TEXRAY: Textile Identification via Raman Spectroscopy

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2. Project Description

2.1 Motivation and Background

As the 21st century consumer is becoming increasingly conscientious of their buying power in the global market, many shoppers opt to spend more in hopes of receiving a higher quality, environmentally-friendly product that makes them feel good about their purchase. More and more consumers are swearing off synthetic fabrics in favor of natural textiles only, such as 100% cotton, wool, or silk. This is due to increasing awareness of the fact that synthetic materials utilize high amounts of fossil fuels during production, and are non-biodegradable, leading to persistent environmental pollution as the fabric will never break down (“Plastic in textiles: towards a circular economy for synthetic textiles in Europe”). This change in mindset is reflected in the growth of the natural fiber market, which is projected to reach a value of 74.99 billion by 2030 (Swati). This has also led to a rise in merchants misleading shoppers about the materials used in their goods, hoping to cash in on the consumer shift towards eco-friendliness without committing to such an initiative. In a report released by Applied DNA Science, the company found that of 29 products tested, 89% of them were not compliant with their labeled fiber content (“The Truth About Testing Processes for Premium Cotton”). These kinds of deceptive practices lead to consumers buying goods that don’t actually align with their personal ethical standards.

Aside from the topic of sustainability, collectors of luxury goods also have a high stake in ensuring that the products they purchase are authentic and high-quality. Many consumers buy vintage luxury goods from second-hand retailers, where the reputation of the seller is often the only indicator of authenticity they have, leaving them susceptible to buying counterfeit goods. One prominent example of this is well-known luxury consignment retailer The RealReal, which was sued by Chanel in 2018 for hosting counterfeit Chanel merchandise on their site and implying an affiliation to the official brand (Ell). While real Chanel bags are made of genuine leathers with “exquisite luster and color absorption,” customers unknowingly received low-quality faux leathers or synthetic materials (Taylor). The retailer has similarly been caught selling fake Christian Dior sneakers that a suspicious customer sent to a 3rd party to be authenticated, upon which they were declared a “lower-grade replica” (Kestenbaum). Rather than authentic calfskin, the RealReal was selling knockoffs made of cheaper textiles. Such examples are abundant, and consumers are unlikely to know they’ve been ripped off just by visual inspection of their goods.

The bottom line is, consumers want and need to trust that the products they buy are made of the exact material they claim to be. Currently, the only way for the average consumer to verify the composition of the items they purchase is if they’re willing to invest time and money into sending their goods off to an authenticator for peace of mind. This is generally impractical for most people, as well as a hassle. Though hand-held textile identification devices do exist commercially, they cost thousands of dollars and are generally not affordable. Motivated by these issues, our Senior Design group aims to create a table-top spectrometry system that can quickly and accurately identify the composition of a fabric sample and convey this information to the user, while being more cost-effective than competing commercial products.

2.2 Current Commercial Technologies and Existing Projects

2.2.1 Sagitto

There are currently a few commercial products that are able to accurately identify textile composition without any sample preparation. One such technology is the Sagitto handheld spectrometer. This is a portable device that enables the user to simply hold the spectrometer up to the sample for a few seconds before it conveys the sample's exact material composition via the connected smartphone app. For example, if a t-shirt sample was composed of 63% polyester and 37% cotton, the app will quickly display this information to the user. This product utilizes near-infrared spectrometry to acquire the unique absorption spectrum of each test sample in the NIR range and utilize machine learning models to accurately identify the material in question within a few seconds. The Sagitto website boasts examples of this technology being applied to fabrics and textiles, plastics, kava, hop cones, and essential oils, demonstrating the variability of their device's applications. There are varying levels of specificity in the material composition and data shown to the user depending on the material the spectrometer is being used to analyze. This product costs $2,500 commercially. ("A Miniature NIR Spectrometer That Fits In Your Hand")

2.2.2 Fabritell

Similarly to Sagitto, the company Matoha has its own commercial spectrometer that can quickly identify sample composition. However, whereas Sagitto seems to advertise a single device that can identify a variety of different materials, Matoha has two separate spectrometers for sale, with one being dedicated to identifying plastic samples, and the other being dedicated to identifying fabric samples. Their fabric spectrometer, Fabritell, utilizes NIR reflectance spectrometry within a band in the 1-2 μm range combined with machine learning techniques just like the Sagitto device, displaying sample information to the user via an app. They claim their spectrometer can identify the fabric sample in .5 seconds, and the device can be powered by an adaptor or a battery pack. Both the fabric spectrometer and plastic spectrometer also come in handheld or desktop varieties. Fabritell's latest model supports the identification of 10 pure materials and 13 fabric blends, stating that it is not possible to separate chemically identical fibers such as wool vs. alpaca, though it can separate cotton vs. wool. The product site also states that the accuracy of the device depends on the correct measurement technique of the user, as well as accuracy being ±10% for blends and a 5-10% detection threshold for contamination in pure materials. They also state they cannot reliably identify non-uniform samples. The Fabritell desktop version retails for €2,499 whereas the handheld version goes for €3,499. ("Portable NIR Spectrometer")

