expected to be a significant expense. Therefore it is important that the digital control aspects of the project be cost efficient. Microcontrollers are the cheapest of the three technology choices. The prices range from cents to tens of dollars depending on the speeds and features offered by a component. FPGAs cost the most out of the three potential technologies. The price of an FPGA can range from tens of dollars to thousands of dollars, depending on the speed grade, number of specialized blocks offered like DSP, PLL, etc. CPLDs fall between microcontrollers and FPGAs in terms of cost. Generally CPLDs are priced in the range of dollars to tens of dollars. Technology choices of an FPGA or CPLD incur costs of additional external components needed to interface with the sensors such as ADCs and levelshifters. The current projected number of iterations needed to finalize the electrical design is three. Therefore the above costs of each type of technology and any support components are expected to triple. An additional cost for the FPGA or CPLD technologies is the intellectual property blocks that may be needed. The cost of these intellectual property blocks can range from hundreds dollars to thousands of dollars. There are some open source intellectual property blocks available for use, but some of these may have restrictions on use depending on the application.

Complexity of design is a factor when selecting technology for the digital control software. The LIBS project does not have an extremely complicated control algorithm which could benefit from a customized hardware implementation scheme. Nor does the LIBS project have highly specific input data types that would benefit from a form of specialized parallel hardware processing. The digital controller is not expected to deal with a wide variety of radically different tasks that would require a high degree of flexibility. While the FPGA or CPLD would excel in many of these areas, however with the LIBS system it is not imperative to support any of these features. Most of the tasks that the digital controller are expected to perform require a high degree of speed and precision, but are of a more general nature. Table 3.1. Shows the comparison of various digital controller technologies.

For the LIBS project, the best technology to use for the digital control is that of a microcontroller. A microcontroller provides very high speeds and precision timers and interrupts for triggering or alerting about external events. A microcontroller provides sufficient I/O resources with integrated analog to digital components and communication protocols. A microcontroller is low cost and has very few to no external support components required for implementation. A microcontroller provides sufficient coverage of the tasks that are expected to occur in the digital control algorithm.

Table 3.1 Digital Control Technology Comparison

Category	**Microcontroller**	**FPGA**	**CPLD**
Speed	High (1Mhz - 1GHz)	Moderate (10KHz - 500MHz)	Moderate (2MHz - 22MHz)
I/O	Low(2 - 293)	High(32 - 2072)	Moderate(5 - 360)
ADC	Integrated	External	External
Cost	Low ($2 - $3053)	High ($34 - $173,901)	Moderate ($9 - $598)
Design complexity	low (100s of features)	High (100,000+ logic blocks)	Moderate (1000s of logic elements)
Hardware Type	Fixed hardware	Fully customizable hardware	Fully customizable hardware

The software language used to program the microcontroller will likely be C. As most embedded systems are programmed with C, but it may depend on the final microcontroller selected.

3.4 Serial Communication Protocols Technologies Overview

With the introduction of higher and higher clock speeds for digital devices, forms of serial communication have become dominant over “long” distances. Forms of serial communication are used by various digital devices and their peripherals to communicate at high speeds.

For the LIBS system serial communication protocols will be used by the digital controller to communicate with the various sensors. Serial communication will also be used to output and display relevant sample data. There are a variety of serial communication protocol technologies for designers to choose from. Serial communication protocols are described as being full-duplex meaning that they can send and receive data simultaneously. Half-duplex communication protocols cannot send and receive data simultaneously, and must send or receive signals one at a time. Communication protocols are either asynchronous or synchronous. With asynchronous protocols both devices must be configured at the same speed ahead of time. Synchronous protocols use a clock signal to sync devices. Each protocol has its own protocol for connecting to devices and transmitting data. There are a variety of factors that need to be considered to ensure that the selected communication protocols meet the design constraints. Some of the most common serial communication protocols seen on embedded devices include: UART, SPI, I^{2}C, and USB.

3.4.1 UART

UART is a two wire serial communication protocol. UART is an asynchronous protocol that can be setup for half or full duplex. UART has a moderately complex data transmission format, which requires start and stop bits. The UART protocol is of moderate speed, this is mostly due to its asynchronous nature [8]. While theoretically possible, using UART for more than one device can become cumbersome as one to two more wires would be needed to connect each device, or some sort of custom hardware is needed for multiplexing the signals. UART requires no clock, and has hardware level single bit error checking. UART is commonly seen in debugging interfaces. It is sometimes used to connect to external devices that don't support clock signals natively.

3.4.2 SPI

SPI is a three or more wire serial communication protocol. SPI is a synchronous protocol which is typically configured for full duplex. The data protocol for SPI is simple, only requiring the clock be driven and data sent. There is a single master device, typically a microcontroller and one or more slave devices. With more than one slave device, a slave select wire is needed for each slave device. When the master wants to communicate with a slave, it asserts the slave select line and drives the clock, and full duplex data transmission occurs. The SPI protocol can easily communicate with several devices. The SPI protocol is high speed. The SPI protocol requires more I/O for every device added.

3.4.3 I^{2}C

I^{2}C is a two wire serial communication protocol. I^{2}C is a synchronous protocol. I^{2}C is half duplex due to the single data line. I^{2}C is of moderate speed. I^{2}C has a data protocol that is very complicated, requiring an addressing scheme that can communicate with several devices. With I^{2}C there can be multiple master devices sharing the clock and data wires. Slave devices will indicate when they can receive data. Master devices will transmit a slave address, the slave device with that address will acknowledge and send or receive data. The I^{2}C protocol can be used to communicate with many devices, I^{2}C uses few I/O resources. I^{2}C is fast. I^{2}C may be used by fewer devices due to the address fee.

3.4.4 USB

The USB protocol covers a variety of protocol iterations and evolutions. It can provide power to devices, in addition to serial communication. USB is extremely fast. USB is extremely complicated, requiring the use of generic or custom drives. USB requires a large amount of I/O resources. The USB protocol can be used to communicate with a large number of devices.

3.4.5 Communication Protocol Technology Comparison Categories

Due to the specialized nature of the sensors required for the LIBS project, and the limited number of suppliers for these sensors. Several communication protocols may be required depending on the available sensors. The number of sensors expected to be used in the LIBS system is not projected to exceed the single digits. Additionally data transmission requirements are not expected to exceed 48 Mbps. Therefore very complicated high speed protocols such as USB will not be required directly. As more than a single sensor will be used, UART is not an ideal choice due to its limitations when handling more than a single device. Since SPI or I^{2}C are designed to handle several devices and are of moderate to high speeds, either would be a good technology choice. Ultimately as I^{2}C requires a fee to obtain an address, potentially fewer devices have I^{2}C support. Table 3.2. Shows the comparison of serial communication protocols.

Table 3.2 Serial Communication Protocol Comparison

Category	**UART**	**SPI**	**I^{2}C**	**USB**
Protocall complexity	Full or half duplex	Full duplex	Half Duplex	Half Duplex
Speed	10 Mbps	60 Mbps	3.4 Mbps	40 Gbps
I/O requirements	4 pins	3 + N (devices) pins	2 pins	24 pins
Devices connectable	1	Primarily limited by I/O	128 - 1024	Primarily limited by I/O

For the LIBS system the communication protocol selected for use in subsystems when available is the SPI protocol. SPI was chosen as several devices and or sensors are expected to communicate with the MCU, and will provide the needed speed for the project. However as noted before several protocols may be required based on sensors chosen.

3.5 Spectral Emission Sensor Technologies Overview

Image and light sensors are ubiquitous due to the high rate of adoption of various smart devices. The two most prominent for image and light sensing technologies are CCD and CMOS. For the LIBS system, spectral emission light is captured and diffracted into its various wavelengths. This emission spectra is aligned with the pixels or sections of the sensor, so that each pixel or section corresponds to a specific wavelength. This emission spectra is collected by the one dimensional or linear sensor. The sensor then converts spectral intensity to output data in the form of voltages or bits. The LIBS project requires a sensor technology that can capture emission spectra with a high degree of accuracy, and has a high dynamic range to identify emission or absorption lines. It should be noted that there are some variations of CMOS and CCD technologies such as SCMOS and EMCCD, however due to cost and sourcing constraints, these technologies were excluded.

3.5.1 CCD Sensor Technology

Charged Coupled Device or CCD is an extremely sensitive photon detector. The surface of the CCD sensor is broken up into sections of photodiodes. The number of photons collected in each section generates electrons. The number of electrons in a specific section signifies how intense that wavelength of light is. A clocking sequence is used to move the charge collections through these sections to an amplifier sequentially. That single amplifier is used to produce a corresponding voltage for that section. CCDs have a very high dynamic range, and are low noise. The CCD output is sequential in nature, which can be slow [9].

3.5.2 CMOS Sensor Technology

Like CCDs CMOS sensors have their surface divided into sections, each of these sections corresponds to a wavelength. Photodiodes convert the amount of photons to electrons, which is amplified to produce a corresponding voltage. Each section of the CMOS sensor has its own amplifier. This means that any section of the CMOS sensor can be read in any order, not in a specific sequence like CCDs. CMOS sensors are generally faster at outputting their data and require less power [10].

3.5.3 Spectral emission sensor technology comparison categories

CCDs provide a higher dynamic range than CMOS sensors. This high dynamic range is required to accurately capture the emission or absorption spectra of the sample. Cost is another important factor, CCDs tend to be cheaper compared with CMOS sensors. Power consumption was also considered, The available linear CCD sensors had low levels of power consumption. Compared with the

CMOS. CMOS sensors completely dominate with regards to data transfer speed. Data transfer speed was less important for the LIBS project. Because only one dimensional required capture. Therefore sensor delays are less of an issue, than with two dimensional image sensors. Table 3.3. Shows the comparison of spectral emission sensor technology

Table 3.3 Spectral Emission Sensor Technology Comparison

Category	**CCD Sensor**	**CMOS Sensor**
Dynamic Range	High (66dB - 90dB)	Moderate (52dB - 73dB)
Cost	Low ($30 - $900)	High ($800 - $2000)
Power consumption	Low (160mW - 400mW)	Moderate (0.5W - 3.85W)
Data transfer speed	Moderate (6MHz - 30MHz)	High (10 - 80MHz)

For the LIBS system, a high dynamic range is a predominant factor in sensor technology selection. As without a high dynamic range, spectral emission lines are hard to differentiate. On average the cost for linear CCDs was lower than their CMOS counterparts for the speeds and resolutions needed for the project. Therefore the CCD technology was chosen for the spectral sensor.

3.6 Sample Alignment Sensor Technologies Overview

The sample alignment system is an advanced project goal. It will be implemented if all of the core goals are completed in the project time frame, and additional time remains. The LIBS system requires samples to be placed accurately under the firing point of the laser. Particularly in the case of controlling the system remotely or for very small samples. Remote LIBS systems require more complicated sensor solutions to align the sample with the primary laser of the LIBS system correctly. Any distance that a sensor is expected to measure is less than 1 meter. There are a variety of technology choices that would ensure correct sample placement for local or remote LIBS systems. These sensor technologies include LEDs, Laser Diodes, Microwave Radar, Ultrasonic distance sensors, IR Diodes and Receivers, and Lidar.

3.6.1 LEDs

LEDs are very cheap costing in the range of cents to several dollars. LEDs are an easy solution for manual sample alignment, and they are intuitive for users to understand. An LED in conjunction with a small focusing lens could be used to create a sort of “landing zone” to indicate where the sample should be placed. This sample “landing zone” would be used to illuminate a very specific area under the LIBS laser. The required lens for the LED would increase costs. However LEDs would not work for any remote sample alignment, additional sensors would be required. LEDs are affected by temperature and can be occluded by dust which could be an issue.

3.6.2 Laser Diode

Laser diodes offer another cheap sensor option priced in the range of cents to several dollars. Like LEDs, using a laser diode to indicate sample placement is very intuitive. A laser diode can be mounted on the LIBS system to indicate the expected laser excitation spot with a high degree of precision. The laser diode could be used to target specific portions of the sample. However like LEDs, a laser diode would only be sufficient for manual sample alignment. For remote sample alignment supplementary sensors would be required. Laser Diodes are affected by temperature and might be occluded by dust.

3.6.3 Microwave radar

Microwave sensors would allow for accurate placement of the sample, however they have high costs ranging from tens of dollars to hundreds of dollars. Microwave sensors tend to have higher power consumption. A Microwave radar sensor could be used to align the sample with the laser excitation point physically or remotely. Most microwave sensors provide speed, motion detection, and degree of motion detected. Some microwave sensors offer distance measurements, but not all. Microwave radar sensors use the doppler effect to detect motion and or speed of objects. The sensor emits a series of microwave pulses, of a specific frequency. These pulses strike objects and are reflected back.When an object is moving towards or away from the sensor, the reflected microwave pulses are stacked closer together or further apart, which is used to determine direction and speed of objects. For microwave sensors that don't directly provide distance data, one way to calculate an object's distance is to use speed and direction data. This data would be passed to a microcontroller. An algorithm would be implemented to assign an initial distance to the object entering the sensor's maximum range. Then the sensor’s speed and direction data would be used to calculate the position of the object relative to the laser excitation point.

3.6.4 Ultrasonic

Ultrasonic sensors can provide a high degree of accuracy for sample placement. Ultrasonic sensors costs are in the moderate range, priced from dollars to several dollars. Ultrasonic sensors have low power requirements, when compared with the other sample detection technology. Ultrasonic sensors use an emitter to throw out ultrasonic sound pulses which reflect off of objects. The ultrasonic receiver detects these reflections. The time between the emission and detection of the ultrasonic sound pulses is used to calculate the distance to the object. Ultrasonic transmitters require analog circuitry to generate the ultrasonic sound wave. The analog circuitry includes an oscillator to create waveform and driver circuitry for the ultrasonic transducer [11]. This circuitry would need to be located close to the ultrasonic sensor. This would either require a prebuilt ultrasonic sensor module, or more likely a small secondary PCB. There are also MEMS ultrasonic modules. ultrasonic sensors would provide a remote and physical solution to sample alignment.

3.6.5 Laser distance measuring

Laser distance sensors provide a high degree of accuracy for sample placement. Laser distance sensors have a moderate cost, priced from dollars to several dollars. Laser distance sensors have low power requirements. Laser distance sensors emit a laser of a specific wavelength which reflects off of objects and is detected by the sensor's receiver. The distance of the object is calculated based on the time it takes the reflected beam to return. Laser distance sensors are affected by the reflectance of the object being ranged. Reflectance is affected by a variety of factors, such as object color, material type, and angle. The laser wavelength is also a factor in distance measurement accuracy.

3.6.6 IR beam break

An IR emitter and detector could be used in pairs to function as beam break sensors. IR diodes or IR laser diodes, along with IR receivers are low cost. IR diodes and IR laser diodes have low power requirements. A beam break sensor could be placed so that it intersects with the laser excitation point, indicating when the sample is aligned.

3.6.7 Sample alignment technology comparison categories

For the LIBS system, the sample alignment sensor will be utilized by the user to ensure that the sample is placed correctly physically or potentially remotely. The choice of technology used for sample placement was influenced by the following factors. The primary concerns are cost, accuracy, and ease of use. The secondary considerations are technological flexibility for remote sample placement, and impact of environmental factors on the sensors. Power consumption was not a major consideration in the sensor technology selection. This is because the distances involved with sample placement were small enough that most of the potential technology choices did not show major variations in power consumption when compared. Additionally the sample distance sensor is only expected to be on for a short period of time when placing the sample. The maximum potential distance that any sensor would need to function in is 1 meter. LEDs and Laser diodes are low cost, and could provide adequate accuracy for physical sample placement, however they could not provide any form of feedback to remote users who are not physically present. Other sensors would be required to work in tandem with the LED or laser diode to accurately place the sample remotely. Microwave sensors are highly accurate, but finding a lower cost microwave sensor that can provide distance measurements is challenging, due to the limited number of reliable suppliers. A microwave sensor that primarily detects motion could be used for sample placement. This would require the sample to be placed at an expected initial position. Then the sample would need to be moved in the direction of the microwave sensor to calculate speed, from which the sample's distance from the laser excitation point could be calculated. For physical placement a user would be required to follow a specific procedure when moving the sample to ensure accurate distance information is presented, which would be unintuitive. Microwave sensors would provide an option for remote sample placement, as distance data could be calculated to determine the sample's position. Microwave sensors also have the potential for interference from other devices or sources that are in the same frequency range. Shielding the sensor from those forms of interference can be difficult. Ultrasonic sensors would also be intuitive to use as they could be set up to provide distance feedback of the sample to the laser excitation point. Ultrasonic sensors are capable of providing remote sample alignment data easily. However, the ultrasonic sensors could only be used in areas with sufficient atmosphere to transmit sound waves. Some ultrasonic sensors are created using MEMS technology, which as a newer technology, could have some reliability concerns. Laser distance sensors are intuitive to use as sample distance to the laser excitation point is easily displayed. Laser distance sensors could be obstructed by dust. The laser distance sensor’s beam has a specific cone shaped FOV. The greater the distance from the sensor the larger the area of that cone is. This could cause interference issues if other objects are located within that cone. However, as the sample is expected to be in an enclosed chamber, interference of this nature is not a major concern. The reflectance of the sample material is also a concern. The IR beam break is low cost. The IR beam would have to be mounted in a very specific fashion to ensure the sample breaks the beam in the right place, this could limit design flexibility. The comparison of alignment sensor technology can be seen in table 3.4.

The technology chosen for advanced sample alignment was the laser distance sensor. It provided high accuracy which means small sample sizes will not be an issue. The laser distance sensor is easy to use as it provides distance data directly. The laser distance sensor is also capable of being used remotely, and could easily work in environments with little to no atmosphere. One concern was the reflectance of the sample material affecting the accuracy of distance readings. However the laser distance sensors of interest for the LIBS system are all within the 850 nm to 1000 nm range, which is expected to perform well with the expected sample types.

Table 3.4 Sample Alignment Sensor Technology Comparison

Category	**LED**	**Laser Diode**	**Microwave Radar**	**Ultrasonic**	**Laser distance**	**IR beam break**
Accuracy	General location	Precise location	Quantifiable distance	Quantifiable distance	Quantifiable distance	Precise location
Cost	Low ($0.1 - 8$)	Moderate ($5-$14)	High ($20 - $87)	Moderate ($3 - $28)	Moderate ($4 -$17)	Low ($0.2- $9)
Power consumption	Low (34mW - 162mW)	Low (5mW - 20mW)	High (600mW - 1.4W)	Low (12mW - 75mW)	Low(84 mW - 165mW)	Moderate (110mW - 300mW)

3.7 Display Technologies Overview

Sensor data along with Spectral data is expected to be passed to an external computer or device for further review and or analysis. An advanced goal of the LIBS project is to display data locally. The capability to display this data locally could provide physical present users with an advanced look at acquired data, to indicate if measurements are acceptable, or if they need to be retaken. It would also allow a local user to immediately understand the sample's makeup. There are a variety of display technologies that could be used for this application. These technologies include: 7-segment displays, LED matrix/clusters, E-ink displays, LCD displays, and OLED displays.

3.7.1 7-Segment Displays

7-segment displays are made up of 7 or 8 LEDs, encased in plastic or other hard container. The container has 7 transparent segments arranged for the number eight. Sometimes there is an eighth segment for a decimal point. All of the LEDs in the 7-segment display share a common anode, and separate cathodes. By connecting the cathodes individually the 7-segment display can form the numbers 0 to 9. 7-segment displays are low cost, prices are usually around the low single digit dollars. 7-segment displays are limited to displaying individual numbers and letters, therefore to display larger amounts of data either requires more 7-segment displays or scrolling the data along in the fashion of a ticker tape. The size of the segments for the numbers and letters of a 7-segment display are fixed, therefore design choices regarding how data is displayed need to take this into account, when using these 7-segment displays as components. The power consumption of 7-segment displays is moderate.

3.7.2 7 LED matrix/clusters

An LED matrix or cluster is a collection of LEDs arranged in rows and columns. They come in a variety of sizes ranging from area in mm to area in several cm. There are a variety of designs. How the LEDs are controlled along with color and brightness depends on the LEDs used in the matrix. Sometimes LED matrix panels control the by having LEDs in the same row share anodes and LEDs in the same column share anodes. This allows for specific LEDs to be controlled by selecting its associated row and column in the matrix. Other designs may use specific bit train sequences or addressable LEDs. LED matrix displays are often connectable, allowing for larger matrix panels to be built. LED matrix panels cost vary with panel size and type. For the LIBS project only smaller sizes would be required for a local display. Therefore the median cost for the system would be in the middle single digit dollar range. LED clusters have moderate adaptability, since any letter, number, or shape can be displayed by activating the correct LEDs. Additionally, since they are modular, it is easy to scale up or down the design. However to change the image or text displayed can require additional work. This is because depending on the LEDs used in the matrix, the node connections that need to be made or the pulse train required will vary with the LEDs used. Therefore to transpose images or text to the LED cluster, custom solutions are required, rather than a provided interface. LED clusters typically have high power consumption due to the LED density. LED clusters can convey a moderate amount of information, as they have a moderate amount of LEDs. Controlling an LED matrix may require custom circuitry or driver.

3.7.3 E-Ink Displays

E-ink Displays are high contrast, greyscale displays that can display text, graphics, or images. E-ink display is made up of segments which contain black and white opposite polarity charged particles. By Applying a small electric field to each segment, that segment or pixel will display as black or white. E-ink displays have a poor refresh rate. Often E-Ink displays are controlled via an external communication protocol to display text or images. E-ink displays are high cost generally around the high 10s to low 20s dollar range. E-ink displays have high adaptability, as images or text simply needs to be modified to be displayed on the display. E-ink displays are commonly used, so software libraries are available for many E-ink displays. This means that no new specific bit sequences need to be determined manually. E-ink displays have low power requirements when compared with other display technology. E-ink displays can convey a moderate amount of information. They have high segment density, however they don't support color. They only support greyscale.

3.7.4 LCD Displays

Liquid Crystal displays or LCDs are a Ubiquitous display technology. LCD displays come in many sizes running from small micro displays to full sized monitors. LCDs are made up of a grid of pixels. A backlight provides light for all of the pixels. In color LCDs, Each pixel has several color filters that only allow specific colors to pass. Each pixel has a layer of liquid crystals, which are used to pass light through a polarized layer when a voltage is applied. By varying the voltage of each liquid crystal section in a given pixel, more or less of a specific colored light is allowed to pass. This allows each pixel to emit a variety of colors [12]. LCDs are controlled in a similar manner to LED matrix or clusters using rows and columns to address specific pixels. However the primitives are generally abstracted away, and a serial interface is used to control the LCD. Prices of LCDs are in the range of dollars to hundreds of dollars, due to the variety of size and feature options. When size is controlled for, LCDs have a moderate price. LCDs are highly adaptable, as the only limitations of what can be displayed are dictated by the screen size, pixel density, and color options. Power consumption varies with display size, however for LCDs power consumption tends to be high due to the panel backlight. LCDs can convey a high amount of information as they tend to have high pixel densities and color.

3.7.5 OLED Displays

Organic LEDs or OLEDS are a newer type of display technology. OLED displays are made of light emitting diodes. Each pixel of an OLED display is comprised of a red, green, and blue LED. Each pixel in an OLED display is controlled in a similar manner to an LCD or LED cluster. Row and columns are used to address pixels, however with OLED displays require additional transistors for each OLED. in addition to this a more complicated control scheme is required to maintain constant current through the OLEDs, as OLEDs experience degradation [13]. OLED displays generally have primitives abstracted away, using a serial interface to control the display instead. OLED displays have a high cost when controlling for size, generally ranging from tens to hundreds of dollars. OLED displays have a high level of adaptability allowing for images and text to be displayed easily. Power consumption of OLED displays is moderate. The OLED display can convey a large amount of information due to high pixel density, and precise color output.

3.7.6 Display technology comparison categories

The results from the LIBS system sensors and potentially the sample data need to be displayed. There are a variety of technologies to choose from. The main concerns for technology selection are cost, power consumption, adaptability, and information conveyance. Secondary concerns were screen size, viewing angle, and refresh rate. The cost of all displays vary with size, however for the LIBS project the display is not expected to exceed a diagonal length of 6 inches. 7-Segment displays are low cost and low power, but they can only convey number or letter information. Changes in the design such as other sensors being added or more data needed to be displayed. Then more 7-segment displays would need to be added. Whereas with other display technologies, data could easily be added, adjusted or resized on the same display. LED matrix clusters can convey a large amount of information. However LED matrix clusters would likely require more work to translate images or text to the display. As without a provided interface or control circuitry, solutions to transpose image or text would need to be designed. Premade chip solutions are potentially available, however since many display technology choices offer this solution built into their displays, pursuing this route would be redundant and would add unnecessary complexity. E-ink displays are very low power, and can convey a moderate amount of information. But they are expensive. Additionally all of the display technologies except for E-ink, offer sufficient refresh rates. The E-ink technology has a slow refresh rate. A slow refresh rate will present an issue for any rapidly changing sensor data such as sample alignment distance. LCD displays have moderate costs, and there are a variety of size options. LCDs also have high adaptability to design changes. However they require more power than some of the other display technologies. OLED displays cost more due to the manufacturing process and additional circuity and transistors required. Finding a range of sizes can also be a challenge, due to fewer suppliers. OLED displays have high adaptability, and low energy requirements. Table 3.5 shows the display technology comparison.

The display technology chosen for the proposed system was the LCD technology. LCD technology is of moderate cost. It will also allow for a higher level of flexibility in the design, if additional sensors are added whose data needs to be displayed. The LCD allows for text and graphics to be shown in color. Therefore the LCD also has the potential to show the LIBS sample data on device in addition to other sensor data. The design complexity factor in this technology choice. The 7-segment display and LED matrix would both likely require a form of custom control circuitry. Although the LCD has a higher power consumption than some of the other options, The higher power consumption was deemed appropriate for the trade offs of decreased costs and greater design flexibility.

Table 3.5 Display Technology Comparison

Category	**7-Segment**	**LED Matrix/Cluster**	**E-Ink**	**LCD**	**OLED**
Cost	Low ($1 - $7)	Moderate ($3 - $9)	High ($89)	Moderate ($5 - $30)	High ($34 - $117)
Display ability	Letters and numbers	Letters , numbers, and graphics	Letters , numbers, and graphics	Letters , numbers, and graphics	Letters , numbers, and graphics
Power consumption	Moderate (500mW - 600mW)	High (1.12W - 2.625W)	Low (0.017mW - 40mW)	High (1.1W - 1.3W)	Moderate (300mW - 500mW)

3.8 Temperature Sensor Technology Overview

One of the stretch goals of the LIBS system is to include a temperature sensor to measure the plasma temperature, or temperature changes on samples at the laser excitation point. One of the issues for measuring the temperature of the laser excitation point, is the extremely high temperatures involved in the LIBS process. Many sensors from a variety of technologies would struggle capturing the temperatures involved with plasma generation. Due to the economic constraints of the LIBS project, it is not feasible to expend a significant portion of the budget for LIBS temperature measurements as a core goal. Should all of the core goals of the system be met, and sufficient budget remains. A high range temperature sensor may be added. There are a variety of technologies that are used in temperature sensing. These include thermistors, thermocouples, and IR sensors. There are a variety of different materials and designs for each technology type.

3.8.1 Thermistor

Thermistors are resistive materials that are sensitive to changes in temperature, If the temperature increases or decreases, the resistance of the thermistor increases or decreases. Thermistors are low cost, running in price from cents to dollars. Thermistors have a short range wherein they can measure temperature changes. Thermistors need to be in contact with, or close to the source of heat to measure temperature changes. Thermistors are highly accurate typically being within several points of a degree to a degree or two of the true temperature.

However thermistors require calibration to accurately measure temperature. Many thermistors have a slow response time to changes in temperature, generally a few seconds. However few if any of these do not have the temperature range to detect plasma.

3.8.2 7 Thermocouple

Thermocouples are made of two different alloys that are connected together. Heating the connection point will create a small voltage differential between the two metals or alloys, which is used to calculate the temperature based on the types of alloys used. Thermocouples are of moderate cost, generally ranging in price from several dollars to tens of dollars. Thermocouples have a short temperature measurement range, and must be close to or in contact with the heat source. Thermocouples have moderate accuracy generally within a few degrees of the true temperature. The response time of a thermocouple is a function of its enclosure, and diameter [14]. Generally the response time is high, usually microseconds to milliseconds. There are some thermal couples that could detect plasma temperatures.

3.8.3 IR temperature sensor

IR temperature sensors detect infrared radiation from objects. The amount of infrared radiation detected is proportional to voltage or current the sensor outputs. In IR temperature sensors, typically a thermopile is used to collect the infrared radiation. The thermopile converts thermal energy into electrical energy. IR temperature sensors are of modrage cost, generally in the range of several dollars to tens of dollars, although very high performance IR temperature sensors can cost hundreds of dollars. IR temperature sensors have a long measurement range when compared with the other temperature sensing technologies. IR temperature sensors can measure the infrared radiation from a good distance. IR temperature sensors have moderate accuracy, generally in the range of a degree or two, however the measurements accuracy is a function of distance. After a certain point, the measurement accuracy decreases as the distance from the object increases. IR temperature sensors have a fast response time, generally on the order of milliseconds. Although faster options exist at higher cost.

3.8.6 Temperature Sensor Technology Comparison Categories

The primary concerns for the temperature selection technology are: cost, range, accuracy, and response time. The costs of IR temperature sensors and thermocouples are relatively close for the same sensing range. To measure much higher temperatures such as plasma, the cost of the IR temperature sensors increases significantly, as does the cost of high temperature thermocouples. Thermistors are cheaper. The IR temperature is the only one that is designed to take readings from a distance, the other technologies generally need to be in close proximity to the heat source. This would require placing them on the sample, or having some sort of apparatus to hold the sensor close to the laser excitation point. Accuracy is relatively close between the IR temperature sensors and thermocouple, the thermistor had the highest accuracy. For the purposes of the LIBS system an accuracy of within a few degrees is acceptable. Each technology had different response times, the IR had the fastest. Due to the speed of the laser excitation events, a fast response time is required to capture the temperature event. The IR sensor could also be used to determine initial sample temperature as a form of information about the environment for remote applications. Temperature sensor technology comparison is shown in table 3.6.

Table 3.6 Temperature Sensor Technology Comparison

Category	**Thermistor**	**Thermocouple**	**IR**
Cost	Low ($0.1 - $3)	Moderate ($6 - $20) High($100 -$400)	Moderate($5 - $15) to high($900-$1300)
Accuracy	High ($\pm 0.05^{\circ}C$ - $\pm 0.1^{\circ}C$)	Low ($\pm 0.5^{\circ}C$ - $\pm 1^{\circ}C$)	Moderate ($\pm 0.12^{\circ}C$ - $\pm 0.15^{\circ}C$)
Response	Slow (1s - 2s)	Fast (0.15ms - 0.800ms)	Moderate(4ms - 600ms)

The technology selected for sample temperature sensing was the IR temperature sensor. The IR temperature sensor can easily take ranged measurements. The other technologies could not achieve this. Some IR temperature sensors have the response time to capture the laser excitation event. The cost of the IR sensor varies with the range of temperatures it can sense. Higher temperature reading cost more. If the opportunity to implement the stretch goals is reached, the IR temperature sensor would be the technology of choice

3.9 Software Technology Comparison

While the firmware for the digital controller will likely be C. A software language is needed to convert the spectral data from the LIBS system into a human readable form. There are a variety of software languages which could accomplish this. The primary concerns for the software technology choice were speed, Difficulty and flexibility. The three software languages that were compared were Rust, Python, and C++. Rust and C++ both offer very high speeds for a software language. This is due to both languages using a compiler. Python is slightly slower, as it uses an interpreter rather than a compiler. Popularity of the language was also considered, as this can indicate the number of packages and resources that are offered in a language. Sometimes it can correlate with compatibility. Popularity was measured based on the number of pull requests on github. Python was the most popular, C++ was 5th, and Rust was 13th. Rust and C++ both require recompile times. A comparison of software languages can be seen in table 3.7.

Table 3.7 Software Technology Comparison

Category	Rust	Python	C++
Speed (Binary tree sorting)	Fast(1.19)	Moderate(50s)	Fast(1s)
Popularity	13th	1st	5th
Code processing	Compiler	Interpreter	Compiler

Python was chosen as the software technology for the LIBS system. Python is commonly used for data analysis and processing. This means that any spectral data could easily be passed to other processing applications with minimal alterations. Since displaying the data is expected to happen on a human timescale, python has sufficient speed to display the received spectral data. Python offers a higher level of portability for the system, as any machine with the required python packages could run the code. There would be no need for any software installations or Architecture targeting. In addition to these considerations python would allow for rapid on the fly alteration to be made to the code which could be very beneficial in the testing stages of the system.

3.10 LCD Product Comparison

For the advanced goal of displaying data locally, several LCD products were compared. The LCD needs to display the results of the sample distance sensor. The display may also display LIBS sample data results. The selected display should be large enough that it is easy to read. But not so large as to become a major cost. Based on comparing prices with sizes from different manufactures, a display that is around 9 cm or 3 inches diagonal is sufficiently large. The resolution of 9 cm or 3 inches diagonal displays is typically 480x320. A display of this size and resolution is easy to read, and has room for displaying additional data or features depending on the size of the font. Three LCD displays of this size and resolution were selected from three different manufacturers and compared. The three selected displays cost less than $40. One of the displays has both TFT and IPS LCD technology. The IPS technology can provide better viewing angles for the LDC. However because this screen is meant to simply display sensor data, viewing angles are not a primary concern. Many Displays come with controllers attached. A display controller or driver is used to drive the individual transistors of the LCD to display images and text. Trying to control an LCD without a controller or driver would require a significant number of I/O resources from the MCU, in addition to a very detailed program to trigger the transistors. The controller abstracts these complications away, and allows for simpler methods of control. Controls generally have a set of commands that are used by the MCU to communicate with the display controller. These commands are sent via various communication protocols like SPI or UART. Since the size and resolution have been chosen, the next things to consider is selecting a specific display manufacturer. The factors that need to be considered for a specific display or manufacture are cost, power consumption, brightness, data sheet detail, controller documentation, communication protocols, and power usage. Cost was considered due to the economic constraints of the system. The cost of the displays are ~15-20 dollars for the TN displays: WF35UTYAIDNN0 and AFK320480A0-3.5N12NTM. The IPS display: 4DLCD-35480320-IPS is ~$40. For the LIBS project, due to economic constraints, the lower priced displays are preferred. For Quality of the data sheet, all three data sheets were considered to determine if sufficient info about each display was provided. The WF35UTYAIDNN0 datasheet was more sparse when compared with the other two display's data sheets. For power consumption the WF35UTYAIDNN0 display uses a supply voltage of 3.4V and 160mA current draw for the backlight. Which gives a total power consumption of 544mW. The logic current is listed at 13.6mA, and the voltage is 3.3V. Resulting in a logic power draw of 44.88mW. To be on the safe side for power requirements it will be assumed that the WF35UTYAIDNN0 draws 600mW. The 4DLCD-35480320-IPS display's data sheet lists that each LED uses 25mA and 3.4V, however 5 volts is recommended. resulting in power consumption of 125mW. It is listed as having 6 LEDs therefore a total power consumption of 750mW. The logic is listed as using 3.3V and 13mA, resulting in a power consumption of 49.9mW. adding the logic power consumption results in 799.9mW. The AFK320480A0-3.5N12NTM display's data sheet lists 20mA as the typical current draw for the entire display. The driver voltage is listed at a maximum of 19.8V. Therefore the power consumption is 396mW. Although the driver for the AFK320480A0-3.5N12NTM lists an operating voltage of 3.3V and current consumption of 16mA. For a power consumption of 52.8mW. Therefore by adding these results in 448.8mW which is rounded to 450mW to be safe. These power conditions often assume certain conditions such as all pixels are black, therefore real power consumption may be higher. The brightness of the two TN displays are relatively close, as expected the display with IPS technology has a higher brightness. The WF35UTYAIDNN0 datasheet is sparse in details when compared with the other two. The 4DLCD-35480320-IPS has some values cutoff, making specific details hard to read. The controller documentation for all of the displays are good. All three displays offer MCU parallel interfaces and SPI interfaces. The WF35UTYAIDNN0 also offers an RGB interface. A direct comparison of these LCDs are shown in table 3.8.

