ECOspec

Microplastic Identification with Raman Spectroscopy

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2.1 Project Motivation and Background

Annual production of plastic has increased rapidly since the first synthetic plastic was produced in 1907. In 2024, 413.8 million tons of plastic was produced globally. 2 million of those tons end up in our ocean, and 52 tons end up as environmental pollution [1]. One of the side effects of this plastic waste is microplastic (MP) pollution in our ecosystems. Even though these tiny plastic particles seem small, less than 5 millimeters in size, they pose a major environmental and health crisis that requires their detection [2]. Humans consume an estimated 74,000 microplastic particles a year, and its impact on our health is just beginning to be understood [3].

Microplastics are typically manually analyzed with microscopes or burn tests. This process is time consuming, leaves room for human error in visual identification, and in the case of the burn test, destroys the sample of interest. A spectroscopic measurement of a given plastic sample is a reliable method of determining its chemical composition. A type of reliable chemical identification spectroscopy is a technique called Raman spectroscopy. Raman analyzes the shifts in frequency that occur when a sample is excited with incident laser light. Raman allows for high specificity of analysis, minimal sample preparation, and is non-destructive. Certain materials are associated with unique Raman fingerprint spectra that allow them to be identified from other materials. Plastics are one such material.

Each type of plastic, ranging from PET water bottles to EPS from styrofoam, is associated with a unique Raman spectrum. This unique Raman spectrum is consequent of the materials molecular and atomic structures.

2.1.1 The Concept of ECOspec

ECOSpec is a compact, pre-packaged microplastic detection system that contains a laser excitation source, spectrometer, and Raman filtering components. The user can introduce a sample of interest into the system and will receive a live Raman spectrum. This configuration enables the acquisition of characteristic Raman spectra, which allows for the precise identification of microplastic polymer types based on their unique Raman fingerprint. Therefore, not only will the device tell the user if microplastics are detected, It will also provide the type of microplastic. A 785 nm laser will be used for excitation, and the system will be able to detect microplastic particles < 1 mm by 1 mm in size, in a water sample.

ECOspec would be useful for real-world applications on a large scale. Numerous companies, governments, and research facilities would benefit from having their water noninvasively analyzed for microplastics and other harmful materials. Public health can easily be compromised if water is not monitored and maintained. ECOSpec allows for a non-intrusive method to identify and characterize plastics that could be found in consumable products or drinking water. It has value in both consumer safety and regulations put in place by different agencies. Governments at all levels would benefit by using ECOspec for analysis of plastic contamination, whether it be in large water sanitation plants or small measurement stations implemented in residential buildings.

ECOspec could also be implemented at research facilities. Many labs require a certain level of purified water as the impurities in tap water could interfere with experiments and compromise results. Allowing a water source to be monitored by ECOspec would increase confidence that the purity of water in a lab is at a sufficient level. On the other end, it could also be used by labs to research microplastics and problems caused by microplastics.

ECOspec would also be perfect for environmental water monitoring where it would detect and identify microplastics in natural water sources such as lakes, rivers, and oceans. This ability allows for pollution tracking and efforts for remediation once hotspots of contamination are located. Additionally, involving ECOspec with monitoring output of runoff and discharge from operations such as farming, plants, industrial facilities, and urban/residential areas is beneficial. Many of these produce and then introduce harmful chemicals and materials to natural water ways, damaging ecosystems.

2.2 Project Background Research

2.2.1 Environmental and Health Impact of Microplastics

Throughout history, toxic materials have been used in a wide variety of products that were commonly in close physical proximity to humans and other living creatures. Some of these more well-known materials are lead, arsenic, and plastic. In modern times society has pushed a lot of effort into removing arsenic and lead from our environments, but there has been little pushback against plastic in comparison. Movements to remove plastic straws and bags from select areas have been popular in recent years, but they are largely limited to small areas in cities or natural parks.

Plastics are a convenient material. They do not breakdown easily, are resistant to many chemicals, and are hydrophobic. Overall, they provide a platform for mass production of material with desirable properties that are widely customizable for a wide range of applications and are otherwise not found in nature.

But for these very reasons, plastics are actively contributing to a decline in human and general environmental health. While they do not breakdown easily in bulk, plastic items are almost constantly leaving behind micro and nano plastics. These tiny particles of plastic, over the decades of their increasing prevalence, have become extremely pervasive. They are estimated to have touched almost every point on Earth. Microplastics are found in city water supplies, plants in fields miles from civilization, food, human blood, and even snow samples in Antarctica [4].

Microplastics are suspected to be toxic to the human body when built up in large quantities. They have been found to cause cell death and disturb the cellular reproduction cycle [5]. There have also been multiple studies on the adverse effects of microplastics on hormones, the thyroid and reproductive organs of mammals in general [6].

2.2.2 Principles of Raman Spectroscopy

Raman spectroscopy is a measurement technique that is often used for material identification. This is enabled by the principles of Rayleigh and Raman scattering. Rayleigh scattering is the most common type of scattering and defines the scattered photon to have the same frequency (energy) as the incident photon. Raman scattering occurs roughly every 100,000,000 interactions and defines the scattered photon to have a shifted frequency (energy) from the incident photon [8].

There are two outcomes for Raman scattering: Stokes and Anti-Stokes scattering. In stokes scattering, the frequency of the scattered photon experiences a reduction in frequency (loss of energy), which is perceived as an increase in wavelength. In Anti-Stokes scattering, the frequency of the scattered photon experiences an increase in frequency (gain in energy), which is perceived as a decrease in wavelength.

In a typical Raman spectrometer system, the laser spot size is minimized to focus all the optical power to as small of a point as possible. This increases the likelihood of generating and receiving a Raman signal in the precisely selected area, increasing the confidence of obtaining a true Raman spectra associated with a known material.

2.2.3 Advantages for Microplastic Analysis

Plastic molecules are organic molecules. They are molecules made of a chain of hydrocarbons. They have unique geometries and unique energy levels associated with them. These unique molecular structures and properties give plastics unique Raman spectra associated with each type. Because plastics have uniquely identifiable Raman spectra, it is logical to conclude plastics are easily identifiable with Raman spectroscopy [9]. From polyethylene terephthalate (PET) in water bottles to expanded polystyrene (EPS) in styrofoam, the plastics commonly used in modern light each have unique Raman spectra.

2.2.4 Spectrometers

Spectrometers are instruments that measure how light is dispersed across different wavelengths. It takes incoming light, separates that light into its component wavelengths, and measures each wavelength intensity. There are many different types of spectrometers including prism, diffraction grating, Fourier transform, Raman, mass, and miniature spectrometers. These broad classes mainly differentiate between how the light is being dispersed, and its application. The first spectrometer was a prism spectrometer built in 1802, where sunlight was focused through a slit, and sent through a prism. Prism spectrometers use a glass or quartz prism to refract and disperse the light into different wavelengths. It is historically important and simple in design, but it has a few limitations, such as nonlinear dispersion through the prisim, and typical low resolution. Diffraction grating spectrometers use an optical component that has thousands of grooves that separate light into its component wavelengths by the principles of diffraction. Each wavelength is diffracted at a different angle, which creates the different intensities at each wavelength. Using a diffraction grating over a prism for dispersion can be beneficial because a higher resolution is possible with a uniform wavelength separation. Complications include straylight from other diffraction orders and the complex design which requires precise alignment. Fourier transform spectrometers use interferometry to measure all the wavelengths at once, and then a Fourier transform is applied to extract the spectrum. It provides a very high resolution, and high throughput, but it requires moving mirrors, which complicates the design, and it won't work well for a demonstration because of its sensitivity to vibrations.