2.2.3 trinimaX: Mobile NIR Spectroscopic Solution

Similarly to Sagitto and Matoha products, trinamiX creates a handheld, non-destructive, commercial spectrometer, which can be used for fabric, plastic, PV pipe, and liquid analysis. Notably, the Mobile NIR Spectroscopic Solution provides a spectroscopic material analysis on an article of clothing at "the push of a button". The product is paired to an application which displays the data of material composition. No note was provided on the analytical method used towards the data processing. The supported textile materials of the device include: acrylic, cotton, polyamide 6/6.6, polytrimethylene terephthalate (PTT), polyester, polypropylene (PP), silk, viscose, and wool. Blended materials are typically identified if the content of the minor material is > 5%. Further specifications include a spectral range of 1450 nm to 2450 nm and a spectral resolution that is 1% of the wavelength. The detector used is a 256-pixel PbS line array detector. ("trinamiX's Mobile NIR Spectroscopy Solution")

2.2.4 OceanOptics: NIR Quest+2.5

The NIR Quest+2.5 provides high sensitivity and low noise spectral assessments for the authentication of products. The wavelength range is 900 nm to 1240 nm, with an optical resolution of 6.46 nm to 25.50 nm. Signal-to-noise ratio of a single 10 ms scan is 10:000:1. This product is applied towards not only product authentication, but for the determination of hydrocarbon solvents, plastics in recycling, and moisture in fruits and grains. ("NIR Spectrometers")

2.2.5 Study on characterizing microplastic fibers using Raman spectroscopy

Spectroscopy published an exploration of macroscopic and microscopic Raman spectroscopy to identify different commercial microplastic fibers. This study on characterizing microplastic fibers using Raman spectroscopy is justified to account for the excess of microplastics in the form of fibers that shed from textiles. For samples larger than 1 mm macroscopic Raman spectroscopy is deemed appropriate. For samples smaller than 1 mm, or for heterogeneous samples, a Raman microscope is recommended due to its "high spatial selectivity". Two fiber samples are used in the study. Sample 1 is a white polyester soft felt fabric made up of rayon and high quality acrylic craft felt. Sample 2 is red and white patterned that is 100% cotton. Sample 1 used a MacroRam benchtop Raman spectrometer (Horiba), equipped with a TouchRaman BallProbe (Marqmetrix). The MacroRam uses an excitation wavelength of 785 nm, which helps to suppress fluorescence that would otherwise be present at shorter laser wavelength excitation. The probe is pressed onto the sample and a spectrum is recorded. The Raman measurement confirmed the sample contained PET and there was no detection in acrylic (which would correspond to a 2240 cm^-1 band). For sample 2, spectral measurements were taken using an XploRA Plus (Horiba) confocal Raman microscope. This system is equipped with a combination of three different excitation lasers (532 nm, 638 nm, and 785 nm), four gratings (600 gr, 1200 gr, 1800 gr, and 2400 gr), and a 100x magnification objective (numerical aperture of 0.9). The system also used a deep-cooled SynapseEM electron multiplying charge coupled device (EMCCD), for sensitivity and speed. They were able to identify PET, cellulose, and a red pigment. (Lee and O'Donnell)

2.2.6 Textile material identification using Shifted Excitation Raman Difference Spectroscopy

The research explored how Shifted Excitation Raman Difference Spectroscopy (SERDS) can be employed to determine the material composition of textile samples while avoiding fluorescence interference from the fiber materials and dyes. Their system uses a dual-wavelength diode laser emitting at 784.6 nm and 785.2 nm as an excitation light source. The detector used was a MityCCD H10141. SERDS was used to assess 22 dyed and undyed textiles produced from various commercially relevant textiles. For all investigated samples, SERDS was successful in separating the Raman signals of fibers and dyes from the fluorescence interference. Reliable fiber identification was sustained from SERDS derived Raman signals for undyed and light-colored textiles made of cotton, viscose, wool, and polyester. Principal component analysis (PCA) and linear discriminant analysis (LDA) allowed for a “very good” discernibility amongst the four textiles. (“Textile material identification using Shifted Excitation Raman Difference Spectroscopy”)