Table 3.8 LCD Product Comparison

Company	**Winstar Display**	**4D LCD Pty Ltd**	**Orient Display**
Part #	WF35UTYAIDNN0	4DLCD-35480320-IPS	AFK320480A0-3.5N12NTM
Cost	$21.08	$39.66	$16.33
Controller type	ILI9488	ILI9488	ST7796S
Resolution	480 x 320	320 x 480	320 x 480
Power Usage	600mW	800mW	450mW
Brightness(Nits)	320	600	360
Datasheet detail	low	Moderate	Moderate
Communication protocols provided	8/16/18 bit RGB, MCU, SPI	MCU, SPI	18-bit RGB, SPI

The display selected for the LIBS project is the AFK320480A0-3.5N12NTM. It was the lowest cost, and provided sufficient brightness at a good level of power consumption. It also offered a SPI interface for communication with the MCU. the WF35UTYAIDNN0 was similar in brightness to the AFK320480A0-3.5N12NTM, but it was higher cost, and had a higher power consumption. The 4DLCD-35480320-IPS was the most expensive of the three, likely due to the IPS technology, which would provide higher brightness, richer colors and better viewing angles. It also had the highest power consumption of the three. Finding the introduction date of any of the displays proved to be difficult, however both the ILI9488 and ST7796S appear to be commonly used controllers. Plenty of open source projects appear to use them both, based on google search results. The display could have been selected to operate in extremely hazardous conditions. However in those cases it is likely that data would simply be transmitted to remote users rather than having physical users on site with the LIBS system. Therefore display toughness was not a consideration in display selection.

3.11 Laser Distance Product Comparison

For the advanced goal of having a remote form of sample alignment, several laser distance sensors were compared. The laser distance sensor is used for aligning the sample under the LIBS's laser excitation point. The sample is expected to be within a meter of the distance sensor, therefore longer ranged sensors can be ignored. The laser sensor selected needs to be capable of continuous measurement or rapid consecutive single shot measurements. This will allow the display to be updated continuously with the samples distance from the laser excitation point. The distance sensor does not require multi-object measurements, as only one sample will be placed under the LIBS laser. Therefore only that single distance needs to be measured. The laser sensor needs to have a maximum range of close to 1 meter. 1 meter is likely more than the sample distance that the sensor will need to measure. However, selecting laser sensors with this max range will allow for flexibility in where the sensor can be placed in the design phase, and does not limit the size of any safety enclosures that need to be created for sample excitation. The laser distance sensor also needs to be low cost. Sample placement detection should not account for a large amount of the system budget. It would be preferable for the sensor to have a digital communication interface. This would allow for direct communication between the MCU and the sensor. A sensor that has the capability of ignoring reading over or under a given distance, would be a useful feature. However this is not required, as it may increase costs. Three distance sensors were compared, they are the VL53L4CDV0DH/1, SOT24-001, and GP2Y0D02YK0F. Cost was the first thing that was compared between the three sensors. The VL53L4CDV0DH/1, and SOT24-001 were both close to the same price at around four dollars. The GP2Y0D02YK0F was at a higher price point of around 12 dollars. The range of the VL53L4CDV0DH/1 and SOT24-001 sensors exceeded the 1m mark, at 130 cm and 400 cm respectively. The GP2Y0D02YK0F sensor had a range of 0.8 m, this was deemed sufficient range for the sensor's applications. The max range distance comparison itself is less important, as all three only needed to have a range of close to meter to detect the sample's distance from the laser. Accuracy is an important characteristic for the sensor to have. The VL53L4CDV0DH/1 sensor has an accuracy of ±8mm at a range of between 101mm and 200mm. For distances greater than 200mm the VL53L4CDV0DH/1 sensor has an accuracy of ±4%. The SOT24-001 sensor has an accuracy of ±10mm between the range of 25mm to 250mm. For objects beyond 250mm the accuracy of the SOT24-001 sensor is ±4%. The GP2Y0D02YK0F lists its accuracy a a flat ±10 cm, however no specifics are given about the test conditions other than the object was white with a 90% reflectance. whereas the VL53L4CDV0DH/1 and SOT24-001 both tested against gray objects with 17% reflectance at specific distances. Because the system does not implement any form of sample micro adjustments. The accuracy is not paramount, however higher accuracy sensors would allow for more flexibility if future functionality calls for higher accuracy applications. Cost versus accuracy would be a concern in general, however the compared sensors have relatively close accuracies not seem to correlate with an increase in cost or size. Both the VL53L4CDV0DH/1 and SOT24-001 offer I^2C interfaces for communicating with an MCU. The GP2Y0D02YK0F uses an output voltage pin, which uses the hysteresis width as the output changes from low to high. The I^2C interfaces offer a fast simple solution for data transfer, it also allows for more complicated commands to be sent to the sensors. The Digital hysteresis width can provide distance data, however additionally circuity or programing would be required to transform the hysteresis width into a distance. The VL53L4CDV0DH/1 sensor is capable of performing Continuous ranging, via polling from the microcontroller using the ST's API layer. The VL53L4CDV0DH/1 can also trigger interrupts via a GPIO pin when a specific distance is measured. The SOT24-001 is capable of ranging at a rate of 90Hz based on the data sheet. The GP2Y0D02YK0F indicates that its worst case measurement period is 47.9 ms, or ~21 Hz. The power consumption of all three devices are listed in table 3.9, and were calculated based on voltage and current figures present in the data sheets. The VL53L4CDV0DH/1 and SOT24-001 are somewhat close in power consumption. The GP2Y0D02YK0F has a higher average power consumption due to higher operating voltages and larger current draw. All of the laser sensors compared had laser wavelengths that were within the desired 700 to 1550 range. The laser alignment products are directly compared in table 3.9.

Table 3.9 Sample Alignment Product Comparison

Company	STMicroelectronics	Goertek Microelectronics Inc.	Sharp
Part #	VL53L4CDV0DH/1	SOT24-001	GP2Y0D02YK0F
Price	$4.28	$3.82	$11.62
Range	130 cm	400 cm	80 cm
Accuracy	±8mm ±4%	±10mm, ±4%	±10mm
Communication	I^2C	I^2C	Digital Hysteresis width
Continuous measurements	100Hz	90 Hz	21 Hz
Power consumption	86.4 mW	72 mW	220 mW

The distance sensor selected is the VL53L4CDV0DH/1. It provides a high level of accuracy for a reasonable cost, it offers the required continuous ranging features. The accuracies of the VL53L4CDV0DH/1 and SOT24-001 close enough that there would not be a major advantage in accuracy for either sensor. Additionally for the applications of the distance sensor. The power draw for the VL53L4CDV0DH/1 is a little higher than the SOT24-00. The SOT24-001 was ultimately not chosen due two reasons. The data sheet provided a sparse amount of information about its features and specific software commands. A search of the internet did not provide any additional information about the sensor official or otherwise, except for its datasheet. This might present issues in the design and testing stages if troubleshooting is required. Second this lack of information may indicate a relatively new product as there appear to be no open source products using it. The GP2Y0D02YK0F was not selected due to higher costs, power consumption, and fewer features.

3.12 CCD Sensor Product Comparison

The CCD sensor will be used to capture the spectral emission of the sample after the laser excitation. Three CCD sensors were compared, The UPD8828AD-A and UPD3747D-A from Renesas Electronics America Inc and the TCD1209DG(8Z,K) from Toshiba Semiconductor and Storage. The main concerns when selecting a CCD sensor were the cost and dynamic range. Some secondary concerns were the number of photocells and the saturation time. The Max operating frequency of the CCD sensors was compared, however all three sensors had roughly the same operating frequencies of around 20MHz. The UPD3747D-A and TCD1209DG(8Z,K) sensors were both close in price, around the $50 range. The UPD8828AD-A cost close to 75 dollars. As mentioned previously with other components, due to cost constraints for the LIBS project. It is important to select cost effective components. The UPD8828AD-A appears to cost more than its counterparts due to additional features like split Red, Green and Blue wavelength apertures. The dynamic range of a CCD sensor is very important for spectroscopy purposes. Without sufficient dynamic range differentiating different peaks and valleys in the emission spectra becomes challenging. Which can result in data that is more difficult or impossible to analyze. Therefore high dynamic range was one of the primary considerations when selecting the CCD. CCDs are known for their high dynamic range, however when comparing different CCDs there were stark differences depending on the manufacture. All of the CCDs used a metric for dynamic range, which was $DR = \frac{V_{sat}}{V_{Dark}}$. as explained in the datasheets for the CCDs, V_{sat} is the voltage at which a pixel on the CCD loses its linear characteristic for received photons, the pixel has been saturated. V_{Dark} is the voltage signal for a pixel in darkness. Both CCDs from Renesas Electronics America Inc had significantly lower dynamic ranges, when compared with Toshiba’s TCD1209DG(8Z,K) CCD. The TCD1209DG(8Z,K) had a dynamic range of 2000, whereas the UPD8828AD-A, and UPD3747D-A had 1000, and 250 respectively. The number of photocells was considered, the CCDs from Renesas Electronics America Inc had more photocells, which would potentially allow for a smaller quantization of wavelength, after diffraction of the light due to the laser blast. However the unit scale of wavelength is irrelevant if the dynamic range is not high enough to truly separate the emission lines. The Saturation exposure time was considered as well, a higher saturation exposure time would potentially allow for a higher spectral resolution. The CCDs from Renesas Electronics America Inc had higher saturation exposure times than the Toshiba CCD. However once again the need for a high dynamic range trumped the Saturation Exposure time comparison. Finally frequency was considered. All of the CCDs had a maximum frequency of close to 20MHz. The data sheets for the Renesas Electronics America Inc CCDs indicate an effective maximum frequency of 40MHz, however this is due to the addition of extra channels in the CCD. The speed of any individual channel is rated at around 20MHz. The direct comparison of the potential CCDs is shown in table 3.10.

Table 3.10 CCD Sensor Product Comparison

Company	**Renesas Electronics America Inc**	**Renesas Electronics America Inc**	**Toshiba Semiconductor and Storage**
Part #	UPD8828AD-A	UPD3747D-A	TCD1209DG(8Z,K)
Cost	$73.92	$46.23	$48.61
Dynamic Range	1000	250	2000
PhotoCells	7500	7400	2048
Saturation Exposure time(lx*s)	0.37	0.10	0.06
Max Frequency	20 MHz	22Mhz	20MHz
Channels	3 R,G,B	2	1

Toshiba's TCD1209DG(8Z,K) CCD was selected as it offered superb high dynamic range performance. The frequency of the TCD1209DG(8Z,K) CCD was comparable to the other compared CCD sensors. The TCD1209DG(8Z,K) did have a lower photocell count at 2048. The saturation exposure time of the TCD1209DG(8Z,K) CCD was also lower at 0.06 lux seconds. However it was determined for spectroscopy applications that a high dynamic range was critical, when compared with any other potential deficiencies.

3.13 MCU Product Comparison

The microcontrollers compared for use in the LIBS project had to meet the I/O and Communication protocols required of all the sensors. In addition to this the MCU had to have the speed to control and or detect events in the LIBS system that occurred on a very fast timescale. The expected pins required for sensors and components can be seen in table 3.11. The components needed to achieve the core goals of the system are listed in green. components associated with advanced and stretch goals are in orange.

Table 3.11 Needed MCU Sensor Interface Resources

Sensor type	**Part #**	**Pins needed**	**Pin types needed**
CCD	TCD1209DG(8Z,K)	6	1 ADC 5 GPIO
IR Photodiode	SFH213FA	1	1 interrupt pin or 1 GPIO pin
External data transfer	FT231XS-R	2-5	GPIO
Temperature Sensor	NA	1	1 ADC
Distance laser sensor	VL53L4CDV0DH/1	4	2 I^2C, 1 interrupt pin, 1 GPIO
LCD	AFK320480A0-3.5N12N TM	5-6	5-6 GPIO
Total Pins Needed		13-23	2 I^2C pins 2 interrupt pin 14 - 18 GPIO pins 2 ADC

Core goal requirements Advanced & Stretch Goal requirements

The laser distance sensor requires 4 wires to connect to the MCU. These are used for the SDA and SCL lines of the I^2C interface, A GPIO pin for interrupts, and an optional second 3.3V digital pin for togeling the distance sensors between active and standby mode. The IR temperature sensor will likely require a single ADC pin to read the thermopile of the sensor. The LCD needs a 3 or 4 wire SPI interface. The MCU will need 2 digital pins for data in SDI, and data out SDO. There is also a digital slave select pin, and a reset pin. For 4 wire SPI, there is an additional pin digital to indicate whether the MCU is transmitting a command or Data. The CCD needs an ADC pin for the analog output data voltage. The CCD needs a GPIO pin to control the CCD’s shutter. The CCD also requires 5 GPIO pins, as there are 5 periodic signals. The spectroscopy system will need an interrupt pin or GPIO pin to detect or trigger the laser blast.

The four MCUs that were compared were the STM32G030K8T6, SPC5601PEF0MLH6, ATSAM3S1AB-AUR, and STM32G0B1RET6. The costs of these microcontrollers range from around a few dollars to several dollars. The SPC5601PEF0MLH6 was the most expensive at $14.84, whereas the STM32G030K8T6 was the cheapest at $2.06. Due to budget constraints, a lower priced controller would be preferred, however this is contingent on the MCU meeting all of the needed criteria. All of the compared controllers have a speed of 64MHz. Controllers of this speed were chosen, as 64MHz gives a maximum temporal step size of around 16 ns. This was deemed fast enough to accurately capture or trigger events during the LIBS process, while reducing the prices of the controllers. Generally cost relates closely to speed for the microcontrollers. Both the STM32G030K8T6 and ATSAM3S1AB-AUR MCUs had a GPIO count of around 30 pins. Exceeding 23 expected pins required, which would provide sufficient head room for a few unexpected additional components. The SPC5601PEF0MLH6 controller had 45 GPIO pins, and the STM32G0B1RET6 had 60 GPIO pins. All of the microcontrollers have a sufficient number of ADCs or ADC channels for the expected sensors. The resolution of the STM32G030K8T6, ATSAM3S1AB-AUR, and STM32G0B1RET6 ADCs is 12-bit. The ADC of the SPC5601PEF0MLH6 has a 10 bit resolution. The STM32G030K8T6 and STM32G0B1RET6 have ADC sample rates of 0.4 us each. The SPC5601PEF0MLH6 has an ADC sample rate of less than 1us. The ATSAM3S1AB-AUR has an ADC sample rate of 1 us. A faster sample rate would be beneficial as it would allow the CCD to run at a higher frequency which may help get better spectral intensity from the samples. It is possible to add an external ADC with a much higher sampling rate, rather than using the ADC built into the MCU. However this would introduce additional complexities into the design, which would be preferable to avoid. The SPC5601PEF0MLH6 has 20 Kbytes of ram available. The ATSAM3S1AB-AUR has 16 Kbytes of RAM available. The STM32G030K8T6 only has 8 Kbytes of RAM, and the STM32G0B1RET6 has 144 Kbytes of RAM. The expected ram usage due to the CCD readings is 2088 elements times 12-bit ADC resolution equals 25.056Kbit then divided by 8 results in 3.132Kbyte per CCD measurement. For the 10 bit ADC it would be 2.61 Kbyte per CCD measurement. Potential temperature and distance measurements would also be taken. Therefore assuming averaging temperature and distance measurements are the average of 3 results then 12-bit times 6 divided by 8 gives 9 Bytes or 7.5 Bytes for the 10 bit ADC. Power consumption was another factor to consider when selecting an MCU. The power requirements of each controller were estimated based on the specifications presented in the data sheets. The STM32G030K8T6 had a maximum current draw of 205mA. This assumes all IO pins and control pins are sinking or sourcing the maximum amount of current simultaneously. At 3.3V this results in a power consumption of 667mW. In reality the power consumption is expected to be lower than this. The SPC5601PEF0MLH6 has a current consumption of 65mA, at 1.3V. A 10mA flash memory current draw at 5V. A 4mA current draw from the ADC at 5V. An oscillator current draw of 3.2mA at 5V. And a 10mA current draw for its internal regulator at 5.5V. The I/O running at high speed has a current draw of

110mA at 5V. The sum of these result in a total of power consumption of 725mW. The ATSAM3S1AB-AUR had a total current consumption of 80mA for I/O and 38.24mA for the core. The I/O runs at 3.3V and the core runs at 1.8V resulting in power consumptions of 677mW and 69mW which is a total of 745mW. The STM32G0B1RET6 had a current consumption of 205mA and would be expected to run at a voltage of 3.3V. Therefore the total expected power dissipation would be 677mW. A direct comparison of the potential MCU options can be seen in table 3.12.

Table 3.12 MCU Product Comparison

Company	**STMicro Electronics**	**NXP USA Inc.**	**Microchip Technology**	**STMicro Electronics**
Part #	STM32G030 K8T6	SPC5601PE F0MLH6	ATSAM3S1A B-AUR	STM32G0B1R ET6
Price	$2.06	$14.84	$3.79	$6.46
Clock frequency	64 MHz	64 MHz	64 MHz	64 MHz
GPIO	30	45	34	60
ADC resolution	12 bit	10 bit	12 bit	12 Bit
ADC sample rate	0.4 us	<1 us	1 us	0.4 us
RAM	8 Kbyte	20 Kbyte	16 Kbyte	144 Kbyte
Power Consumption	677 mW	725 mW	745 mW	677 mW
14 - 23 GPIO pins	✅	✅	✅	✅
2 ADC	✅	✅	✅	✅

The STM32G030K8T6 MCU from STMicroelectronics would have been selected. However the limited program memory size would likely require that low level assembly be written for space efficiency. This could introduce additional complications to the project as there would be limitations around potential code expansions, which could add more features. In addition to this, there may be fewer resources available to support assembly development. Assembly is also less portable, and may have more difficulty interacting with other tools. Therefore the STM32G0B1RET6 was selected for the LIBS project as it had a moderate price, offered the highest ADC sampling rate, along with sufficient GPIO resources and RAM. The trade off of higher onboard ADC sampling rate and more RAM resources for higher price was deemed appropriate. With 144k Byte the controller could hold 44 consecutive LIBS readings without any overflow, in addition to many other miscellaneous sensor readings like temperature or distance. The other three potential controllers could only hold two to five CCD readings at most. The STM32G030K8T6 and STM32G0B1RET6 also had the lowest maximum power consumption of all the controllers.

3.14 Light Collection for LIBS system

A LIBS system works by collecting photon emissions for plasma generated by a high-powered laser. The system consists of two important elements: a wavelength selector (spectrometer) and an optical detector (multi-element solid-state detector. The job of this system is to produce the spectral composition from the radiation emitted by the plasma to determine and identify the spectral fingerprint of the sample being examined, on the atomic scale. The photons are collected by a lens system near the plasma and then transmitted to a spectrometer by a fiber-optic cable. There are other methods to collect the photons generated from the plasma, one such example is the method used by NASA called the ChemCam. This LIBS system uses a telescope to capture the photon emission, then uses a fiber-optic cable in the same method as other LIBS systems to transmit the light to the spectrometer. This is called stand-off LIBS and it is used on exploratory off-world rovers.

3.14.1 Spectrometer

There is no “one size fits all” solution when choosing a detection system for LIBS. Detection systems use 3 main parameters for LIBS, wavelength range, sensitivity, and speed to gate the exposure of the spectral image that is being captured. There are charge-coupled device-based spectrometers (CCD). These spectrometers are used extensively because of their high accuracy, low-cost, and wide abundance. CCD spectrometers typically use a Czerny-Turner or crossed Czerny-Turner design. Echelle Spectrometers use a combination of two dispersive elements, a prism and a grating, to spit the light in two dimensions for a square detector. This would give a two-dimensional spectral field, wavelengths in one and various orders in the other. Software can be used to sort through this to give a spectrum image output between 200-900 nm. These spectrometers can easily outperform CCD based systems, but the cost is substantial because of the need for an intensified camera giving a resolution of 0.05nm or better. This system does not provide the best throughput for light and given the cost is a suboptimal choice for the system. A traditional Czerny-Turner spectrometer has high levels of throughput light and light can be dispersed using a strong first order diffraction grating. A Czerny-Turner style spectrometer will be designed, because it is the most commonly used and cost-effective system for LIBS. These systems can be tailor-made through component selection based upon scope and needs of the project as well as budgetary constraints. The following section will compare and select components that will best fit the needs for the design.

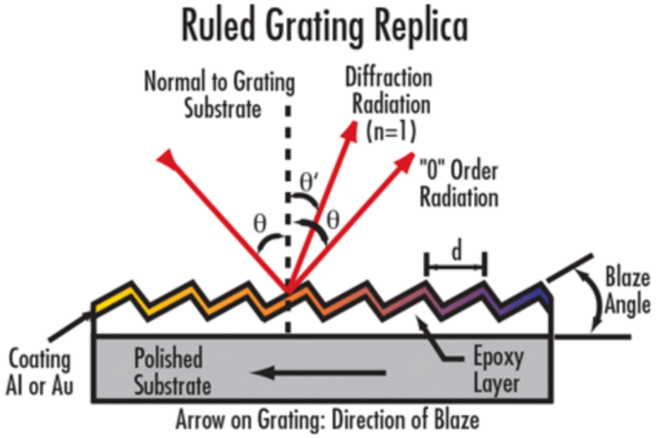
3.15 Optical Components of a Spectrometer System

This section provides an overview of optical components in a spectrometer and how each one functions. Specifically an optical grating and its diffraction of wavelengths and how it will be used in the project.

3.15.1 Diffraction Grating

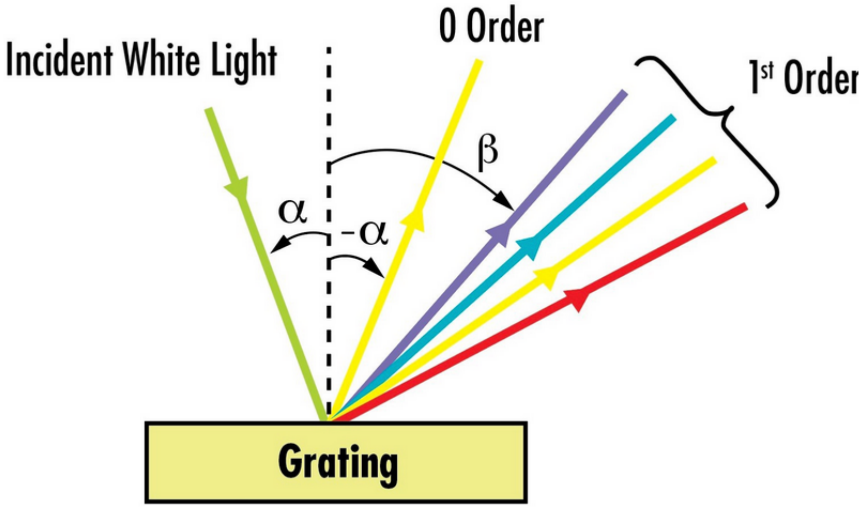
A diffraction grating as seen in figures 3.1, 3.2. Is a passive optical element that separates an incident light upon its surface using the optical property of diffraction. Light of different wavelengths will propagate in different directions. This diffraction is due to a phase change as the light encounters the grating surface.A diffraction grating consists of parallel grooves that are evenly spaced on a reflective or transparent surface. There are two important characteristics that determine design use of a diffraction grating. Those are the distance between each groove and the angle at which each groove forms with respect to the surface.

Figure 3.1 Features of Ruled Grating



There are two questions that need to be considered when designing a diffraction grating. What specific wavelength is needed? What groove density and blaze angle are desired? The groove density is the number of grooves in an area of grating; it is used to determine the range of wavelengths that is going to be dispersed by the grating. The blaze angle provides the first order of diffracted angle of the blaze wavelength. The blaze wavelength is the diffracted spectrum with the highest efficiency.

Figure 3.2 Characteristic Dispersion of Diffracted Light



3.15.4 Types of Diffraction Grating

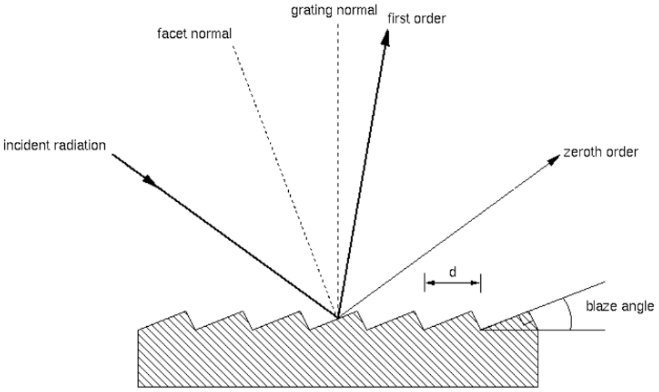
There are two commonly used categories of diffraction gratings, a reflective type or a transparent type. Reflective gratings act like mirrors and reflect this incident light off the groove surface, splitting the light into its distinct wavelength components. Transmission gratings behave like a lens, all incident light passes through the groove like a screen and the light beam is then split in this manner. Reflective diffraction gratings have higher diffraction efficiency over their transmission counterpart because much less of the incident light is absorbed by the reflective surface. This makes them ideal for spectroscopy and will be the category of grating that is chosen for the system.

There are two main types of manufactured diffraction gratings to choose from, ruled and holographic. They are both constructed in a different manner, and each has a characteristic benefit of use. Ruled diffraction gratings are created with a diamond, mounted on a ruling engine. This apparatus physically forms the grooves into a reflective surface, usually aluminum. A holographic grating has its grooves formed by a laser, creating a constructed interference pattern by a photolithographic process. Ruled gratings are best for efficiency for high resolution spectroscopy, while holographic is best for reducing light scattering, so it would be ideal for stray light sensitivity application, like Raman spectroscopy. For the system's specific applications a ruled reflective diffraction grating is chosen. There is a third type of diffraction grating, which is a transmission-based grating. This allows light to pass through a diffraction grooved film, diffracting the light as it passes. This is not an ideal grating as it is not used in spectroscopy. Another type of ruled grating is an echelle grating. These gratings are coarse , have a low groove density, and a high blaze angle. They primarily use a high diffraction order by providing a high dispersion and resolution in a compact system build. The limitation of this system is that it requires another optical element such as a prism or another grating to separate the other higher orders. This makes it not an ideal choice for the spectrometer design.

3.15.5 Diffraction Grating Characteristics

The three most important characteristics of a diffraction grating for a spectrometer are wavelength range, efficiency, and blaze wavelength. The proposed LIBS system will be looking at the visible spectrum. The number of grooves per mm ruled on the diffraction grating surface (groove density) determines the total amount of light dispersion. This characteristic will determine the spectral range and is also a key factor in spectral resolution. The wavelength spectral range of a spectrometer system is inversely proportional to the dispersion of the grating. Increasing groove density yields greater dispersion from a grating, higher spectral resolution, and this gives higher resolving power. Decreasing the groove density, decreases the dispersion but increases the total wavelength coverage of the system. This would also lower the spectral resolution, which is not ideal for the system. As stated earlier, the distance between grooves will determine the spectral range, thus the visible wavelength range of 380-700 nm will determine the groove spacing. On ruled diffraction gratings, the grooves have a saw-toothed pattern, and the blaze angle is the angle that is formed by the longer side of the saw-tooth shape and the surface of the grating, as seen in figure 3.3.

Figure 3.3 Ruled Grating Surface Showing Blaze Angle

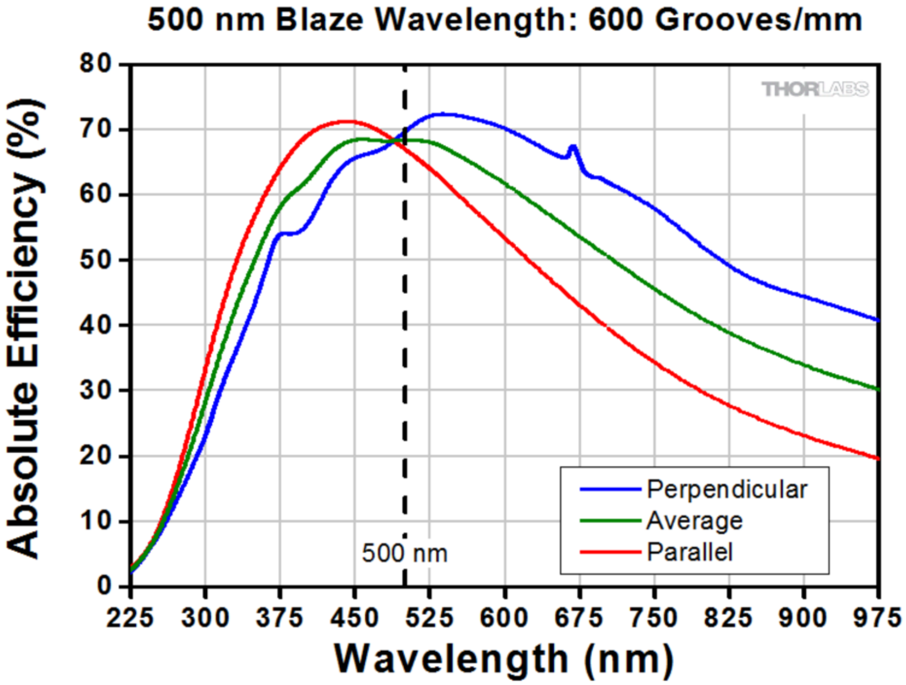


3.15.7 Diffraction Grating Efficiency

Changing the blaze angle alters the concentration of diffracted light for a specific region of the radiated spectrum, increasing efficiency. Where the maximum efficiency occurs is called the blaze wavelength. The last key characteristic in determining the right diffraction grating for a project is efficiency. There are three determining factors that affect efficiency, and they are shape of the grooves, reflectance of the coating, and angle of groove incidence. Efficiency of a diffraction grating is determined by “absolute efficiency”. This takes the percent of incident (monochromatic) light that is diffracted, which is the ratio of energy diffracted into a desired order and the energy diffracted by a plane mirror that is treated with the same reflective coating as the grating.

Gratings used in visible wavelength are normally aluminum coated. Aluminum is used over the choice of silver because it is more resistant to corrosion from oxidation, and it has superior reflectance for certain spectra (ultraviolet). Aluminum also has great reflectance at over 90% for wavelengths from 200 nm to the far infrared, it drops to around 85% from 750 to 900 nm. Figure 3.4. is an example of a 500 nm blaze wavelength reflective diffraction grating.

Figure 3.4 Blaze Wavelength Showing Grating Efficiency



The graph shows that at 500nm the highest absolute efficiency can be achieved with this grating. This is a good starting design choice, as all of the spectral data will be taken around this wavelength.

3.15.9 Diffraction Grating Selection

Design selection of a diffraction grating takes all the characteristics from above and combines that together for the best available grating choice. Many factors are involved in this choice, the first and foremost will be cost and the rest will fall into a pros and cons ideal option.

Edmund optics reflective ruled diffraction gratings claim up to 80% efficiency, have a bare aluminum coating, and say their blaze wavelength has options from 250 to 1600 nm. Thor labs claim their visible ruled reflective diffraction gratings utilize an aluminum reflective coating and have an efficiency of 60-80% at the blaze wavelength when measured in the Littrow mounting configuration. Here is a comparison of several options and sizes from the two known companies in optical component manufacturing. These two companies were chosen for ease of use and transparency of classification characteristics and pricing. This is an “apples to apples” comparison of what each company has to offer for a diffraction grating with either 600 or 1200 grooves/mm, a wavelength range of 200-900 or 200-1600 nm, dimensionality of 12.7x12.7 or 25x25 and a blaze wavelength of 500 nm. The wavelength of 500 nm is the optimal choice for material identification since it sits right in the middle of the visible spectrum. Table 3.13 is a direct comparison of the different diffraction gratings.

Table 3.13 Comparison of Plane Ruled Reflective Gratings

Brand	Groove Density (groove/mm)	Wavelength range (nm)	Blaze wavelength (nm)	Dimensions (mm)	Price
Edmund Optics	600	200-900	500	12.7x12.7 25.0x25.0	$80 $134
Edmund Optics	1200	200-1600	500	12.5x12.5 25.0x25.0	$80 $134
Thor	600	200-900	500	12.7x12.7 25.0x25.0	$76.58 $125.77
Thor	1200	200-1600	500	12.7x12.7 25.0x25.0	$76.58 $125.77

Edmund optics also has a newer “high-end” diffraction grating called the Richardson Grating high precision plane ruled reflective diffraction grating. They claim it has excellent efficiency at the blaze wavelength, superior dimensional tolerances, and it is ideally suited for spectroscopy. Table 3.14 uses the same comparison characteristics as above.