There are also many different spectrometer configurations. From simple transmissive systems and lens-grating-lens (LGL) to the Littrow and Czerny-Turner configurations, spectrometers can range from simple designs to more complex systems. The Czerny-Turner spectrometer is compact and common, and can have a high resolution, and cover a wide range of wavelengths. But it can be limited by aberrations and stray light. The Echelle spectrometer uses a specific grating called an echelle grating that has a low groove density and a large blaze angle in high diffraction orders, and typically is set up with a cross disperser, which could be a prism or second grating. It can have

extremely high resolution, but the tradeoff is a very complex optical alignment, and its price. The Littrow setup is compact and simple, where the incident and dispersed beam share the sampe optical path, but the overlapping beams can decrease the resolution and makes involvement of straylight harder to navigate.

2.2.5 Initial Testing

To ensure that using Raman spectroscopy for microplastic detection is truly a viable project for senior design, basic initial testing was conducted to determine the ease of the task with premade tools. An Ocean Optics QEPro Raman Spectrometer, Ocean Optics Raman Probe, and 785 nm fiber laser was employed to obtain the Raman signal of various macro plastic samples. The Raman probe contains filtering to remove the laser signal and fluorescence. Raman shifted frequencies were able to be detected and plotted accordingly.

One scan was used with an integration time of 10 seconds. The integration time of a spectrometer is the amount of time the sensor is exposed to a light signal for data collection. The number of scans is the number of times that period of data collection is repeated. If multiple scans are taken, the multiple intensity values for each pixel are averaged together and then plotted.

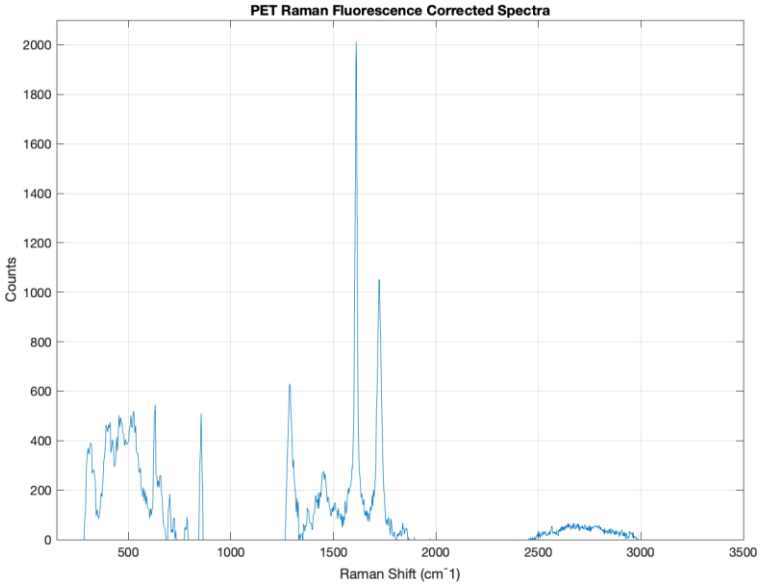


Figure 1. Raman Spectra of PET

Raman spectra of a water bottle. Using a 10 second integration time with 1 scan.

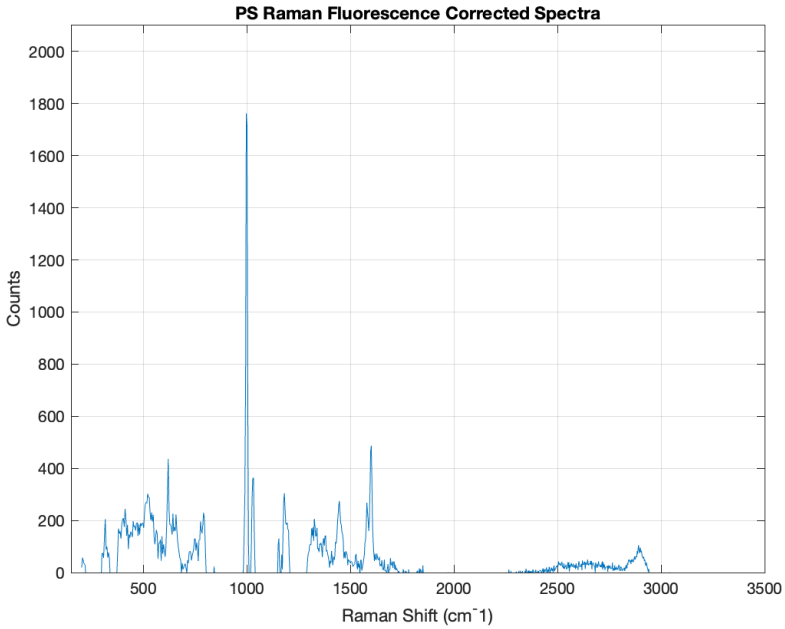


Figure 2. Raman Spectra of PS

Raman spectra of a piece of styrofoam. Using a 10 second integration time with 1 scan.

2.3 Existing Project/Past project/prior related work

2.3.1 Past Senior Design

2.3.1.1 TEXRAY

TEXRAY was a past senior design project. It was a Raman spectroscopy system used for analysis of different types of fabrics. The goal was to utilize machine learning to match collected Raman spectra to previously confirmed datasets. The team used a 532 nm laser as a light source, basic optical components to focus and collect the light, a lens-grating-lens (LGL) spectrometer layout to separate the light, and a CCD to detect the spectra.

However, the final product was not a fully functioning device. The optics functioned as intended and a Raman spectrum was able to be gathered, however a signal from the CCD could not be resolved. This issue could have resulted from a variety of reasons, ranging from the CCD being oversaturated to a faulty signal amplification circuit.

They originally planned on using a Czerny-Turner spectrometer configuration but used LGL for simplicity. While a 532 nm laser is suitable for Raman spectroscopy, some sources have suggested a 785 nm laser will produce less fluorescence.

2.3.1.2 W.A.T.E.R.

W.A.T.E.R. was a previous Raman spectroscopy focused senior design project sponsored by Ocean Optics. It utilized a different type of spectroscopy, spatial heterodyne spectroscopy, for water contaminant analysis. Spatial heterodyne spectroscopy utilizes Fourier transform to analyze Fizeau fringes. [5-7] The layout is like a Michelson interferometer, but instead of two mirrors utilized for reflection and creation of a spatiotemporal dependent point of interference, two fixed diffraction

gratings are used create a point of interference that is wavelength dependent. The team was successful in obtaining Raman spectra for various contaminants such as sulfur, ammonium nitrate, and potassium perchlorate.

