ECD512 Raman Spectrometer for Soil Sample Classification

Design Report

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Client: Binghamton University Rover Team

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Submitted by:
Rebecca Carpenter, Team Lead, Computer Engineering
James Plummer, Software Lead, Computer Engineering
Christian McCormack, Hardware Lead, Electrical Engineering
Devan Bade, Financial Manager, Electrical Engineering

Project Advisor: Prof. Douglas Summerville

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Thomas J. Watson College of Engineering and Applied Science
Binghamton University
Binghamton, NY

Abstract

This report presents the development of a custom Raman spectrometer designed for the Binghamton University Rover Team (BURT) to analyze soil samples for signs of life during mock planetary exploration missions. The spectrometer uses Raman spectroscopy to detect organic compounds by analyzing unique light patterns scattered by aqueous soil solutions, providing critical data for BURT's Science Mission in the University Rover Challenge (URC).

The project's goal was to create a portable, durable, and user-friendly device that could be integrated into the rover for real-time field analysis. A 24V source powers the spectrometer, stepped down using buck converters, and controlled via an user interface built on a Raspberry Pi 4 and a Raspberry Pi Pico 2 microcontroller. The device displays real-time Raman spectra to offer insights into the chemical composition of the samples, allowing the team to identify potential signs of life quickly.

A 532nm laser was chosen for its superior performance with organic materials and a charge-coupled device (CCD) sensor was carefully sourced to ensure precise spectral data capture. The $1500 budget was strategically managed, with $726 spent primarily on optical components to maximize accuracy. To promote sustainability, we minimized waste by 3D printing parts and designed the system to be energy-efficient.

This report covers the development, integrations, and testing from the initial problem definition and design requirements to hardware and software integration, safety considerations, and environmental impact. By developing this Raman spectrometer, the Binghamton University Rover Team will have a valuable scientific tool for future URC missions, enabling advanced soil analysis in competitive and real-world scenarios. This project not only enhances the Binghamton University Rover Team's capabilities but also sets a foundation for future rover teams to push the boundaries of field research and scientific discovery.

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1 Introduction

1.1 System Overview

This report is for the ECD512 Raman Spectrometer project of 2024-2025.

The Raman spectrometer project is being developed for the Binghamton University Rover Team to aid in the classification of soil samples. This system is designed to detect the status of life in soil by analyzing aqueous soil solutions using Raman spectroscopy. The primary goal is to create a portable, compact, and self-contained device that can eventually be mounted on the rover for fieldwork.

The spectrometer will operate with a 24V power source and utilize standard electrical components to ensure durability and compatibility with the rover's power infrastructure. It will feature a graphical display, enabling real-time visualization of the resulting spectra,in order to provide efficient and clear analysis for the Rover Team.

The Raman Spectrometer will be tested separately from the rover to ensure it meets all design specifications. Once the testing is complete and the device is validated, it will be used to identify organic compounds and possible signs of life in soil samples, making it a valuable tool for the Binghamton University Rover Team.

The final deliverable includes a user guide for operating the spectrometer and comprehensive technical documentation, ensuring future teams can integrate, maintain, and utilize the device effectively.

1.2 Document Overview

This report provides a detailed description of the design, development, and testing of the custom-made Raman Spectrometer for the Binghamton University Rover Team. It begins with an introduction to the project's goals and requirements, followed by a thorough system overview. The report also includes a summary of relevant documents and references.

Key sections cover the problem definition, technical challenges, and specific design requirements. The system design section outlines the decision-making process, components, and interfaces, along with hardware and software design specifics, safety measures, and potential environmental impact.

The project development section addresses risk management, scheduling, and budgeting. This is followed by a breakdown of the system implementation and the results of the evaluation phase, which includes testing outcomes and project assessment.

The report concludes with an analysis of the system's future potential, a glossary of acronyms, and a list of references for further information.

2 Referenced Documents

The following documents of the exact issue are shown from a part of this report as specified herein.

a. ECD 512 Raman Spectrometer for the Binghamton University Rover Team Project Specifications
b. A review of 3D printing techniques for environmental applications
c. Basics of Raman Spectroscopy: Applications and Methods
d. Environmental Impacts of Lithium-Ion Batteries
e. Fabricating a Low-Cost Raman Spectrometer to Introduce Students to Spectroscopy Basics and Applied Instrument Design

3 Problem Definition

3.1 Problem Scope

The Binghamton University Rover Team requires a portable device to analyze soil samples for signs of life, which is crucial for the Science Mission of the URC competition. This project aimed to design a custom-made Raman spectrometer that can determine the presence or absence of life by analyzing aqueous soil solutions. The device must be compact, durable, and self-contained, with dimensions not exceeding 300mm x 200mm x 100mm, to ensure it can be easily mounted on future rovers.