Table 3.14 Comparison of Edmund Optics High Resolution Diffraction Grating

Brand	Groove Density(groove/mm)	Wavelength range(nm)	Blaze wavelength(nm)	Dimensions (mm)	Price
Edmund Optics	600	350-800	500	12.7x12.7 25.0x25.0	$152 $168
Edmund Optics	1200	200-1600	400	12.5x12.5 25.0x25.0	$131 $168

3.16 Light Collection System

Light collection is significantly important in LIBS systems. The use of a proper collection and collimation lens improves a systems sensitivity, reliability, and accuracy for proper elemental analysis. The light emitted by the plasma plume created by our laser will need to be collected for an accurate spectral scan.

3.16.1 Ways Spectrometers Collect Light

There are many ways light can be collected by a spectrometer. In absorption spectroscopy, light is passed through a sample and as the light is absorbed the reduction of intensity is measured. Specific wavelengths of the light are absorbed by the material being sampled and this is used to determine its characteristic build. Fluorescence spectroscopy is a form of emission spectroscopy in which it uses a high-energy light source to illuminate a sample causing it to “fluoresce” or generate its own light. A spectrometer is then used to analyze the fluorescence emission so that the sample can be analyzed for specific compounds. Emission spectroscopy is the collection of light that is emitted from a sample by means of excitation from an external source like a laser or an electrical discharge. A spectrometer is then used to capture the emitted light to characterize the emission spectrum. An example of this would be atomic emission spectroscopy or in the case of the proposed system, laser-induced breakdown spectroscopy. Raman spectroscopy is more complicated, using a method that collects light that has been scattered after interacting with a sample. This “inelastic” scattering is when there is a transfer of energy by the incident x-ray or neutron to the sample and vice versa. Mostly used in chemistry to identify molecules and study chemical bonding and intramolecular bonds, so it will not be a method used by the team in this project. LIBS light collection system is emission spectroscopy, this is due to the use of a high-powered laser to create plasma on a sample. From this captured light that the plasma creates, the system will be able to determine the elemental characteristics by analyzing the spectrum that is collected.

3.16.2 Capturing the light

A spectrometer is used to collect and separate light into its varying wavelengths for analysis. One very important factor is making sure the correct light from the source that is being analyzed is collected. A spectrometer does this by using a slit entrance so that only a narrow band of light gets through. This slit acts as a spatial filter to separate out the range of wavelengths not needed and to pass those that are, ensuring that only the desired region is analyzed. The slit is used to reduce the amount of “stray light” that enters the system. This stray light can come from scattering or reflections and is unwanted. To control this incoming light, the width of the slit can be adjusted. This is pivotal in controlling the signal to noise ratio in spectrometer measurements. A narrow slit would allow less light to enter the spectrometer, used in instances of high intensity light sources and a wider slit is good for low light intensity sources. The slit width also has a direct effect on the spectral resolution of the spectrometer. The point of a spectrometer is to distinguish between closely spaced wavelengths to give a “spectral fingerprint”. Having a narrow slit produces higher spectral resolution because it only allows for a narrow range of wavelengths to be passed to the system for analysis.

3.16.3 Comparing components to capture light

A collimating lens system can be used to collect light and then direct the light into a spectrometer. This lens system helps to make divergent incoming rays parallel before they enter the spectrometer. This is an advantage for beam alignment and optical correction but is not the only way to steer light into a spectrometer. Collimating lenses or mirrors are often used in conjunction with other optical components and are part of the overall system.

A condensing lens can be used to focus the collected light into the entrance slit and maximize the amount of light that enters the spectrometer. The focal length can be adjusted to control the spot size on the entrance slit and this would maximize the amount of throughput light. This lens system is necessary to achieve very accurate measurements with the focused light. This would be a costly lens system and overkill for the system.

Reflective optics like a concave mirror can be used in a light collection system to steer and align incoming light. This light is then collimated and focused by the mirror to a directed point, minimizing optical aberrations like defocus, spherical, coma, astigmatism, image distortion, and field curvature. Chromatic aberrations can occur when different wavelengths are not focused to the same point and can be axial (longitudinal) or lateral (transverse). Reflective optical components will usually be used in combination with other components to direct light efficiently in a spectrometer. Off-axis parabolic mirrors are used to collect light and direct the light in a way that is not obstructed by the mirror. Parabolic mirrors carry a high dollar value, usually several hundreds of dollars, and this would not be economically feasible for the system.

Microscope objectives are used in microscopy spectrometers. They collect and focus light from very small samples under a microscope, usually used in Raman and fluorescence spectroscopy. Since the sample will not be under a microscopy this type of collection optic will not be used.

Fiber optic cable accompanied with a lens, such as an achromatic, is another great way to collect light into a spectrometer. It is an efficient way to collect and couple light from the sample being analyzed. The small core of the fiber can collect light over a wide range of angles, maximizing light throughput into the system. The flexible positioning of the fiber optic cable can make it easy to collect light and tune the system to improve performance. Fiber cables also allow for remote sensing. This means that a fiber optic cable can be used for light collection from a sample in a hazardous or difficult to reach environment. It can be used in both multimode and single-mode optical cable variants. This allows for a broad spectrum of light to be collected from a wide range of angles by the multimode and single mode fiber is used to capture specific wavelengths where precise control over light collection is needed. The use of fiber optic couplers and connectors will make it easy to adjust or adapt the system to suit the needs of the user without altering the spectrometer itself. This makes the system versatile for a wide range of needs, not limiting it to one experimental use. Fiber optic cables are designed to allow minimal light loss during transmission, maintaining nearly all its original spectral characteristics. This high efficiency also reduces the risk of spectral contamination by other light sources distorting the spectral sample. All these characteristics make the use of fiber optic cables one of the best methods for light collection in a spectrometer system.

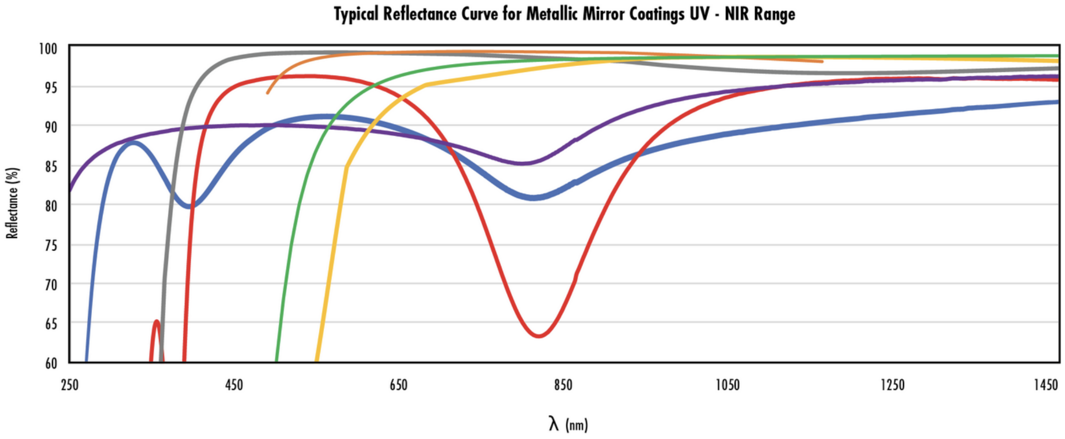
3.16.4 Spectrometer Optical Component Selection

The proposed LIBS system requires two concave mirrors located inside the spectrometer. Concave mirror selection for the spectrometer system is based upon several factors. Each concave mirror acts as a focusing mirror, steering the beam from the entrance slit to the diffraction grating and from the diffraction grating to the linear CCD. These mirrors help to align and focus the beam so that their spectral components follow a parallel path. The alignment of the spectral components makes sure that different wavelengths are focused onto the same area of the CCD, ensuring accurate spectral measurements. The concave mirror, both before and after the diffraction grating, serves to correct the collimation of the light entering the system from the sample. As light enters the system it disperses or spreads out. The concave focusing mirror corrects this by converging the dispersed light back into a collimated beam. It is necessary that the light coming from the entrance slit be collimated for efficiency before it hits the diffraction grating and after because the diffraction grating will disperse the light into different wavelengths as well. This is all done to ensure that the system will produce the most accurate spectral scan. Collimation and realignment done by the concave focusing mirrors improves spectral resolution. This is the system’s ability to distinguish between tightly spaced wavelengths, giving a more accurate scan. The path that the light travels through the spectrometer can introduce optical aberrations such as spherical or chromatic. The concave focusing mirrors minimize the effects of the aberrations on the system, increasing quality and accuracy of the spectral measurements. The concave focusing mirrors also increase signal intensity. By focusing the dispersed light, the mirrors ensure the entire spectrum is concentrated onto the detector. This concentrated light has a higher signal intensity, leading to greater signal-to-noise ratio (SNR) measurements. If the SNR is higher, the quality and accuracy of the spectrometer is greater, leading to an overall better system.

There are four main characteristics that are looked at when selecting a concave reflective mirror: diameter, effective focal length (EFL), aperture (F#), and coating. The most concerning one for us right now is coating. The other characteristics can be changed depending on the needs and design of the system. When looking at coating, the wavelength range and reflectivity characteristics of the mirror is being dealt with. Aluminum coated mirrors are the most commonly used and affordable. They handle the visible and near-infrared spectrum (400-2000 nm). Aluminum coated mirrors provide good reflectivity through these wavelengths making them an ideal choice for visible light. Silver coated mirrors have excellent reflectivity as shown in figures 3.5 and 3.6, approaching nearly 100%.

Silver is also good for a broad range of wavelengths, ranging from visible and near infrared where high reflectivity is required in a system. The drawback to silver is that it is generally more expensive, and it is sensitive to environmental factors, tarnishing and degrading more quickly over time than, say, aluminum or gold. Gold coated mirrors are used mostly in the mid-infrared range. They have good reflectivity at this wavelength and are good for IR spectroscopy, making it not a suitable choice for visible or near-infrared spectrometers. There are also UV-enhanced aluminum and silver coated mirrors, which are not applicable since the system will be viewing the visible spectrum. In table 3.15 two companies are compared, Edmund Optics and Thor Labs, Their protected aluminum coating line of concave reflective mirrors is examined.

Figure 3.5 Edmund Optics: Reflectance Curves for Metallic Mirror



Protected Aluminum		Enhanced Aluminum		UV Ehanced Aluminum		Protected Gold		Bare Gold		Protected Silver		Ultrafast Enhanced Silver	
Range (μm)	% Reflection	Range (μm)	% Reflection	Range (μm)	% Reflection	Range (μm)	% Reflection	Range (μm)	% Reflection	Range (μm)	% Reflection	Range (μm)	% Reflection
0.4 - 0.7	85	0.45 - 0.65	95	0.25 - 0.45	89	0.7 - 2.0	96	0.7 - 0.8	94	0.45 - 2.0	98	0.6 - 1.0	99
0.4 - 2.0	90	–	–	0.25 - 0.70	85	2.0 - 10.0	96	0.8 - 2.0	97	2.0 - 10.0	98		
								2.0 - 12.0	98				

Figure 3.6 Thor Labs: Reflectance Curves for Metallic Mirror

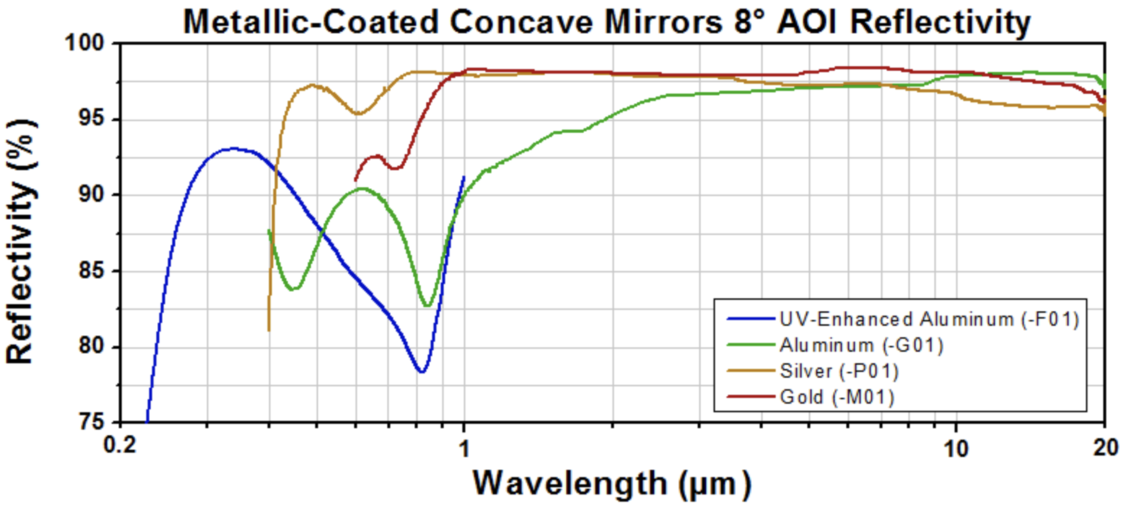


Table 3.15 Concave Mirror Comparison

Brand	Part number	Coating	Reflectivity	Wavelength range(nm)	Aperture	EFL (mm)	Diameter (mm)	Price
Edmund Optics	43-465	Protected Aluminum	>90%	400-2000	f/1	25	25	$46
Edmund Optics	43-466	Protected Aluminum	>90%	400-2000	f/2	50	25	$46
Thor	CM127-012-G01	Protected Aluminum	>90%	450-2000	f/1	25	12.7	$42.51
Thor	CM254-075-G01	Protected Aluminum	>90%	450-2000	f/3	75	25	$66.24

3.17 Laser System

There are a number of lasers that can be used for the proposed system. This section provides a summary of the different laser technologies and compares some of the benefits and detriments of each type.

3.17.2 CO2 Laser

In order to make a LIBS system one of the decisions that needed to be made was what kind of laser was the system going to use. For a LIBS system there are two main types of lasers to choose; neodymium-doped yttrium aluminum garnet (Nd:YAG) laser or the carbon-dioxide (CO2) laser [15]. The CO2 and Nd:YAG laser have been around for a while (as far as lasers are concerned), both were discovered at Bell Telephone Laboratories, Incorporated in 1964. The CO2 laser by Kumar Patel and the Nd:YAG by Joseph Geusic and LeGrand Van Uitert.

There are many different optical gain mediums used for creating lasers. In order to create a laser, the beam needs to be coherently focused so as to make the photons from stimulated emission from the gain medium. The stimulated emission from the gain medium is by the transitions of energy from high to low. This is done by means of electrical or molecular stimulation. Different optical gain mediums are transitioned into the excited state by external sources of energy. Two mirrors will be placed around the gain medium, one on either end. The photons will then bounce back and forth inside of the optical gain material, gaining more and more photons till it reaches a critical point and then exits the cavity. In a CO2 laser the carbon-dioxide is mixed with nitrogen, helium, and hydrogen in order to make the population inversion of the laser. The percentage of the gas in the chamber is usually 10-20%.

3.17.3 Nd:YAG laser

The Nd:YAG is one of the most widely used materials to create solid-state lasers. The chemical properties of the Nd:YAG and its optical properties are very beneficial to creating lasing. This is due in part to the Nd:YAG having high thermal conductivity and the cubic crystallographic structure is beneficial for narrow fluorescent linewidth. The results of which lead to low threshold and high gain for lasing performance. The sturdy YAG structure is consistent from the lowest temperatures to its melting point with no change in the solid phase. It is a four-level system which will increase the population inversion for creating a more efficient laser.

Nd:YAG solid state lasers are well suited for making Q-switched pulsed lasers. Changing the percentages of the neodymium to yttrium aluminum garnet will change some of the characteristics of the wavelength. Normally the crystal is doped to 1% with neodymium which changes the nature of the crystal. For example the doping with neodymium will change the crystal to violet from blue. The optimal amount of neodymium doping is 1-1.4%, this allows the higher energy level to have greater storage of energy which is better for a pulse laser.

3.17.4 Pulsed vs Continuous Wave (CW) Lasers

The optical gain medium needs to be stimulated and the method used to achieve this will determine if it is a Continuous-wave laser or a Pulsed laser. One of the aspects of a pulsed laser is that it needs to not be continuously emitting photons, but rather building up many photons within the cavity so as to reach a point of criticality. Then all the light is released over the course of a nanosecond or attosecond. This huge release of energy is within such a small amount of time that when the light hits the target it can destroy the surface it has hit. The pulsing of the laser is desirable for a number of applications. For example, laser range finders, soft tissue surgery, LIBS, tattoo removal, and data transfer which is huge for high-speed communication, especially over fiber optic cables and satellite to satellite communications [16]. One of the rising applications of pulsed lasers is its use in nanomaterial manufacturing. Pulsed lasers are used to verify the atomic structure of manufactured nanomaterials which are created for electrocatalysis [17]. Electrocatalysis is a specific sphere of electrochemistry and focuses on the ability to control the electrochemical reaction of chemicals. To create a laser a population inversion must be created within the laser cavity. This usually takes the form of a flash lamp which ‘pumps’ the optical medium which will create the required state, which will then stimulate emission from the medium. The continuous-wave laser must be putting out laser strength to penetrate missile walls and for laser manufacturing by welding and cutting different materials. These applications of lasers have been very beneficial to the world economy.

3.17.5 Focusing Lenses

The exiting beam from a laser cavity needs to be focused to a maxed intensity at the focal point. The focal point being where the rays converge for maximum intensity. Knowing where this is and designing a lens system with this in mind is crucial for any application. This is done by either purposely expanding the ray trace of the beam to then enter a larger lens that can focus the beam close to its surface. This type of lens is a converging lens and is very common in gaussian optics.

3.18 Plasma

There are 4 main states of matter, plasma being the rarest on earth, but the most common one, making up 99.9% of the visible universe. The 4 different main states of matter are solids, liquids, gasses, and plasma (sometimes known as ionized gas). There are others such as Bose-Einstein condensates and Fermionic condensates to name a few, but those are out of the scope of this paper. The classic view of the states of matter is very focused on how it is affected by temperature, pressure. The nucleus of the atom is separated from some or all of its circulating electrons. Plasma also conducts electricity which helps differentiate it from a normal gas.

3.18.1 Plasma Applications in everyday items

Plasma may be the least common form of matter on earth, but it has many applications in Society. Because of plasmas ability to conduct electricity, one of its applications is to illuminate signs. These used to be called neon lights since that is one of the substances used in it. However, most companies have moved away from neon due to the lead used in the design. They have now moved over mostly to fluorescence. Plasma is also used for some television screens to give better display quality. This is done by lighting up the plasma in the different RGB (red, green, blue) pixels.

3.18.2 Plasma in Metal

Plasma has many applications in metal works and manufacturing. There is plasma cutting which melts and cuts using a plasma arc at a very high temperature. This method is widely used for trimming metal plates into desired shapes for manufacturing ships, airplanes and rockets. Plasma welding for metal is also a great application. This method for welding is very beneficial as it can create very strong and “clean” welds. This method of welding is very beneficial for welding structures that are going into space. Plasma welding was also the first method tested of welding in space. This was first tested by the then Soviet Union in 1969 with their “Vulcan” facilities. Plasma is also used for metallurgy, this is a method to discover new alloys or “combinations” of metals.

3.19 Power Supply of the Laser

The proposed system uses a Q-switched Nd YAG laser, which requires a 1 KW power supply. Since a commercial laser is being purchased, designing and building a laser power supply would be a complicated addition to the project. There are also safety concerns to consider when dealing with designing and testing such a large power supply. Therefore, the team decided to use the power supply that is included with the laser. The laser selected is a Q Switch ND YAG Laser Machine used for tattoo removal. The specifications for the laser are shown in table 3.16.

3.20 System Power Supply

In this system, a variety of electrical components require power. These include the microcontroller, the linear CCD, op amps, and potentially a display. The power source used to supply the system and its components can have a large effect on the overall cost of the system. In addition to this the power source can affect the level of noise and the stability of the system. The two potential technologies for powering the system are an AC wall outlet, or a DC battery. Specific types of battery technologies are investigated. The pros and cons of the AC wall outlet and DC battery technologies are compared and reviewed in the following sections. Based on the results of these technology comparisons, specific components for the selected technology type are made. Some of the specific categories that were used to compare these power source technologies included stability, cost, mobility, efficiency, and availability. Since the power will ultimately be supplied by the traces of a PCB, how these potential power sources might affect the PCB are also considered. These included factors like noise and costs. Table 3.17 contains the expected power, voltage, and current requirements of the system’s components. These power requirements will affect what components are selected. The listed values are based on what was provided in the data sheets of each of the components. However these values may change based on the results of testing.

Table 3.16 Projected System Power Distribution

Item	Power	Voltage	Current
Q-Switched Nd YAG laser	1 KW	110 v	9 A
FT231XS-R	2.5 W[1]	5V	0.5 A
Laser Sensor	87 mW	3.6v	24 mA (40mA peak)
MCU	720 mW[2]	3.6V	180 mA
CCD sensors	400 mW[3]	12V	0.5 A
Small Display	480 mA[4]	3.3v	30 mA

1: Thermistor power consumption, the IR thermopile acts similar to a photodiode generating current from heat.
2:This is the power consumption of the MCU for all GPIO pins sourcing current. Consumption will likely be lower
3: This is the max power dissipation, typical is 160mW
4: The voltage of the drivers for the LCD is ~20V hence the higher power requirement

3.20.1 PCB Power Supply Sources

There are two primary options to choose from with regard to powering the system. These are a DC battery and a wall outlet. These two options each have their own advantages and disadvantages. These power sources will be compared on a variety of criteria. These include stability and reliability, how much power is required for the input and output, system voltage requirements, the voltage requirements of each component, the cost of the power supply, stability of the power source, safety and health considerations, accessibility in different areas. Many of these considerations were based on the expected power requirements of the proposed system. Which in turn were based on the expected requirements of the subsystems, and their components. Which was derived from the team's preliminary designs along with the expected applications of the system.

3.20.2 WALL OUTLET (AC)

Wall outlets are common sources of power for many commercial devices. Wall outlets can be found

The Stability of the power source is very important. In the United States of America, a typical wall outlet provides 120 volts. Wall outlets provide an alternating current (AC) current which will need to be converted to direct current (DC) current. Wall outlets provide more reliability. Wall outlets are connected to a stable power grid, which will provide a higher level of reliability and stability to the system.

Since the system is expected to be working consistently and continuously, a wall outlet would be a great choice for the system. A wall outlet would provide power until the end of the system's operations, meaning that there would be no interruption in use.

The cost of using a wall outlet is lower than many other sources of power such as a DC battery. The main reason for the low price of using a wall outlet is the wall outlet will likely only require an AC-DC converter. This converter will transform the AC wall current to the direct current DC that is required by the system devices. The price of this converter is affordable, typically in the range of $10-20. There are many types of these adapters available depending on the size and the power specifications needed**.**

One of the most important goals of the project is to provide this system in unreachable and dangerous places to detect the samples. The wall outlet is only provided indoor places or in a certain place with a developed electrical structure, which makes the accessibility of the wall outlet limited. The limitation of the wall outlet will affect the availability of the system in these hazardous areas.

3.20.3 DC Power supply (DC)

There are many types of DC power supplies in the power industry. Such as DC batteries, and generators. In this project, DC batteries are a good option for powering the system. There are many types of batteries that are great options for the system such as a Lead Acid, Lead-Carbon and Lithium-Ion Battery. All of these types are able to provide a consistent amount of power for the PCB system. Since it is possible that the proposed system may use a battery for power, the types of batteries will be compared to determine the best choice for a battery powered system. The comparison of the batteries will not be the same as the wall outlet because batteries are more complicated than a simple power supply as the wall outlet. These power sources are associated with constant current and voltages. These batteries come with a specific amount of voltage, such as 24 and 36 voltages. The amount of voltages vary from one application to another.

DC batteries can only supply power to the system for a specific duration of time. These batteries are not stable because of the voltage drop and current reduction. There will be a reduction in current while these batteries will run the system and the system will need to recharge before it supplies the power again. Which can cause a delay in the reading data of the MCU. In other words, there will be delays in system operations and it will have a big impact on the system performance. There is a chance of losing data of the MCU due to voltage drop. If the voltage drops to very low voltage the MCU and other components will shut down and lose its data.

3.20.4 Battery Technologies

In the following section various types of batteries are compared to act as a power supply for the system. The categories of comparison include power density, cost, weight, life cycle, efficiency, along with some other features are all considered.

Lead acid batteries are a very common type of battery. They are commonly used in vehicles, to start the engine. Lead acid batteries have a low power density and high weight. The high weight of this battery due to it is the most important component which is the Lead plates. These plates allow this battery to store the energy. Lead acid batteries have a low efficiency, around 50%. Lead acid batteries also have the lowest cycle life when compared with the other batteries. However lead acid batteries tend to cost the lowest, when compared with the other choices.

Lead carbon is one of the lead batteries that has a carbon as the main part. This type of battery is a great option for an environmentally friendly battery. The carbon added to the negative plates allows enhancing the battery recharge which also Improved cycle life. Lead carbon batteries have moderate power density. Lead-carbon batteries also have a moderate cycle life, and a moderate cost. Lead carbon batteries have a relatively high level of efficiency, approaching that of the lithium ion, which is the most efficient.

Lithium-Ion Batteries are one of the most suitable types of battery to use in a variety of environmental conditions. Lithium-ion batteries have many valuable advantages such as their high-power density and lightweight. Lithium-ion batteries have the highest cost of all the compared battery types. They also have the highest power density of all the battery types. Lithium-ion batteries also have the best cycle life. They also have the best efficiency of all the battery types compared.

3.20.5 Battery Technology Comparison

The comparison of battery types focuses on aspects of batteries for the project's applications. Each type of battery has its own advantages. One of the most important factors to the project would be price and power density. The other factors were also considered. The Lithium-Ion Battery is the best option comparing all the features except the price. It is the most efficient type, has a short recharge time, the highest power density and it has long battery life that could be suitable for the system. The main challenge of selecting this battery is its cost. The cost is very high, it is typically around $500-2000$ which is well outside the budget constraints of the project. Therefore, the battery comparison will be between the two remaining types. The lead acid battery has low battery life and high recharge time. The lead acid battery is also the heaviest and has the lowest power efficiency. However, the price of this battery is very cheap. Which is one of the reasons it is commonly used. The lead-carbon battery has good energy density, life cycle, and high efficiency. All at a moderate price, Although its weight is a factor. The direct comparison of battery technology can be seen in figure 3.18.

Table 3.17 Battery Technology Comparison Table

Type	**Lithium-Ion Battery**	**Lead Acid**	**Lead-Carbon**
Cost / Price range	Most Expensive (up to 2000$)	Low (20-200$)	Moderate (100- 500$)
Weight	(7.5-15Kg)	35kg	(31- 35 kg)
Energy density	200-300Wh kg−1	30-40 Wh kg−1	30-45 Wh kg−1
Cycle life	High (~4000–5000)	Low (~500–1000)	Moderate (~1500–2000)
Power density	High (800-900 W kg−1)	Low (~40–50 W kg−1)	Moderate (~100-500 W kg−1)
DOD	High (~80–95%)	Low (~30–50%)	Moderate (~50–80%)
Efficiency	Most efficient (90%)	Low (50%)	High (85%-90%)

The lead-carbon battery as seen in figure 3.7. is the best option between all of the batteries comparing all the features. The system PCB will not require the highest level of power efficiency and it does not require many high specifications. The lead-carbon is a great option because it has moderate efficiency and is lighter than the acid lead. It is also having more capacity of energy stored. The recharging time is also high when compared with lead acid batteries. The price of this option is more than the lead acid, however it is valuable due to higher level of performance.

Figure 3.7 Lead Carbon Battery 12V 160Ah

Should the system be battery powered, the team would likely select a lead carbon battery from Victor energy. The cost of this battery is around $525. This company would be chosen as it provides a detailed datasheet for the battery. Which will allow the team to have enough information about the battery to accurately design a power system around. The datasheet provides very important information such as: Recommended charge voltage. Float service and cycle service, Specifications of weights : (36 Kg , 56 Kg), Temperature, Cycle life: ≥ 500 cycles @ 100% DoD, Safety concerns, Warnings, manufacturing information

3.20.6 Power Source Technology Comparison

Based on the investigations of both battery power and AC power, table 3.19 provides a full comparison between selecting a battery or an AC wall outlet as the power source for the system. A battery would provide more stability, and require no conversion from AC to DC, however batteries would need to be recharged, and have a limited life span before they must be replaced, which can be costly. An AC wall outlet will have some noise associated with it, and would require an AC to DC converter, however the price of an AC to DC converter is cheap when compared with a battery. In addition to this there would be no need to consider recharging or replacing anything. However this would limit the system's mobility somewhat. An AC wall outlet was chosen as the power source for the system. The wall outlet was chosen over a battery as the power source for many reasons. For example, The AC power outlet is a stable power source which unlike a battery does not require any form of recharging. Introducing the circuitry and components to facilitate recharging a battery would add an additional level of complexity to the design that would not be integral to the primary functions of the system. In addition to this the current supplied from a power outlet is stable and there will be no current reduction with the time. However, the AC current will need to be converted to DC current with an AC-DC converter.

Table 3.18 Power Source Technology Comparison

Types	DC batteries	AC Wall outlet
Stability	More	Less
Recharging	Required	Not Required
Replacement	Yes	No
Cost	Expensive($20-$500)	Cheap($10-$15)
AC-DC convertor needed	No	Yes

3.20.7 Summary of AC-DC converter

AC-DC converter is an adapter that transfers energy from high AC current to less DC current from the wall outlet to use it in other devices such as cameras and chargers. The AC adapter's structure includes a transformer, rectifier, and capacitor. The transformer is the responsible part of reducing a high AC current to a lower AC current. Then there is a full rectifier that is responsible for converting the AC current to a DC current by using 4 diodes. After this step the DC current is not very clean so, it goes through another process which is a smoothing circuit which has a capacitor that can reduce the ripple voltage and make this DC current ready to use for any other devices.

The team opted to go with a commercial AC adapter rather than a custom built solution, as there are a variety of different options to choose from. The selected converter is capable of handling a larger range of input voltages. This allows for the device to function in a range of countries as the voltage inputs vary from one place to another. For example in Oman and the Middle East, the voltage input is 240 V. Whereas in the United States, the wall outlet voltage is only 110 V. The team chose a 12 V, 2 A Power Supply AC Adapter. Its specifications are listed in table 3.20. With an input AC range of 100-240V, which will supply an output voltage of DC 12 Volt. This provides the input voltage range that will not limit the input to the system to a single country for its use.

Table 3.19 AC-DC Convertor Specifications

Item	**Specification**
Voltage input (AC)	100-240 voltage (AC)
Voltage output DC	12 Volt (DC)
Current output	2 amp
Wattage	24 watts
Connecter type	2-pin
Wall plug Dimensions	2.1 mm X 5.5 mm

3.21 Voltage regulators

Voltage regulation is a very important aspect of the PCB. The PCB will have a 12 V DC input. However, not all the components on the PCB will require 12 V. Many of the components will require less power. This can be seen in table 3.17 projected system power distribution. There are many types of voltage regulators that are commonly used. The first distinction that needs to be made when selecting a voltage regulator is the type of regulator. There are linear voltage regulators and switching voltage regulators. There will be a full comparison between these two types of regulators. The comparison will focus on many different aspects that will affect the system. These include things such as efficiency, heat, voltage drop, size, output noise, and cost.

3.21.1 Switching Voltage Regulators

Switching voltage regulators are one of the most commonly used regulators in the electrical industry. Switching regulators provide many benefits. They can step up and step down the voltage, so the output voltage can be higher than the input voltage. This is a feature which not all regulators can provide. Switching regulators are very efficient and lightweight. However, these benefits are contrasted with a higher level of design complex, which involve reactive circuit elements. In addition to this an external clock or oscillator must be connected to the circuit. This clock or oscillator is required to switch the transistor(s). Many switching regulators now come as a single integrated circuit. This IC will often include the oscillator, feedback control circuitry, and transistor(s) required for a switching regulator. The nature of switching regulators is that their outputs produce a high level of noise compared to linear regulators. This noise can cause interference issues, or can potentially damage extremely sensitive components or devices. Therefore designs that include switching regulators may need to have sufficient noise protection to ensure that other components are not affected by this switching noise.

3.21.2 Linear Voltage Regulators

Linear voltage regulators are one of the most popular used regulators due to their simplicity and ease of use. The cost of using linear regulators is less than the cost of switching regulators. Linear regulators can only provide step-down voltage regulation, which drops the input voltage to a lower level at the output. The linear regulator dissipates the excess energy as heat. The calculation of the voltage drop, and the power consumption is :

Voltage drop = $V_{in} - V_{out}$ Power = $V_{D} \bullet I_{Load(Heat)}$

The heat dissipation required in a linear regulator may result in the device overheating, which can cause damage to the regulator. Overheating may happen due to design mistakes, fabrication errors, or environmental factors. Some linear voltage regulators offer thermal shutdown protection. This is when the regulator is temporarily shut down until it has been cooled to a usable level. To avoid this process systems may require a method of cooling. Another issue with linear regulators is that they are inefficient when compared with switching regulators.

3.21.3 Voltage Regulator Comparison

For the proposed system there were several criteria to consider for selecting a type of voltage regulator. Some of the primary considerations for selecting a regulator technology were power efficiency and noise. Cost, heat, and design complexity were also factors in this decision. In terms of noise Linear voltage regulators have the advantage. Linear regulators have less noise on their output when compared with a switching regulator. A high level of regulator output noise can affect the design in many ways. Some examples of where this noise may affect the operation of components or systems are as follows. Sensor data capture, GPIO triggering, and cost. For sensor data capture it is desirable to minimize the noise that can affect the output results of analog sensors. With GPIO a few of the pins are expected to trigger based on the input from an opamp, acting as a level shifter. Noise on the op amps inputs could affect how or when that triggering process occurs. In terms of cost, noise may require additional decoupling capacitors to remove noise. This can increase the total cost of the electrical systems. Using linear voltage regulators would save more time and money because there would be no need to alter the design or implement noise protection systems. However the switching regulator has a much greater power efficiency. Looking at power efficiency, the switching regulator performs at a much higher level than the linear regulator. Switching regulators often have power efficiency of around 80 to 90 percent. Whereas linear are much lower in terms of power efficiency. Cost is another factor that needs to be considered. Minimizing the costs is important to create a system within the team's budget range. However, low cost components must be balanced to ensure that they will meet the design requirements. Linear regulators tend to be cheaper than switching regulators. Heat dissipation is primarily an issue with linear regulators, as linear regulators dissipate more heat than switching regulators. Selecting a linear regulator might require design changes to facilitate cooling. The design complexity was also a factor. The switching regulator would also be a more complex design. It would require reactive elements, which might take up more space on the PCB. Table 3.21. shows the direct regulator technology comparison.