2.2.7 Raman Spectrometer General Operations

Light from a monochromatic light source is directed onto a sample. The scattered light off of the material can be defined as Rayleigh and Raman scattering. Rayleigh Scattering is of the same energy level as the incident light, where Raman scattering is of a different energy level. The whole of the scattered light is sent through a filter which will eliminate the Rayleigh signal. The Rayleigh scattering is then sent through a diffraction grating which will separate the Raman light into its constituent wavelengths, allowing us to determine how the light interacted with the sample. This separated Raman light is then directed onto a CCD. The grating used will dictate how much separation of light we see (spectral resolution). The longer the Raman range we’re looking to detect off the sample, the lower line density should be, as to not spread the light too much, impacting the received light signal. However, having a higher line density will allow for a better spectral resolution. (“Raman Spectrometer Optics Explained”)

2.3 Objective and Goals

The main goal of our Senior Design project is to create a portable system that will allow the user to place a fabric sample within a designated area, upon which the device will quickly identify characteristic information about the sample, displaying this information to the user via a LCD screen (Fig. 1). It should be noted that practically all of the previously mentioned commercial products intended for fabric identification rely on NIR spectrometry, a technology that requires an InGaAs sensor as a receiver within the device. A single InGaAs photodiode array can run upwards of $1,000, a significant factor in why these products average around $2,500 for the consumer. Such an expensive component limits the cost-effectiveness of the device. As such, our group intends to avoid NIR spectrometry as a technique and instead rely on Raman spectrometry to achieve material identification.

We intend to develop a proof of concept for a commercial Raman-spectroscopy system that can determine the authenticity of a product and conduct a material analysis. To limit the scope of the project and avoid taking on more than we can complete within a Spring-Summer course, we will be honing in on a few particular fabrics that we aim to identify as well as separately conducting a product comparison for a few clothing items.