Project requirements include powering the spectrometer with a 24V source, weighing less than 2kg, and displaying the resulting spectra graphically on a screen. The spectrometer must handle standard cuvettes for soil solution samples and be built using standard electrical components. Additionally, the system must be user-friendly and well-documented with clear instructions in the user guide, for future use by the Rover Team. The design must also stay within a budget of $1500, covering all necessary components and safety equipment.

3.2 Technical Review

Raman spectroscopy is a technique used to analyze various materials' composition by studying how light interacts with their molecular structure. When a laser is directed at a sample, a small portion of the light scatters in a unique pattern, revealing specific details about the material's chemical makeup. This method is especially useful in identifying organic compounds and detecting possible signs of life in soil samples, making it an ideal tool for use in the URC competition.

For the Binghamton University Rover Team, a portable Raman spectrometer will enhance their ability to classify soil samples directly in the field. The spectrometer will be designed to analyze aqueous soil solutions, providing insights into the presence or absence of life by identifying organic molecules. Currently, the Rover Team lacks any spectroscopy capabilities that can perform these analyses reliably while mounted on their rover.

To address this, the Raman spectrometer will use a 24V power source and rely on standard electrical components to ensure compatibility and durability. The spectra generated from the analysis will be displayed on a computer for clear visualization and interpretation, enabling users to assess the results quickly. Additionally, the spectrometer will feature a user-friendly design, making it accessible for future teams to operate without extensive technical knowledge.

The development of this spectrometer aims to provide the Rover Team with a valuable scientific instrument, capable of collecting crucial data about soil composition in competition environments.

3.3 Design Requirements

The following section contains the requirements and stretch goals that should be met by the designed Raman spectrometer. For a more comprehensive list, including qualification methods and requirement categories, see the specifications document in Appendix A.

3.3.1 Derived Hardware Requirement Specification

- The device shall be powered using a 24V source {ECD512-R-001}
- The device shall use standard electrical components {ECD512-R-005}
- The device shall be a self-contained unit {ECD512-R-006}
- The project shall include a comprehensive user guide describing the device's functionality with a bill of materials {ECD512-R-007}
- The device shall process samples contained in standard cuvettes {ECD512-R-004}

3.3.2 Derived Software Requirement Specification

- The device's resulting spectra shall be displayed graphically on a screen {ECD512-R-002}
- The device shall be able to produce a Raman spectra suitable for status of life analysis of a selected aqueous soil solution {ECD512-R-003}

3.3.3 Derived Hardware Stretch Goals

- The device should measure no more than 300mm x 200mm x 100mm (LxWxH) {ECD512-G-001}
- The device should be capable of integration onto the 2025 Rover {ECD512-G-004}
- The device should not draw more than one amp from the 24-volt source {ECD512-G-005}
- The device should not weigh more than 2 kilograms {ECD512-G-006}

3.3.4 Derived Software Stretch Goals

- The device's firmware should be written in C/C++ {ECD512-G-002}
- The results display should include insight into the chemicals found in the solution through analysis of the resulting spectra within 5-10 minutes {ECD512-G-003}

4 System Design

4.1 System-Wide Design Decisions

4.1.1 Laser

One of the major design decisions needed for this project was the choice of laser. This significantly impacts the quality of the Raman spectra, and as such, significant research was put into this decision. Several factors were considered to decide which laser model would be chosen, including wavelength, cost, safety, and power, as these affect the resolution of the spectra. After researching several other Raman spectrometer designs, it was noted that most used a 532nm or a 785nm laser. Ultimately, a 532nm laser was chosen for this design because it is more efficient when working with organic materials than the 785nm laser, making it the superior choice for working with soil samples.

After determining which wavelength laser to use, research was done to find a low-cost but relatively high-power laser. Based on research of similar spectrometer designs, most used a laser with an output power of at least 5mW, with many designs reaching closer to 50mW. Taking into account product availability, cost, and safety, a laser diode with an output power of 50mW was chosen for this design.

4.1.2 Microcontroller

For this project, a wide variety of microcontrollers would sufficiently meet the processing and input and output (I/O) needs of the spectrometer. Initially, a Teensy 4.1 was considered due to its high processing speed, large memory, and compatibility with the Arduino IDE. It has an ARM Coretx-M7 processor running at 600MHz and 1024 Kb of RAM made it seem like an excellent choice especially due to the fact that it was used by the Rover team previously.