Table 3.20 Regulator Technology Comparison

Voltage regulator type	Liner	Switching
Design	Simple(non-reactive elements)	Complex(reactive elements)
Efficiency	Low (30%-60%)	High (84%-97%)
Heat output C	High (up to 160°C)	Less (20°C ~ 85°C)
Noise/ripple voltage	Low (10 Vrms -20Vrms)	High (30mV)
Overheat protection	Thermal shutdown protection	Overheat protection
Step up / Step Down	Step down only	Step UP & Step down. Buck & Boost
Size	Small (1.00 mm × 1.00 mm)	Big (2.90 mm × 1.60 mm)
Cost	Low (0.24$)	High ($4.53)

The switching voltage regulator was selected instead of the linear regulator. Power efficiency was one of the primary reasons that the switching regulator was selected. The team believes they are capable of overcoming any noise issues produced by the switching regulator, with additional circuitry, and careful component placement and routing on the PCB. Therefore trading power efficiency for an increase in noise was considered acceptable. However there were other factors such as heat and the size that were also considered. The reduced heat dissipation of the switching regulator allows for components to be placed closer on the PCB. This can help minimize the trace lengths required and can allow for a smaller overall PCB. There are also some specific quantities that must be examined when choosing the right voltage regulator. These include things such as, Vin (Max -Min) , Vout (Max – Min) ,Noise level (Vrms), Pin count ,Thermal resistance , and I out max.

3.21.4 Switching Voltage Regulator Component Comparison

The switching voltage regulator being used in the LIBS project has to meet the voltage and current requirements of the components on the PCB. In addition to this the voltage regulator is required to have an acceptable level of noise. The cost of the regulator, along with its efficiency are also factors that were considered. Three different switching regulators were compared. This direct comparison can be seen in table 3.22. The three regulators compared were the LMR50410XDBVR from TI, the AOZ1280CI from Alpha & Omega semiconductors, and the AP62300TWU-7 from Diodes Incorporated. The AP62300TWU-7 was the cheapest of the three at fifty cents. The LMR50410XDBVR and AOZ1280CI were close in price at $1.23 and $1.17 respectively. The LMR50410XDBVR had an expected efficiency of 90% for the expected output voltage and current draw. The AOZ1280CI and AP62300TWU-7 were also close to 90% at 87% and 89% respectively. The LMR50410XDBVR had the lowest output ripple voltage at 5 mV. The AOZ1280CI and AP62300TWU-7 had higher ripple voltages of 9 mV and 18 mV respectively. The AP62300TWU-7 had the highest output current of 3 A. the LMR50410XDBVR and AOZ1280CI both provided around 1 A. All of the regulators had the needed input voltage range and could accept 12 volts. The LMR50410XDBVR had the highest output voltage potential of 28 V. The AOZ1280CI had a max output voltage of 26 V. and the AP62300TWU-7 had a max output voltage of 7 V. the LMR50410XDBVR was the most expensive, however it had the best efficiency and lowest output ripple voltage. It could also supply an output voltage well above the needed 5 V. The AOZ1280CI also could provide a high output voltage, but had a lower efficiency. The AP62300TWU-7 was the cheapest, and could supply the required 5 V, however its output ripple voltage was quite high compared with the other two regulators.

Table 3.21 Switching Voltage Regulator Component Comparison

Component	**LMR50410XDBVR**	**AOZ1280CI**	**AP62300TWU-7**
Company	Texas Instrument	Alpha & Omega Semiconductors	Diodes Incorporated
Cost	$1.23	$1.17	$0.50
Expected Efficiency(3.3V)	90%	87%	89%
Output ripple voltage	5 mV	9 mV	18 mV
Output current	1 A	1.2 A	3 A
Input voltage range	4 V - 36 V	3 V - 26 V	4.2 V - 18 V
Output voltage Range	1 V - 28 V	0.8 V - 26 V	0.76 V - 7 V

The LMR50410XDBVR was selected as the primary regulator for the design. It was chosen due to its lower output ripple voltage, and high efficiency. It is capable of supplying 1 A of current which is more than the expected current requirements of the design. It does cost more, and could potentially provide higher output voltages than the design calls for. However, the tradeoff in price for efficiency and lower noise was deemed appropriate.

4.Standards and Constraints

Standards and Constraints are used so products designed and manufactured at one company can be used with other goods made by a different company. Standards and Constraints are also implemented for safety purposes which reduces industrial accidents and makes a safer environment for employees and consumers. Standards and Constraints are a metric for industry and academia to verify a new product for safety and implementation in the market. There are many constraints to any product whether it be financial or just design of the product itself.

4.1 Requirements

- Using a 532/1065 Nd YAG laser to “blast” a sample (rock, metal, etc) to determine elemental composition and identify know sample against a database
- Require the use on a focusing system for the laser and a collection system for the analysis of the light leaving the sample
- Light weight, low cost system
- Power desired to power the Nd YAG laser systeming and spectrometer
- Data acquisition system that is affordable and gives the most accurate readings

4.2 Constraints

The LIBS project has the following constraints: safety, supplier limitations, cost, time, lack of detailed Information, maturity of selected parts.

4.2.1 Safety

Safety is a major constraint of the LIBS project. Laser induced breakdown spectroscopy requires a powerful laser to atomize the material and create plasma for the spectrometer to measure. Without proper safety procedures in place it is possible that the laser could cause eye damage to bystanders during testing.

To prevent this from occurring, any laser testing must be done in a secure environment. The testing environment must contain the light emissions that occur during the testing procedure. The testing environment should have sufficient warning posted on its entrances that instruct individuals on what safety gear is required and the procedures for entering the testing environment. Only required individuals for the testing process will be in attendance for any laser testing procedures. Any individuals within the testing area must be wearing sufficient eye protection.

Two pairs of laser safety goggles need to be acquired at minimum. These laser safety goggles need to be rated to protect from a class 4 laser system. Laser safety glasses of this grade generally cost around $100+ each from a reputable vendor. The adequate laser safety glasses which will be used are OD 5+ rated, which means it blocks 0.001% of the light of a certain wavelength. In the case of the laser of the proposed system which is 1064 nm. These goggles comply with industry standards such as EN 207.

In addition to eye protection, the safety constraints will limit the number of areas that can be used to safely test the laser. At sufficient distances light emitted from the laser loses its potency, and can be viewed safely without eye protection.

However the distances required for individuals to view the laser emission would force the use of a remote exterior location. It would be impractical to test the laser in exterior environments. Doing so would require a remote location with sufficient resources for the laser and the testers. In addition to this the team would have no control over the area, so there would be nothing to stop curious individuals from moving closer to investigate. Indoor environments are a far more practical option for testing the laser. Although not all indoor environments are appropriate for testing. The testing space would need to have no exterior windows, along with no major fissures or splits which would allow the laser's emission light to escape.

The CREOL building at UCFs main campus has laboratory spaces used for student course work. Many of these labs would provide sufficient space to safely test the laser for the LIBS project. These labs have indicated on their exterior to indicate when lasers are in active use within the lab. However many of these labs are in active use by undergraduate students for their photonics laboratory requirements. Permission from the lab manager would need to be obtained to perform any testing at specific times in these undergraduate labs. Due to the already tight schedule of these labs, it is unlikely that any testing can be performed there. The CREOL building at UCFs main campus does have a senior design lab, which is free to use for all senior design students. However because this is expected to be used as a shared space with other senior design students as the semester proceeds the volume of students in the lab will increase. Therefore testing the LIBS laser there could be problematic, testing would need to occur when no other students are present. This could limit testing of the laser to inconvenient times such as very early in the morning or very late at night. This type of testing arrangement would require a significant shift in the team members schedules, which is unrealistic. One team member lives close to the UCF campus, and has a free room to use for testing the laser. Since the primary concern with the laser is eye safety, this space will provide a shielded area to perform initial testing of the laser, this space will be used when laboratory space is not available.

As the LIBS system is intended for use in non-isolated areas. A containment area for the laser is required for the LIBS system. This containment unit or chamber will ensure that no laser excitation light escapes, which will ensure eye safety of users and bystanders. The containment unit will need to hold the sample and the laser emission aperture. The containment unit will need to be constructed of a durable material that is not expected to fracture or tear. It will need to be capable of withstanding everyday wear and tear without forming cracks or degrading. The material selected for the containment unit needs to be non-porous or of sufficient thickness to ensure that no laser excitation light escapes the containment chamber. This containment unit may increase the overall size of the system, and may limit specific design choices based on available space for the sample.

Electrical safety is another type of safety constraint for the LIBS project. Electrical safety constraints the project with regard to the laser power system. The power system needed for a laser to create plasma is very high. This will necessitate one of two paths forward for the laser's electrical systems. Either the power systems for the laser need to be designed and created by the team, or a pre-existing power system needs to be used. If the team were to create a custom power system for the laser, it would be required to be completely isolated from the rest of the electrical systems. This would mean creating separate PCBs for the laser power system and electrical control and sensor systems. Because the team is expected to handle the PCB containing the control and sensor systems while troubleshooting and testing the overall LIBS system. The other option is to use an existing power system. Many laser systems come with a power supply for their laser. This second option is more beneficial from the perspective of safety. Because it would stop the team from having to interact and test a high voltage power system. However this safer option will require some design adjustments as it involves using a pre-established system, which may be more rigid when attempting to fit it into the overall system design. The second option will most likely be the option chosen for its higher safety factor. There are sub classes for lasers, such as 1M, 2M, 3R, and 3B. Table 4.1 lists the general classes of lasers and the safety hazards/precautions for them.

Table 4.1 Laser Safety Classes Table

ANSI and IEC laser classification	Class 1	Class 2	Class 3	Class 4
Hazard Zone	No	No	Yes	Yes
Direct Eye damage	No	No	Yes	Yes

4.2.2 Supplier Limitations

Supplier limitations are present throughout many of the components used in the LIBS system. The specialized nature of many of the parts or subsystems used in the LIBS system means that there are few suppliers for many components. These include components like the laser, digital spectral sensor, and other optical components.

One major supplier limitation was sourcing the laser for the LIBS system. The power required to generate plasma is significant. Therefore only lasers of sufficient power and of the correct type can produce a laser beam of sufficient power required to create plasma. The cost associated with a sufficiently powerful laser is $500 minimum, and can easily soar into the thousands or tens of thousands dollars. In addition to the cost of the laser, because it is such a specialized component there are far fewer suppliers. This affects the cost of the laser in addition to the manufacturing and or shipping time to receive the component. Therefore if the laser were to fail it could take weeks to order a replacement. This could result in missing critical deadlines. Therefore if the laser were to fail, and the team believes that time to receive a second laser would put the project in jeopardy. An alternate plan will be used as a backup. Were the primary LIBS laser to fail, the team would alter the front end power source and optical design of the system to that of an IR spectrometer design. This would allow for the digital control, power, and spectrometer aspects of the system to have minimal to no changes. The system would still provide spectral analysis, just using a different method.

Another issue with such a limited number of laser suppliers is the presence of sufficiently thorough documentation. Many suppliers of sufficiently powerful lasers at a competitive price have limited documentation. The applications or specifications are limited to a general set of minimum expected performance metrics. To ensure that the purchased laser is truly capable of meeting the performance requirements of the LIBS system, a process of careful comparison of suppliers will be used. In addition to this the laser will be prioritized as the first component to be purchased and tested as early as possible to ensure that a laser of sufficient performance is secured for the project.

Sourcing the CCD or CMOS spectral sensor was another supplier constraint. The CCD or CMOS spectral sensor has to capture diffracted light that is emitted from the sample. Most CCD or CMOS light sensors being manufactured are for traditional or scientific cameras. These CCD or CMOS sensors have a two dimensional array of light sensors that are used to capture images. For spectroscopy applications one dimensional or linear sensors are required. This is because the nature of the diffraction process means that the different wavelengths of light are spread out along a single axis. This reduces the number of image sensor manufacturers to a much more limited number of suppliers. This can create issues in finding competitive spectral sensor prices. This can also limit the range of specifications available when selecting the spectral sensor. Which could reduce performance of the LIBS system depending on what sensors are available. The specialized nature of the LIBS process also has effects in many other components in the system.

For the Digital controller high speeds are required. This is due to the speed at which the laser fires and the speed at which the plasma dissipates. Therefore to ensure that these events can be triggered or measured, the digital controller is required to be of sufficient speed to track these events. The speeds needed for the LIBS process means that a large swath of digital control manufacturers are eliminated from consideration. This may reduce the number of technologies that are available for digital control, as some may not offer the speeds needed, or they may offer the speeds but not at a price that is consistent with the project's budget. The number of choices in a specific digital control technology may also be reduced.

Optical components are another form of component that are difficult to source. Due to the power of the laser, optical components used in the front end of the system need to meet specific high energy standards. This limits the available number of suppliers to a smaller subset that can provide lenses and mirrors that can withstand the high energy discharge of the laser. To ensure that optical components meet the necessary thresholds of the laser's energy, in addition to component research it is required to interface with suppliers to communicate the necessary project criteria, and determine if their products will meet the required specifications. This interfacing can create delays as often it can take a supplier a day or two to respond to queries. These supplier limitations also mean that supply chain issues could result in consequences that are catastrophic to the LIBS project. As finding replacement or alternate parts would be very difficult. As the team may not be able to easily order a comparable component from a competitor. Or could require major changes in the design of the system to overcome a missing component.

Similar issues are present regarding factory lead times or low component stock, which could complicate hitting project deadlines if parts are not sourced quickly enough. Another factor to consider regarding supplier limitations is customer service and shipping. The nature of the LIBS project is that there are no pre-existing relationships between the suppliers and the team. Large companies and organizations build relationships with suppliers and partners over time. These relationships allow these companies and organizations to receive a higher prioritization of orders and or faster response times. Which allows these organizations to deal with issues like technical information requests, tracking, and replacement shipments in a more effective manner. The lack of relationships means that the LIBS project is primarily ordering parts through common commercial channels. Therefore any component information requests or customer service issues are expected to take a low to average priority. One way to attempt to mitigate these issues is by trying to select suppliers that have a good track record with regards to customer services and order tracking and replacement. However this can be difficult as sometimes supplier priorities change. A history of good customer services to small consumers does not bar the possibility of anomalies or changes in priorities. A more reliable way to mitigate any issues due to lost orders or other customer services issues is to order components early. This will ensure that any delays or quality issues in components can be addressed without creating bottlenecks or causing major delays in the project.

4.2.3 Cost

Cost is another major constraint in the LIBS project. Most LIBS systems that are commercially available on the market are very expensive. LIBS systems commonly exceed the $10,000 price point. Some of this cost is due to the level of precision that is achieved with the systems. Some of the cost can be attributed to the required labor that is needed to create the system. However a large portion of the cost is due to the specialized components that are required to create a LIBS system.

One major cost in any LIBS system is the laser. A laser of sufficient power is required to atomize material, and generate plasma, these tend to be very expensive. Costs of the LIBS laser alone are easily a few hundred dollars to thousands of dollars.

The optical components such as focusing lenses and mirrors are also expensive. Due to the power of the laser, the optical components that are selected need to be able to withstand high amounts of energy over a small surface area. These specialized components also drive up the cost of the LIBS system.

The emissions from the sample after the laser blast need to be transmitted into the spectroscopy system. This requires mirrors and lenses to direct and focus the emission light into a light capture system. These components are also costly, usually costing tens to hundreds of dollars. Usually the light capture system transmits the light to the spectroscopy system via fiber optic cables, which are another expensive component required for the LIBS system. The spectroscopy system itself requires specialized mirrors, lenses, and prisms or gratings to diffract the light. These are all costly components, each costing from tens to hundreds of dollars. The diffracted light needs to be projected onto a specialized optical sensor for analysis. All of these optical components and systems need to go through a testing phase which can damage or degrade the components. Any damaged or altered components will need to be replaced or substituted. Not to mention the backup components that may be required to avoid stall or bottlenecks in the project.

There are also the electrical components used for processing data and powering sensors, along with the accompanying PCBs. These electrical components are likely to be lower cost when compared with the optical components. However their cost is not insignificant. The electrical components generally range in price from dollars to tens of dollars. Without being cognisant of component prices the expenditures for the LIBS systems could easily reach several thousands dollars. This would be antithetical to one of the goals which was to create a low to medium cost LIBS system.

There are several methods in which the team could approach the costs of the project. One simple way to address costs would be to seek out sponsors for the libs project. These sponsors would cover a portion of the project's cost, reducing the total expenses that the team would be required to cover. There would be several considerations that would need to be taken into account when attempting to obtain sponsorships. One issue with acquiring sponsorship for the LIBS project is difficulty of persuading potential sponsors that there is a market for a low cost LIBS system. Queries regarding sponsorship could be sent out en masse to any company of interest in LIBS systems. However to truly secure sponsors, a persuasive argument would likely need to be made in many cases considering the costs of many of the components. While the team sees a clear gap in the market for low to medium cost LIBS systems. Convincing a potential sponsor of this may require a significant amount of research and leg work. Considering the time table of the project, this may be difficult to do. Another potential trade off for the economic benefit of acquiring sponsorship could be some form of NDA or design rights to the project.

A few team members may be capable of securing funds through their professional employment. Securing funding via a sponsor or through other means would help remove or reduce the financial burden the project might place on the individual team members. However securing a form of funding does not address lowering the overall cost of the system.

One way to reduce the overall costs of the system is to attempt to prioritize selecting and sourcing low cost components where possible. This could reduce the overall system costs. However a balance would need to be struck to ensure that the lower cost components provide sufficient performance to meet the systems requirements. To achieve this balance a deep understanding of each of the systems process is required, along with sufficient research of technologies and components to understand what different technologies and components can truly achieve.

In the LIBS project, the ordering of some duplicate components may be necessary. This would ensure that the project stays on its expected timeline when a component fails. Sometimes a component might fail or become damaged. If a key component fails, work on the project may be forced to halt until that part is replaced. Most components won't be pushed to their failure point, particularly if the limits of the component are understood. However manufacturing tolerances and other factors can result in some component failure. Even when components are operated in their absolute limits. Therefore some critical components may need to be ordered in duplicate. To reduce the costs of the project duplicate components should be limited to only vital components, or components with a very long lead/shipping time. Depending on the type of component, it may be possible to return an unopened duplicate to receive a refund. However this depends on the supplier's refund policy.

4.2.4 Time

Time is another constraint for the LIBS project. The team needs to complete the project within 2 semesters. While a timeline and milestone expectations have been set, time is still a finite resource. All of the team members have other commitments like work and family. It is important for the team to hit all of the project milestones and complete the necessary objectives. However the demands of the LIBS project need to be balanced with the other commitments the team members have. In addition to the expected commitments which consume time, unexpected events or setbacks can occur. This could cause the project to miss deadlines. One potential way to balance the workload of the LIBS project with other commitments is to schedule the entirety of the expected workload in such a way that nothing slips through the cracks. The nature of unexpected events is that they cannot be planned for. However, if enough of a time buffer is put in place to ensure that work is completed before a deadline. Then setbacks can be absorbed by this time buffer without the project suffering. Although this time buffer can be difficult to implement depending on the circumstances.

4.2.5 Lack of Detailed Information

Lack of Detailed Information is another constraint of the LIBS project. A LIBS system is extremely complicated. Many of its parts are specialized. Sources of detailed information on LIBS systems and its parts can be difficult to find. General information about the LIBS system and its parts can be found online and in datasheets. However detailed information regarding best practices and design methodology is more difficult to locate. Some of this is likely due to trade secrets regarding the design and implementation of commercial LIBS systems. Additionally there are few low to medium priced libs systems on the market. This can make the task of comparing or benchmarking the project LIBS system with other commercial LIBS systems challenging. Therefore from a technical perspective this can make understanding where the created LIBS systems stand with respect to speed, size, and spectral resolution difficult. Some rough estimations can be made by comparing these quantities in different systems versus their price point. However these estimates are not the most reliable. The team does have access to many scientific journals and periodicals through the UCF library. These may yield some detailed information regarding LIBS systems, however non-novel or non-experimental system references or practices may be difficult to find. Another source of detailed information for the team is the reviewers of the project. They can bring a highly detailed level of information about different aspects of the project.

4.2.6 Maturity of Part Selection

Maturity of part selection is another constraint of the LIBS project. Designing any system with new components can lead to issues cropping up in that system. The system being created may involve edge cases for a component that the manufacturer didn’t think of or test. This can lead to bugs in the system that need to be fixed. Depending on the manufacturer it is possible that some new products may be released, without thorough testing. This can result in customers effectively acting as beta testers for these new components. Depending on the length of the project, along with the experience of the team involved, this may or may not be an issue. Sometimes the advantages of a new product such as speed, power consumption, or size can be worth the additional fault finding that is required. For the LIBS project it is more desirable to minimize the amount of error component correction that would be required for new components. Partially due to the size of the team, but also because of the time table of the project. Selecting mature components can be difficult. Many manufacturers do not list a product introduction date of specific products. It is possible to find product brochures or data sheets that have a year listed, or when revisions were made to the product. However, this is not always the case. One way to try and check the maturity of a component is to use component sellers such as Digikey, or Mouser often have filters to only include parts that are “Active” or “Normally stocking”. However these filters generally only remove obsolete or older components from the lists. Another way to check for component maturity is to search for the component’s part number on the internet. The search results can be used to give an indication of how commonly the part is used. More commonly used parts will likely have fewer bugs, or if they do have bugs there are likely found fixes or workarounds.

4.3 Standards

Standards are important in any system or device. They allow for seamless interconnectivity between systems and devices, along with creating commonalities across a discipline. While standards are often not mandatory, they often provide the best practices and safety specifications for devices and systems in specific categories. The LIBS system has a variety of standards associated with it. These include optical, electrical, and safety standards along with a variety of other standards.

4.3.1 Laser

The industry guidelines related to this project include: General requirements (29 CFR 1910.132), along with the eye and face protection (29 CFR 1910.133) requirements. There are additional voluntary guidelines which are provided by the American National Standards Institute (ANSI). The ANSI guidelines related to the project are: Safe Use of Lasers (Z136.1), Recommended Practice for Laser Safety Measurements for Hazard Evaluation (Z136.4), Safe Use of Lasers in Educational Institutions (Z136.5), Safe Use of Lasers Outdoors (*Z136.6*). These are some of the safety standards required for operation of a class 4 laser which is the required class to create plasmas for the LIBS system project. These standards will be adhered to to the best ability of the group to ensure the safety of the group members and those who will be around the laser while in operation.

Using optical lasers falls under the OSHA standards for laser hazards. The State of Florida does have some regulations and standards for the use and manufacturing of lasers as well. High power lasers (classes 3b and 4) fall under the jurisdiction of the Florida Department of Health in the Bureau of Radiation Control. The Bureau of Radiation Control oversees and registers many different sources of radiation emissions. These include Ionizing Radiation Machines (or X-ray machines), Radioactive Materials, Radiologic Technology, Environmental Radiation Programs, and Laser Radiation. The Florida Department of Health Bureau of Radiation Control has registered over 1700 lasers within the state. This laser will not be used on humans for any medical reason. The

4.3.2 Electrical

The electrical standards that are relevant to this project are as follows. IEC60027 are the standards for engineering symbols and units. This standard ensures that all the system specifications are in the preferred units, and that any system diagrams are labeled with the preferred notation. IEC60050 are the standards that cover the International Electrotechnical Vocabulary. This standard covers the words, and terms that are used to describe various electrical and digital attributes and phenomena. This standard ensures that a common vocabulary is used to describe electrical systems. These two standards are used in the project to ensure that the report and design documentation for the LIBS project are using the standard terminology and symbols that are used by the professional electrical engineering community. A failure to follow these standards could result in a failure of understanding and readability of the system. There may be cases where new terms not covered by IEC60050 need to be used to describe a novel system or process. This is not expected to occur in the LIBS system design process. However should the need arise, then the procedure would be to first ensure that the term covering the phonama exists in the IEC60050 database, then coin and explain in detail the new term. IEC60073 is the standard for the colors, sounds, and tactile feedback of indicators in a system. This standard relates to safety indicators along with general system indicators. In the LIBS system this standard will be used for two purposes. The first purpose will be to indicate safety information regarding when the laser system is safe to fire. A series of LEDs may be used to indicate that a containment chamber is open or closed. A red LED will indicate that the sample test chamber is open and that it is unsafe to fire the laser. A green LED will indicate that the sample chamber is closed and it is safe to fire the laser. LEDs may also be used to indicate the status of the electrical systems or indicate errors. For the LIBS system following the IEC60073 standard is important as it is a common color code used to indicate warnings or danger throughout a large number of electrical systems. Not using this standard for safety indicators might result in injuries. For instance using some custom color selection for danger and warning LEDs would require the system users to understand what specific custom colors mean. Unfortunately the documentation regarding safety information, even in many dangerous systems is often ignored. Therefore by using the IEC60073 standard hopefully users will understand the warning indicators, even if the safety information was skipped. IEC61010 is the standard that covers safety requirements of electrical equipment for measurement, control, and laboratory use. This standard provides the general safety requirements of electrical equipment and accessories used to take measurements. The LIBS system would be considered a form of laboratory equipment, which is covered by IEC61010. IEC61010 indicates how safety should be handled for lab test equipment in a variety of categories. For the LIBS system the relevant sections of the standard include: electric shock, and protection against radiation from laser sources. The safety for electrical shock encompasses what parts should be reachable by the user, what level of protection against electrical shocks is required during ordinary use of the device, and how the system should be constructed to facilitate this. The IEC 61010 standard also describes some of the practices that should be used to ensure that excess current in the electrical systems does not start a fire. IEC60812 is the standard for performing a systematic evaluation of hardware, software and other processes. This systematic analysis involves modes of failure and the effects of the failure. Due to the use of a class 4 laser in the LIBS system, it is imperative to create a fail safe system. Using the IEC60812 standard a framework could be created to understand the specific modes of failure that are likely to occur. Based on this countermeasures or safety features could be created in the LIBS system to cover those modes of failure in a comprehensive manner. Another electrical standard is IPC-2221, and IPC-2222 are sets of standards that cover the dimensions, designs, and other aspects of PCBs.

4.3.3 Communication

Communication standards for digital communication may include the RS-232, RS-422, and RS-485 standards. The LIBS system may use one of these communication standards to communicate with external devices or machines. These standards describe the voltage logic levels and speeds that are expected to be used by devices to communicate with one another. The voltage levels described in this standard indicate the voltages used to indicate a logic high and logic low signal. The speed at which data is transmitted is also listed by the standard. For the LIBS system this will likely be abstracted away via the digital controller, or communication protocol chip. However it is important to be aware of what communication standard is being used in the system. Without understanding the voltage logic levels and communication speeds used in the system, the ability to provide forward compatibility for new devices could be limited. The MCU offers RS-232 and RS-485 for UART communication.

4.3.4 Surface quality of an optic

The grading of surface quality on an optic is a measure of surface imperfections. These can be a variety of cases, scratches, pits, and digs, being some of the most common that occur during manufacturing or handling. The surface quality of a lens is one of the most important factors in the use of lasers. If there are any damaged areas or imperfections, this can be a point on a lens surface where laser-induced damage can occur. In image applications the same damage risk would not be experienced, but it would influence image quality. In light sensing systems that are sensitive to any imperfections, like spectroscopy, any degrading feature on a lens surface would have a direct effect on the strength of the signal, light throughput, and scattering. The shorter the wavelength that is being used, the greater the impact an imperfection can have on the system. Surface quality also is directly correlated with the cost of the optic, the better the surface quality the greater the cost. It is preferable to use an optic that suits the system and not anything that is higher quality than what is needed. There are standards that exist that assist in understanding surface quality specifications and how they impact performance of a system. The U.S. Military Performance Specification MIL-PRF-13830B and ISO 10110 are two of such standards that help users identify needs of their system.

4.3.4.1 U.S. Standard MIL-PRF-13830B

This standard describes surface quality by identifying a “scratch” number, any marking or tearing of the surface, followed by a “dig” number, a small rough pit or spot in the surface. This is based on calibration and quality assurance inspection standards widely used in the optical industry. The scratch number is an arbitrary number scale used to describe the brightness of a scratch on the lens, lower numbers being better. It also covers fractures and edge chips on a lens. The purpose is to define the allowable defects in a lens or coating or on the surface of an optical component. Dig numbers are the diameter of a pit or spot, specified by 1/100 mm. An example would be a lens that is rated 80-50, would have a surface dig somewhere on the lens of 0.5 mm in diameter and one with 80-20 would have a dig of 0.2 mm in diameter . The standard will only allow one “dig” of that maximum stated size for every 20 mm of lens diameter. The scratch number is measured by method of comparing to a calibrated sample standard by visual inspection under dark-field illumination conditions. This “by-eye” matching can lead to different evaluators scoring lens either higher or lower depending on what is observed. The evaluator is looking at each lens and matching the brightness of the two surfaces by eye. It is not a measure of the size of the scratch but the visibility of the scratch. The scratch standards as described in “Surface Quality Standards for Optical Elements (scratch and dig) Drawing C7641866” (Revision R as of 2010). The prototype calibration samples are kept at Picatinny Arsenal in New Jersey. They follow the order of (80, 60, 40, 20, 10), there is a pair for each number, one defining the maximum allowable visibility and the other defining the lowest allowable visibility to fit the criteria for each number. The military and its vendors can use these prototypes or working copies calibrated from them. The private sector relies on the working copies calibrated from the original prototypes costing several thousands of dollars, these can vary in quality from maker to maker but are close enough to be used as a standard. For this reason, it is important for a commercial supplier to include a surface quality inspection specification manufacturer name for the optical component being compared.

4.3.4.2 ISO 10110-7 Part 7: Surface Imperfections

The ISO (International Organization for Standardization) is a worldwide federation of national standards bodies. They work to prepare international standards through technical committees. Each member represents a different technical interest on the committee, and they work with international organizations, governmental and non-governmental entities. Unlike MIL-PRF-13830B, ISO 10110-7 is a more quantitative method to characterize scratches and digs on an optical element. It specifies surface quality based on the physical sizes and frequency of surface defects. MIL-PRF-13830B, can be a more economical and faster method to characterize surface imperfections but ISO 10110-7 is a more precise method to identify these blemishes if it is required. This method is more time consuming because it requires the use of a microscope with strong enough magnification to identify all sized surface defects. Many measurements are required to image the entire sample and to visualize these requires a small field of view. This standard does not make a difference between scratches and digs, treating both as surface imperfections. It will indicate the allowed number of imperfections and equate a grade number to each optical element defined by the square root of the area of the maximum allowed imperfection. This measurement is known as the dimensionality measure, but ISO also can use the visibility method identical to MIL-PRF-13830B. The benefit is that they can both be used interchangeably and if the need for a high-precision application arises, the use of ISO is there but if application is not as strict, the more expedient and cost effective method of MIL-PRF-13830B can be used.

5. ChatGPT

ChatGPT is an “artificial intelligence” chatbot designed to answer input prompts. Developed by the company OpenAI, a company founded by Elon Musk, Sam Altman, Greg Brockman, Ilya Sutskever, Wojciech Zaremba, and John Schulman. It is a transformer-based language model, meaning, it is a neural network that learns context and then meaning, by tracking relationships in sequential data , like each word in a sentence. These AI systems are here to stay, if individuals and groups do not embrace their use, optimize their abilities, and use them as the tools for a competitive edge, the competition will. They are a fantastic productivity tool to use when stumped on a starting point or have writer’s block. They can help organize ideas and thoughts on a process, giving a good start point, but do these tools have negative effects? Can they stagnate creativity and imagination?

5.1 Pros

There are a number of advantages using AI in the modern world. The 21st century is known as the ‘Information Age” and it can be overwhelming sifting through information to find what someone needs. AI can assist in this task as well as other applications.

5.1.1 Saving time

There are many pros to ChatGPT, a few are listed above but one that stands out is its ability to save time. Some examples of questions that might be asked of ChatGPT include “Can you give me a ten slide outline on chirped pulse amplification”?, “what is the best way to direct light in an LED system?”, “how can I calculate the angle of incidence for a fiber optic communication cable?” ChatGPT then will produce outputs for these questions in a matter of seconds. This can be used to generate ideas on where to begin researching, how to structure an outline, what information can be covered on a topic. It is an excellent tool to use to guide the user down a constructive thought path. This can save the user lots of time on disorganized brainstorming and staring at a blank document.

5.1.2 Assist with writing

ChatGPT is an excellent grammatical source, it can provide definitions, synonyms, correct punctuation rules, and so much more direction on the English literature that is easy to forget. For example, where to put the comma or how to properly use a semicolon? ChatGPT can act as an English teacher helping the user along the way. It can give the user different ways to start an essay, guide the user on the proper format of a research paper, and coach the user on how to structure a proper paragraph. All of this help is available in seconds when prompted to ChatGPT.

5.1.3 Improves the users ability to learn

Using LLMs are analogous to the early days of google, the user doesn't have to filter through five to ten useless websites only to find one that is usable an hour later. Using an LLM for learning allows the user to take the time to learn from each prompt, absorb the information, and then use that to start a path of research along with helping the user grow and develop as a student and researcher. Every prompt provided to ChatGPT can return a piece of useful knowledge within a few seconds. The user can start to ask themselves questions about each prompt, how does this help?, where was this information taken from?, will this improve the understanding of the topic? What can be learned from this? All of these self-reflective questions help the user to better understand the process and hopefully help the user to become more reliant on themselves and less on AI in the future. Every time a user uses ChatGPT it is a chance for them to learn something new, about a topic, about themselves, and about AI in general. It is a great tool that comes with a lot of responsibility with its use.

5.2 Cons

With all new technological advancements there are downsides and LLM are no exception. The following sections expand on some of the negative aspects of using LLMs. Some of these are heuristics that the team discovered through testing. Others are from news or academic sources, which have done research on the detriment of LLM's use in academic, industrial, and personal use.

5.2.1 Dependency

Is using ChatGPT lazy? Will users become over-reliant on LLMs? The use of large language models or LLMs can certainly turn into a dependency. Human beings are always looking for a way to improve, make something more efficient, essentially making things faster and easier to use. In the context of doing research or studying or completing work, this tool can be abused. Too much reliance on this tool can have its downfalls, eliminating the users ability to think through, write, or answer questions on their own. Like a drug, the user can develop a dependency on its use, and they need it for everything they do. ChatGPT will not always be available, the user might not have power, or the internet is down, the ability to be able to work through situations and problems without its use for every task that is important.