2.4 Goals and Objectives

2.4.1 Goals

2.4.1.1 Basic Goals: Detection and Identification of 2 – 5 mm sized plastics in water

The device will:

1. Collect Raman spectra of 1 – 5 mm sized plastic samples utilizing a 785 nm laser. Specifically, PET, polystyrene, and nylon.
2. Detect the presence or absence of specified microplastics in water using Raman spectral fingerprints. Refer to Appendix B for a collection of the peaks of interest. These samples will be prepared without mixes of plastic types.
3. Maintain a CCD operating temperature of sub 40° C.

2.4.1.2 Advanced Goals: Detection and Identification of < 1 mm x 1 mm sized MP in water

The device will:

1. Identify the type of plastic a certain microplastic (< 1 mm x 1 mm) sample is.
2. Identify microplastics down to 500 micrometers in length and 100 micrometers in width.
3. Addition of a database server to connect to the device, which would be able to host records of previous identification runs and utilize the data for more robust known-material libraries.

2.4.1.3 Stretch Goals: Mixed MP Samples < 5 mm and Imaging of MP

The device will:

1. Detect and identify microplastics of mixed pre-made water solution samples, rather than individual polymer samples.
2. Detect and identify microplastics from a sample from the environment, such as tap water, or lake water sample.
3. Detect and identify microplastics in powdered form.
4. Implementing an additional system to image microplastics in addition to detection and identification to give the user a more accurate view of what they are measuring.
5. A larger scale version of ECOspec that could be set up for stationary real-world uses. It would be established in waterlines and natural bodies of water to detect high concentrations of harmful materials in the water.
6. Portable, battery powered, field deployable version instead of a bench system. It would be useful for outdoor environmental sampling, or for personal use for microplastic detection in your home.
7. Integrate a second 1064 wavelength source for Raman spectra with reduced fluorescence.

2.4.2 Objectives

2.4.2.1 Basic Objectives

- Basic alignment of Raman spectrometer with white light source.
- Calibration of spectrometer so the pixel spaces accurately map to nanometer space.
- Obtain Raman spectra using our system with large pieces of common plastics > 5 mm in size.

    - Plastics of interest: Polyethylene terephthalate (PET), polystyrene (PS), and nylon
- Confirm that Raman spectra collected matches known fingerprint peaks of those polymers
- Using our samples of interest, we will create microplastic samples in DI water. These samples will each only contain one type of microplastic.
- Obtain Raman spectra using our device with individual microplastic samples.
- Obtain Raman spectra of the water for reference comparison during the output processing.
- After collecting the needed references, we can use the device to detect if microplastics are present or not in more individual microplastic water samples that we made at varying concentration levels.

2.4.2.2 Advanced Objectives

- Create more individual microplastic samples that include a broader range than the initial samples of interest.
- Collect a reference library of known fingerprint peaks of the samples we intend to test.
- Create microplastic samples of various types and sizes, confirmed by visual inspection with a microscope.
- Take Raman measurements of our individual, pre-made microplastic samples.
- Implement software changes needed to include identification, in addition to detection.

2.4.2.3 Stretch Objectives

- Implement software changes to include mixed-microplastic detection.
- Create known mixed pre-made samples to test our post-processing with.
- Collect environmental samples to detect microplastics, including tap or lake water.
- Test if identification is possible with the environmental samples.
- Direct the reflected 785 nm light into a CCD or infrared camera after back reflection off the dichroic mirror
- Implement another mount, lens systems, and dichroic mirror to stabilize, collimate, and direct a secondary 1064 nm laser source into the pre-established path of the 785 nm source.
- When establishing the known material library, inclusion of a small, non-linear, regression model. This model would require a more intensive calibration to allow the model to establish the required relationships between Raman shift intensity, material, and material concentration in a fluid sample.
- A website/app connected to a database where the results could be stored so a multitude of people have access to the data. This could also replace the basic GUI we included previously. This would also allow for crowdsourced data collection. Crowdsourced data can provide more detailed material libraries, enabling more accurate identification.
- Real-time monitoring that allows for continuous sampling of water. For example, using it in a waterline that would trigger alerts if a certain concentration threshold were to be exceeded. This would be beneficial for labs or municipalities to maintain clean water for their facilities.

2.5 Subsystems

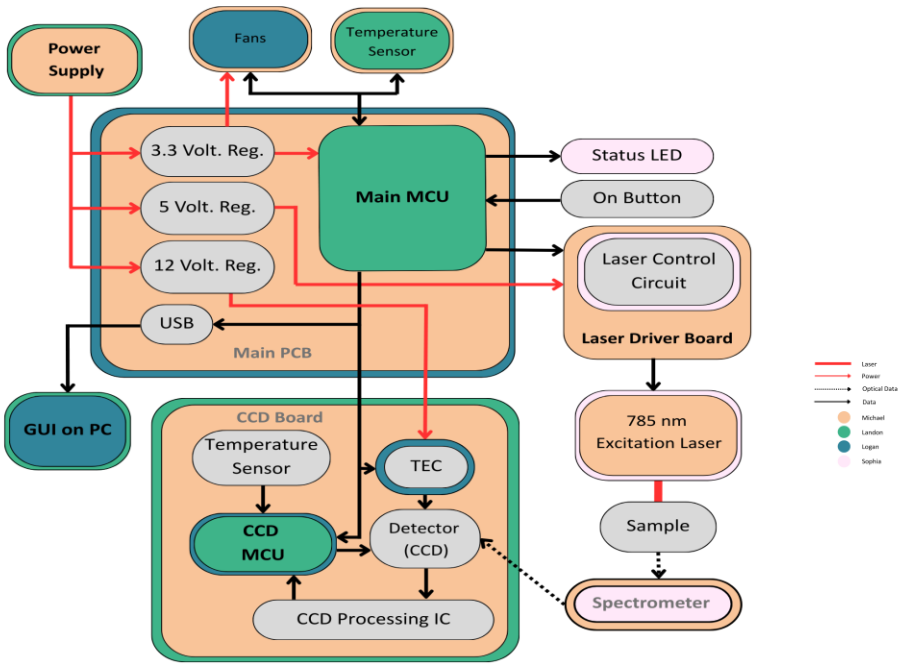


Figure 3. Hardware block diagram

Hardware block diagram visualizing larger components and PCBs for primary subsystems.