However, during development and testing, significant timing issues were discovered when using the Teensy's on-board ADC. The delays introduced during the CCD readout and data acquisition were inconsistent and held an unacceptable level of precision. As a result, our team switched to a Raspberry Pi Pico 2. This microcontroller offered much more predictable and malleable timing behavior due to the bare-metal programming used. The lower-clocked dual-core ARM Cortex-M0+ processor, running at up to 133 MHz, provided enough performance to generate the required signals and reliably read the analog values. Importantly, the ADC's behavior was much more consistent and easier to synchronize with our inputs.

4.1.3 Charged Coupled Device (CCD)

Selecting the linear CCD sensor was guided by several factors, primarily cost, precision, clock frequency, and product availability. Research was done into similar Raman spectrometer designs to provide guidance when choosing a specific CCD sensor model, to ensure similar specifications were met. The greatest challenge faced when determining the final CCD sensor was product availability. Many CCD sensors would have been compatible with this project, but finding an option from a reliable manufacturer and supplier proved difficult. Ultimately, a linear CCD sensor from Toshiba, available on Digikey, proved to be the best option. This sensor has an input voltage of between 3-5.5V, matching that of other electrical components, and thus reducing the complexity of the circuitry. Additionally, the chosen CCD sensor has 3648 sensing elements, providing high-resolution results, and its required clock frequency is between 0.8-4.0MHz, which is easily achievable with the Pico 2 microcontroller.

4.1.4 Results Display

Based on this project's requirements, it was determined that a graphical user interface (GUI) would need to be designed to graphically display the resulting spectra, allow for user interaction with the system, and provide insight into a sample's chemical composition. For the implementation of the results display GUI, several options were considered. First, the decision was made to utilize a Raspberry Pi to run the GUI program to further mimic the Rover Team's system and improve future integrations. The primary language considerations for the GUI were Python or the Flutter software development kit (SDK), which utilizes the Dart language. Originally, the decision was made to use Flutter, as this is what the Rover Team uses for their "Dashboard" GUI. After further consideration and testing however, the GUI was converted to Python, to improve integration with the rest of the spectrometer design and reduce overall software size. The Rover Team was also able to provide a Raspberry Pi 4 for use in this project, further reducing the money spent.

4.1.5 Optics

During the initial research done on Raman spectrometer designs, several different optical setups were used, however, they were all very similar. Each followed the general concept of directing the laser through the sample and then collecting the output Raman signals into a CCD sensor. For this design, it was decided to follow the optical setup discussed in the paper "Fabricating a Low-Cost Raman Spectrometer to Introduce Students to Spectroscopy Basics and Applied Instrument Design", due to its excellent documentation and relatively easy setup. This setup splits the optics into two groups: the probe optics and the spectrometer optics.

Within the probe optics, the laser is directed into the sample using a beam splitter and focusing lens. Then, any Rayleigh scattering is removed with a long-pass filter and another lens is used to direct it into the spectrometer optics. The Raman scattering is then redirected using mirrors towards a diffraction grating where the wavelengths are separated and collected by the CCD. The main decisions needed for the optical setup were the exact versions of each component as well as their positioning. Although the optical setup presented here is very similar to that of the paper, the exact components, and therefore the distances and angles needed, are slightly different. The component decisions were made by inspecting those used in the paper, as well as by other rover teams, and compiling those that matched the needs of this project.

4.2 System Components and Interfaces

Most of the system components compose the optics of our design, and the rest comprise the electrical and computing infrastructure. The optical system will consist of a laser, beam splitter, here a microscope slide, two bi-convex lenses, a long-pass filter, 2 concave mirrors, a diffraction grating, and a linear CCD sensor. The electrical and computing components will comprise a 24V battery, three buck converters, the CCD sensor, a Raspberry Pi Pico 2, and a Raspberry Pi 4. The CCD sensor acts as the interface between the optical setup and the computing system, by converting the light spectra into a data stream. This data will be sent to the Pico 2 and Raspberry Pi for further manipulation and analysis. The buck converters allow for the efficient conversion of the 24V input voltage to the lower voltages needed for the remaining electrical components.