5.2.2 Zaps creativity

ChatGPT can generate whole paragraphs and populate those paragraphs in any manner or fashion that is desired. When asked to write like a 16th century philosopher or statesmen, it will. If it is asked to finish the conclusion paragraph to a thesis paper, it will. This takes all the creativity out of the user's body of work. Using ChatGPT to create full bodies of work, stunts the user's ability to grow as an individual and learn along the way. Everyone has a different perspective, a unique soul that is the voice of their work. If everyone uses ChatGPT, then that soul, the creativity of the human spirit, and it will all be the same, an AI generated prompt with no depth of character or uniqueness. This is what separates us from the machine and from each other, making each human being unique by nature, nothing can replace the human experience even if humanity creates AI.

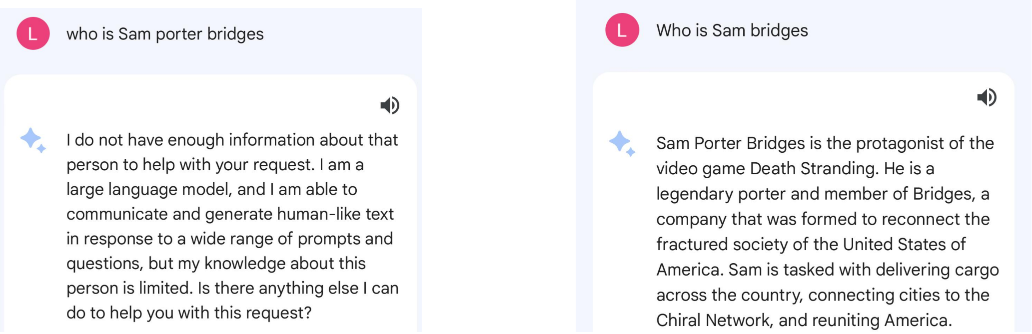
5.2.3 Plagiarism

If an individual is using ChatGPT to generate their entire body of work, this work is no longer created by that individual, it is created by ChatGPT, this, by definition, is plagiarism. ChatGPT is a tool that generates content from an extremely large database, the internet, and it takes that information to populate its prompts, to include uncited quotes and whole paragraphs of existing works. Using this information, uncited, is plagiarism and constitutes copying an answer, cheating, and stealing the work of others.

5.2.4 Accuracy and reliability

LLMs can provide answers to questions,but is it true? ChatGPT is not a perfected machine, it is being improved every day, most likely by hundreds of people. It has been shown in the past to sometimes provide incorrect or misleading information. Like with any tool, the user should critically evaluate each output that is given by ChatGPT and corroborate it with another vetted and reliable source to verify that the information provided is correct. Factors such as the way an input is structured, the training data set, and the weights given to specific neurons in an LLM all affect its performance. For example, when asking google's LLM “bard” about a specific fictional character. The inclusion of that character's full name results in bard being unable to provide any information about the character. However when just the first and last names are used in the input, bard is able to return an accurate biography of the character. This can be seen in figure 5.1.

Figure 5.1. Bard Character Biography Error



who is Sam porter bridges

I do not have enough information about that person to help with your request. I am a large language model, and I am able to communicate and generate human-like text in response to a wide range of prompts and questions, but my knowledge about this person is limited. Is there anything else I can do to help you with this request?

Who is Sam bridges

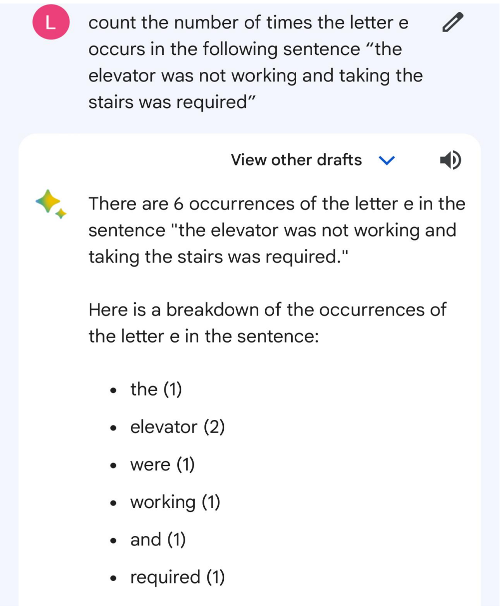
Sam Porter Bridges is the protagonist of the video game Death Stranding. He is a legendary porter and member of Bridges, a company that was formed to reconnect the fractured society of the United States of America. Sam is tasked with delivering cargo across the country, connecting cities to the Chiral Network, and reuniting America.

Note that in the second prompt, bard even produces information that includes the characters full name, which was used in the first input. This shows how small changes in the input for a LLM can result in significant changes in the output. From an engineering perspective using LLMs to search for part or component information could result in similar problems. Depending on the data sets used to train the LLM, it may only be able to identify information about parts or other topics when a specific input or input format is used. Therefore using LLMs to compile componente or research information without using any other methods could result in incomplete findings.

5.2.5 Logical Problem Solving

LLM is also sometimes have problems with logical tasks. For example when asking google's LLM "bard" to count the number of times the letter e occurred in the sentence "the elevator was not working and taking the stairs was required". Produced the output shown in figure 5.2.

Figure 5.2 Bard Letter Counting Error



count the number of times the letter e occurs in the following sentence "the elevator was not working and taking the stairs was required"

There are 6 occurrences of the letter e in the sentence "the elevator was not working and taking the stairs was required."

Here is a breakdown of the occurrences of the letter e in the sentence:

- the (1)
- elevator (2)
- were (1)
- working (1)
- and (1)
- required (1)

Bard was able to count the number of times the letter e occurred. However when presenting a breakdown of the number of times the letter e occurs in the words. The LLM misidentifies words it thinks has the letter e, such as "and". It also often misses the number of times the letter e occurs twice in the word "required". In addition to these issues it indicates that the word "were" as in the original sentence, when it was not. These mistakes show that sometimes LLMs can struggle with tasks that humans would see as trivial. Therefore care must be taken when asking LLMs for things that have a logical component. Another example of how LLMs have difficulties with logic problems is provided by David Johnston of ThoughtWorks. David ran a variety of LLMs through a series of problems that school children are capable of solving. These problems required no forms of specialized information to solve, however the LLMs had problems solving most of these questions. David indicates that without the LLMs having been trained on a data set which included the answers to questions, limits their ability to provide preconceived or synthesized answers. The LLMs inability to identify critical information in a rigid problem statement results in a poor output

[18]. Therefore an LLM may have a limited ability to assist in solving many engineering problems. If an LLM is used for this application, care must be taken to ensure the validity of the LLM’s outputs. particularly when the problem is less open ended and the model lacks training data.

5.2.6 LLM Hallucinations

Another issue with LLM accuracy is hallucinations. LLMs have been known to hallucinate or fabricate things that don't exist in response to queries. An example of this was a lawyer who was using ChatGPT to cite case precedents for a lawsuit. ChatGPT hallucinated six cases for the lawsuit that didn't exist. And the lawyer using ChatGPT claims that he specifically asked the LLM to confirm that the cases were real. ChatGPT's response was that all six cases were real. Later in court, it was discovered that no such cases existed. This has created problems for the lawyer and his client [19]. Similar problems could occur in engineering. During the research phase of a project. LLMs might fabricate information about a specific subject, which could lead an engineer to approach a problem in a way that is not feasible. This could cause the research phase of the project to be expanded unnecessarily. It's possible that LLMs might generate false components, this could waste time in looking for that componente when it doesn't exist. LLMs might also hallucinate specifications about real components, which if used could result in damage to other components or devices in testing. This could also incur additional economic costs if there is no way to implement the components in the design in another way. As with any new form of technology, care must be taken when applying it to critical tasks. if large language models are used to assist in critical aspects of a project or design, their outputs must be verified independently. This is the only way to ensure that no erroneous information is used. This can be a time consuming process, as verifying claims or sources can be difficult. Some organizations may have the manpower to easily perform this verification. However for smaller organizations it may be wiser to only use LLMs to assist with non-critical tasks. Due to the manpower of the four person LIBS team. The use of LLMs was limited to non-critical aspects of the project, if at all.

5.2.6 Information Confidentiality

LLMs are primarily controlled by large corporations or organizations in the tech field. These include Google, Microsoft, OpenAI, ect. Many of these organizations have very specific terms of services to use in their LLMs. These terms of service often include things such as collecting inputs and responses between the LLM and user. This data is often used for updating and strengthening the LLM. Other forms of user information such as location, and some personal data is also collected. Individuals or corporations using LLMs that are owned by another organization could result in proprietary information being collected. Depending on what is input to the LLM this could range from trade secrets to novel engineering ideas. There is the potential of this information being exploited by the owners of the LLM, or other users of the LLM. An organization that owns a LLM could potentially attempt to parse out trade secrets or useful other data from user inputs. Another potential issue that arises is that depending on how a specific LLM is updated or modified with collected user inputs. There is the potential that a specific conclusion to a set of user inputs could be used to answer similar queries from other users. Therefore if a LLM is used to assist a user in finding a novel solution to a problem. There is a chance that that solution could be presented to other users who ask the same, or similar questions. These situations could result in costly cost cases and legal expenses. Therefore anyone using these LLMs need to exercise caution with the kinds of information they input into these systems.

An example of how ChatGPT could be used in this project would be to have it help create an outline of what would be required to create a LIBS system. The results of entering “How do you create a LIBS system” can be seen in the following blue text.

“Creating a Laser-Induced Breakdown Spectroscopy (LIBS) system is a complex task that requires specialized equipment and expertise. LIBS is a technique used for elemental analysis and is often employed in fields such as materials science, environmental monitoring, and chemistry. Here are the basic steps to create a LIBS system:

1. Select Components:
- *Laser: Choose a suitable laser system that can deliver the required energy and pulse duration. Nd:YAG lasers or pulsed diode lasers are commonly used in LIBS systems.*
- *Optics: You'll need lenses, mirrors, and beam splitters to focus and direct the laser beam.*
- *Spectrometer: Select a spectrometer for analyzing the emitted light. Czerny-Turner or Echelle spectrometers are often used in LIBS setups.*
- *Detector: Choose a suitable detector, such as a photomultiplier tube (PMT) or charge-coupled device (CCD), to capture the emission spectra.*

2. Sample Preparation:
- *Prepare the sample that you want to analyze. Ensure it is clean and properly characterized. The state of the sample (solid, liquid, gas) will determine how you prepare it for analysis.*

3. Laser Focusing:
- *Focus the laser beam on the sample surface. The laser pulse should generate a plasma on the sample surface, and the emitted light from this plasma will contain information about the elements present.*

4. Plasma Emission:

- The laser pulse ablates the sample, creating a plasma plume. The elements in the sample are excited in this plasma and emit characteristic spectral lines.

5. Light Collection:
- Collect the emitted light using the optics and direct it into the spectrometer for analysis.

6. Spectral Analysis:
- The spectrometer disperses the light into its constituent wavelengths. The emitted spectral lines correspond to the elements present in the sample.

7. Data Processing:
- Analyze the spectral data to identify the elemental composition of the sample. Calibration using known standards is typically required to quantify the elemental concentrations accurately.

8. Data Interpretation:
- Interpret the results and draw conclusions about the sample's composition. This may involve comparing the acquired spectra with reference spectra or databases.

9. System Optimization:
- Fine-tune the system's parameters, such as laser energy, focusing, and integration time, to optimize the analysis for specific sample types.

10. Safety Considerations:
- Ensure that the LIBS system is operated safely. Laser safety protocols and eye protection are essential.

11. Maintenance:
- Regularly maintain and calibrate the system to ensure accurate and reliable results.

It's important to note that building a LIBS system is a specialized task that requires expertise in lasers, spectroscopy, and analytical chemistry. Many researchers and institutions purchase commercial LIBS systems due to the complexity and cost associated with building one from scratch. If you are new to LIBS, it's advisable to collaborate with experts or seek training in the field before attempting to build your own system."

6. Hardware Design

The Electrical hardware design of the SpectraLaser Elemental Analyser can be seen in the following section. It includes both the electrical subsystems and the full schematic electrical design schematic. Optical systems design schematics are also presented for laser focusing and the spectroscopy systems.

6.1 Electrical Control and Sensing Design

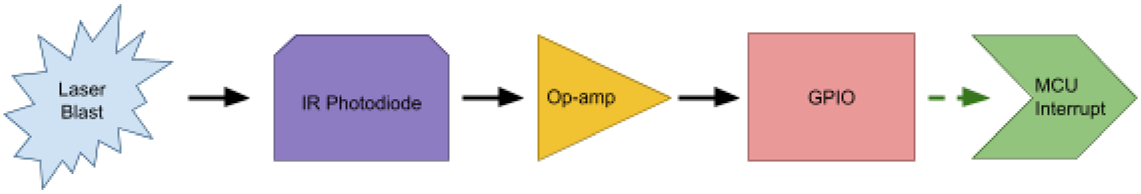
The electrical control and sensing design of the system is broken down into subsystems. There are three core subsystems, and two additional subsystems related to the advanced goals. The core subsystems of the electrical design are listed in the following sections. All schematics were connected by net name.

6.1.1 Laser Blast Detection Subsystem

The sensors used in the LIBS system measure a variety of parameters. One of the primary sensors in the system will be to detect the laser blast. Options to control the laser directly from the MCU were investigated, however there were a number of factors that removed this from design consideration. First, the speeds needed to accurately track from the laser pulse and count until a specific time to open the CCD shutter, would have increased costs for the MCU. Another issue with this approach is that the laser is controlled by a pressure peddle. This peddle appears to be connected to analog circuitry as the peddle connects to the laser through some sort of parallel port. The pedal could likely be replaced with an analog circuit instead. However this would require analog circuitry, in addition to this there is no real documentation on the internals of the laser, so current and voltage limits would have to be based on heuristics. Due to the expense and time required to acquire the laser avoiding damage to it is imperative. Therefore a design that is minimally invasive to the laser is preferred. Therefore having a way to detect the laser blast instead of triggering it was chosen. Detecting the laser blast requires a way to register a change in light or heat. The change in heat could be used, however this could require a sensor close to the laser impact point, which would be cumbersome, as it would need to be adjusted each time the sample was changed. In addition, the speed at which the laser blast occurs might make detecting a heat change difficult. However, the flash of light emitted from the laser blast is easily detected with a photodiode or infrared photodiode. An infrared photo diode would be preferred, as it would be less susceptible to interference from daylight, which might trigger false positives. Due to the safety concerns of the laser affecting bystanders, there will likely be some sort of containment chamber for the sample and laser aperture. The IR photodiode could be mounted in close proximity to the laser aperture, this would ensure a high signal to noise ratio, however caution needs to be taken to ensure that the photodiode is not so close as to be damaged or degraded with consecutive laser shots. With a sufficiently close distance the IR photodiode would likely not need to be extremely sensitive. The block diagram for the laser detecting sub-system can be seen in figure 6.1.

The IR photodiode chosen will have a short circuit current of around 47 uA. All of the GPIO pins on the MCU can sink or source at least 8 mA, so there is no danger of damaging the MCU, if the IR photodiode is connected directly. One option for detecting the laser blast would be to connect the photodiode directly to one of the ADC pins. This would require the ADC to be continuously sampling the IR photodiode until the voltage exceeds a specific threshold. This would allow for an easy way to change the distance of the photodiode from the laser aperture, as the threshold could simply change. However once the design is set, this distance will not likely change. The main issue with using the ADC, is that it can only capture signals at 0.5 us intervals. This is fast enough to capture the results from the CCD as that happens on the order of microseconds.

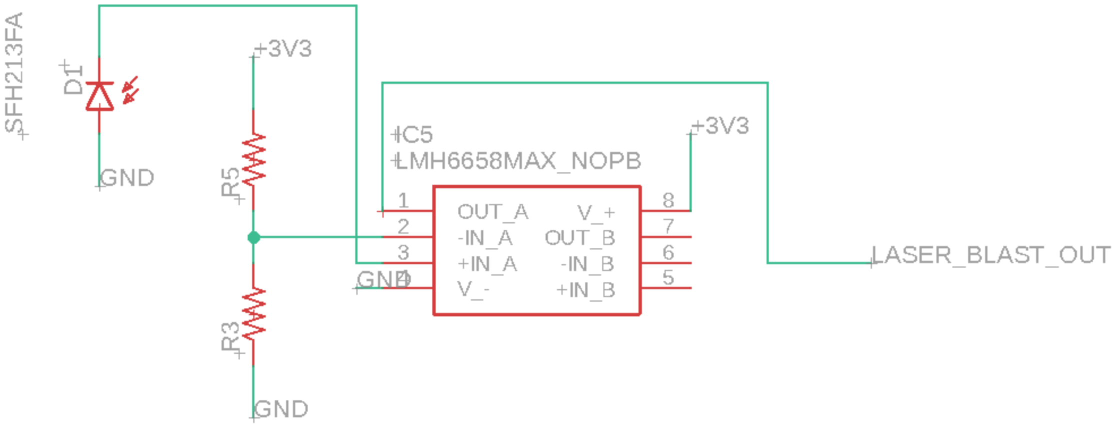
Figure 6.1 Laser Blast Detection Subsystem Block Diagram



The ADC can be set to sample faster, if a lower resolution is used. The lowest resolution possible is 6-bit, which would complete a full sample in 125 ns, if it was clocked at 64 MHz. An extra initial delay of 125 ns in detecting the initial laser blast could result in reduced spectral intensity. Therefore, it is better to use the GPIO logic directly, which is faster. The microcontroller has pull up or pull down resistors in front of the schmitt trigger, which pass the signal to the internal logic of the MCU. These pull up or pull down resistors have impedances in the range of 25KΩ to 55KΩ, Therefore at maximum current of the IR photodiode, the input to the schmitt trigger would be between 940mV to 2.6V. The GPIO logic levels of the MCU vary based on the voltage supply. Assuming 3.3V is used for the MCU voltage. Then based on the data sheet, the GPIO logic levels are $V_{HI} > 1.877\,V$ and $V_{LO} < 1.227\,V$, depending on the impedance of the pull-down impedances of the GPIO, this could be sufficient to hit the high logic threshold with a direct connection to the GPIO pins. However there is a chance that the voltage directly from the IR photodiode will not be sufficiently high to trigger the required interrupt for the MCU. Therefore an adjustable comparator circuit will be used as seen in figure 6.2.

This comparator circuit converts the output voltage of the IR photodiode to be in the range of the GPIO logic levels. This circuit also allows the sensitivity of the comparator to be adjusted based on the resistors, which provides a level of flexibility, if the MCU or logic levels changed. The resistors could be adjusted to reflect that. The voltage threshold for the comparator will be set around 100 mV. The op-amp for this circuit needs a sufficient slew rate or rise time for the speed of the laser blasts. Any op-amp with a slew rate of greater than $300\,\frac{V}{us}$ which provides a logic rate of change of around 10 ns, which should be sufficient, although a faster response time could produce higher spectral intensity for the system. The GPIO pins of the MCU have response times of 8 nanoseconds to hundreds of nanoseconds, depending on register settings of the MCU. TI's LMH6658MAX was chosen for its high slew rate of $420\,\frac{V}{us}$. The LMH6658MAX rise time is listed at 8 ns. The output of the opamp will be connected to an interrupt pin on the MCU, to generate a software interrupt.

Figure 6.2 Laser Blast Detection Subsystem Schematic

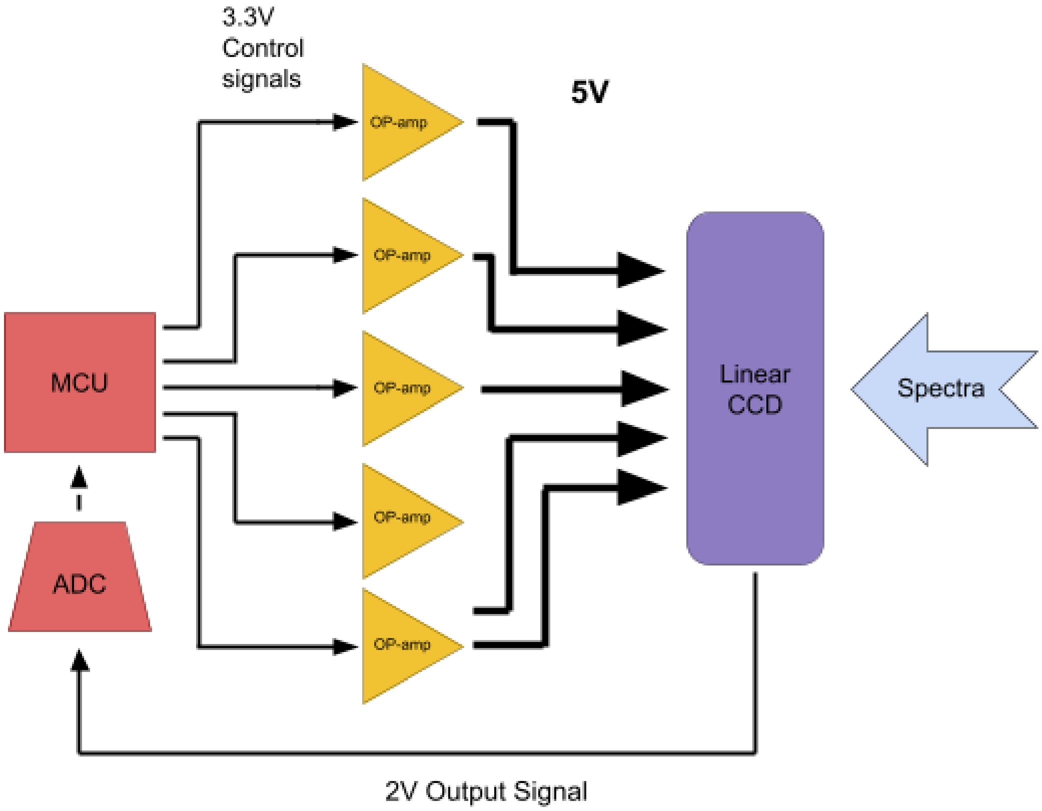


6.1.5 Spectral Emission Measurement Subsystem

The spectral emission measurement subsystem primarily consists of the Linear CCD, and op amps for level shifting. Opamps were chosen for level shifting the logic rather than traditional level shifter ICs. The reason for this is that opamps provide a higher degree of flexibility, as the logic levels can be set based on the design. Therefore if a component needs to be replaced in the later stages of the project, some minor adjustments could be made to the op amp inputs to facilitate new logic levels. Both are connected to the MCU to drive the CCD and receive analog data from it, via the MCU’s ADC. To capture the emission spectra from the diffraction grating, the linear CCD is controlled by the MCU and is triggered after the laser blast has been detected. The MCU has an output voltage of around 3.3V on its GPIO pins. The CCD typically uses 5V inputs. Therefore level shifters are required to convert the 3.3V output to 5V. It may be possible to run the CCD at lower voltages, however further testing is required. There are a total of five signals that drive the CCD. These signals are used to control the process of shifting the charges from each of the individual charge wells to the output cell for amplification. The sequence for moving these charges requires a precise timing sequence. The block diagram for the spectral emission measurement subsystem can be seen in figure 6.3.

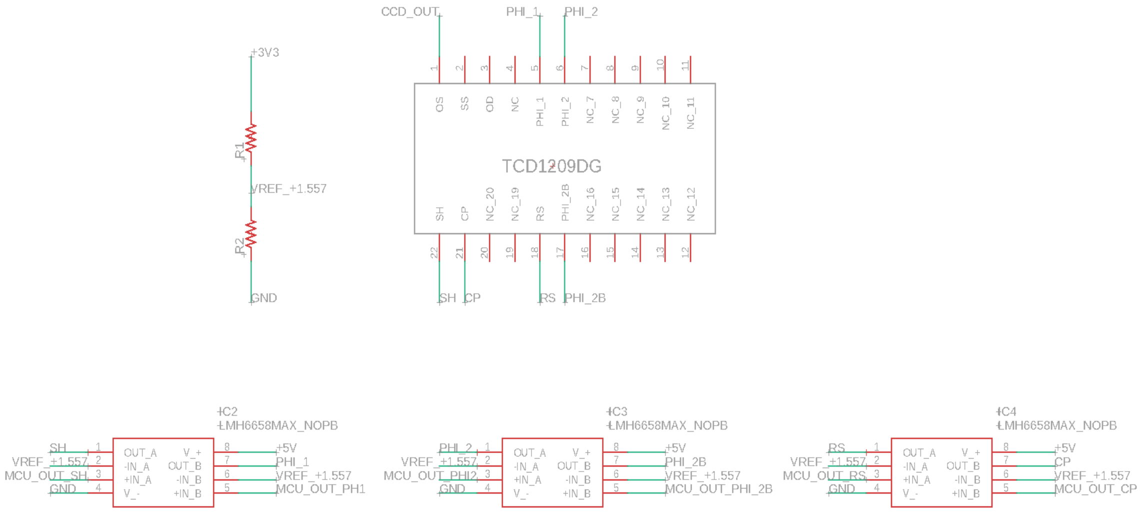
The Linear CCD requires a sequence of pulses on five of its input pins. These pulses reset the CCD at the beginning of the capture sequence and control how the values of each discrete photo detection element are shifted to the analog output. The CCD is capable of being run at a maximum frequency of 20MHz. The op-amps that were chosen as level shifters need to have a sufficient slew rate to ensure that they can switch quickly enough to drive the CCD at 20MHz. The LMH6658MAX was selected for its output voltage range, and speed. This opamp exceeds the 20MHz requirement, The chosen op amps allows for room in the design, should the current CCD need to be replaced with another that has a different voltage range or higher speeds. Additionally the LMH6658MAX will not create a bottleneck if there is a larger delay between the MCU and CCD. For instance if there is a larger delay from the GPIO pins or other elements of the PCB then expected. This will allow for sufficient rise time for all of the pulse signals as they are converted from 3.3V to 5V. Opamps were chosen over level shifters due to their design flexibility. Based on the data sheet for MCU, the rise and fall time of the GPIO for a 50pF pin capacitance running at 3.3V is around 11ns. The schematic for the spectral emission measurement subsystem can be seen in figure 6.4.

Figure 6.3 Spectral Emission Measurement Subsystem Block Diagram



The schematic for the spectral emission subsystem can be seen in figure 6.4. The op amp selected for the design provides two op amps per IC package.

Figure 6.4 Spectral Emission Measurement Subsystem Schematic

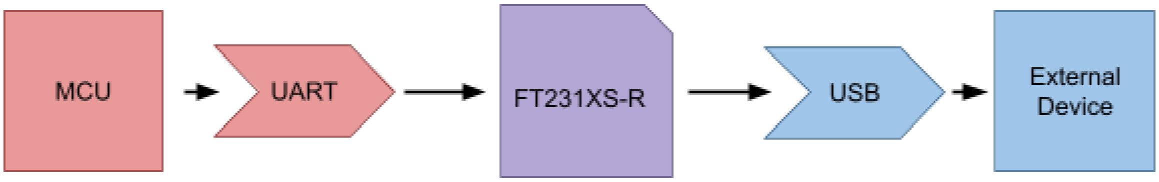


The CCD(TCD1209DG) data sheet did not provide a CAD model or footprint, therefore one was created in Eagle based on the dimensions given in the CCD's data sheet. The logic values of the MCU GPIOs are $V_{HI} > 1.877\,V$ and $V_{LO} < 1.227\,V$. Therefore a reference voltage of 1.557 will be created with a resistor voltage divider. The output of the CCD is an analog voltage signal with a maximum amplitude of 2 volts. This output pin will be directly connected to one of the MCU ADC pins. Neither of the datasheets for the CCD and op-amps list any additional capacitors or resistors that are required for noise or limiting current.

6.1.9 Data output Subsystem

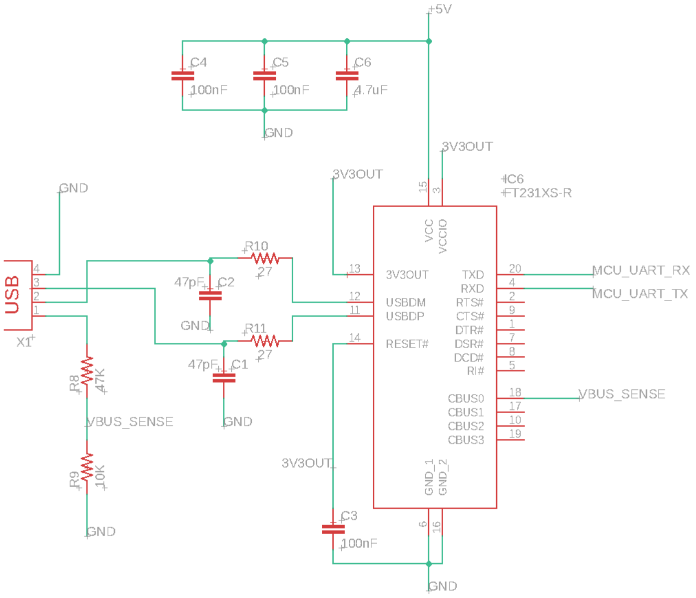
Spectral data captured by the CCD is stored in the MCU. The data is held there until it is output to an external device such as a PC, MAC, etc. The spectral data is transferred to the external device using serial connection. The STM32G0B1RET6 MCU offers a USART communication protocol. Most devices however, do not have a dedicated USART port. Therefore a converter is required to translate the USART protocol into a more common serial data protocol. USB is a very common protocol, used by many devices. Converting the data sent on the USART protocol to the USB protocol would provide the system with a widely accepted data transfer medium. There are dedicated circuits that are available for purchase which can perform this protocol translation. The converter used to do this is the FT231XS-R. The FT231XS-R can transmit at USB 2.0 speeds, requiring no external clock or oscillator. Because the expected distances between the external machine and the PCB are expected to be relatively short. Therefore the use of a longer range standard such as RS-232, RS-422, or RS-485 are not required. If signal integrity issues are present, the design can be adapted to support these standards, as the MCU offers support for several of these. The block diagram for this subsystem can be seen in figure 6.5.

Figure 6.5 Data output Subsystem Block Diagram



The FT231XS-R requires 5 volts, which can be supplied by a USB hub, or supplied locally on the PCB board. For this subsystem power will be supplied to the FT231XS-R from the PCB. This will likely allow for more precise control of voltage fluctuations and noise. The FT231XS-R also needs a variety of capacitors. Since the converter is connected directly to the UART pins of the MCU no form of level shifters or signal converters are required. The MCU offers 4 pins for USART: TX, RX, CTS, and RTS/DE. TX and RX are standard transmit and receive for UART. CTS and RTS are used for hardware control flow in RS232. The RTS pin doubles as the DE or driver enable pin for RS485 hardware mode. The USART will be run as a standard asynchronous UART. Based on the results of testing the hardware configuration may be changed. The overall schematic for the data output subsystem can be seen in figure 6.6.

Figure 6.6 Data output Subsystem Schematic



The design is based on what is recommended for the FT231XS-R in its datasheet. There are decoupling capacitors. The FT231XS-R has 4 CBUS pins.

These are general purpose pins that can be programmed to perform various functions depending on the communication protocol being converted, how the IC is powered, and other factors. When the FT231XS-R is provided with power via the PCB, the datasheet warns against driving any current onto the USB bus when the USB host or hub is powered down. This is likely to ensure that the FT231XS-R does not cause any damage to a usb host or controller when it is powered off. If the FT231XS-R was powered directly from the usb, then the controller could only drive current when the USB hub is powered on. There are two primary reasons for powering the FT231XS-R from the PCB. First the PCB already requires a 5 volt source for the CCD. Second, by powering the FT231XS-R converter on the PCB, there is no concern about the over or under current draw, which would require the FT231XS-R to use one of its CBUS pins to detect current flow. Depending on the mode of operation the FT231XS-R may need to have its internal memory programmed for its hardware configuration.

6.1.13 Digital Control Design

The LIBS project uses the STM32G0B1RET6 MCU for the digital control aspects of the project. The MCU will convert any analog sensor signals to digital ones. The MCU will handle the pulse timing that is required to run the CCD, allowing it to capture spectral data. The MCU will also handle communications with an external machine via UART. If there is enough time, the MCU will also handle output data to an LCD and measure sample distances. These components are connected via communication protocols, or analog to digital converters. Some of the systems require level shifters to ensure they meet the logic level of the MCU.

6.1.14 MCU I/O

The MCU provides a variety of I/O pins that can be multiplexed for different functionality. These pins needed to be examined to ensure that all of the desired functions for the project could be achieved without any overlap. The IC package used is the LQFP64. This package offers I/O ports which are named A, B, C, etc. There is a port F which has an input for an external oscillator, an output for the IC’s internal oscillator, and an output for some other functions. The MCU can run at a voltage of between 1.7 to 3.6 volts. For the project, the MCU will be supplied with 3.3V. The MCU also has a port for a battery power source, and supplies voltage to the low speed oscillator and some backup registers, since the datasheet of the MCU mentions that for IC packages that don't offer the VBAT port, it is tied to the main voltage rail. Therefore the VBAT port will also be connected to the 3.3V supply, in the design. There is an external reference voltage pin known as +VREF. This pin supplies a reference voltage to the analog peripherals. +VREF can be between 2V and the supply voltage of the MCU. In the proposed design it will be set as 3.3V, tied to the main voltage supply. The MCU offers an external reset pin named NRST. This pin should be held at logic high, and pulled low to reset the MCU. A switch that connects the 3.3V source voltage or ground with the reset pin. All of the I/O ports offer external interrupts, and many of the I/O ports have various alternative functionality that can be multiplexed to the pin. The Functions of interest for the LIBS design are UART, SPI, I^{2}C, ADC, Timers, and interrupts. The schematic for the MCU can be seen in figure 6.7. This pinout is subject to change based on placement and routing for the PCB. The MCU is capable of multiplexing many of its individual functions to several of its GPIO pins. The power, ground, and the reset pin must remain the same. The decoupling capacitors were placed based on the data sheet recommendations for the MCU. The SWCLK and SWDIO pins will be used for programing and debugging purposes. Table 6.1 shows the pins required for the core functions of the project. Pins required for advanced goals are listed in table 6.2.