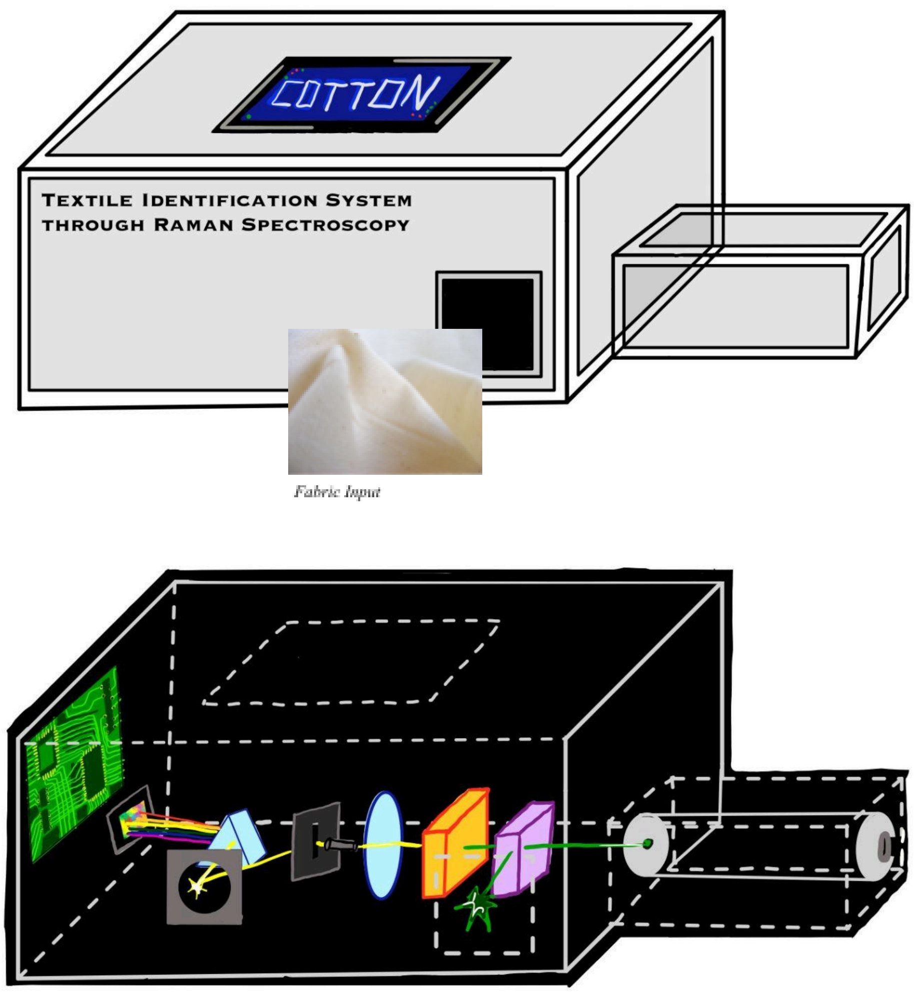


Figure 1 *Textile Identification System Through Raman Spectroscopy Prototype*

2.3.1 Goals

Basic goals

- The material analysis function will be able to classify 3 types of textile samples based on their spectral signature. The three textile types will be cotton, silk, and polyester. All of the samples will be undyed and unblended.
- The device will display the results of the analysis to the user via an LCD screen.

Advanced goals

- Introduce a second system functionality which would be able to determine if two clothing products are identical
  - The user will be able to select either “Material Analysis” or “Product Comparison” on the home LCD screen
  - The product comparison function will conduct a spectral comparison between a clothing sample being tested to a database of previously scanned clothing items. If a match is found, this indicates the sample is identical to a reference clothing item.
  - The scanned and stored items will not need to be undyed, unblended, or one of the three textile types from material analysis.
- The material analysis function will be able to classify 2 additional types of textile samples based on their spectral signature. The additional textile types will be nylon and linen.

Stretch Goals

- A mobile app will be integrated to replace the functions of the LCD screen.
- The material analysis function will be able to identify undyed, blended fabric samples and give portion ratios.
- The material analysis function will be able to differentiate between the key textiles regardless of whether or not the sample is dyed or undyed.

2.3.2 Objectives

Basic Objectives

- Build an effective Czerny-Turner Raman spectrometer to analyze the materials while keeping cost efficiency in mind
- Determine a lens setup to enable efficient Raman-illumination and high Raman signal acquisition from samples
- Implement an efficient power source for the system while maintaining portability
- Create a database with reference spectral signatures of cotton, polyester, and silk for comparison during material analysis
- Utilize machine learning to improve the accuracy of the material analysis comparison system

Advanced Objectives

- Create a more robust fabric analysis system to include the classification of nylon and linen.

- For the secondary product comparison feature:
    - Create a more specified fabric analysis system to determine a unique clothing item's spectral signature.
    - Implement an efficient data processing algorithm which can accurately determine the correlation between a sample clothing item and the existing items in the database to find a match.
    - Store reference clothing items into a database.

Stretch Objectives

- Determine a method utilizing machine learning to find the material ratio of blended fabrics.
- Determine a method of identifying dyed materials.
- Implement a mobile app that allows for a more user-friendly interactive display
    - Use Flutter for frontend development
    - MongoDB for database management
    - Postman and visual studio code for api configuration and testing

2.4 Features and Functionality

This project will act as a proof of concept for a Raman-spectroscopy based commercial fabric scanner and will likely have limited functions compared to the commercial product alternatives that were previously discussed. However, it will display the practical features a future fully functioning product might include, while maintaining a lower total cost.

2.4.1 Optical System

The system will include a sample tray upon which the user can place their fabric sample, with no prior sample preparation. The sample will then be illuminated by a laser light source via a series of probe optics, such as one or multiple lenses and a beamsplitter, which will cause Raman scattering and Rayleigh scattering to be reflected off of the sample. The beam splitter will guide the back-reflected light back towards the collection path of the system, where a longpass filter will block all Rayleigh scattered light from continuing. This light will then be coupled into a fiber which will guide it to the spectrometry system's entrance slit. Mirrors will be used to align the Raman scattered light onto a diffraction grating which will disperse it into its constituent wavelengths. A second mirror will focus this diffracted light onto a detector.