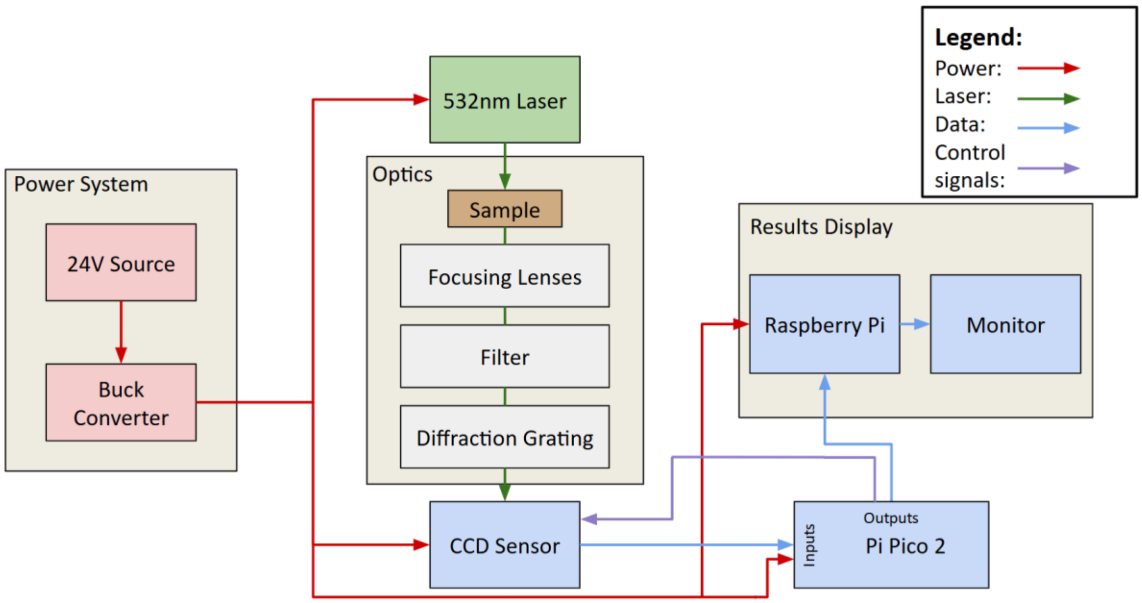

Figure 1: High-Level System Diagram

Figure 1 shows the project's high-level system diagram, which illustrates the interfaces between all of the components. The center of the diagram is the optical array, which will be discussed in greater detail in the Hardware Design section. The laser will first be directed through the sample, then the Raman scattering will be isolated with a long-pass filter and directed into a diffraction grating. This will separate the light into its spectral components which are collected by the CCD sensor. The CCD sensor will then send that data to the Pico 2, where the relevant information will be separated and sent to the Raspberry Pi. Here, additional data processing is conducted to reduce environmental noise. Additionally, the spectra will be displayed graphically and can be further analyzed for the chemicals present.

4.3 Concept of Execution

The Raman spectrometer's intended use is for the BURT. The Rover Team competes in the University Rover Challenge, an international competition where university teams must design and build a mock Mars rover. The URC consists of four missions, one of which is the Science Mission. During this 30-minute mission, the team must use the rover to collect and test soil samples from the Utah desert. Currently, the BURT is limited to tests that can use simple sensors, such as a CO_2 sensor, or that are colorimetric, meaning that there is a visible color change in the solution. The Raman spectrometer will significantly increase the Rover Team's testing capabilities. While the spectrometer is planned to be fully integrated with the Rover Team, for this project it is a stand-alone device. To ensure integration, later on, the power and communication schemes mimic those of the BURT.

The spectrometer is powered by a 24V source, mimicking that of the BURT. Three buck converters will then be used to step down this voltage into the 3.3V, 3.7V and 5V necessary for the CCD sensor, laser, and Raspberry Pi respectively. Users are able to load an aqueous soil sample into the spectrometer, and then use the push button and results display to start collecting data. The results display uses a Raspberry Pi 4 to interface with the user as well as the Pico 2, which runs the firmware code. Users can start a testing sequence via the results display, a power switch for the laser, and a push button on the side of the enclosure. The laser is directed through the sample, and a series of optics before reaching the CCD sensor. This ensures the Raman scattering can be detected by the system.

The Pico 2 firmware code sends several critical signals to the CCD to successfully collect data. Once the CCD sensor has collected the Raman scattering, the Pico 2 will interpret the data package, and send the relevant information back to the Raspberry Pi for display. The results display will then show the user the sample's Raman spectra graph.