Figure 6.7 Preliminary MCU Schematic

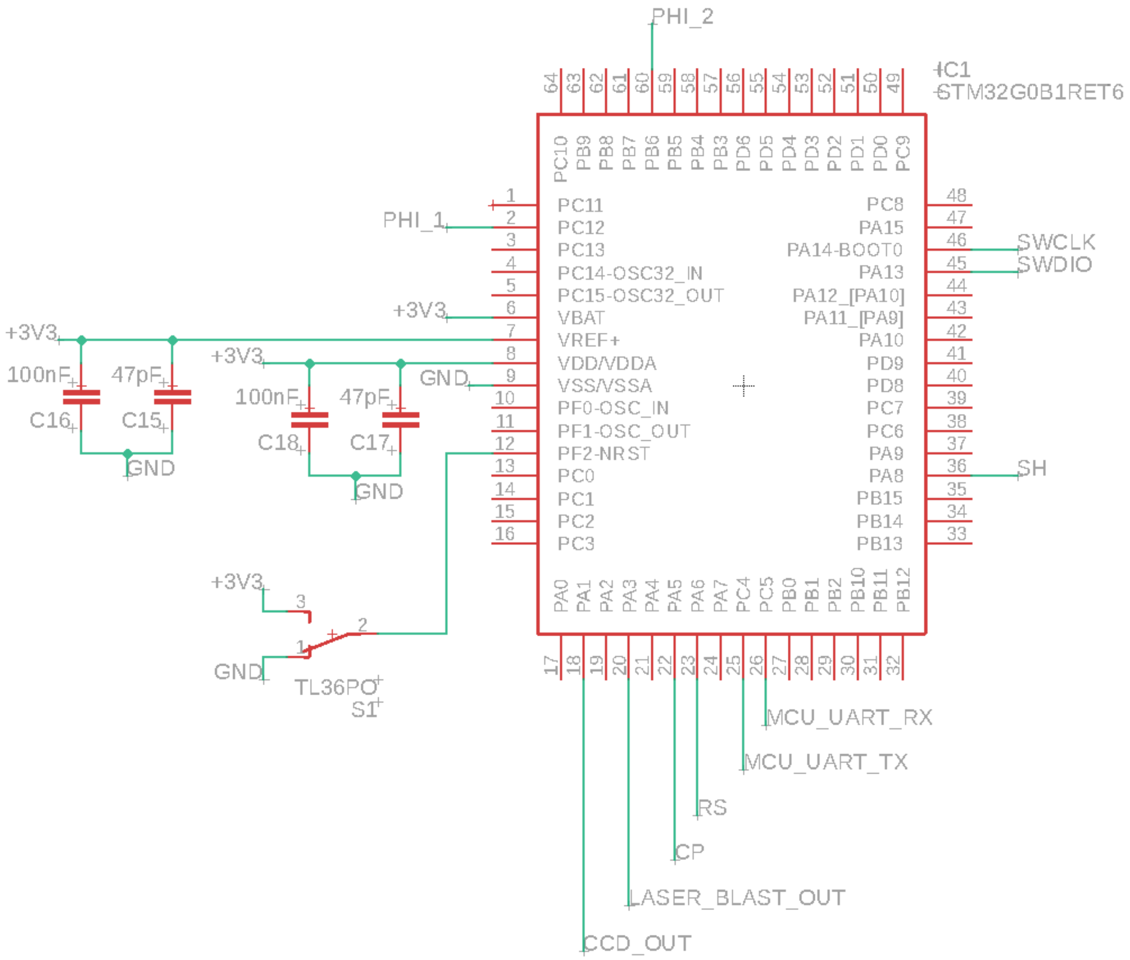


Table 6.1 MCU Core Goals Function Pinout

Function	**Interface**	**Pin**
MCU Power	Power Supply Ground Analog Reference Backup Power Programming/Debug Clock Programming/Debug Data	VDD(8) VSS(9) VREF+(7) VBAT(6) PA14-BOOT0(46) PA13(45)
Laser Interrupt	GPIO	PA3(20)
CCD Input	TIM1_CH1 TIM2_CH1 TIM3_CH1 TIM4_CH1 TIM14_CH1	PA8(36) PA5(22) PA6(23) PB6(60) PC12(2)
CCD output	ADC1_IN1	PA1(18)
Data output external	USART1_TX USART1_RX	PC4(25) PC5(26)

Table 6.2 MCU Advanced Goals Function Pinout

Function	**Interface**	**Pin**
LCD Input	SPI1_SCK SPI1_MOSI SPI1_MISO	PD8(40) PA11(43) PA2(19)
Distance sensor Input	I2C1_SCL I2C1_SDA	PA9(37) PA10(42)

6.2 Power Systems Design

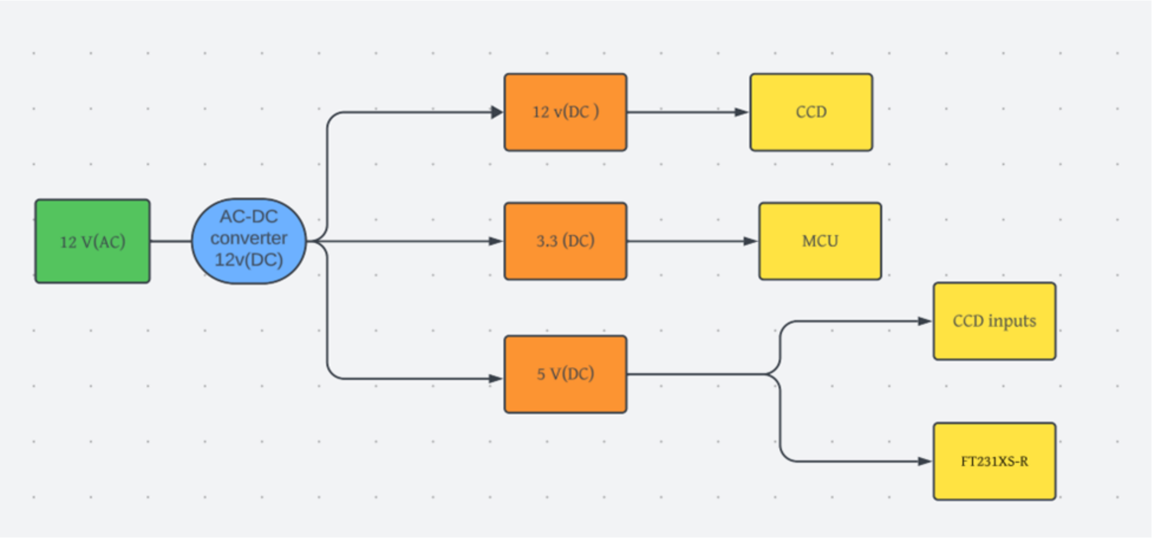
The various electrical components in the system all have different requirements for their operating voltage levels. The team decided to design two voltage regulators. These voltage regulators will be used to supply power to the CCD, MCU, and FT231XS-R. The FT231XS-R and the inputs to control the CCD both require 5 volts to operate. The CCD itself requires 12 volts to operate. The MCU only requires 3.3 volts to operate. The output voltages of the voltage regulators will likely change based on the results of testing. Losses due the PCB may require that slightly higher output voltages are used. The expected voltage and current requirements for each of these components is shown in table 6.3.

Table 6.3 Component Power Sources

Item	Voltage input	Voltage output	I out max
MCU	12 V (DC)	3.3 V (DC)	0.5 A
CCD	12 V (DC)	12 V (DC)	0.5 A
FT231XS-R	12 V (DC)	5 V (DC)	0.5 A
CCD inputs	12 V (DC)	5 V(DC)	0.5 A

The preliminary design for the voltage regulators in the overall system can be seen in figure 6.8. The input of these voltage regulators is 12 v (AC) from the wall outlet. There will be an AC-DC converter to convert the AC voltage to the DC voltage. Therefore, the input will be the 12 v (DC). The first voltage regulator is 3.3 V (DC) to the MCU. The 12 v will supply the CCD . The 5v VR will supply the CCD inputs and the FT231XS-R.

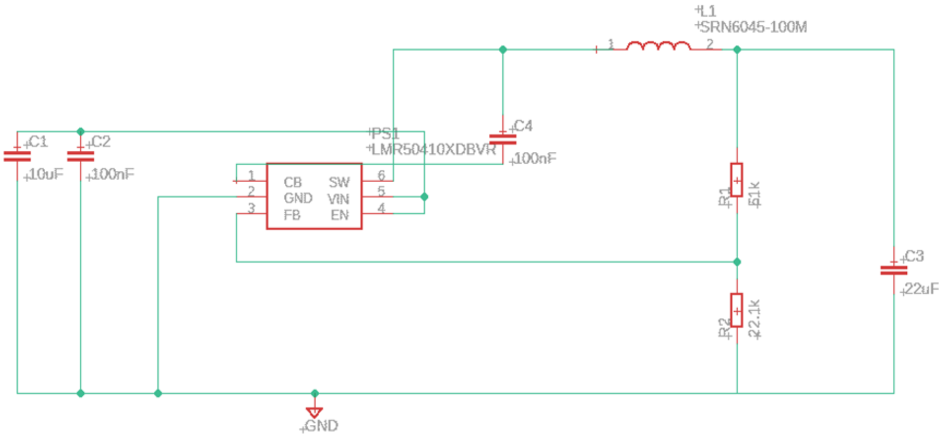
Figure 6.8 Voltage regulators Block Diagram



6.2.3 MCU Power

The MCU will be powered by a 3.3 V regulator. The proposed design of this regulator can be seen in figure 6.9. The input voltage is 12 V and it will be converted to 3.3 to supply the MCU by using LMR50410. The circuit is designed to accept maximum voltage of 13 V and minimum voltage 10v. However, the nominal voltage is 12 V. The maximum current for this circuit is 0.5 A.

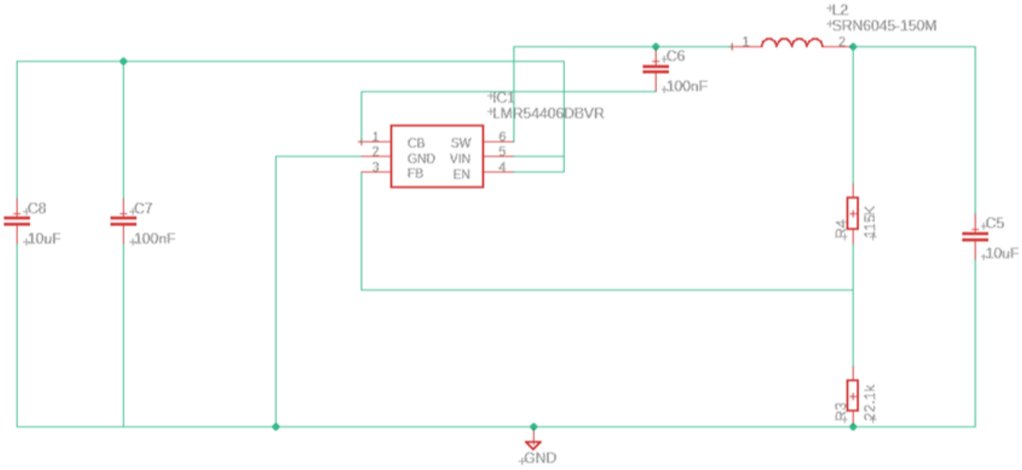
Figure 6.9. MCU Voltage Regulator Schematic



6.2.4 CCD Control Power

The CCD will need a 12 V power supply and 5 V for its inputs. The CCD is being controlled by the MCU via op amp level shifters. The MCU output is 3.3 V, but the CCD requires 5 v inputs. Therefore, a voltage regulator with a 5 V output, to supply power to the level shifting op amps was designed. The LMR5440 was selected for this. This is another switching regulator that is also in the LMR5 series. This was selected over the LMR50410 for this circuit because, of the higher operating frequency, which can make a difference in the voltage regulator's efficiency. The LMR54406 operating frequency is 1100 kHz. Whereas the LMR50410 has an operating frequency of 700KHz. High frequencies can also cause high noise in circuits. However, the noise of this voltage regulator is the same as the LMR50410 which is 0.5% output voltage ripple. Therefore no voltage irregularities are expected. However further testing will confirm the level of output noise. This circuit design can be seen in figure 6.10.

Figure 6.10 CCD input Voltage regulator Schematic



6.3 Overall Electrical Design Schematic

Figure 6.11 shows the overall design schematic for the electrical systems of the project. The design is subject to change based on results of testing the various subsystems as the project progresses.A larger version of Figure 6.11 Can be seen in the appendix. The wires of all the subsystems in figure 6.11 are connected by sharing the same net names rather than with direct connections. This allows for the sub systems to be connected, without creating an extremely disorganized schematic. The overall schematic is composed of the MCU, CCD, UART to USB converter, four op amps, and two voltage regulators. There are a total of 18 capacitors, 10 resistors, 1 photodiode, and 1 switch. This is a total of 39 components to be placed on the PCB. in addition to that a pin header will be required on the PCB for the SWCLK and SWDIO pins. This pin header will be used by the MCU to connect to the ST-LINK for programing and debugging purposes. The total bill of materials of all the major components needed to create the electrical systems can be seen in figure 6.4.

Figure 6.11 Overall Electrical Design Schematic

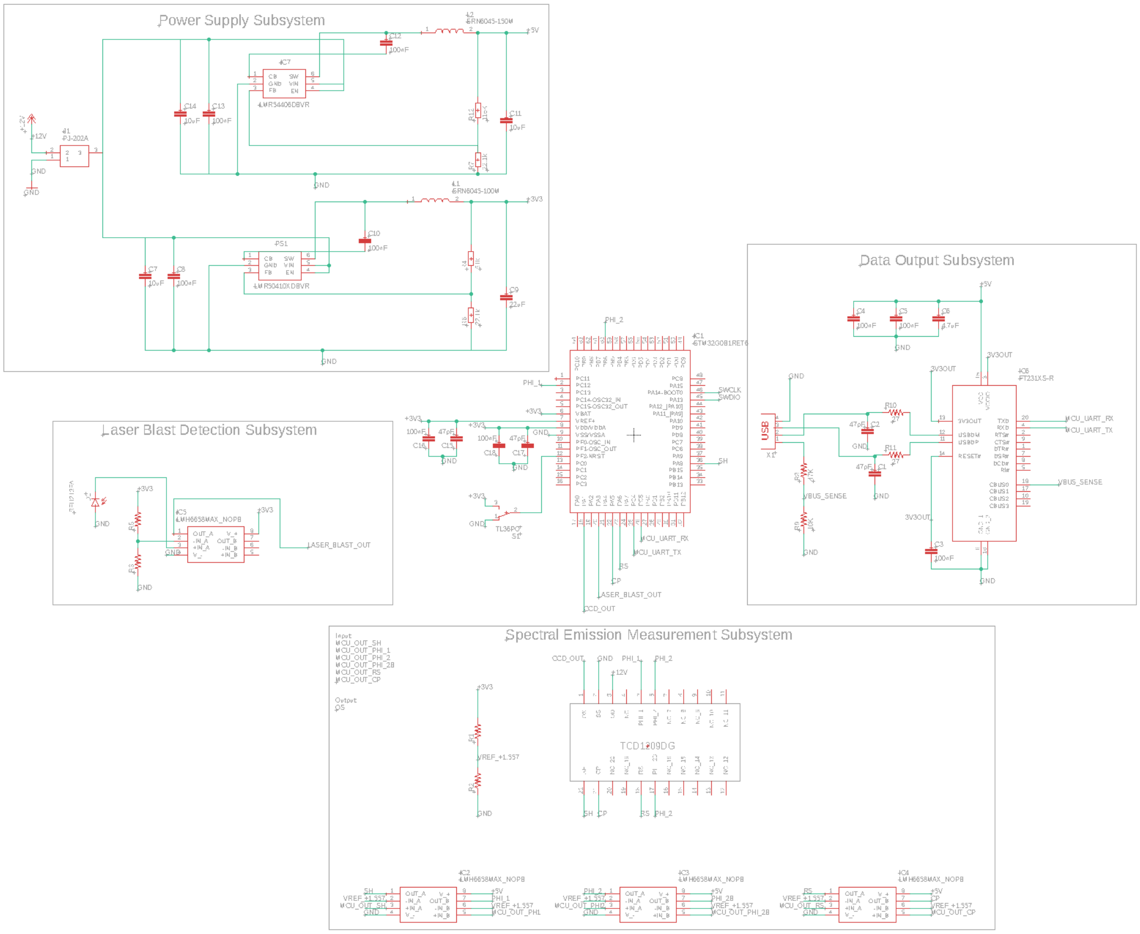


Table 6.4 Bill of Materials Electrical Systems

Item	**Quantity**	**In stock**	**Price ($)**	**Footprint (mm)**	**Part name**
Photo Diode	1	96272	0.85	DIP (4)	SFH213FA
CCD	1	41	48.61	WDIP-22 (35x9.7)	TCD1209DG
Opamp	3	4101	1.79	SOIC-8 (5x6.2)	LMH6658MAX/NOPB
UART to USB Converter	1	101000	1.83	SSOP-20 (8.7x6.2)	FT231XS-R
MCU	1	589	6.46	64-LQFP (12.7x12.7)	STM32G0B1RET6
VR	1	4k	0.86	SOT-23 (14.82)	LMR54406 DBVR
VR	1	15k	1.23	SOT-23 (14.82)	LMR50410XDBVR
Total cost			67.00		

As expected the CCD accounted for the largest expenditure in the electrical system. The other electrical components cost a total of $19.

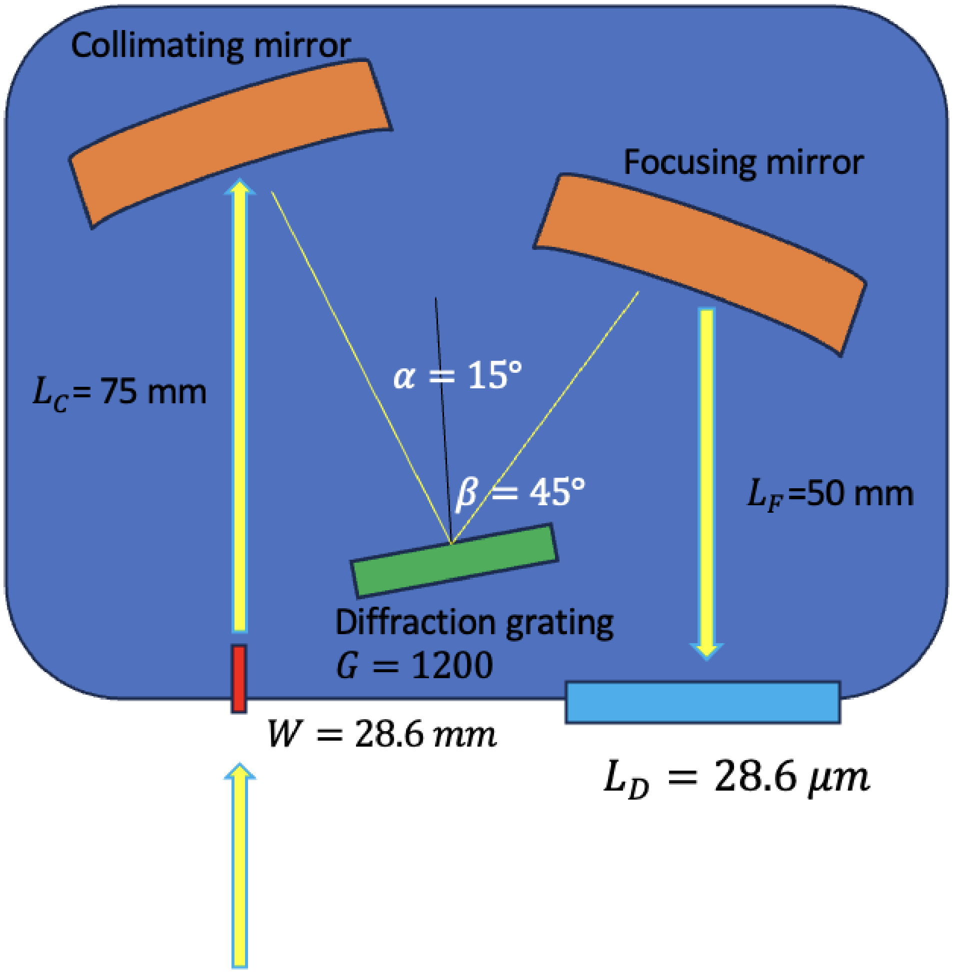
6.4 Spectrometer Design

The spectrometer style selected for this project was the crossed Czerny-Turner. As stated in the technology comparison section of this report, the crossed Czerny-Turner provides high spectral resolution, minimized stray light, superior collimation and focus in a compact system. There are few optical components which keeps the overall cost of the project low. The design will also allow for wavelength calibration for accurate elemental characteristic identification with spectral lines. The proposed design can be seen in figure 6.12.

Figure 6.12 Spectrometer Design

Φ=30°

Optical performance, diffraction efficiency, and practical considerations.



There are two important factors used to design a spectrometer system: wavelength range being measured and optical resolution to be resolved. The system will be observing the visible spectrum, 380 nm to 700 nm, from the plasma created by the laser system. For elemental characterization it is desirable to have a high spectral resolution. The parameters used for the spectrometer calculations can be seen in table 6.5.

Table 6.5 Used Parameters in Spectrometer

Minimum wavelength	λ_1	Angle of incidence	α
Maximum wavelength	λ_2	Diffraction angle	β
Wavelength range	λ_R	Grating groove density	G
Resolution	$\Delta\lambda$	Focal length collimation	L_C
Center wavelength	λ_c	Focal length focus	L_F
Detector width	L_D	Input slit width	W

To determine the wavelength range and central wavelength the equations are:

$$(\lambda_2 - \lambda_1) = \lambda_R \qquad \frac{\lambda_R}{2} = \lambda_C$$

From these formulas, using $\lambda_2 = 700\,nm$ and $\lambda_1 = 380\,nm$ results in 320 nm for the range and $\lambda_C = 540\,nm$.

Next, geometry for the Czerny-Turner spectrometer is selected. A geometry of $\phi = 30°$ is commonly selected for this type of spectrometer because it strikes a good balance between diffraction efficiency and minimizing aberrations in the system. If a larger angle was selected closer to 45°, it would provide higher diffraction efficiency but would introduce more pronounced optical aberrations. At 30° geometry, aberrations like coma and astigmatism are significantly reduced while maintaining diffraction efficiency. At this selected angle, a good compromise between dispersion and spectral resolution is achieved.

The grating was already selected for peak efficiency, G = 1200 lines/mm. This will give a blaze wavelength of 500 nm, right in the middle of the observed visible spectrum. The chosen linear CCD has a width of $L_D = 28.6\,mm$. This will give us the ability to view a broad spectral range with high resolution. From these values the angle of incidence can be calculated with the following formula:

$$\alpha = \sin^{-1}[\frac{\lambda_C G}{2\cos(\frac{\phi}{2})}] - \frac{\phi}{2}$$

This gives a value of $\alpha =- 14.98°$. With this value, it is possible to solve for the diffraction angle with the formula:

$$\phi = a + B$$

This yields a diffraction angle value $\beta = 44.98°$. Knowing the angle of incidence for the system will determine the efficiency of the diffraction process. The efficiency of the system depends on this first angle to align the incoming light with the diffraction grating ruling. If These calculations are accurate for the angle of incidence. It can minimize the undesirable effects like higher-order diffraction and loss due to absorption or reflection. This angle will also ensure that the maximum amount of light is diffracted into its respective spectral order. This improves the systems overall spectral quality and signal-to-noise ratio.

The diffraction angle is critical in determining the dispersion of light by the grating. If this is not calculated appropriately the dispersed light will not be separated properly for analysis of the spectral components. The diffraction angle is used to find the angular spread of different wavelengths at the detector. A smaller angle system will result in better spectral resolution as the closely spaced wavelengths are better resolved. The order of diffraction is also associated with the diffraction angle. This affects how the spectral components are distributed spatially on the detector.

The angles and geometry have been calculated. To calculate the focal lengths of the spectrometer, the following must be done. First, the focal length of the focusing mirror L_F is found using the equation:

$$L_F = \frac{L_D \cos(\beta)}{G(\lambda_2 - \lambda_1)}$$

Which results in a value of $L_F = 52.66\, mm$. Magnification of a spectrometer system is usually a 1:1 scale, the input slit for an ideal image matching that 1:1 ratio onto the detector array. For magnification M=1 is selected for an unmagnified system. Using this magnification value and the focal length of the focus mirror the focal length of the collimation mirror L_C can be determined with the formula:

$$L_C = \frac{L_F \cos(\alpha)}{M \cos(\beta)}$$

It is calculated that the needed focal length of the collimation mirror is $L_C = 71.93\, mm$. The ability to find the exact measurements for each mirror would require mirrors of this exact specification to be manufactured. This would not be possible for this project, so the team will find mirrors with values as close to the calculated values as possible. The focal length of the focusing mirror will be $L_F = 50\, mm$ and the focal length of the collimation mirror will be $L_C = 70\, mm$. These values are very close to the calculated theoretical results.

Last, the input slit width to the spectrometer is calculated. This value will have a direct impact on the spectral resolution of the spectrometer. The narrower the slit width, the higher spectral resolution, allowing for the resolution of more closely spaced spectral lines. If this is not calculated and a wider slit is selected, more light would be allowed to enter the system, increasing the intensity of the signal. This would reduce spectral resolution as more wavelengths are collected at the detector. If the proper sized slit width is found, the signal-to-noise ratio will be more efficient because background noise and stray light will be reduced. The overall angular and spatial resolution is influenced by an efficiently calculated slit width with this comes a reduction in the optical aberrations seen by the system, specifically coma and astigmatism. All of this will help to distinguish the spectral features across the detector that the system was created to observe. Slit width is determined by the equation:

$$W = \frac{G\, \Delta_{\lambda} L_{C}}{\cos(\alpha)}$$

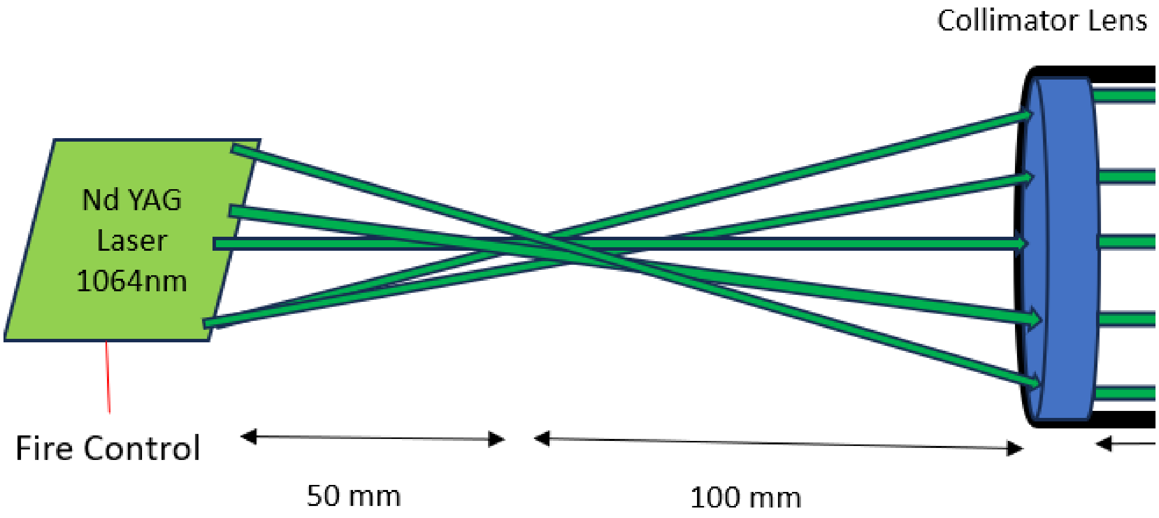
From that equation the value calculated for the require a slit width is $W = 28.6\ \mu m$. There are always trade-offs when calculating the needs of a system and selecting the components. This will be discovered in further detail during the testing of the completed spectrometer. A different sized slit width might be needed for different elemental samples that are analyzed based on the spectral characteristics or the emission intensity. The proposed spectrometer will be using a 905-fiber cable with a collimating lens attached to the end to guide the light to the spectrometer. A core width at or close to the calculated slit width of $W = 28.6\ \mu m$ will be used.

6.5 Laser Focusing System

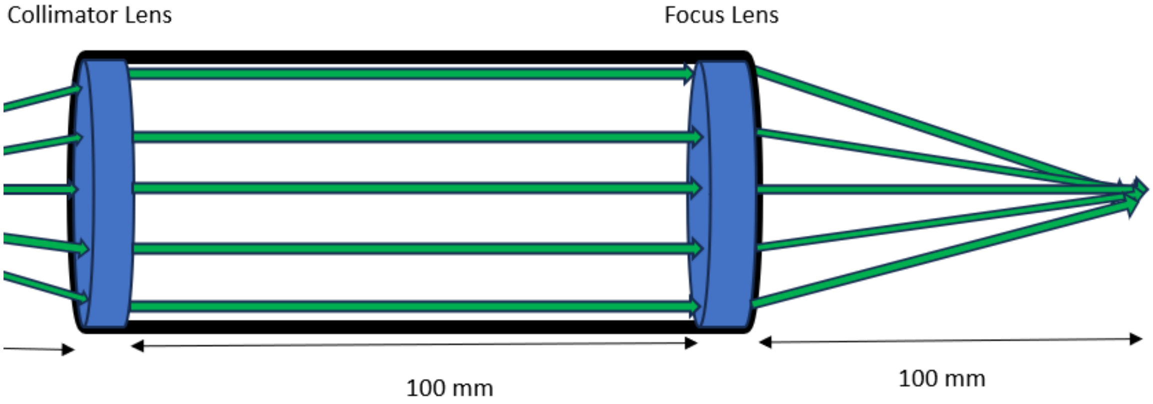
The current focal point for the tattoo removal laser is approximately 50 mm away from the last optical element. This introduces several issues as the laser is being used, the debris created will impact the optical components of the laser and could damage it. To mitigate this problem, we aim to increase the approximate focal length from the last optical element to 100 mm away. This should mitigate the debris issue. However, it introduces some new challenges to overcome. Optical elements have a limit of optical power it can transfer before it is damaged, this is the Laser Induced Damage Threshold (LIDT). This constraint had to be considered when selecting lenses for the optical system. With the aim to increase the focal length the team decided to use a collimator lens and focusing lens. The collimator lens will be placed after the initial focal point, 50 mm, where the beam waist will be approximately 25 mm wide. This was roughly 100 mm from the focal point.

Many lenses have a diameter of 25 mm so this will be one constraint as those are usually more affordable. The collimator lens will be placed about 150 mm from the current exit of the beam, this will collimate the beam to reduce aberrations of the system. A focusing lens will then be placed 100 mm from the collimating lens, which will then focus the beam to a focal point 100 mm from the last optical element. The distances between the collimator lens and the focusing lens is fixed because of the depth of field.

6.13 Laser to initial Focal point and then to Collimator Lens



6.14 Collimator lens to Focusing lens to Focal point



The team selected the pair of lenses from Edmond Optic which will meet these needs. The specifications for the lenses are in table 6.6. Two 25.0 mm Dia. x -100 FL, 1064nm V-Coat, UV Plano-Concave Lens were purchased and will be put through testing when they arrive. These lenses meet our requirements for extending the focal length.

Table 6.6 Lens selection Specifications

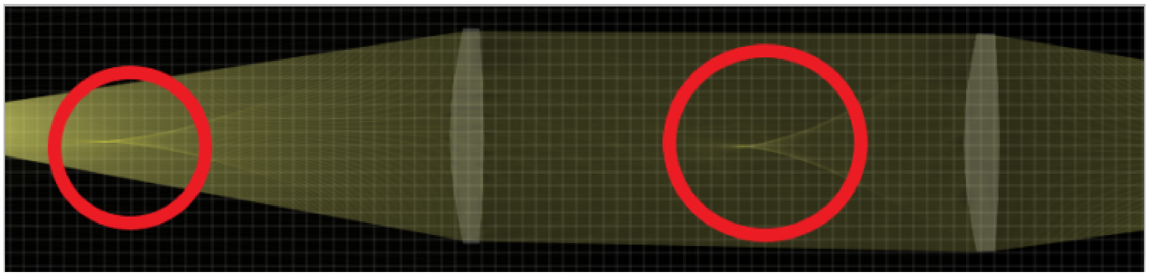
Diameter (mm)	25.00, +0.0/-0.025	**Effective Focal Length EFL (mm)**:	-100
Substrate	Fused Silica	**F/#**	4
Numerical Aperture	0.13	**Coating**	1064nm V-Coat
Type	Plano-Convex Lens	**Wavelength Range (nm):**	1046 – 1074
Center Thickness CT (mm)	2.5	**Back Focal Length BFL (mm):**	-101.71
Centering (arcmin):	<1	**Center Thickness Tolerance (mm):**	±0.10
Edge Thickness ET (mm):	4.15	**Clear Aperture CA (mm):**	24
Focal Length Tolerance (%):	±1	**Design Wavelength DWL (nm):**	1064
Damage Threshold, By Design:	15 J/cm^	@ 1064 nm	@ 10 ns

Now that the lenses have been selected they will be assembled together in a 3D-printed housing to protect the laser and people around it. The laser will be removed from the current handle housing and be secured to a wooden structure to secure it. It will then be aligned to point straight down the 3D-printed housing into the focusing system. This will be a hard task as this will not be on an optical table, but we will have calipers to ensure the distances are appropriate and the beam path is correct.

Another challenge the team overcame is the danger of back reflections. This is when some or all the laser beam is reflected back into the system. This is usually caused by the polished surfaces of prisms and fiber ends. This is a reason why fiber ends have an angular cut to reduce this issue. Curved surfaces, such as the lens used in our system, are less susceptible to damage due to back reflection. Except when focused back into the system. If the 1064 nm pulsed laser is reflected into itself and into the laser cavity it will cause damage and destroy our laser.

To reduce this, we ran a Ray Optics simulation where the lenses are placed at the described distances. The beam is then fired through, and the back reflection focal points are shown in figure 6.15. Where the focal points occur are before the previous optic. This is necessary to demonstrate that our laser focusing system will not focus back onto itself and destroy its optical system.

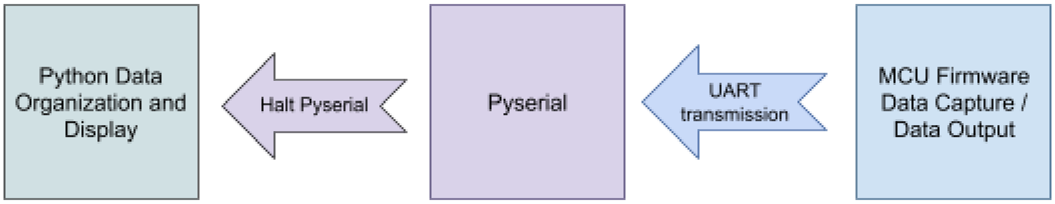
6.15 Back Reflections check



7. Software Design

There are two primary forms of software for the LIBS project. There is the embedded software that is required to run the MCU to drive the other components. There is also the Software for the external machine to capture and organize spectral data from the MCU. The software for the MCU is written in C. The software for interpreting and displaying the spectral data is written in python. Since the software systems are more flexible than the hardware, the functions and control loops are expected to change rapidly based on results of testing and building the system. The overall block diagram for the software of the system can be seen in figure 7.1.