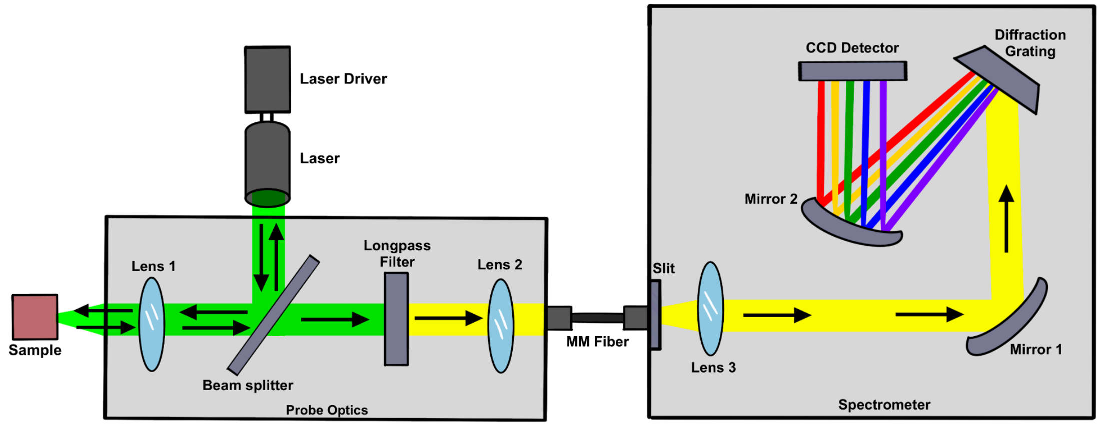


Figure 2 *Preliminary design of optical system, including raman illumination and spectroscopy. Distances will be added as the design progresses.*

2.4.2 Electrical Hardware

The PCB for the system will include a battery source to power the components. In order to accomplish this, the battery source will be connected to a switch which will be wired to a 3.3V and 5V voltage regulator. From the 5V regulator voltage will be distributed to the LCD screen and to the Raspberry Pi. LEDs would be used to indicate the power is being properly distributed and they will be soldered onto the PCB and be receiving voltage from being wired to the 3.3V regulator. The laser component will be powered via a wall outlet separate from the PCB. Once the system is powered on, the detector will then receive the spectral analysis of the sample provided by the spectrometer. The detector will be wired to the MCU to transmit the collected data for the information to be processed. Once the classification is determined by the program in the MCU, the results will be transmitted through a wire to the LCD screen and be displayed onto the screen for the user to see.

2.4.3 Software

The Raman scattering of the material will be captured by the spectrometer’s detector. The captured signal is then processed by the raspberry pi, creating a graph to show the intensity of light at all points across the wavelength spectrum (measured in nanometers). The resulting graph will be compared to a database of similar signatures through machine learning methods such as k-nearest neighbors, support vector machine, principal component analysis, or convolutional neural networks. The user will communicate with the raspberry pi via a graphical user interface on the attached LCD display. First they will be prompted to select between settings of product comparison and material analysis. In the case of product comparison, the user will be asked whether they are making a comparison or adding a product to the “closet” database. When making a comparison the code will search through the database of prior scanned products to find if any pass a correlation threshold designed to identify identical products. If this threshold is cleared the user will be told through the LCD that the product is a match, listing the product from the id label attached to the matched item inside the database. If there is no match detected the user will be prompted to input a name tag for the signature so that it can be saved into the closet database as a new product for future scans. When material analysis is selected, machine learning methods like those listed before will work to sort the signature into the most similar group of prior scans, displaying the label of the selected group (cotton, polyester, silk) on the LCD as the material the user's scan has been matched with.

2.5 Engineering Requirement Specifications

Parameter	Specification	Units
Material Analysis Accuracy	>90%	Percent
Total Response Time	<5	Seconds
Product Comparison Accuracy	>90%	Percent
Spectral Resolution	<30	cm^{-1}
Laser Power	<100	mW
Battery Life	>5	Hours
Battery Voltage	3.7 < x < 5	Volts
Battery Charge Capacity	>10,000	mAh
Battery Energy	>= 37	Wh
Maximum Current Required	<2	Amps
Unit Size	<24"x18"	Inches
Unit Weight	<10	lbs
Cost	<$2,500	USD

Table 1 *Prototype Engineering Specifications*

Component	Parameter	Specification	Units
Plano-convex Focusing Lens	Focal length	10 - 50	mm
Beamsplitter	Reflection/Transmission	30:70	Percent
Laser diode	Wavelength	532	nm
Concave Mirrors	Focal Length	50	mm
Entrance slit	Slit Width	50	µm
CCD	Resolution	1000 x 1000	Pixels
Longpass filter	Cutoff Wavelength	532	nm
Diffraction grating	Grating period	1200	Lines/mm
LCD	Resolution	800 x 480	Pixels
LCD	Screen	4 x 2	Inches
LCD	Color	18	Bits (262,144 total colors)
Voltage Regulator	Voltage Maintenance	3.3, 5	Volts
LCD	Current	2	Amps
Raspberry Pi	RAM Capacity	4	GB
Raspberry Pi	Processing Speed	2.4	GHz