4.4 Hardware Design

4.4.1 Circuit Design

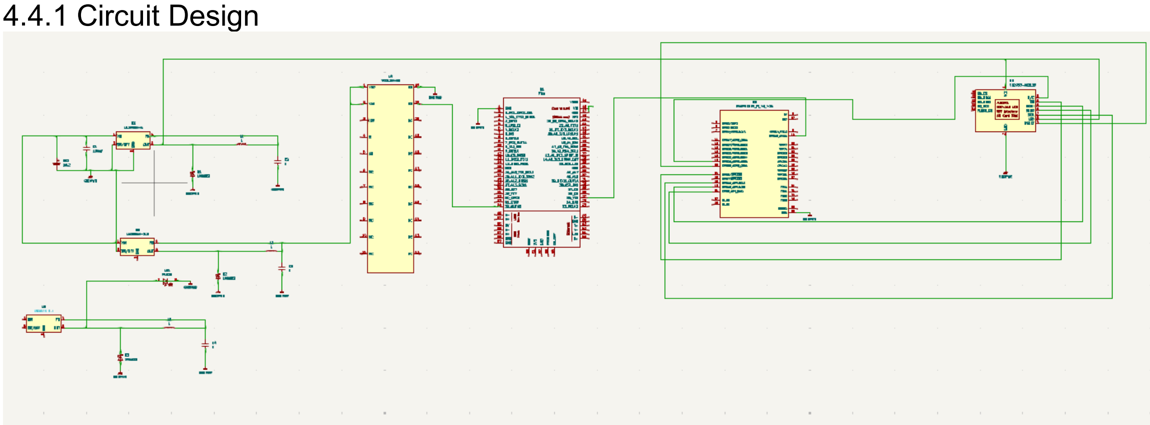

Figure 2: Circuit Design Schematic

As required by the project's specifications, the spectrometer must be powered by a 24V source. The maximum voltage of the chosen battery is 25.2V, which needs to be stepped down for the CCD sensor, laser, Pico 2, and Raspberry Pi. Figure 2 shows the overall schematic used for the spectrometer. On the left are three buck converters, one of which will output 5V, one that outputs 3.3V, and another that outputs 3.7V. The buck converter that is outputting 5V powers the Raspberry Pi. Since no other components use this power line, the Raspberry Pi will receive a constant voltage and be able to draw the necessary current. The buck converter that outputs 3.3V powers the CCD sensor. The laser is powered by the buck converter that is outputting 3.7V. The CCD sensor will collect the resulting Raman scattering from the optics, and this data will be converted and sent to the Pico. The Pico will then send the formatted data to the Raspberry Pi, and the results will be displayed on the display screen.

4.4.2 Optics

The optics of our Raman Spectrometer play a critical role in ensuring the accuracy and clarity of the spectral data we collect. The system starts with a 532 nm solid-state laser diode, chosen for its strong Raman signal generation and low fluorescence interference, making it ideal for organic materials. The laser's high-energy photons efficiently excite the molecules in the soil samples, causing inelastic scattering that generates distinct Raman signals. This wavelength also strikes a good balance between cost, availability, and performance, making it suitable for our compact and budget-conscious design.