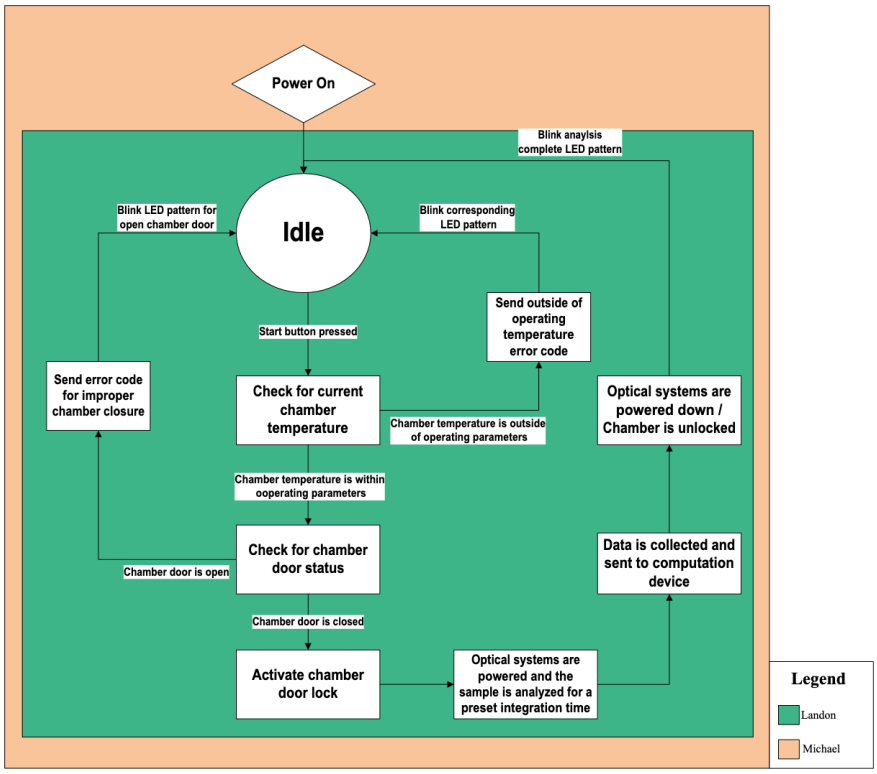


Figure 4: Software block diagram

Software block diagram that describes analysis chamber control systems.

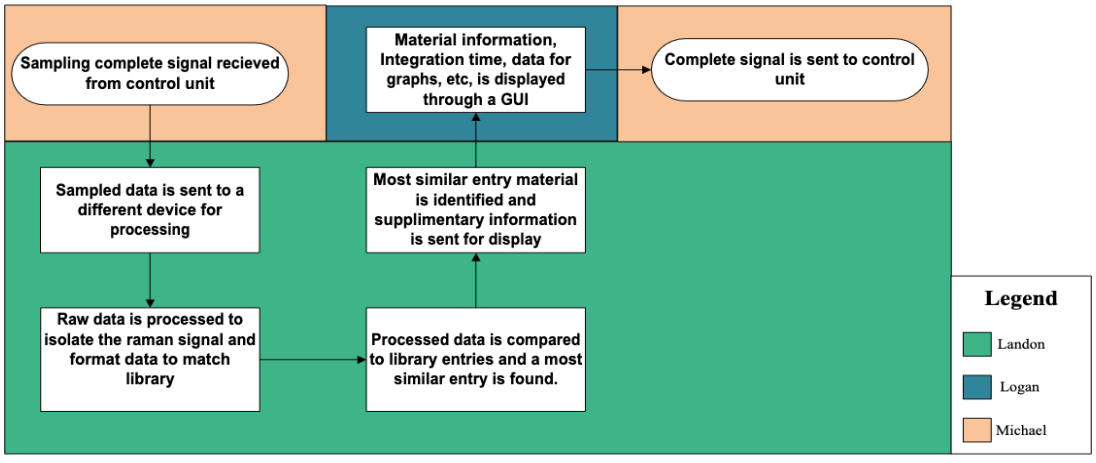


Figure 5. Signal Processing Software Block Diagram

Software block diagram that describes signal post processing.

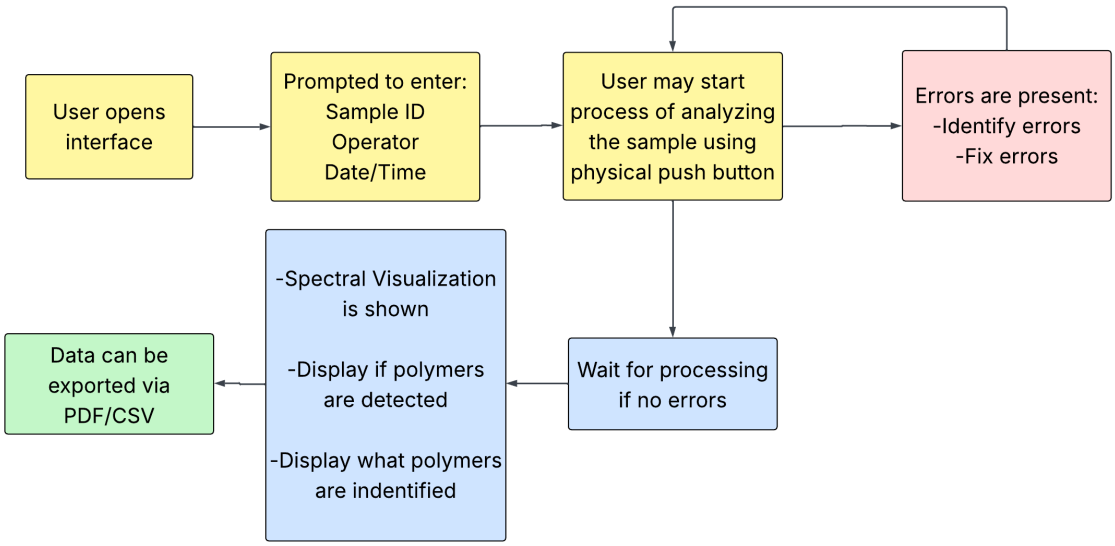


Figure 6. User Interface Diagram

Diagram that describes the flow of the user interface.

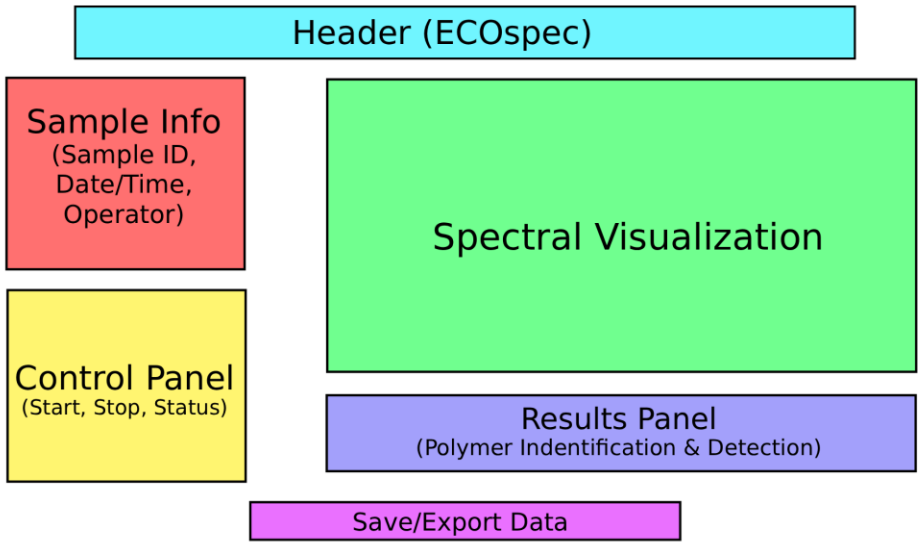


Figure 7. User Interface Layout

Diagram that displays a potential user interface layout.