Table 2 *Component Specifications*

2.6 Hardware Block Diagram

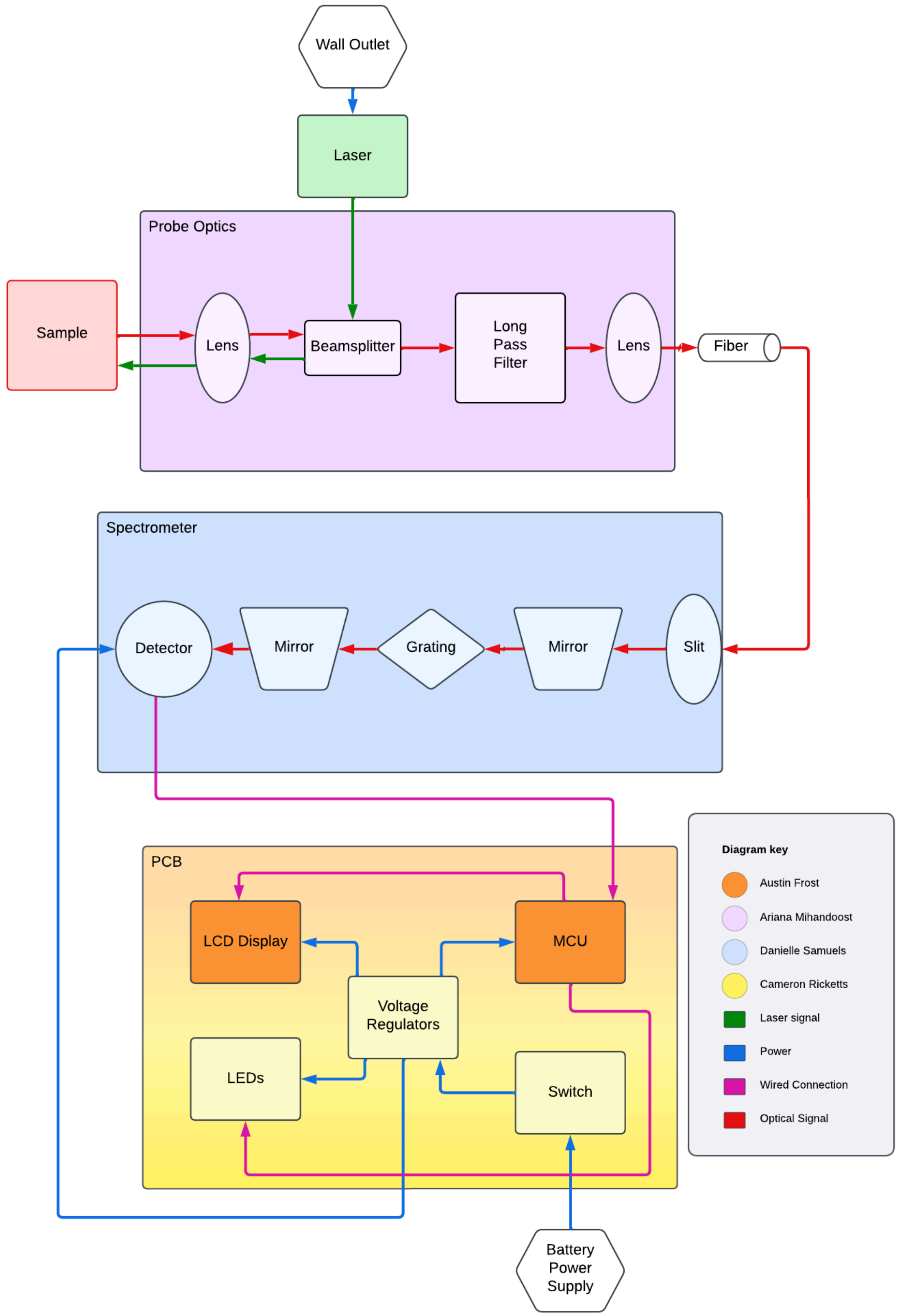


***Figure 3** Hardware Block Diagram*

2.7 Software Block Diagram

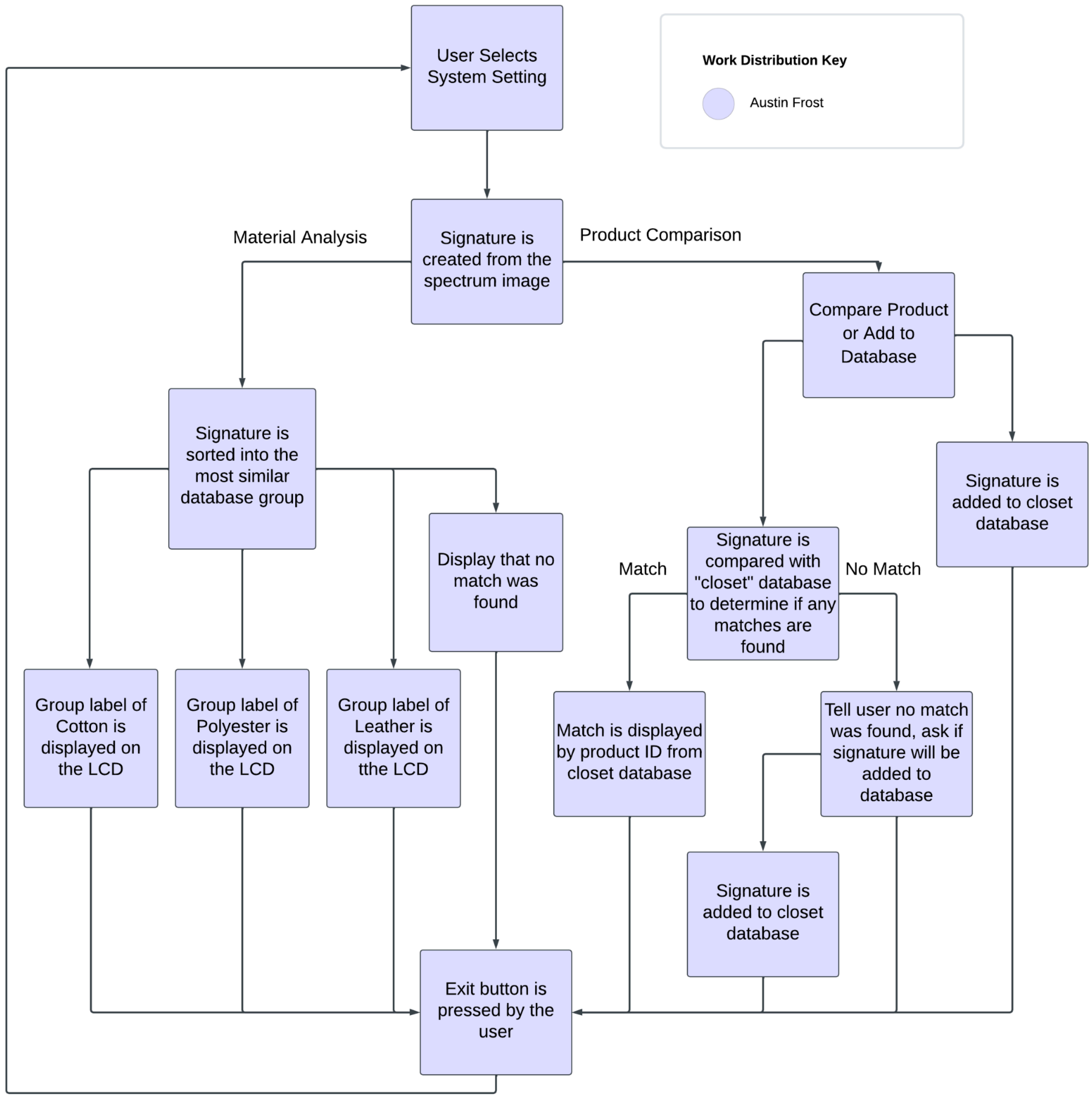


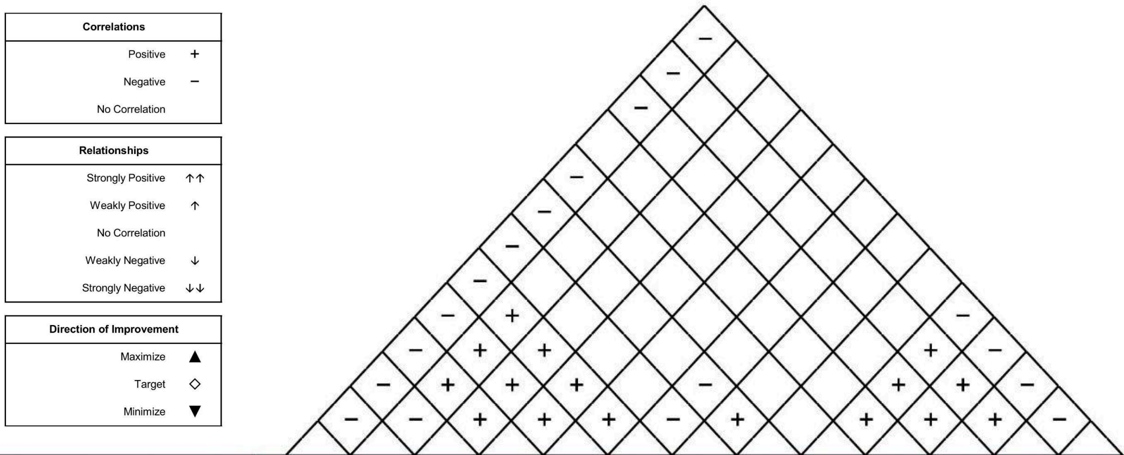
Figure 4 *Software Block Diagram*

2.8 Budget and Financing

This Senior Design project does not currently have an external sponsor, and will be funded entirely by the 4 members of the team. We will be actively searching for a sponsor throughout the documentation and production of our system.