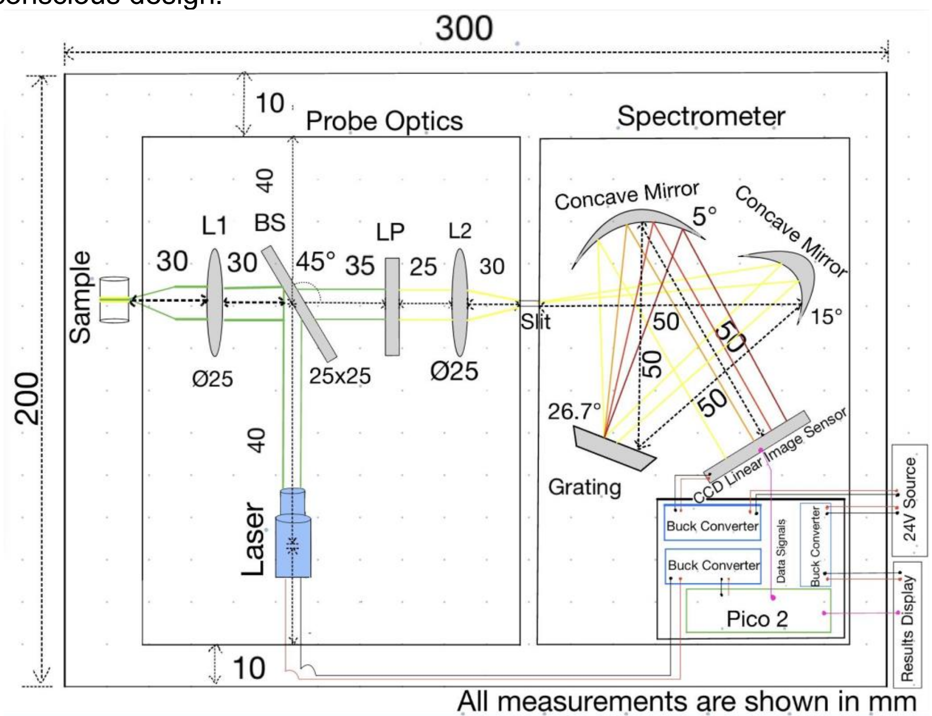

Figure 3: Optical Configuration

To direct and refine the laser beam, we implemented several optical components. A microscope slide acts as a simple yet effective beam splitter, reflecting the laser beam toward the sample while allowing the scattered Raman light from the sample to pass through. Both the scattered light and laser beam are focused using a bi-convex lens (Ø1", f = 30 mm), ensuring these essential signals remain on precise paths. We included a longpass filter (550nm cut-on) to eliminate Rayleigh scattering, allowing only the Raman-shifted light to continue through the system. This isolation step is crucial for obtaining clean and interpretable spectra.

The final stage of our optical path involves two dielectric-coated concave mirrors (f = 50 mm), which focus the filtered light onto a ruled diffraction grating with 1800 grooves per millimeter. This grating disperses the light into its component wavelengths, enabling the CCD sensor to capture a detailed spectrum. Although a 50μm pinhole was originally planned to be used to reduce background noise; it was found to reduce the spectral intensity significantly, and was removed from the optical setup. By carefully selecting and aligning these components, we will ensure that the spectrometer provides high-precision data while remaining within our $1500 budget. Each component was chosen not only for its performance but also for its compatibility with the rugged field conditions the Rover Team may encounter during competition missions.

4.4.3 Enclosure

To ensure the optical components remain stable and dust-free in the rugged environments faced by the Rover Team, a 3D-printed enclosure was designed. This enclosure features mounting points for each optical component, as well as space for the system's custom circuitry. Figure 3 shows the optical layout of the spectrometer, including the required measurements to ensure the optics function properly while maintaining the desired 300x200x100mm footprint. Additionally, Figure 4 shows the final CAD model of the enclosure used. All wires exiting the enclosure, such as the USB cable needed for the Raspberry Pi, will pass through a grommet to prevent the accumulation of dust in the spectrometer. In addition to the enclosure, all optical mounts were also custom-made and 3D printed. Most of these components feature screw slots instead of holes, allowing for additional flexibility when fine-tuning the optical angles. An example of this can be seen in Figure 5. Additionally, several screws were used between the lid and base of the enclosure to further improve dust-proofing.

Figure 4: CAD Model of Enclosure Design

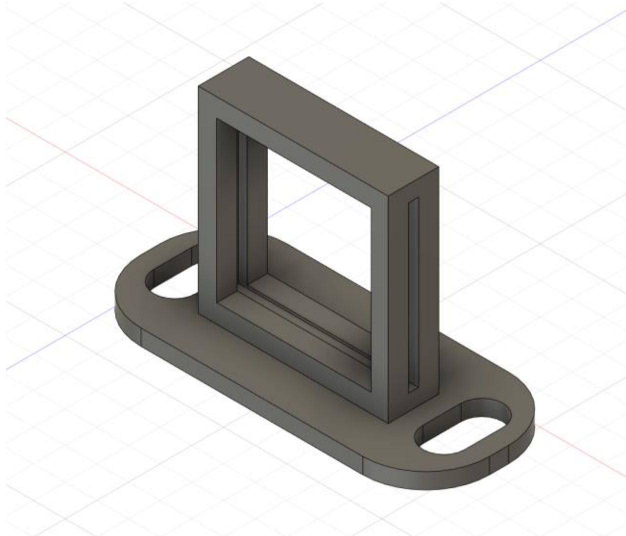

Figure 5: CAD Model of Beam Splitter Mount

4.5 Software Design

4.5.1 Firmware

A Raspberry Pi Pico 2 serves as the main microcontroller for our project. The Pico 2 is programmed using a bare-metal environment in C. The firmware code's primary function is to act as the bridge between the hardware and the Raspberry Pi. A button press will send a start signal to the Pico 2, which will then send signals to the CCD sensor and collect the corresponding data. The signals being sent to the CCD are as follows. A 2 MHz master clock is used to control the timing of everything in the CCD, a shutter signal allows the light sensors to start collecting data, and an integration clear gate signal sends the data to the sensor's output pin where it is collected by the Pico's on board ADC. The output of the CCD sensor consists of "Dummy" output bits at the beginning and end of the data array. The Pico 2 processes the data by removing these bits and isolating the effective data. Then, this data is sent to the Pi for further processing and visualization using the results display.