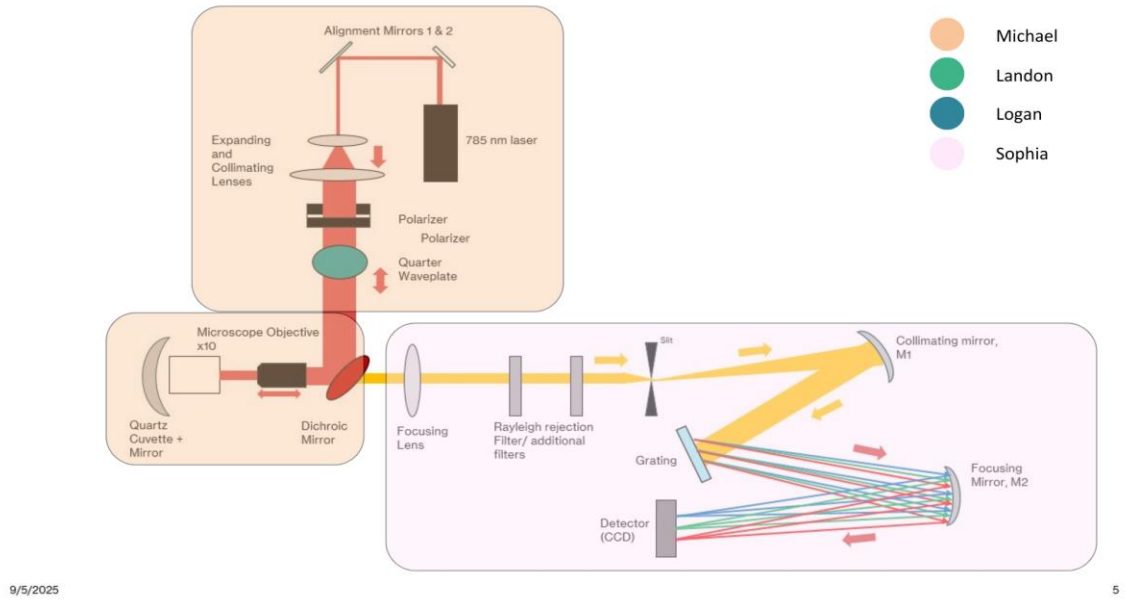


Figure 8. Optical Diagram

Optical design concept for collimation, illumination, and collection optics, along with task delegation.

2.5.1 Hardware

2.5.1.1 Main PCB

An ESP32 acts as the system's primary MCU. The ESP32 has a clock rate of 240 MHz, making it fast enough to handle most of the system's slower processes (user-response and UI). This primary MCU is responsible for all main service routines. This includes system start up, status LED indication, monitoring temperature, controlling the cooling system, controlling the laser for the spectra collection routine, control of safety interlocks, and sending formatted CCD data to the primary computer for processing and visualization.

A physical button will be implemented to turn on the device. LEDs on the device will act as status indicators for multiple system states: "On," "Laser On," "System Processing," "Device Locked," etc. A temperature sensor will be included to detect the internal ambient temperature of the device. A USB port will communicate with an external computer via UART or SPI. The external computer will be responsible for further post processing of the CCD output, graphing of spectral data, and overall control of the spectrometer.

2.5.1.2 CCD Board

A CCD detector is used to obtain the Raman spectra. The CCD would traditionally output directly to the signal analysis, but a Raman signal is notoriously weak. In order to detect the Raman signal, both strong cooling of the CCD and amplification of the CCD output will be necessary. A heatsink and thermoelectric cooler (TEC) will be the primary mechanisms to maintain operating temperature of the CCD. A signal amplification circuit, or premade CCD processor IC, will be utilized to amplify and digitize the CCD output.

A Teensy 4.1 acts as the system's CCD signal analysis MCU. The Teensy 4.1 has a clock rate of 600 MHz making it a more suitable option for control of the CCD electron collection/emptying

cycles and for basic processing of the data output from the CCD. The Teensy 4.1 will take in the amplified CCD output, organize the data into a format easy to begin processing with on the external computing side, and send the formatted data to the primary MCU for export to the external computer. Sidestepping of transfer from the Teensy 4.1 back to the primary ESP32 may be able to be sidestepped.

For system cooling, metal heatsinks, fans, a thermocouple, and a TEC device will be utilized to maintain temperature. A metal heatsink will be attached to the CCD, a thermocouple will be used to monitor the CCDs temperature, the TEC will be attached to the metal heatsink to continuously draw heat away from the CCD, and a fan to vent out general hot air from the system's internals. These cooling operations will be controlled by the ESP32 on the main PCB. The sole responsibility of the Teensy 4.1 is to control the CCD timing and prepare the CCD output for transfer to an external computer.

Raman spectroscopic measurements are very sensitive to thermal fluctuations. A certain operating temperature is required to obtain a high enough signal-to-noise ratio (SNR) from the CCD. Ideally, the CCD will operate at temperatures sub 40° C, but it appears that in practice applications involve temperatures as low as 20 C.

The type of CCD sensor itself must also be taken into consideration. There are front-illuminated and back-illuminated sensors. Back-illuminated sensors are typically more sensitive and have lower noise than front-illuminated sensors. In these devices, the bulk silicon substrate the sensor is been fabricated on is etched thin, allowing more photons to come in contact and absorb within the actual active region of the CCD sensor. However, because of how thin these structures can be, longer wavelengths, like some of the Stokes-scattered signals we want to detect, may pass through the active region. This light can then reflect off the insulator layer, creating an etalon-effect within the semiconductor layers themselves, creating noise and distortion in the output of the CCD.

2.5.1.3 Laser Driver board

The laser driver board will supply power and allow control of the laser. It will be required to control power to the laser, allow modulation of laser power, and closely monitor the status of the laser for integration with safety protocols of the device.

2.5.1.4 Power

A main 12 V 120 W PSU will be used to supply power to the whole system. High amperage draw is expected due to multiple sensors, cooling devices, multiple MCUs, and laser. Voltage regulators, mainly buck converters, will be used to supply power to devices requiring a lower voltage. This includes 3.3 V for the MCUs and fans, 5V for the laser and CCD, and 12 V for the TEC device.

2.5.1.5 Mechanical Components

A sample holder for the quartz cuvette will be needed to ensure proper placement and alignment with the laser for consecutive measurements. There will also need to be compensation to place macroplastic materials for testing. The diffraction grating will also have to have a very stable mount. Any misalignment of the grating and the lens focus the spectrum onto the CCD will distort the accuracy of the received spectrum signal. Use internal baffles and improved filter mounting to decrease background noise, stray light, and external fluorescence as much as possible.

An enclosure will be developed to house the optical and electrical components. The enclosure will allow for better physical stability and ease of transporting the ECOspec. The enclosure would also

help prevent other light sources from impeding our data and include interlocks for safety with laser use. A window made of laser safety glass to see the sample measurement taking place could provide a safe way for the user to partially view the sample excitation setup.