Item	Cost	Quantity	Total Cost
Laser diode (532 nm)	$250	1	$250
Beamsplitter	$100	1	$100
Long Pass Filter	$50	1	$50
Collimating lens	$40	2	$80
Multimode Fiber	$15	1	$15
Slit	$200	1	$200
Mirror	$40	2	$80
Diffraction grating	$100	1	$100
CCD	$100	1	$100
PCB	$70	1	$70
LCD display	$67	1	$67
Raspberry Pi	$35	1	$35
Switch	$3	1	$3
Battery power supply	$15	1	$15
Switch	$0.80	1	$0.80
LEDs	$0.42	4	$0.42
Fiber Samples	$10	1	$10
Total Cost			$1,176.22

Table 3 *Budget breakdown*



Column #		1	2	3	4	5	6	7	8	9	10	11	12	13
Customer Requirements (Explicit and Implicit) / Engineering Requirements	Direction of Improvement	Maximum Cost	Material Analysis Accuracy	Total Response Time	Product Comparison Accuracy	Spectral Resolution	Laser Power	Unit Size	Unit Weight	Battery Life	Battery Voltage	Battery Charge Capacity	Battery Energy	Maximum Current Required
Direction of Improvement		▲	▲	▼	▲	▲	◇	▼	▼	▲	◇	▲	▲	▼
Accuracy	▲	↓	↑↑		↑↑	↑	↑							
Speed	▲	↓↓	↑	↓↓	↑	↑	↑							
Performance	▲	↓↓	↑↑	↓↓	↑↑	↑↑	↑↑			↑	↑	↑	↑	
Safety	▲						↓↓							↑
Portability	▲							↑↑	↑↑	↑↑	↑	↑	↑	
Cost	▼	↑↑	↓↓	↓	↓↓	↓↓	↓↓	↓↓	↓↓	↓↓	↓	↓↓	↓↓	↓
Target		<$2500	>90%	<5 sec	>90%	>50 cm^{-1}	<100 mW	Approx. 24" x 18"	<10 lbs	>5 hours	3.7 V < x < 5 V	>= 10,000 mAh	>= 37 Wh	<2 A

Figure 5 *House of Quality*

2.9 Project Milestones

Senior Design I Project Documentation Milestones - Spring 2025			
Task	**Time Period**	**Dates**	**Responsibility**
Brainstorming	1 week	1/11	All
Finalize Project Idea	1 week	1/17	All
Divide and Conquer Document	1 week	1/17 - 1/24	All
30-Page Milestone	~1 month	2/24	All
60-Page Milestone	~1 month	3/23 Due 3/24 @ 12	All
90-Page Milestone	~2 weeks	4/2	All
120-Page Milestone	~2 weeks	4/15	All
Final Draft	5-7 days	4/20 Due 4/22 @ 12	All

Table 4 *Senior Design I Project Documentation Milestones*

Senior Design I Project Design Milestones - Spring 2025			
Task	**Time Period**	**Dates**	**Responsibility**
Optics Midterm Demo	~4 weeks	2/25 (9-11:30)	Ariana & Danielle
Electronics Prototyping	~2 months	3/24	Cameron & Austin
PCB Ordering	~2 weeks	4/26	Cameron & Austin
Optics Final Demo	~1 week	4/15	Ariana & Danielle
Upload Mini Demo	5-7 days	4/22	All

Table 5 *Senior Design I Project Design Milestones*

Senior Design II Project Design Milestones - Summer 2025			
Task	**Time Period**	**Dates**	**Responsibility**
PCB Testing	~3 weeks	5/31	Austin & Cameron
Optical Systems Integration	1 month	6/9	Ariana & Danielle
Total Systems Integration	~1.5 months	6/30	All
Short-form Report	TBD	TBD	All
Practice Final Presentation	~2 weeks	TBD	All
Final Presentation	TBD	TBD	All

Table 6 *Senior Design II Project Design Milestones*

Appendix

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