4.5.2 Results Display

The results display allows the user to easily interact with the Raman spectrometer during use. The software was written with Python, allowing for easy integration and testing both within the scope of this project as well as in the Rover Team's future uses. The results display runs off of a single Python script, and utilizes saved data text files for noise reduction. To run this code, the user simply needs to open the Python code, and start running the program in their chosen software editor. For this project, all testing was done using Thonny, a common editor that is pre-downloaded on many Raspberry Pis. Within the software code, the spectral data is read in from a Serial USB connection with the Pico 2. The data is first checked to ensure it is within a valid range, and is then saved in an array. Data processing steps are then taken to improve the quality of the displayed Raman spectra.

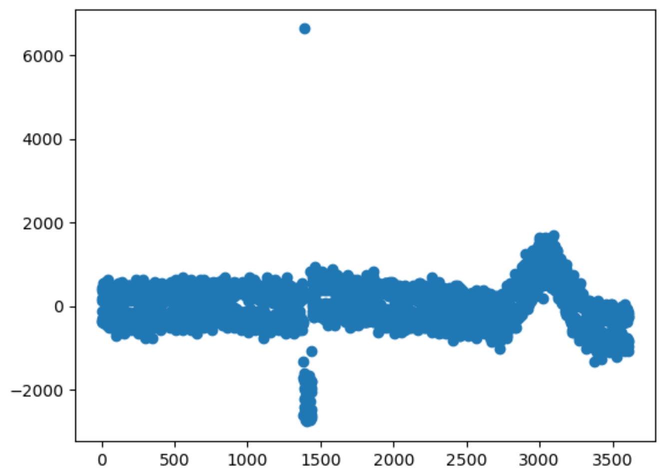

Figure 6: Spectra Results for Water Sample

First, the data array is inverted, so that higher light intensities produce peaks, rather than dips. Then, the data array is reversed (i.e. the first value becomes the last value) to account for the CCDs physical orientation and the way the diffraction grating scatters the light. Next, the environmental noise saved in the text files is subtracted from the data array. Currently, data taken without the laser on is subtracted, however, more environmental data could be saved and subtracted to further improve spectral quality. The first 50 data points on either end of the array are then removed, as there are commonly errors seen in these areas. Lastly, the data is centered around zero on the y-axis, and each point is multiplied by a factor of 50 to amplify spectral features. An example output spectra for a pure water sample can be seen above in Figure 6.

4.5.3 Communication Protocols

The Raspberry Pi and Pico 2 will be connected over a USB cable, allowing for Serial communication, a simple yet reliable method of streaming data. On the Pico 2 side, a serial connection has been created using the bare-metal environment and the data from the ADC is sent over it. For the Raspberry Pi, the standard Python library “pyserial” is being used to facilitate the Serial connection. By using a standard library, future integrations with the rover have been improved, as the networking protocols can be easily merged. Additionally, the Raspberry Pi will utilize HDMI to display the results display GUI on an external monitor, to allow for easy user interaction.

4.6 Safety Considerations

To ensure safety when assembling, testing, and using the Raman spectrometer, laser and battery safety are the primary concerns. Proper safety goggles rated for the 532nm wavelength and 50mW power laser will be used to prevent any accidental exposure during testing. In the final design, the laser beam is fully contained in the enclosure box, limiting any accidental exposures during use. Additionally, since a Lithium-ion battery is being used as the power supply, precautions will be taken when storing and using the battery. Since the Rover Team also uses Lithium-ion batteries for their rover, they are aware of the necessary precautions. Lastly, electrical safety is a concern, so proper wiring and grounding is verified using a multimeter before applying any power to minimize risk from the 24V power supply.