2.5.2 Software

2.5.2.1 Raman Spectra Comparison Library

To achieve the expected functionality of ECOspec, an advanced suite of spectral processing must be employed. This included conversion of raw spectral data into raw Raman spectra, through equipment baseline correction and the Raman shift formula. Following this, the data is run through a pre-processing pipeline, which includes removal of dark noise and fluorescence, rescaling Raman shift intensity values, and interpolation of the data to align x-axis for comparison. With the processed data, ECOspec will be able to compare the spectra of the unidentified sample with a pre-established spectra library of known materials using a similarity metric such as Pearson correlation of cosine similarity to classify the material present in the water sample.

2.5.2.2 GUI

The data collected from ECOspec will be sent directly to a computer for results to be seen and interpreted by the user. A user-friendly GUI will be implemented to show the results of what was found after utilizing the spectrometer and identifying potential microplastics in the samples. This GUI will be basic and easy to comprehend.

2.5.2.3 Calibration and Safety

X-axis pixel to wavelength calibration will be necessary to confirm the repeatability of measurements and so the true Raman shifts can be recorded. Y-axis intensity calibration could be implemented so that no peaks appear weaker than they really are due to how the detector responds to different wavelengths.

Safety checks for interlocks and device temperature will be in place before allowing for collection of Raman signal can occur.

2.5.2.4 Cooling

Another of ECOspec's software goals is component stability, primarily in the form of cooling systems for sensitive components within the test environment. The precision required to perform reliable Raman spectroscopy means that temperature control of both the collector and laser is paramount. To achieve this, the control systems will be able to maintain the desired temperature of the components to allow high quality signals to be achieved.

However, this cooling system involving a TEC is thought to induce noise in the CCD through the thermal fluctuations consequent of a temperature stability control signal. Instead of using a control signal causing the CCD to go through thermal fluctuations, we may be able to keep the TEC constantly running and wait for the temperature to reach a stable level.

2.5.3 Optics

2.5.3.1 Illumination Optics

The excitation laser is 785 nm. This wavelength was selected for a variety of reasons: a suspected decreased level of fluorescence, less detector saturation, and more prominent peaks. 532 nm laser would also be viable, but they are known to produce a lot of excess fluorescence which can saturate the detector and decrease the SNR. A 1064 nm laser is capable of producing Raman spectra with a very high SNR; however they are a very costly item. In traditional Raman spectroscopy setup, the laser spot size is minimized to increase the likelihood of generating a Raman signal. However, our goal is to retrieve a Raman signal from illuminating a large portion of a quartz cuvette. To ensure a Raman signal is generated, the laser will be set at a higher power than typical to compensate for dispersion over a larger area.

2.5.3.2 Filtering

In our research, the laser itself is strong enough to oversaturate the detector and wash out the Raman shift peaks. After the laser illuminates the sample, but before the light is collected and focused into the spectrometer setup, the laser light must be filtered out. To do this, a dichroic mirror will be employed to reflect the laser light away from the collection optics and allow the Raman shifted light in. Additional filtering, such as a long pass filter, will be used to block the broadband fluorescence. This long pass filter is used to block wavelengths shorter than the laser wavelength. Raman shifts in this region (Anti-Stokes scattering) are less numerous and have lower intensities.

After filtering, the Stokes scattered Raman signal is to be collected using the spectrometer setup. The main goal of the device to identify microplastics in water solutions. Water has a low Raman response, but high absorption in the IR spectrum which can contribute to the fluorescence of other molecules in the solution. A quartz cuvette is utilized to hold the samples as it is highly transmissive at our laser wavelength, it is not a Raman active material, nor does it produce fluorescence at the 785 nm wavelength.

2.5.3.3 Collection Optics - Spectrometer design

We plan on employing a Czerny-Turner layout for the spectrometer system. The Czerny-Turner is a common layout employed in many commercial spectrometers. It enables high spectral resolution and high optical flux while allowing a compact form factor. It includes a slit, a collimating mirror, a diffraction grating, focusing mirror, and a detector. Typically, the slit width controls the spectral resolution, and it ranges from 25-200 um. Good design practice for alignment includes starting with a larger slit and adjusting as we go. The first mirror is an off-axis parabolic mirror that collimates the light leaving the slit onto the grating. The beam's f/# directly correlates to the diameter and focal length of this mirror. The diffraction grating controls the dispersion of light. The blaze wavelength needs to be near our laser wavelength to maximize the dispersion efficiency at our chosen laser wavelength. The second mirror focuses the dispersed light onto the detector array. The focal length of this mirror controls the linear dispersion at the detector. Our detector of choice is a CCD, and the pixel size and array length are the main factors to be considered for detector selection. Gold coated mirrors will be selected due to their high reflectivity in a broad IR range. Further optical modeling in software such as Zemax is required to obtain a specific, optimized layout.

A drawback to the Czerny-Turner layout is that the off-axis mirrors more commonly induce coma and astigmatism, which are both unwanted aberrations that will reduce our resolution, and influence alignment negatively. Aberrations can be minimized with careful mirror selection and positioning.

2.5.3.4 Calibration plan for Spectrometer

Calibrating our spectrometer is an important step in the development process to ensure repeatability and collect comparable samples. It is especially important for a spectrometer designed for a Raman

application because the Raman shift on the x-axis of the spectrum is critical for chemical identification. X-axis calibration consists of a 2-stage process- including wavelength calibration and Raman shift calibration. Wavelength calibration includes assigning each pixel a wavelength value, which is done by illuminating the spectrometer with an emission lamp with known strong peaks, such as Hg-2 or Ne, and generating a function to assign all the pixels to a certain value. This assignment could be done with a fitting routine to map pixel to nanometer space. The Raman shift calibration converts the x-axis from wavelengths to Raman shift by using the laser wavelength and subtracting each wavelength from it. [Fig. 7] Y-axis calibration is also done to confirm that the intensities of the peaks are at an appropriate ratio that is accurate to the source being used.