Figure 7.1 Overall Software Design Block Diagram



The MCUs primary software loop will be triggered by the external interrupt of the photodiode detecting the laserblast. The MCU will then drive the GPIO input pins to the CCD via a software loop, or via hardware timers. The outputs of the CCD will be captured by the MCU's ADC. The ADC will use either a software clock counting loop or hardware timer interrupts to control when the ADC samples the CCD's output pin. The MCU will then transmit each of the 2048 CCD output through UART. Depending on the speed at which the CCD is run, it may be possible to begin data transmission through UART immediately once the CCD data becomes available. Once the final piece of spectral data has been transmitted. The MCU will transmit a specific bit sequence causing serial detection from python to halt. A software loop will then be used to organize and display the spectral results.

7.1 MCU Firmware Design

The firmware for the MCU will be written in C. ST provides a software suite for programming and debugging their microcontrollers. This software suite is known as the STMCUBEIDE. This IDE provides a graphical interface for STM products, allowing an easy way to enable and disable the various peripherals, alter clock speeds, and a variety of other features. In addition to the development environment. ST also offers an array of pre-made functions and structures to control their MCUs. These functions and structures are collectively known as the HAL API layer. The primary control loop for the MCU can be seen in figure 7.2

Figure 7.2 MCU Firmware Design Diagram

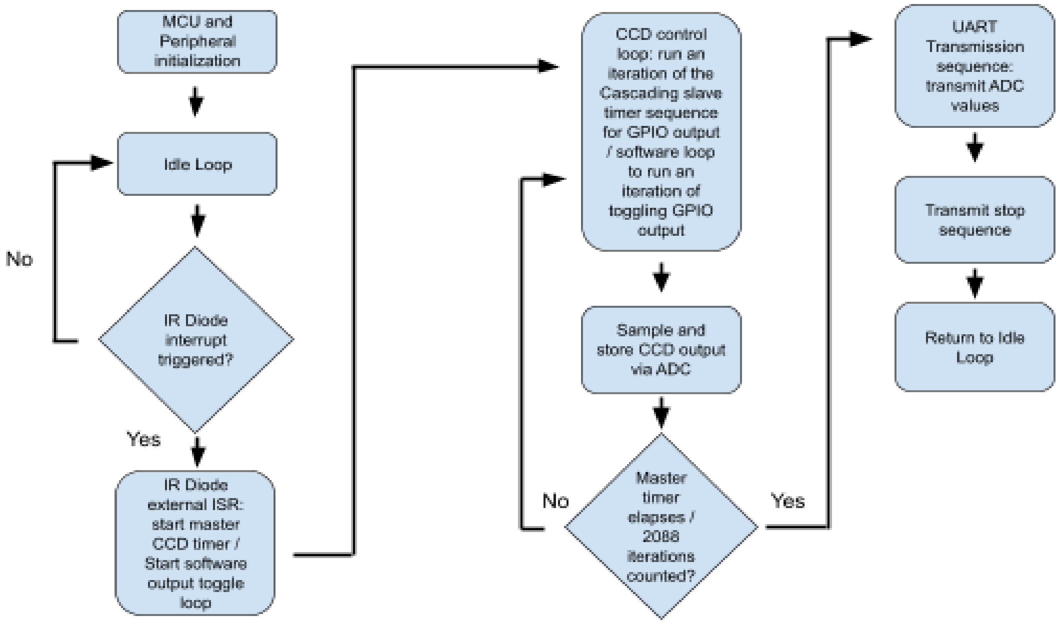


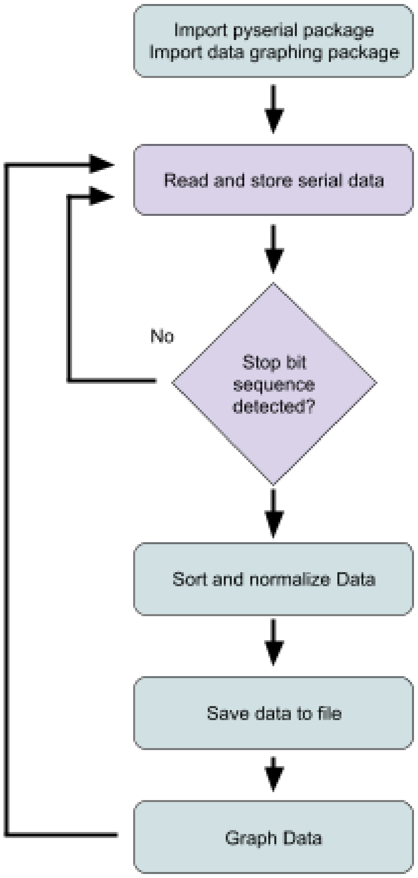
Figure 7.2. indicates the proposed control flow for the MCU. The MCU firmware will idle in an empty loop until the external interrupt from the laser blast is triggered. When the interrupt is received the ISR handler will either start the master CCD timer to trigger GPIO to the CCD, or a software loop that toggles the same GPIO sequence. One of these two methods will be used depending on the

speeds achievable by each method. After the Master timer finishes, or in the other method when the software loop counts 2088 iterations. The UART transmission sequence will then begin. Once all of the data from the sample is transmitted the MCU will transmit a bit sequence to indicate that all the data has been transmitted for that sample. Then the MCU will return to the idle loop until the next laser blast is detected.

7.2 External Machine Software Design

The software for the external machine will be written in Python. Python will easily allow for the ability to organize and graph the spectral data. The package pyserial will be used to read the UART outputs from the MCU and store the data. The data received from the MCU may or may not be rearranged and or normalized. This depends on the order in which the data is sent. The primary control loop for the external machine software can be seen in figure 7.3.

Figure 7.3 External Machine Software Design



After the relevant packages are imported the python program begins reading serial data. All incoming data is stored, and after a specific bit sequence is sent by the MCU. The Python program stops reading serial, and will begin sorting and normalizing the spectral data as needed. The spectral data will be saved to a file on the machine. Finally the python program will graph the spectral data for the user to review.

8. System Fabrication/Prototype Construction

For the fabrication of the system or the construction of a prototype involves the fabrication of PCBs along with any physical construction that is required to house or hold subsystems. Due to the rapidly changing nature of designing and testing subsystems. The physical prototype for carrying the overall system has not yet been designed. However as the project progresses further, and the subsystems and their integration solidifie, the final physical aspects of the system will be formed around the integrated sub systems. It is likely that the system will be transported on a mobile cart, and that the sample containment chamber will be constructed of wood.

8.1 PCB Design & Fabrication

To connect the electrical components for the system, a PCB needs to be designed and fabricated. The design and fabrication of a PCB is a complex challenge. There are many factors to consider such as the material type, number of layers, layer order, component placement, trace routing, fabrication tolerances and suppliers. All of these factors need to be considered to ensure that the final PCB is accurately tailored to the project.

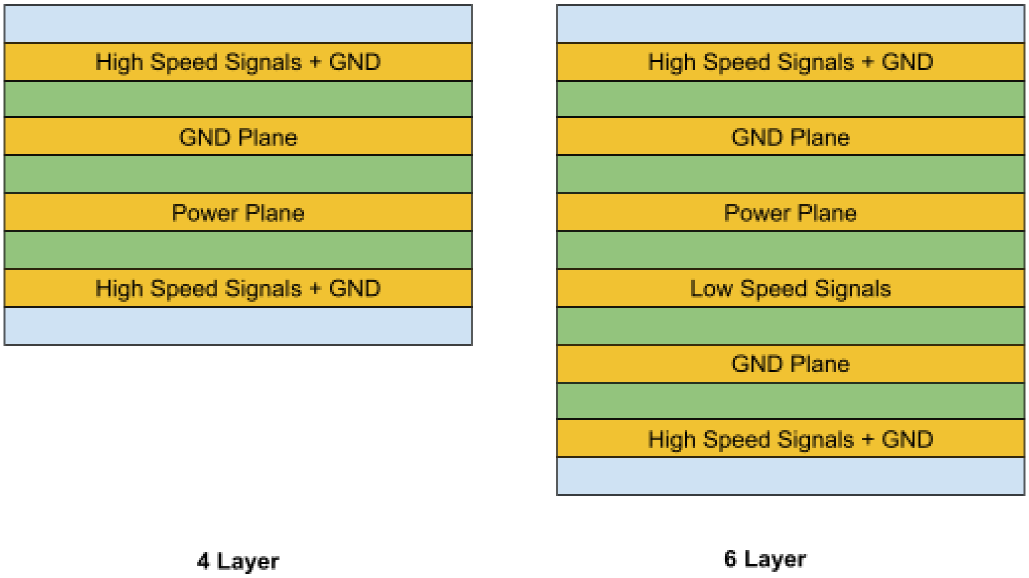
8.1.1 Material Types

There are a variety of materials to choose from when fabricating a PCB. The most common materials that vendors offer are FR-4, aluminum, Rogers, and Teflon. FR-4 stands for flame retardant. FR-4 is a common material used for PCB manufacturing. It is cheap, strong and can handle high temperatures. However it can have signal loss for high frequency applications. Aluminum core PCBs have very good thermal management and mechanical strength, however they are more expensive than FR-4. Typically aluminum core PCBs are used in designs that Prioritize heat dissipation. The Rogers PCB material provides very good performance for high frequency applications, and can be tailored to fit specific applications. However Rogers PCBs are very costly to manufacture compared with FR-4 or aluminum. Teflon PCBs provide good performance in high frequency applications. However they are more expensive to fabricate than FR-4 or Aluminum, and can take longer to fabricate. For the PCB used in the system, the material will likely be FR-4. This is because the frequency of any component in the system will remain under 25 MHz. FR-4 should be sufficient for dealing with these speeds. However if there is an issue with the frequency performance of the FR-4 material, a more expensive material can be used instead [20].

8.1.2 PCB Layers

The number of layers in a PCB is correlated closely to the fabrication cost. The more layers that are added to a PCB the more expensive the fabrication becomes. The proposed electrical systems will likely require between 4 to 6 layers. In addition to the ground plate, the number of electrical components in the design will likely require an additional 3 to 5 layers. ST recommends the stack-up in figure 8.1. for their STM32F4 PCBs [21].

Figure 8.1 STM Recommended PCB Stack-up



Although the MCU being used is the STM32G0, both it and the STM32F4 are from the main line product family. Therefore these stack-up guidelines could be used as an effective starting point for planning the layers of the PCB used in the system. Figure 8.1 may be modified for 3.3 V and 5 V power planes. The only component that requires 12 V is the CCD. This may be connected with an external wire rather than a PCB to avoid EMI issues on the PCB.

8.1.4 Component placement & Trace Routing

How components are placed and the traces between components are routed can have a large effect on the signal integrity and noise. The initial layout will attempt to isolate components that are more sensitive to noise. For example the IR photodiode will likely be placed further from noisier components such as the UART to USB, and other high frequency elements. All of the components will be placed as close together as possible to reduce the lengths of traces. However this must be balanced with thermal management and cross talk issues. The initial power trace widths will need to be able to handle 500 mA. However this will likely be reduced based on system level power consumption testing. Another option would be to use thinner traces, and then link several of them together with vias to carry more current. However this would require a more complex PCB design. When routing the traces, care needs to be taken to minimize the steepness of traces turn angles. This will ensure that the trace width remains constant, and the impedance of the trace doesn't change. This will reduce reflection on the trace [22]. In addition to this some manufacturers have problems maintaining trace integrity with traces that turn sharply. Additionally any component that has multiple traces, and time sensitive signals needs to have identical lengths to all the traces. This will ensure that the delays of each signal are uniform in their propagation delay and there are no timing violations. The traces between the MCU and the CCD along with the traces between the MCU and UART to USB componente are the two groups of signals with the most time sensitive aspects on the PCB.

8.1.5 PCB suppliers and tolerances

There are a variety of companies that supply PCBs. These suppliers range from smaller independent operations to large industrial companies with global reach. The PCBs will likely be sourced from one of the larger companies. As they offer a variety of materials and layer options. Information regarding customer service support and manufacturing times is often easier to find about larger suppliers. Two of the very commonly used PCB suppliers are JLCPCB and PCBWAY. They both offer many of the same features, and the prices and deliver dates are also similar. In terms of tolerances for trace width and spacing they are also very close. JLCPCB has a minimum trace width of 0.09 mm and PCBWAY has a minimum trace width of 0.1 mm. Both suppliers have approximately the same minimum drill sizes. Of around 0.2 mm. Although PCBWAY appears to have better tolerances. PCBWAY lists their tolerance at $\pm$0.08, whereas JLCPCB lists theirs as $+$0.13/-0.08. There are only two through hole components for this system, the CCD and the IR photodiode. The IR photodiode has a maximum pin width of 0.6 mm. Since the IR Photodiode has two flexible pins, its placement precision is less important. The CCD has two rows of through hole pins that are rigid. Based on the data sheet for the CCD, the pins are listed as having a maximum width of 0.62mm. There is also a tolerance of plus or minus 0.25mm for the spacing between the pins. In addition to this there is a lateral tolerance of 0.25mm between the two rows of pins. These must be accounted for to ensure that the CCD can be mounted on the PCB without issues. Therefore by adding 0.25mm to the drill size it will cover both tolerances cases. The drill size is then 0.62+0.25+0.1778 to give a drill size of 1.0478 mm. The 0.1778 is added to the drill size as a rule of thumb for tolerance issues [23]. The annular ring needs to be sufficiently large to deal with any soldering or tolerance issues. Therefore using the minimum land formula produces a pad size of 1.5478 for supported or 1.747 for unsupported [24]. Both PCBWAY and JLCPCB are capable of manufacturing PCBs with these sizes. The rest of the components on the PCB are surface mounted devices. All of these devices were provided with CAD files for the component footprint.

8.1.5 EAGLE

In this project, the team chose to design the PCB by using the Autodesk software Eagle. which provides many helpful tools that can make the PCB design more organized. The team used Eagle to design the electrical subsystem schematics and model several of the components. Eagle allows the team to design schematics and plan PCB Layouts. It provides a variety of premade components to select for the design, such as resistors, capacitors, inductors, and other more complicated components. It also provides a variety of different footprints for these components. While some components are not provided by Eagle, it allows the user to download the library from different online sources. The users can also create their own custom components and use it in the design. One of the Eagle tools is DRC which can define the errors in the PCB layout. Design rule check can find any connection errors in the PCB. This feature is very helpful to us as the team will be able to make sure that the design has no errors before any PCBs are ordered. There are other options for schematic design and PCB planning such as KiCAD, and Altium. KiCAD offers comparable features to Eagle, whereas Altium provides a design suite with a more advanced range of features. While Altium has many advanced features, it is quite expensive to purchase the software license. Therefore the choice in design software for the project was between Eagle and KiCAD. Since members of the team were more familiar with Eagle, it was chosen as the hardware design software.

8.2 PCB Power

Components on the PCB will be supplied power via the PCB traces. The amounts of power required can alter the physical requirements of the PCB or the number of PCBs needed. The following sections address these considerations

8.2.1 Using PCB VS Two PCBs:

There are a variety of components that need to be powered in the system. These include the CCD, sensors, and MCU. all of these components will be powered via the traces on the PCB. Supplying higher levels of current to a single PCB requires wider traces which will increase the overall cost of the PCB. alternatively more than one PCB could be used, however this may reduce the power efficiency, and can introduce design complexities and potential noise issues. The number of PCBs used in the system is an important decision.

8.2.2 Using one PCB:

Using A single PCB has some benefits. Cost is one of the most important reasons to consider. The project required a laser with a $600 price point along with many other expensive parts. Reducing the overall cost of the systems is important to remain within the budget restrictions of the project. While the right selection of electrical components can help with reducing the overall price of the system. Another important aspect with regard to cost is the PCB design.

Including all of the system’s components in one PCB might prove challenging, as in addition to the placement and routing issues, many components sharing the same power traces could require wider traces and a more complicated routing scheme for the power traces. This might require a PCB with more layers, which would increase the cost.

8.2.3 Using Two PCBs

The use of two PCBs in the system would likely provide more space for component placement and routing. However the cost of using two PCBs would likely be when compared to only using one. Another cost factor to consider for using two PCBs is the cost of additional power components such as regulators and AC to DC converters. Two PCBs would require at least two AC-DC adapters to power the components on each PCB. using two PCBs would likely decrease the design complexity as there would be fewer components per PCB. In addition to this the trace width of the PCB may be thinner as fewer components would be drawing current from the same traces. Another factor with using two PCBs is the number of jumped wires that are required for the two PCBs to communicate.

8.2.4 Number of PCBs Comparison

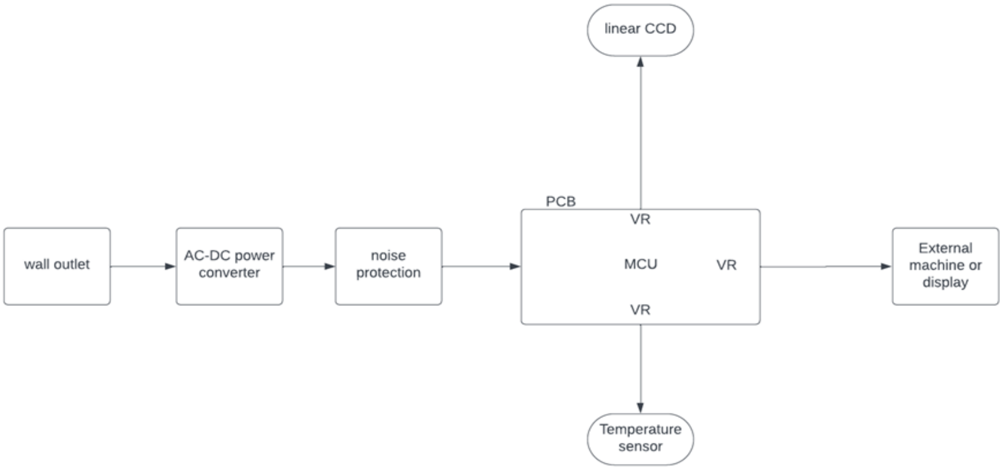
Using two PCBs in the system could provide advantages such as lowering the PCB design complexity, as there would be more space for component placement and routing. However, costs are likely to increase as in addition to two AC to DC converters, additional regulators would be required. As it is likely that the sensors would be located on one PCB, whereas the MCU and other components would be located on the second. Due to the level shifting requirements to properly interface the components, it is likely that both a 5 volt and 3.3 volt regulator would be required on each board. In addition to these costs there are the costs of having two separate PCBs manufactured and shipped. Using a single PCB may require thicker traces to handle the current requirements of various components. This would likely be most prevalent on any of the power traces for the PCB. The power component costs for the AC to DC converters and regulates will also be lower on a single PCB, as only a single set of each will be required. The fabrication costs of a single PCB would also likely be lower. However the traces on a single PCB might need to be closer together due to a lack of space. This could present EMI issues. The comparison of the number of PCBs can be seen in figure 8.1. The team opted to select a single PCB. A single PCB has lower costs regarding fabrication and components. The team believes that a trade off of costs for some EMI or complexity issues was warranted given the cost constraints of the system. The team also believes that it is likely that any issues of trace width or spacing can be mitigated. Careful placement of the components on the PCB may be able to reduce the amount of EMI that is experienced.

Table 8.1 Number of PCBs Comparison Table

PCB	1	2
Power consumption	Less (12v)	More (24v)
Cost	Less (50$)	More (100$)
Design	Complex(harder routing, more layers)	Simple(easier routing, fewer layers)
# Components	Less (x1)	More (x2)
Safety	Less(more/closer traces more EMI)	More(less/spaced traces less EMI)
AC adapters	1	2

The initial block diagram for the power path for the PCB can be seen in figure 8.2.

Figure 8.2 PCB Power Path Block Diagram



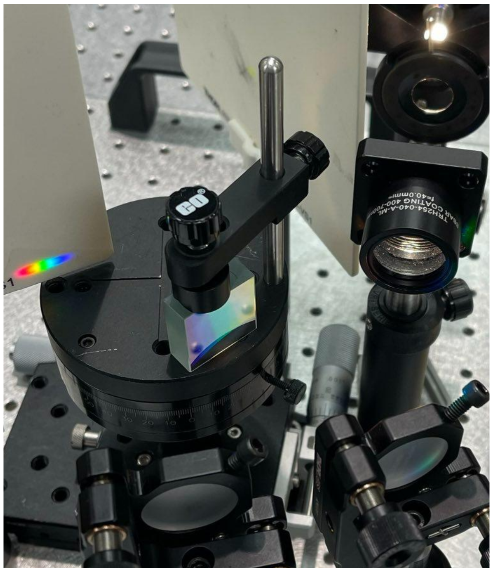
8.3 Laser and Spectrometer Design and Fabrication

To create the plasma for the LIBS system the laser will have to be placed at a certain angle and distance from the sample in order to achieve that goal. The collector for the light from the plasma will be collected and sent to a mirror which goes to the grating which goes to a mirror and is then received by the CMOS sensor. The sample area will be completely enclosed to ensure laser safety for all participants. In figure 8.3 the team shows the results of the laser firing and hitting the surface of the rock and creating plasma.

Figure 8.3 Results of Plasma Excitation of Rock Sample

This result is ideal for the creation of the plasma, but the blast of the plasma can be damaging to the laser system itself so the team intends to modify it to extend the focal point of the laser. The team will attempt to achieve this by using a collimating lens and a focal lens to increase the distance as well as maintain the ability to create plasma.

Figure 8.4 Spectrometer prototype



In figure 8.4 the team used the two concave mirrors purchased from Edmund optics and Thor labs, along with the diffraction grating from Edmund optics to build a prototype of the spectrometer that will be built. This prototype was built, for the senior design final demo for fall 2023, to demonstrate the spectral resolution and wavelength range of the system. What can be observed in figure 8.4 is a high resolution spectral pattern of the entire visible spectrum. This shows that the correct mirrors and diffraction grating were selected for the system. Now these components will be placed at the calculated distances in a case.

9. System Testing

This section provides an overview of the testing of components and structures. Results from testing the laser on a dichroic mirror are presented, along with a number of electrical components. The response time of the IR Photodiode is presented, along with the frequency response MCU GPIO. A future test plan is also presented to be carried out over the winter break and into the Spring semester of 2024.

9.1 Laser/Optics Component Testing

The laser and optics the team had purchased needed to be tested working together. The initial optical design incorporated a dichroic mirror into the system. This design idea was tested and because of the results the design was changed to better suit the needs of the project.

9.1.1 Laser Induced Damage Threshold

In order to make a lens system to properly focus the; the mirrors and lenses must be able to withstand the high energy pulses so as to not damage the system and impact sample readings. The laser was tested to determine its real focal point. The focal point is where the parallel light rays converge and cross one another. For the purposes of the system this is very important as this is where the laser has the greatest intensity and will make the most plasma. The focal point is measured to be 50 mm from the optical aperture of the lens.

For part of the optical design, a dichroic mirror will be incorporated. A dichroic mirror, otherwise known as a dichroic reflector, dual-band mirror, or dual-wavelength mirror, has unique transmission and reflection characteristics at two distinct wavelengths. These types of mirrors are commonly used in broadband for bouncing back certain wavelengths (such as ultraviolet) but not infrared as this can cause damage to some components due to the heat created. In the design, the intention is to use the mirror to reflect the light to the sample and have some of the light bounce back through the mirror. The mirror would be placed one inch away from the aperture of the laser beam so that the focal point (the area that would cause the most damage to the lens) would be reflected to the location of the sample. The team communicated with Edmund Optic and gave them the specifications of the laser and the general idea of the application of its intended use. They determined density of the energy, which is expressed in the total amount of power delivered per unit area, this is in Joules to a square centimeter, to be 7.13 J/cm^2. This was within the Laser Induced Damage Threshold (LIDT) limit of one of their dichroic mirrors, the “19.05 mm Nd:YAG laser mirror”, which is 57.85 J/cm^2. The specifications for the mirror they suggested is listed in table 9.1.

Table 9.1 Edmund Optic 19.05mm Nd:YAG laser mirror Specifications

Surface Quality:	10-5	Type:	Laser Mirror
Parallelism (arcmin):	<5	**Clear Aperture (%):**	90
Back Surface:	Commercial Polish	**Reflection at DWL (%):**	99.9
Coating Specification:	Rabs >99.9% @ 1064 nm	**Wavelength Range (nm):**	1046 – 1074
Surface Flatness (P-V):	λ/10	**Coating Type:**	Dielectric
Coating:	Laser Mirror (1064 nm)	**Design Wavelength DWL (nm):**	1064
Diameter (mm):	19.05 +0.00/-0.13	**Thickness (mm):**	9.53 ±0.25
Angle of Incidence (°):	0	**Substrate:**	Fused Silica
Damage Threshold, By Design:	57.85 J/cm^2	@ 1064 nm	@ 20 ns, 20 Hz

Figure 9.1 Dichroic Mirror Test Damage

This mirror appeared to meet the design criteria, therefore it was ordered. Upon receiving the mirror, it was tested at a distance of one inch away from the laser aperture. The mirror was reflecting the 1064 nm wavelength. The reflected beam was also making plasma which was great. However, the mirror appeared to be taking damage on the surfaces. This was not optimal as the laser was destroying the mirror and therefore the design would not be implementable. The team reached back out to Edmund Optic to ask why this happened to the dichroic mirror after they had assured us it would work. Figure 9.1 shows the damaged dichroic mirror.

Currently there has been no response from Edmund Optic. Additional calculations are performed for the Peak Power of the pulse. This is done by dividing the energy (J) by the Pulse Width (s). The Peak Power is;

$$\frac{0.3\,J}{8\bullet 10^{-9}} = 37.5 \bullet 10^{6}\text{ W.}$$

This is a pretty impressive peak power, then the Peak Power Density is calculated. This is accomplished by dividing the Energy per Pulse (J) by the Pulse Width and the Beam Area (cm^2). The Peak Power Density is;

$$\frac{0.3J}{8\bullet 10^{-9}\bullet 0.05cm^{2}} = 7.5 \bullet 10^{8}\text{W}/cm^{2}.$$

9.2 Electrical Component Testing

The testing for the various electrical subsystems can be seen in the following sections. This includes the testing methodology for each component. The expected results based on data sheets, and true results from testing. Video footage of select components and testing can be found in the appendix.

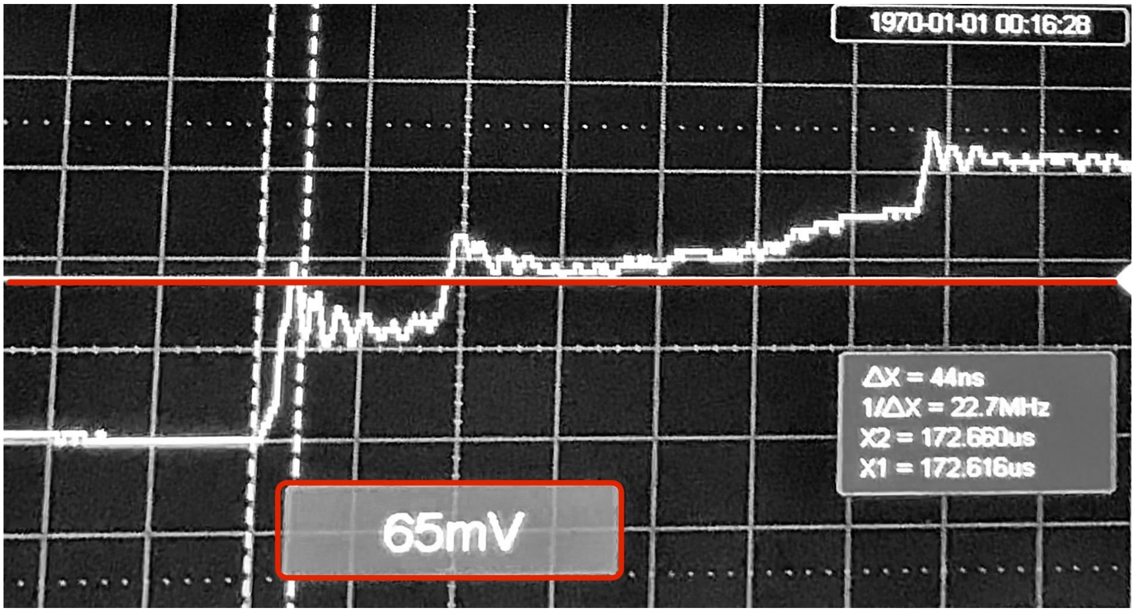
9.2.1 IR Photo Diode Testing

Detecting the laser blast from the laser is critical to ensure that the MCU can quickly drive the CCD after the laser blast. This will allow the CCD to capture the spectral results. To detect the laser blast the IR photodiode needs to have sufficient speed to detect the laser blast. The datasheet for the IR photodiode states that it should have a rise time of around 5 ns. This assumes a reverse bias voltage of 20 V, a load of 50 Ohms and a 850 nm wavelength of light. However applying a 20V reverse bias to the IR photo diode would require additional circuitry. This would raise the complexity of the design which could make the PCB design more difficult. Additionally it would drive up the costs.

First the diode was tested without any external biasing to determine its response speed. For the initial component response time testing. A 100MHz oscilloscope was used to track the time it would take the IR photodiode to move from its low voltage state to a higher voltage state. The diode was placed in a location where no direct sources of light could influence it. The IR diode was connected to the oscilloscope with a 1x probe. The oscilloscope was set to single trigger mode, and the triggering level was set slightly above the diode's idle voltage level. The

IR photo diode was pointed towards a lighter at a distance of approximately 75 cm. The lighter was ignited and the results were measured on the oscilloscope. The results of this test can be seen in figure 9.2. Which is the output of the oscilloscope's single shot measurement.

Figure 9.2 IR Photodiode Response Time



The response time varied based on the desired output voltage level. The more time that passed the higher the diode's output voltage would increase up to a point. From 0 mV to 65 mV took around 45 ns. From 0 mV to around 95 mV took around 210 ns. Ideally the MCU would trigger when the 65 mV output is detected. Based on the available information for contemporary LIBS systems, the delay before triggering the gate of the light capturing element can be in the range of hundreds to thousands of nanoseconds [25a]. Therefore the Photodiode has sufficient speed to capture the laser excitation event.

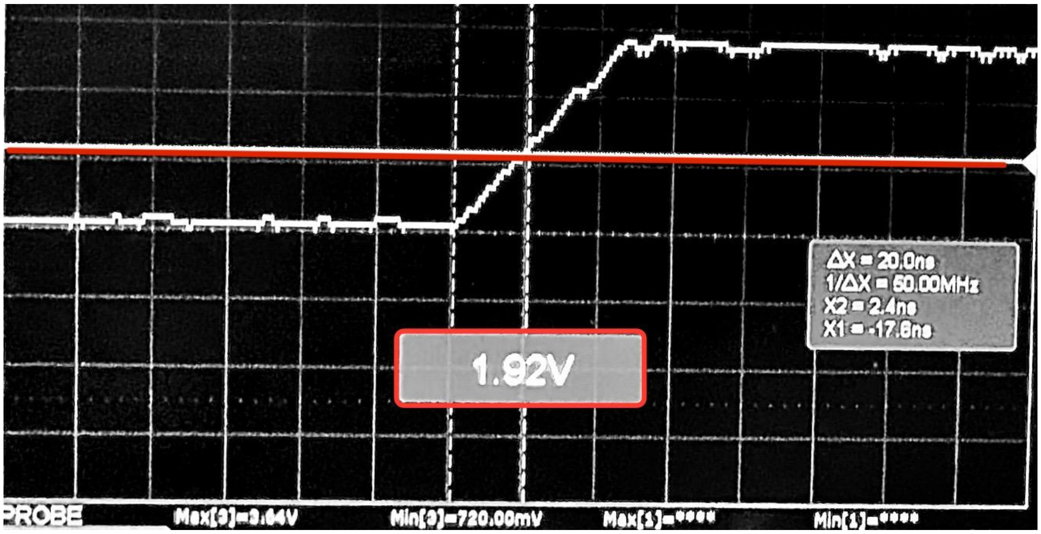
9.2.3 Operational Amplifier Testing

Many of the electrical components in the project use different voltage logic levels, or are analog in nature. For all of the components to communicate, translating logic levels is required. Due to the speed of the components in the system, a fast op amp is required to ensure that all of the timing constraints can be met.

The datasheet for the LMH6658MAX lists the slew rate at 420 volts per microsecond. The large signal step response from -3.5 volts to 3.5 volts is approximately 20 ns. The data sheet lists that test circuit had a large signal gain of 1, a 100 ohm load, and was powered a $\pm\ 5V$.

To test the response time of the LMH6658MAX, the opamp was connected to the bread board. It was supplied with 3.3 V and 0 V to its positive and negative power rains respectively. The inverting input of the opamp was connected to ground. The non-inverting input was connected to a switch that was either connected to 3.3 V or was left floating. A 100 MHz oscilloscope was used in single triggering mode to measure the op amps output. The output of the op amp was connected to a 1x probe. The triggering level of the opamp was set to 1.92 V which is above the expected GPIO logic high. The timing results of the op amps output can be seen in figure 9.3.

Figure 9.3 Operational Amplifier Response Time



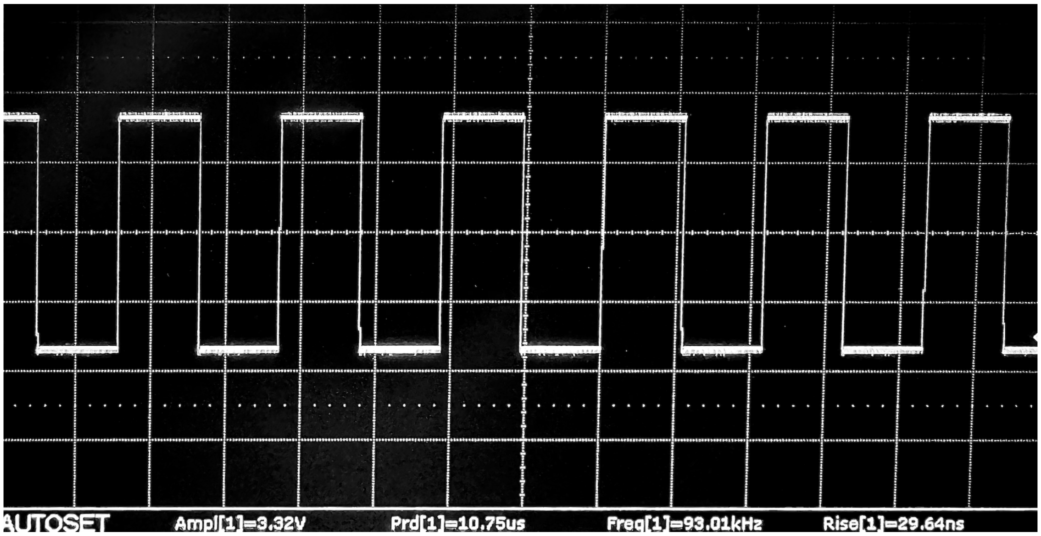
The output of the opamp rose from 0 volts to 1.92 volts in around 20 ns. This is well above what is required in terms of speed. The CCD can only run at a maximum frequency of 20 MHz. Based on this the chosen opamp should meet the speed requirements needed to drive the CCD and convert logic levels for the IR photodiode.