Figure 7: Raman Shift Equation

$$Raman\ shift_i = (\lambda_{ex}^{-1} - \lambda_i^{-1}) \times 10^7$$

The equation for Raman shift is shown above. The excitation wavelength of the laser is subtracted from each wavelength at each pixel. [12]

2.6 Required Specifications

Table 1: Optical and Hardware Component Specifications

Optical Prototype Specifications		
Component	**Parameter**	**Value**
Spectrometer	Short integration time	< 15 seconds
	High Spectral Resolution	< 2 nanometers per pixel
Laser	Wavelength	785 nm
	Laser Power	150 mW
	Beam Diameter	< 2 mm
Excitation Specifications	Microscope Objective	Maybe 10x
	Cuvette size	3.5 mL, 12.5 mm x 12.5 mm x 45 mm
	Cuvette Type	Quartz
Raman Filtering Optical Components		
Component	**Parameter**	**Value**
Dichroic Mirror	Cut-on Wavelength	805 nm
	Reflection Wavelength	400 - 785 nm
	Transmission	825 – 1300 nm
Long pass filter	Rejection Wavelength	<= 785 nm
	Transmission	TBD
Extra filters	Rejection Wavelength	TBD
	Transmission	TBD
Spectrometer Optical Components		
Diffraction Grating	Groove Density	1200 lines/mm
	Blaze Angle	800 nm
Slit	Slit Width	25 um
Concave Mirror 1	Off-axis parabolic	Gold coated

Concave Mirror 2	Off-axis parabolic	Gold coated
Laser Alignment Components		
Mirror 1	TBD	TBD
Mirror 2	TBD	TBD
Polarizer	TBD	TBD
Waveplate	TBD	TBD
Lens 1	TBD	TBD
Lens 2	TBD	TBD
Hardware Component Specifications		
Component	**Device Name**	**Parameters**
Main MCU	ESP32	240 MHz
CCD MCU	Teensy 4.1	600 MHz
CCD Sensor	ESPROS Photonics AG EPC901-CSP32-033	1024 H x 1 V
ADC	MCP3008	10-bit resolution
TEC	TBD	TBD
3.3 V Voltage Regulator	TBD	TBD
5.2 V Voltage Regulator	TBD	TBD
9-12 V Voltage Regulator	TBD	TBD
CCD Amplifying Transistor	TBD	TBD
12 V PSU	TBD	Handles up to 10 A

Table 2: Engineering Requirements for the Performance and physical features of the envisioned system.

Overall System Specifications	
Parameters	**Target Value**
Detection Accuracy*	± 10 nm
Total Integration Time	< 20 seconds
High Spectral Resolution	< 2 nm per pixel
Lowest Concentration Detected	*Requires further research
Microplastics Measured Size	< 5 mm
System cooling	Maintain temperatures < 40° C
Broad Spectral Wavelength Range	> 250 nanometers
Dimensions of Device	< 50 cm x 100 cm x 100 cm

***Refer to Appendix B for peaks of interest for each plastic type**

Figure 8: House of Quality

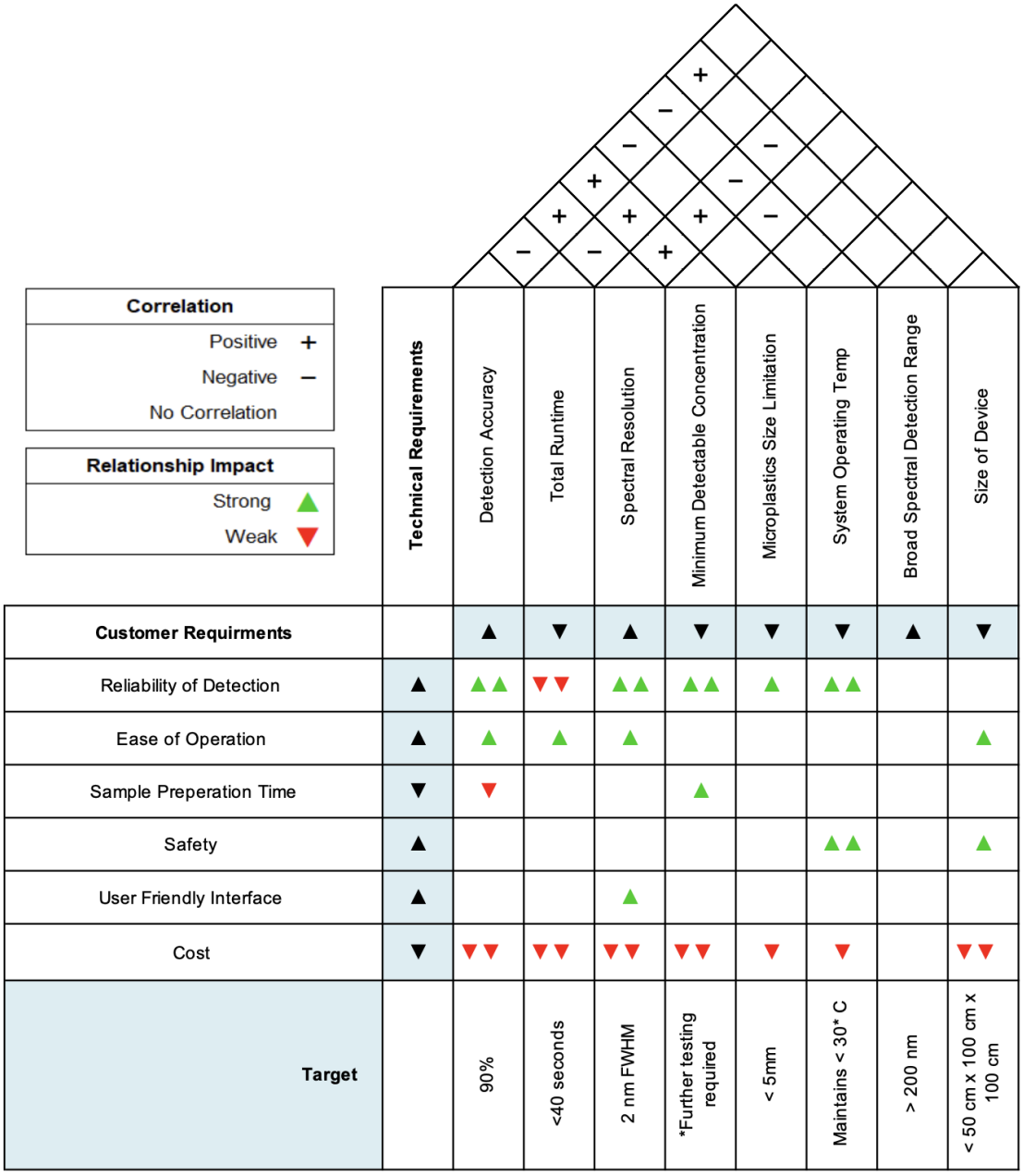
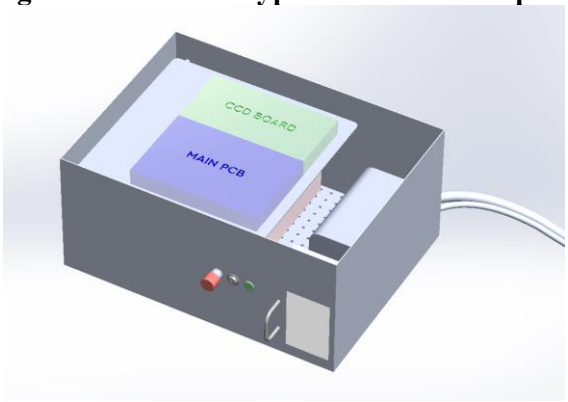
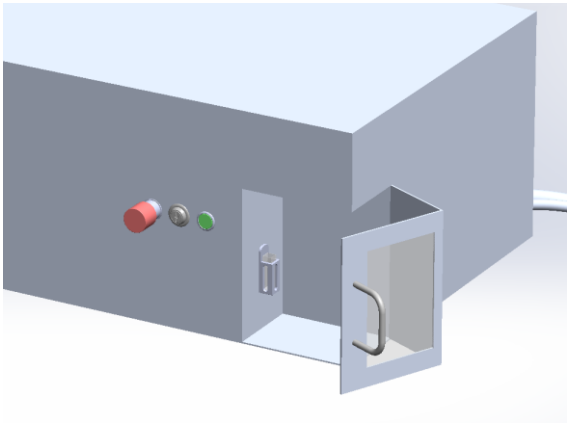


Diagram that displays the relationship between customer and technical requirements, as well as demonstrates the correlation between the technical requirements.

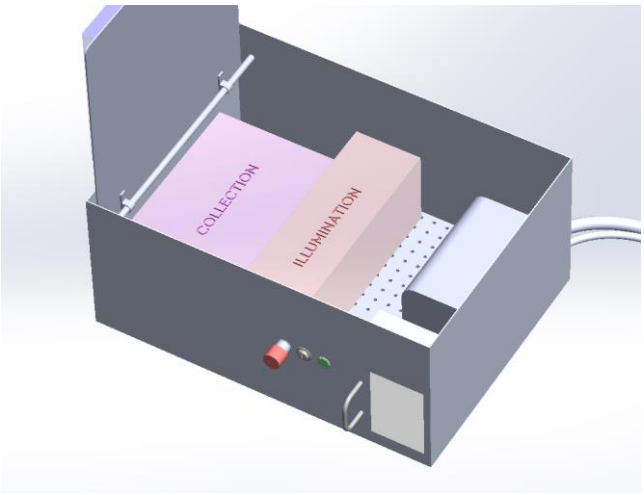
Figures 9-11: Prototype illustration/blueprint



Isometric top view, illustrating potential board placement. A hinge system will be employed for placement of the electrical boards and compactness of the device.



Dimetric front facing view highlighting the door with laser safety glass enclosing where the sample will be placed, the interlock, start button, laser key lock, and an emergency stop.



Dimetric top-down view displaying the optical subsystems placed underneath the hinge system.

3 Administrative Content

3.1 Table 3: Projected Budget Estimate

Component	Part Name	Quantity	Unit Price	Total Price
Optical Components				
785 nm Laser	Ocean Optics Raman Laser 785 nm	1	Borrowed	Borrowed
Flat Mirrors	Gold Flat Mirrors	2	Borrowed	Borrowed
Mirror Mounts	½" Diameter Mounts	2	Borrowed	Borrowed
Collimating Lens	Thorlabs LA1027-AB f=35 mm	1	$52.22	$52.22
Collimating Lens	Thorlabs LA1509-AB f=100 mm	1	$52.22	$52.22
Polarizer	TBD	1	Borrowed	Borrowed
Waveplate	TBD	1	Borrowed	Borrowed
Dichroic Mirror	805 nm Cut-on	1	Borrowed	Borrowed
Microscope objective	10x magnification	1	Borrowed	Borrowed
Collection Lens	TBD	1		
Diffraction Grating		1	Borrowed	Borrowed
MCU and Sensor Components				
Primary MCU	ESP32	1	$8.99	$8.99
CCD	ESPROS Photonics AG EPC901-CSP32-033	1	$32.68	$32.68
Detector MCU	Teensy 4.1	1	$29.60	$29.60
LEDs	RGB multi-pack	4	$9.99	$9.99
Button	TBD	1	$4.99	$4.99
Sample Preparation				
Quartz Cuvette	Quartz Cuvette	1	Borrowed	Borrowed
Signal Amplification Circuit				
Transistor	TBD	1	$7.99	$7.99
Op Amp	TBD	1	$12.99	$12.99
10-bit ADC	MCP3008	1	$4.50	$4.50
Resistors	TBD			
Inductors	TBD			
Capacitors	TBD			
Cooling System				
TEC Cooler	TBD	1	$20.00	$20.00
Thermocouple	TBD	1	$13.99	$13.99
Fans	Computer Fans	3	$15.99	$47.97
Temperature sensor	TBD	1		

Heatsink		1	$50.00	$50.00
Power System Components				
PSU	12 V 30A Switching PSU	1	$26.68	$26.68
12 V Boost	TBD	1		
5 V Buck	TBD	1		
3.3 V Buck	TI TPS62162DSGT	1	$1.98	$1.98
Total Cost				
Optical Components		$104.44		
MCU and Sensor Components		$86.25		
Sample Preparation		$0.00		
Signal Amplification Circuit		$25.48		
Cooling System		$81.96		
Power Systems		$28.66		
Grand Total		**$326.79**		

3.2 Senior Design Milestones

Table 4: Senior Design 1 Milestones

Task	Start Date	End Date	Notes
Group Formation	8/19/25	8/28/25	Form project group on Webcourses.
Project Idea	8/19/25	8/28/25	Brainstorm and finalize project idea.
Commitee Formation	8/28/25	9/5/2025	Find a minimum of 2 ECE and 1 PSE faculty members.
D&C Completion	8/28/25	9/5/25	Make a meeting time to meet with necessary advisors.
D&C Meeting	9/10/25 9:00 A.M.	9/10/25 9:30 A.M.	Meet with Dr. Sundaresh & Dr. Kar.
D&C Document Revision	9/10/25	9/12/25	If needed revise D&C document.
Research Components	9/12/2025	TBD	Begin research on potential components for use.
Begin PCB Design	TBD	TBD	Start CAD for PCB.
Optical Midterm Demo		10/07/25	Physical optical demo in undergrad lab
Midterm Milestone Report	9/13/25	10/31/25	Complete Midterm Report.
Midterm Report Revision	11/3/25	11/7/25	If needed revise Midterm Report.
Final Report		11/25/25	Complete Final Report.
Mini Demo Video		11/25/25	Complete Demo Video.

Table 5: Senior Design 2 Milestones

Task	Start Date	End Date	Notes

Order PCB	TBD	TBD	Initial order for first rendition.
Fabricate PCB	TBD	TBD	Begin fabrication of the PCB.
Complete UI	TBD	TBD	Complete final touches on User Interface.
Finalize Optics	TBD	TBD	N/A
Begin fabrication of housing	TBD	TBD	N/A
PCB design revision	TBD	TBD	If necessary, revise the PCB design and order a new one.
Finalize housing	TBD	TBD	N/A
Testing	All day	Everyday	Testing will be done throughout the entire process of fabrication.
Final Adjustments	TBD	TBD	N/A
Final Presentation	TBD	TBD	N/A

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5 Appendix B Raman Fingerprint Peaks of Plastic

Table 6: Known Raman Peaks of PET, PS, and Nylon.

Polymer	Wavenumber (cm^{-1})
PET	633
	854
	1116
	1178
	1288
	1308
	1414
	1452
	1613
	1724
	2895
	2960

PS	616
	795
	1003
	1030
	1150
	1205
	1310
	1352
	1410
	1455
	1527
	1583
	1600
	2915
	3060
Nylon	880
	953
	1061
	1083
	1112
	1134
	1213
	1257
	1300
	1380
	1440
	1634
	2850
	2907
	2922
	3298