9.2.5 MCU GPIO Speed

The MCU controls all of the external peripherals. This is either achieved via a communication protocol, or manually via its GPIO pins. Many of the processes used in the system require high speed interaction from the MCU. The MCU needs GPIO pins that are capable of high speed interactions. Based on the information provided in the data sheet for the MCU, the GPIO pins should be capable of between 2 to 60 MHz. The speed capabilities depend on the configuration of the I/O's speed register, the voltage source of the VDDIO pin, and the capacitive load on the pin.

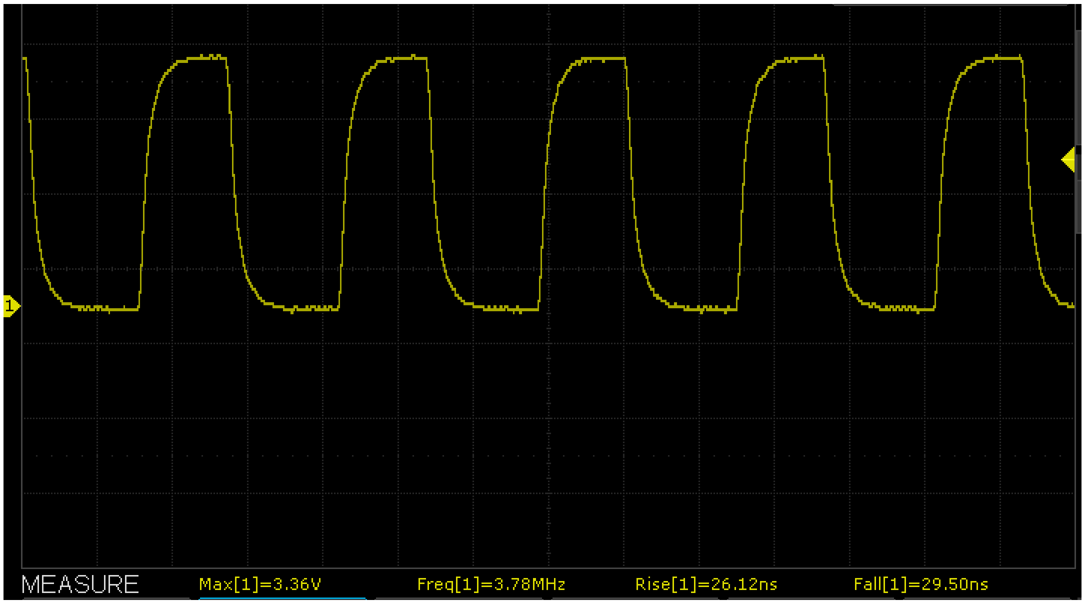
To test the GPIO speed of the MCU, a dev board was programmed to toggle one of its GPIO pins, which was measured with an oscilloscope. The NUCLEO-G0B1RE was used for testing. The dev board was powered via USB. Pin P9 and GND were connected to an oscilloscope via a 100 MHz probe. The MCU was programmed using the STM32CUBE IDE. The system clock and the all purpose bus peripheral clock were set to 64 MHz. The HAL API layer was used to set Pin P9 to output, and set the speed of that port to very high. The HAL API layer was then used to toggle pin P9 on and off in the main loop of the program. The oscilloscope was used to capture the output of pin P9, the results of this can be seen in figure 9.4.

Figure 9.4 MCU GPIO Output Frequency HAL Control



The oscilloscope measured an output signal with a frequency of 93.01 KHz. This is well below what the GPIO should be capable of. To troubleshoot this issue, the oscilloscope was first checked to ensure that it was working correctly. A function generator was connected to the oscilloscope. The oscilloscope correctly measured the frequency that was produced by the function generator. Since the function generator was functioning correctly, the issue must be connected with the dev board. Examining the waveform in figure 9.4. There are no distortions in the waveform. Based on this the low speed does not appear to be due to a capacitive load on the pin, or an issue with the rise time. The Debugger provided in the STM32CUBE IDE was used to check that the expected registers were set to the correct values. No faults were found in any of the registers, they all contained the expected values for the clock speed or GPIO port speed. However stepping through the program manually did reveal that using the HAL API layer to toggle pin P9 seemed to require many steps. API layers can add portability to code, however this can be at the cost of speed as it is much further from the bare metal of the controller. Therefore the next attempt to fix this issue was to manually set and reset the bits that control the output of pin P9. The HAL function used to toggle the GPIO pin was removed and replaced with code that manually set and reset the output of pin P9. The dev board was then programmed with the new code. The oscilloscope was again used to measure the output of pin P9. The results of this can be seen in figure 9.5.

Figure 9.5 MCU GPIO Output Frequency Register Control



The output frequency of the GPIO is now close to 3.8 MHz. The HAL API layer was causing significant delays in the GPIO output. While this result is much faster than the previous one, this is still on the low end of the MCU's described capabilities. This newly measured result is above the 1 MHz speed listed as the typical frequency used to drive the CCD. However higher speeds may be beneficial for greater spectral intensity. There are some slight distortions in the waveform, however the overall wave still resembles a square wave. Rise and fall times are 26 and 30 ns respectively. This seems to indicate that there is still likely room for improvements in the controllers GPIO speed. There may be additional changes that can be made to the MCU's code which could increase speed. Or on the final PCB it may be possible to reduce the capacitance of the traces that connect the MCU to the PCB. If much higher speeds are needed it may be possible to replace the MCU with a much faster model with minor changes to the PCB. However, for the initial implementation of the system, this level of speed should be sufficient to drive the CCD. The HAL API layer could be used to initialize or control systems that are not critical time. However when speed is of the essence, it is better to disregard the API and work closer to the register level for code.

9.3 Future Project Planning

The team plans for production of the prototype over the winter break and into SD2. This is the general path forward, however this is contingent on the results of testing and building the prototype. This plan is subject to change based on unforeseen problems or issues.

9.3.1 Future Electrical Testing Plan

For the remaining electrical components, testing will be done in a sequestered fashion. This will be used to verify that each component can achieve the specifications that are listed in its datasheet. This will ensure that any components that fail to meet expectations can be replaced as soon as possible. Following individual component testing, testing of subsystems will be done. Initial subsystem testing will be conducted on the bread board, and will be used to ensure that the designed subsystems can achieve their required objectives. This testing will help find any design deficiencies. This will allow for any refinements or alterations to be made in the design to address any issues that may occur. Next system level testing will occur. In system level testing all of the subsystems will be connected and an overall test of the electrical systems will be performed. This testing is done to identify any issues that may occur when integrating all of the electrical subsystems. PCB testing will also be done. PCB testing may or may not be monolithic. Subsystem PCBs may or may not be created and tested in addition to the final PCB. Many factors affect this such as time, cost, breadboard results, and PCB complexity. PCB testing will involve continuity, reflection, noise, and crosstalk testing. The tolerances of the IC pads, and mounting points will also be tested, and any required modifications to the PCB will be made. For the process of testing, the expected conditions of the final system will be replicated as best as possible in the testing environments. This includes things such as ambient light levels, sensor distances from measured objects, and electrical noise. It should be noted that some of the system testing of the optical and electrical systems will overlap. This is because to test some of the electrical components, it will require optical components and vice versa. The exact timing of this interconnected testing can be difficult to predict, however the team will communicate as the project progresses to find the appropriate times for these tests to occur.

9.3.2 Software Testing Plan

The software for the project is highly interconnected with the hardware. Therefore software testing will occur in tandem with hardware testing. However some portions of the software may be tested independently such as the software on the external device to organize and display spectral data. In these cases, data sets similar to the expected data sets will be used to confirm the accuracy and stability of the software, and to detect errors or edge cases.

9.3.3 System Integration Plan

After individual system testing has been completed the electrical and optical systems will be integrated to create the overall system. This overall integration will involve mounting all of the electrical systems, optical systems, and sample containment unit on a two tiered mobile platform. The arrangement of the systems will be decided based on laser safety constraints, optical alignment options, physical dimensions, and degree of electromagnetic interference to sensitive components. The preliminary configuration will likely have the sample containment unit well below eye level on the lower level. The apertures for the primary laser and the spectroscopy systems will either be located directly in the containment unit, or they will have their own enclosures that are linked to the containment unit. The process of alignment of the laser system and spectroscopy systems is expected to be difficult and will require several attempts. This will depend on the safety factor, room for optical alignment, and the physical space available. The alignment of the laser into the focusing system is critical, because if not aligned correctly it will destroy the optics and or the laser itself. The laser may not be able to focus properly due to the alignment and therefore can not create plasm. The power supply for the laser, the spectroscopy unit and electrical systems will likely be located on the upper level of the platform. The primary systems that need to be linked are the optical systems for capturing and directing the spectra, and the spectral emission measurement subsystem. This will involve aligning the optics to direct the emission spectra to the CCD. The primary laser needs to be incorporated into the containment unit in such that the laser blast is focused and directed at the specimen. The Laser Blast Detection Subsystem needs to be integrated with the laser emission system. This may require optics to direct the light from the laser blast to the IR photodiode, however this will be determined based on the testing process. All of the electrical systems will need to be secured to ensure that minor vibrations or bumps don't disrupt the PCB or any of its external connections. Any external power cords or communication cables will either need to be securely fastened to the cart, or are free to easily break away. This will ensure that any unexpected tugs on the cables won't damage or destroy the PCB or its external connectors. After all of the system components are connected an initial test will be performed. This test will help determine if there are any changes that need to be made to the physical layout, or to specific systems. Any required structural or system changes will be made for the total system to operate effectively. Following any changes the system will be tested again to confirm any design changes have had the desired effects. Although this is the initial plan, there will likely be changes made based on the results of subsystem and system level testing.

10. Administrative

The team aspires to stay under $4000 spread over two semesters as this will stay within the team’s financial budget. The team finances are due to Benjamin Logan’s employment at ASRC Federal which will reimburse up to a certain point as this is for his professional development for his degree. Benjamin Logan must make the purchases and keep his records to show as proof at the end of Senior Design 1 and 2. The current budget expectations can be seen in figure 10.1

Table 10.1 Budget chart

Part	**Cost range**	**Quantity**
Collimating lens	$20-$80	1
Focusing Lenses	$25-$150	3-6
Q-switched Nd:YAG laser	$300-$1000	1
Mirror(s)	$50-$150	2
Dichroic Mirror	$125-$250	1
Fiber cable	$50-$350	2
Transmission Gratings	$50-$100	2
Diffraction Grating(s)	$25-$130	2
Wood Platform	$10-$50	1
AC-DC convertor (Power Supply)	$10-$50	1-2
Rock Sample Kit	$10-30	1
DC-DC converter	$2-$25	1
MCU / FPGA	$1-$70	3-4
PCB(s)	$50-$150	1-2
Total Cost	**$1022-$3805**	

10.2 Milestones

Milestones are used in a project to measure the progress to access if the development will reach its stated goals. Tables 10.2 and 10.3 lists the projected dates to achieve certain tasks for the project in senior design one and senior design two.

Table 10.2 Senior Design 1 Milestones

Milestone	**Date**
Form Group	08-24-23
Submit Divide and Conquer	9-15-23
Finalize goals	9-15-23
Determination of requirements for critical photonics components and subsystems for Senior Design 1 (PSE)	9-28-23
Midterm Optics Demo (PSE)	10-12-23
60 Page Draft Due	10-27-23
120 Page Final Draft	11-27-23
3 min ECE video demo due	11-27-23
Final Senior Design 1 Demo	11-30-23
120 Final Report	12-05-23

Table 10.3 Senior Design 2 Milestones

Milestone	**Date**
Start of Senior Design 2	01-08-24
PCB Design (EE)	02-02-24
Prototype Ready	04-12-24
Demo Day	04-26-24

The Milestones will become more technically specific as the team’s knowledge increases due to research in the fields and as the project progresses further into testing and designing different components of the system.

The work distribution for the team members can be seen in table 10.4. This table outlines each of the team members' area of primary and secondary focus of the project. This work distribution was agreed upon by all of the team members.

Table 10.4 of work distribution

Task	**Primary**	**Secondary**
Power converter (AC-DC)	Faisal	Liam
Voltage Stabilization	Faisal	Liam
Noise Protection	Faisal	Liam
Lens Design for LIBS	Benjamin	Stephen
Collimating Optic	Benjamin	Stephen
LIBS setup	Stephen	Benjamin
Spectrometer	Stephen	Benjamin
MCU / FPGA	Liam	Faisal
Sensor	Liam	Faisal
LED(s)	Liam	Faisal
Software	Liam	Faisal

The team hereby declares that we have not copied more than 7 pages from the large language model (LLM) in this document.

11.Conclusion

The SpectraLaser Elemental Analyser prototype, originally code named Rockblaster, is a LIBS system designed for the analysis of non-organic samples. The system has been successfully designed with the intention that it is capable of accomplishing the following. Consistently generate a plasma plume, produce measurement results with less than 10% variance over five samples, and identify a known alloy or object to within 70% accuracy of its expected spectral emission. The system is controlled digitally. The system outputs results in under a minute.

The project has faced a number of constraints and challenges. These include: safety, supplier limitations, cost, time, and a lack of detailed information. However, the team has been able to navigate these challenges and succeed in designing the system. The team has begun the testing stage of the project, and expects to move into the system integration phase following any refinements that are needed.

The SpectraLaser Elemental Analyser is designed to be a cost-effective alternative to the highly expensive traditional LIBS systems that are currently on the market. It has the potential to be used in a variety of applications, which include: hazardous environments, extraterrestrial exploration, and educational institutions.

The project team is currently working on testing the optical and electrical components of the system. The team expected to complete this testing phase in senior design two. Then the team expected to focus on systems integration and PCB design and aspects of PCB fabrication.

The SpectraLaser Elemental Analyser is a promising new design that has the potential to offer a low cost solution to analyze non-organic samples.

References

[1] L. Radziemski and D. Cremers, “A brief history of laser-induced breakdown spectroscopy: From the concept of atoms to LIBS 2012,” ISO4, vol. 87, pp. 3–10, Sep, 2013. Accessed: Sep, 10, 2023, doi: https://doi.org/10.1016/j.sab.2013.05.013. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S058485471300116X

[2] Scrap detector, by M. Potzschke et al. (1990, Sep. 24). U.S. Patent US5042947A [Online]. Available: https://patents.google.com/patent/US5042947

[3] Ciucci A, Corsi M, Palleschi V, Rastelli S, Salvetti A, Tognoni E. New Procedure for Quantitative Elemental Analysis by Laser-Induced Plasma Spectroscopy. Applied Spectroscopy. 1999;53(8):960-964. doi:10.1366/0003702991947612

[4] NASA. “Chem Cam.” mars.nasa.gov. https://mars.nasa.gov/msl/spacecraft/instruments/chemcam/ (accessed Sep. 10, 2023).

[5] P. Hsu, et al., “Sensitivity, stability, and precision of quantitative Ns-LIBS-based fuel-air-ratio measurements for methane-air flames at 1-11 bar” applied optics vol.55, no.28 pp. 8042-8048 Oct. 2016

[6] Xilinx. Artix-7 FPGAs Data Sheet:DC and AC Switching Characteristics DS181 (2022). Accessed: Sep. 12, 2023. [Online]. Available: https://docs.xilinx.com/v/u/en-US/ds181_Artix_7_Data_Sheet

[7] Lattice semiconductors. ispMACH 4000V/B/C/Z Family, FPGA-DS-02091-23.6. (2021). Accessed: Sep. 12, 2023. [Online]. Available: https://www.latticesemi.com/en/Products/FPGAandCPLD/ispMACH4000VZ#_C724D0372C7549C09963386B6F1B616E

[8] Cadence PCB Solutions. “*Comparing UART vs SPI speed*. Cadence PCB Design & analysis.” pcb.cadence.com. https://resources.pcb.cadence.com/blog/2022-comparing-uart-vs-spi-speed (accessed Sep. 12, 2023).

[9] Teledyne. “How a Charge Coupled Device(CCD) Image Sensor works.” teledyneimaging.com. https://www.teledyneimaging.com/media/1300/2020-01-22_e2v_how-a-charge-coupled-device-works_web.pdf. (accessed Sep. 12, 2023).

[10] Canon. “CMOS Sensors.” https://global.canon/. https://global.canon/en/technology/s_labo/light/003/05.html (accessed Sep. 12, 2023).

[11] Ti. Ultrasonic Sensing Basics, SLAA907D. (2021). Accessed: Sep. 12, 20203. [Online]. Available: https://www.ti.com/lit/an/slaa907d/slaa907d.pdf?ts=1696838307487&ref_url=https%253A%252F%252Fwww.ti.com%252Ftool%252FBOOSTXL-PGA460%253Flitpdf%253D

[12] Britannica. “liquid crystal display - Supertwisted Nematic, LCDs, Technology.” britannica.com. https://www.britannica.com/technology/liquid-crystal-display/Supertwisted-nematic-displays (accessed Sep. 12, 2023).

[13] Park, K.C. (2021). Pixel Circuits for OLED Displays. In: Kang, I.B., Han, C.W., Jeong, J.K. (eds) Advanced Display Technology. Series in Display Science and Technology. Springer, Singapore. https://doi.org/10.1007/978-981-33-6582-7_8

[14] Omega. “Thermocouple Response Time.” omega.com. https://www.omega.com/en-us/resources/thermocouples-response-time (accessed Sep. 12, 2023).

[15] Geusic, J. E., Marcos, H. M., and Van Uitert, L. G., “Laser Oscillations in Nd-DOPED Yttrium Aluminum, Yttrium Gallium and Gadolinium Garnets”, Applied Physics Letters, vol. 4, no. 10, pp. 182–184, 1964. doi:10.1063/1.1753928.

[16] Theerthagiri, J., Karuppasamy, K., Lee, S.J. et al. Fundamentals and comprehensive insights on pulsed laser synthesis of advanced materials for diverse photo- and electrocatalytic applications. Light Sci Appl 11, 250 (2022). https://doi.org/10.1038/s41377-022-00904-7

[17] Jarju, Jenni & Figueiredo, Marta & Kolen'ko, Yury V.. (2021). Electrocatalysis using nanomaterials. 10.1016/B978-0-12-820055-1.00002-2.

[18] D. Johnston “Intelligence tests that LLMs fail and why”. Linkedin.com. https://www.linkedin.com/pulse/intelligence-tests-llms-fail-why-david-johnston (accessed Oct. 29, 2023).

[19] M. Novak “Lawyer Uses ChatGPT In Federal Court And It Goes Horribly Wrong”. forbes.com. https://www.forbes.com/sites/mattnovak/2023/05/27/lawyer-uses-chatgpt-in-federal-court-and-it-goes-horribly-wrong/?sh=5c9640193494 (accessed Oct. 29, 2023).

[20] M.Khan. “The Ultimate Guide to PCB Materials: Choosing the Best Fit for Your Electronics Project.”Wevolver. https://www.wevolver.com/article/the-ultimate-guide-to-pcb-materials-choosing-the-best-fit-for-your-electronics-project (accessed Nov. 23, 2023).

[21] ST. Getting started with STM32F4xxxx MCU hardware development, AN4488 Rev7. (2018) Accessed: Nov 23 2023 [Online]. Available: https://www.st.com/resource/en/application_note/an4488-getting-started-with-stm32f4xxxx-mcu-hardware-development-stmicroelectronics.pdf

[22] E. Robledo. “Everything You Need to Know About Trace Width” autodesk.com. https://www.autodesk.com/products/fusion-360/blog/trace-width/ (accessed Nov. 24, 2023).

[23] “5 Tips for Specifying PCB Hole Size Tolerance” altium.com. https://resources.altium.com/p/5-tips-for-specifying-pcb-hole-size-tolerance (accessed Nov. 24, 2023).

[24] “PCB Minimum Annular Ring: Formula and Guidelines” pcb.cadence.com. https://resources.pcb.cadence.com/blog/2023-pcb-minimum-annular-ring-formula-and-guidelines (accessed Nov. 24, 2023).

[25] E. Grifoni et all, “Extracting Time-Resolved Information from Time-Integrated Laser-Induced Breakdown Spectra,” Journal of Spectroscopy, vol. 2014, Dec, 2014, Art. no. 849310.

[26] S. Wayne. “Active Low Pass Filter.” electronics-tutorials.ws. https://www.electronics-tutorials.ws/filter/filter_5.html (accessed Sep. 30, 2023).

[27] Keystone Compliance. “IEC 61010 Product Safety Testing of Laboratory and Scientific Electrical Equipment.” keystonecompliance.com. https://keystonecompliance.com/iec-61010/ (accessed Oct. 27, 2023).

[28] Azo materials. “An Introduction to a Spectrometer - Diffraction Grating.” azom.com. https://www.azom.com/article.aspx?ArticleID=13368 (accessed Sep. 04, 2023).

[29] Edmund Optics. “All About Diffraction Gratings.” edmundoptics.com. https://www.edmundoptics.com/knowledge-center/application-notes/optics/all-about-diffraction-gratings/#:~:text=The%20blaze%20angle%20describes%20the,also%20called%20the%20Littrow%20configuration (accessed Sep.04, 2023).

[30] Mks Newport. “Diffraction Grating Physics.” newport.com. https://www.newport.com/n/diffraction-grating-physics (accessed Sep. 09, 2023).

[31] Mks Newport. “Guidelines for Specifying Diffraction Gratings.” newport.com. https://www.newport.com/n/guidelines-specifying-gratings (accessed Sep 09, 2023).

[32] ThorLabs. “Focus or Collimate Light with an Off-Axis Parabolic Mirror.” thorlabs.com. https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=14193 (accessed Sep. 12, 2023).

[33] AZO Materials. “An Introduction to a Spectrometer - The Optical Bench.” azom.com. https://www.azom.com/article.aspx?ArticleID=13367 (accessed Sep. 12, 2023).

[34] Lighttrans. Czerny-Turner Setup, GRT.0030. (2021). Accessed: Oct. 02, 2023. [Online]. Available: https://www.lighttrans.com/fileadmin/shared/UseCases/Application_UC_Czerny-Turner%20Setup.pdf

[35] Edmund Optics. “Metallic Mirror Coatings.” edmundoptics.com. https://www.edmundoptics.com/knowledge-center/application-notes/optics/metallic-mirror-coatings/ (accessed Oct. 02, 2023).

[36] ThorLabs. “Concave Mirrors.” thorlabs.com. https://www.thorlabs.com/navigation.cfm?guide_id=2183&gclid=CjwKCAjw1t2pBhAFEiwA_-A-NBasf-u1rCoJg4-KKZba5OxuUzGuQfXTp-iNJRj4TQLykNapfgUXkhoCLI8QAvD_BwE (accessed Oct. 05, 2023).

[37] Edmund Optics. “System Throughput, f/#, and Numerical Aperture.” edmundoptics.com. https://www.edmundoptics.com/knowledge-center/application-notes/imaging/lens-iris-aperture-setting/ (accessed Oct. 11, 2023).

[38] Ocean Insight. “Why Collimating Lenses are So Important.” oceaninsight.com. https://www.oceaninsight.com/globalassets/catalog-blocks-and-images/hints--tips/why-collimating-lenses-are-so-important.pdf (accessed Oct. 11, 2023).

[39] Shuster, J.R., Gershman, D.J., Dorelli, J.C. *et al.* Structures in the terms of the Vlasov equation observed at Earth’s magnetopause. *Nat. Phys.* 17, 1056–1065 (2021). https://doi.org/10.1038/s41567-021-01280-6

[40] Ratti, M., Naddeo, J. J., Griepenburg, J. C., O'Malley, S. M., Bubb, D. M., & Klein, E. A. (2017). Production of Metal Nanoparticles by Pulsed Laser-ablation in Liquids: A Tool for Studying the Antibacterial Properties of Nanoparticles. *Journal of visualized experiments : JoVE*, (124), 55416. https://doi.org/10.3791/55416

[41] YouTube. (2016, April 13). *Switching voltage regulator (Buck, boost) introduction | AO #18*. YouTube. https://www.youtube.com/watch?v=CPvA-uS0dNY

[42] TI. Linear & Low-dropout (LDO) regulators. TI.com. (n.d.). https://www.ti.com/power-management/linear-regulators-ldo/overview.html

[43] What is a switching voltage regulator? - technical articles. All About Circuits. (n.d.). https://www.allaboutcircuits.com/technical-articles/what-is-a-switching-voltage-regulator

[44] Enos, D. G. (2014, September 1). *Lead-acid batteries and advanced lead-carbon batteries.* Lead-Acid Batteries and Advanced Lead-Carbon Batteries. (Book) | OSTI.GOV. https://www.osti.gov/servlets/purl/1502636#:~:text=The%20lead%2Dacid%20battery%20represents,%2C%20grid%2Dscale%20power%20systems.

[45] Enos, D. G. (2014, September 1). *Lead-acid batteries and advanced lead-carbon batteries.* Lead-Acid Batteries and Advanced Lead-Carbon Batteries. (Book) | OSTI.GOV. https://www.osti.gov/servlets/purl/1502636#:~:text=The%20lead%2Dacid%20battery%20represents,%2C%20grid%2Dscale%20power%20systems.

[46] Battery University. (2021, December 3). *BU-202: New lead acid systems*. https://batteryuniversity.com/article/bu-202-new-lead-acid-systems#:~:text=Unlike%20regular%20lead%20acid%2C%20lead,resembling%20that%20of%20a%20supercapacitor.

[47] *Lithium battery advantages*. RELiON. (n.d.). https://www.relionbattery.com/resource-center/technology/why-choose-lithium

[48] Lead Carbon Battery - Victron Energy. (n.d.). https://www.victronenergy.com/upload/documents/Datasheet-Lead-carbon-battery-EN.pdf

[49] *Part 2: How do switching power supplies work? A historical overview of Revolutionary Power Supply Technologies*. Learn about Technology with TDK. (n.d.). https://www.tdk.com/en/tech-mag/power/02

[50] *AC adapter*. AC adapter - Energy Education. (n.d.). https://energyeducation.ca/encyclopedia/AC_adapter#:~:text=A%20simple%20AC%20adapter%20consists,for%20the%20device%20being%20powered.

[51] National Laser. “Laser Classifications and Safety.” nationallaser.com. https://nationallaser.com/laser-classification-safety/ (11. 6, 2023).

[52] Light Collection and Optical System Throughput

https://www.newport.com/t/light-collection-and-systems-throughput

[53] Liu D, Hennelly BM. Improved Wavelength Calibration by Modeling the Spectrometer. *Applied Spectroscopy*. 2022;76(11):1283-1299. doi:10.1177/00037028221111796

[54] Zhang Y, Ren X, Chen Z, Chen W, Zhang Z, Liu X, Xu W, Liu J, Li C. Wavelength Calibration for the LIBS Spectra of the Zhurong Mars Rover. *Remote Sensing*. 2023; 15(6):1494. https://doi.org/10.3390/rs15061494

[55] Li Xu, Kexin Chen, Qingsheng He, and Guofan Jin, "Design of freeform mirrors in Czerny-Turner spectrometers to suppress astigmatism," Appl. Opt. **48**, 2871-2879 (2009)

[56] Selecting a CCD Camera for Spectroscopic Applications https://www.horiba.com/int/scientific/technologies/detectors/how-to-select-a-ccd-camera-for-spectroscopic-applications/?utm_source=google&utm_medium=cpc&utm_campaign=scip_os_oem_detectors_north_america&device=c&gclid=CjwKCAjwu4WoBhBkEiwAojNdXsRw4kT8ihcmbZv2klhb4mMvlCR7nHHLOyEaGUw5zMf1apPVOrj6jRoC_FUQAvD_BwE (accessed Oct. 23, 2023).

[57] ISO 10110-7 / ISO 14997 Plus Surface Scratch & Dig:Evaluation TargetsUsage and Applications Guide https://www.maxlevy.com/mm5/PDFs/DA074ManualV1-1.pdf (accessed Oct. 29, 2023).

[58] ISO 2017 Optics and photonics — Preparation of drawings for optical elements and systems —Part 7:Surface imperfections https://cdn.standards.iteh.ai/samples/65444/3189fea30d58482e9c216521311cf0dc/ISO-10110-7-2017.pdf (accessed Oct. 29, 2023).

[59] MIL-PRF-13830B - PERFORMANCE SPECIFICATION OPTICAL COMPONENTS FOR FIRE CONTROL INSTRUMENTS; GENERAL SPECIFICATION GOVERNING THE MANUFACTURE, ASSEMBLY, AND INSPECTION OF

https://eksmaoptics.com/out/fck_file/MIL-PRF-13830B%5B1%5D.pdf (accessed Oct. 29, 2023).

[60] Ibsen Photonics: Spectrometer Design Guide

https://ibsen.com/resources/spectrometer-resources/spectrometer-design-guide/#diode (accessed Oct. 03, 2023).

[61] Guidelines for Specifying Diffraction Gratings https://www.newport.com/n/guidelines-specifying-gratings (accessed Sep. 22, 2023).

[62] Diffraction Grating Physics https://www.newport.com/n/diffraction-grating-physics (accessed Sep. 22, 2023).

List of Figures & Tables

Video Links

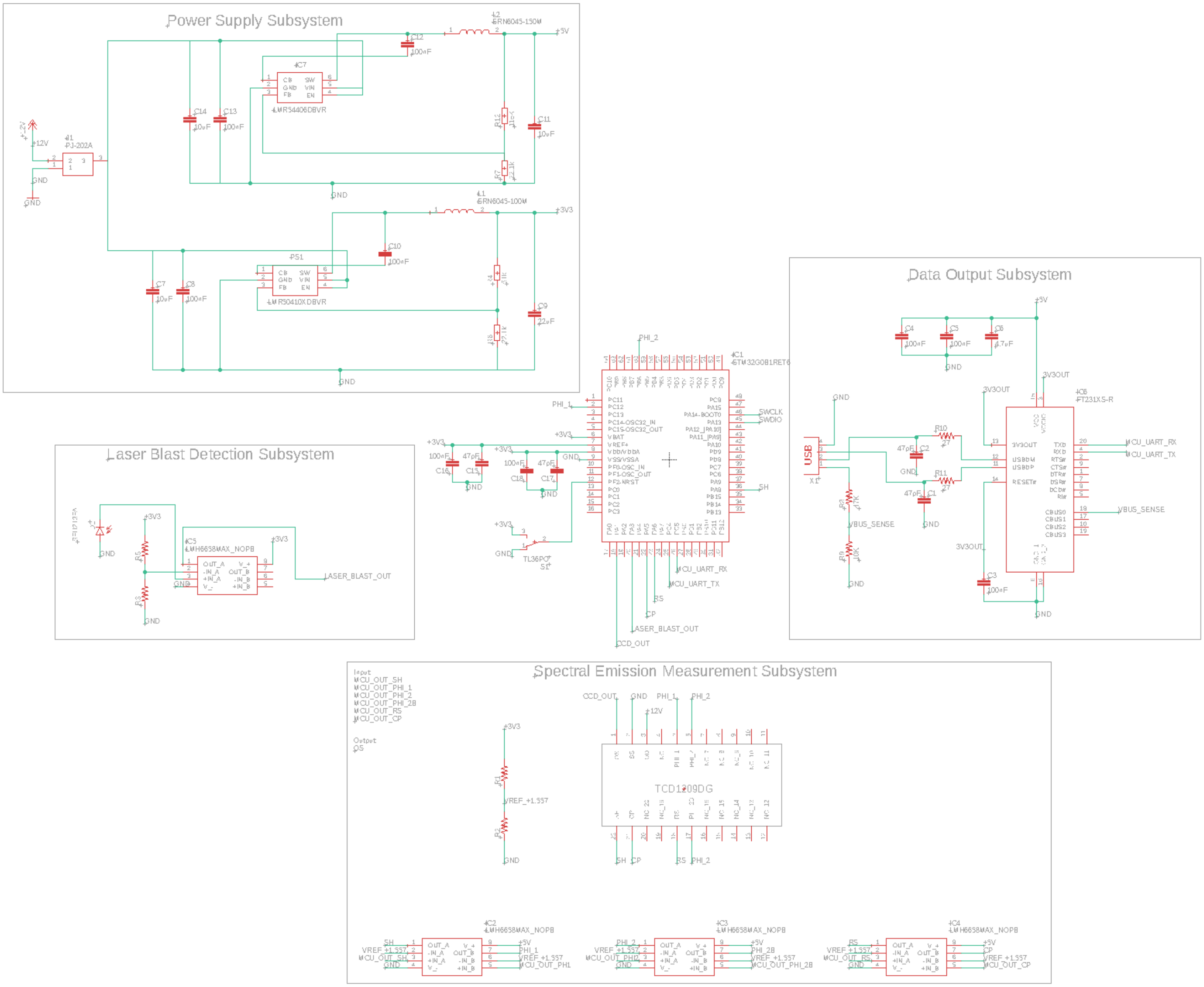
Optics Video: https://www.youtube.com/watch?v=RDbBY4gMZo4

Electronics Video: https://www.youtube.com/watch?v=IqMJB6H0UTo

Additional Figures & Tables

Figure 1:(main page) https://appliedspectra.com/technology/libs.html

Figure 6.11 Larger:



Power Specification for the Laser

Power	1000 W (Peak Power)
Frequency	1-10 Hz
Power Supply	110 V
Pulse Energy	Single Pulse ≥ 160 mJ, Double Pulse ≥ 270 mJ, Multi-pulse ≥ 700 mJ
Spot Area	1-5 mm / 0.03-0.019 in
Laser Housing/Cooling	49x32x31cm
Pulse Width	8 ns

Part Sourcing

Laser - https://www.ebay.com/itm/134528324684

Edmund Optic - https://www.edmundoptics.ca/

ThorLabs - https://www.thorlabs.com/

Digikey - https://www.digikey.com/

Mouser - https://www.mouser.com/

LLM Disclosures

The blue paragraphs on pages 91 & 92 were created using the LLM ChatGPT with the prompt “How do you create a LIBS system”

The first draft of the conclusion paragraph on pages 122 & 123 was created using google's LLM Bard. Bard was asked to generate a conclusion paragraph based on the executive summary. This first draft was altered and finalized to its current state by the team.