4.7 Environmental Impact

This design has limited environmental impact, due to its small scale and limited components. The primary negative impact is the use of a Lithium-ion battery. Both the production and disposal of Lithium-ion batteries have significant environmental impacts. Approximately 40% of a battery's carbon footprint comes from mining the materials, which also use significant amounts of water (IER, 2023). The majority of Lithium comes from the Andean mountains, and the mining process uses 65% of the area's already limited water (IER, 2023). For one of the driest places on earth, this is a significant concern, especially if any contamination occurs. Additionally, only about 5% of Lithium-ion batteries are recycled, due to hazardous and inefficient recycling processes (IER, 2023). This means that most batteries end up in landfills, significantly increasing the likelihood of long-lasting fires. An additional environmental impact may be the disposal of chemicals after testing samples using the spectrometer. Many of the tests the BURT will conduct include mixing various chemicals with a soil sample. The disposal of these samples after analysis must be considered to abide by all state and federal laws. Binghamton University is classified as a Large Quantity Generator, and as such there are governmental regulations that need to be followed when disposing of chemical waste. When disposing of waste, 3 main steps need to be followed. First, a waste tag must be filled out and placed on the container. The container is then taken to a satellite accumulation area, and then a waste pickup can be requested through the Environmental, Health, and Safety (EHS) website (Binghamton University, 2024). The BURT typically works with the Fabrication Lab and its technicians to ensure these steps are followed, minimizing the environmental impact of their testing.

Although this system, and the entire rover, utilizes Lithium-ion batteries, the power consumption when idling is relatively low. Unless actively testing a sample, the only components consuming power are the Pico 2 and the Raspberry Pi. When testing, the largest power consumer is the laser, however, it will only be on for short periods of time. Additionally, the use of 3D printing for the enclosure and optical mounts reduces waste during manufacturing. Since 3D printing is an additive process, there is very little material waste, and production costs, especially on small scales, are significantly reduced (Nadagouda et al., 2020). Additionally, for this project, we used PLA, which is considered to be a renewable material and produces significantly fewer particulates and VOCs as compared to other materials like ABS (Nadagouda et al., 2020).

5 Project Development

5.1 Risk Abatement

The management and abatement of risk were a vital portion of this project's success. Over the year several areas of potential risk were found that would impact the success of the project. These include but are not limited to: parts availability, lab access, technical challenges, both with the software and optics, hard deadlines and scheduling issues, and budget constraints.

Part availability was something that was tackled mainly in the fall semester. For each major part of the design, product sources were found as soon as possible to account for any unexpected problems or delays. For example, when ordering very specific parts, like the CCD sensor, some difficulty was experienced when trying to find the exact part desired from a trusted supplier. In the end, a slightly different sensor than originally planned was purchased, but since this problem was found early, the design was able to be adjusted without causing further delays.

For this project, an optical table was needed to assist in testing and verifying the optical portion of the design. Without access to this key testbed, the integration of the optical elements would have been much slower and possibly introduced alignment errors, which would significantly impact the accuracy of the spectrometer. To avoid this, we reached out to Professor Klotzkin to ask for his assistance in this matter, and he allowed us to use a portion of his lab's optical table for this project. We met with him early in the year, and were able to receive all proper credentials and training to allow us to use the lab throughout the spring semester.

As with any project, technical difficulties were anticipated across all portions of the design, from the firmware code to the optics themselves. To mitigate this, prototyping and integrations started early, to allow for proper time to work through any issues that were found. When problems did arise, they were communicated with the entire group, so that solutions could be found more efficiently.

When dealing with hard deadlines and scheduling issues it is important to have a good plan in place and make sure everyone knows what they are expected to do. For this project, a Gantt chart, which can be seen in the Project Schedule section, was used to help organize the work that needed to be completed. In addition to maintaining the Gantt chart, our team met twice a week, once with our faculty adviser Professor Summerville, and the other just with our group. These meetings helped each member keep track of the tasks they were assigned and our faculty advisor provided us with helpful insights on design aspects.

The last risk covered here is budget constraints. Unforeseen challenges and expenses were anticipated, possibly causing the design to exceed the allotted $1500 budget. To help prevent this from happening, our team made sure to prioritize essential high-cost components early to ensure enough budget remained for smaller components and unforeseen expenses. Our team was also able to use some of the resources the BURT has to offer including a Pico 2 and Raspberry Pi, saving approximately $100. Once essential items were purchased, the majority of the remaining budget was used as reserve funds for any emergencies that could have occurred.

5.2 Project Schedule

The figures below show the Gantt chart that has been followed for this project. They mark all important dates, deadlines, and deliverables that had to be completed during this project. Portions of each task were delegated throughout the team to make sure all assignments were completed on time, without causing undue stress on any one member. These charts were followed and updated regularly throughout the semester as any new information or tasks appeared. This approach served the team well throughout both semesters, culminating in the entire project being completed on time.

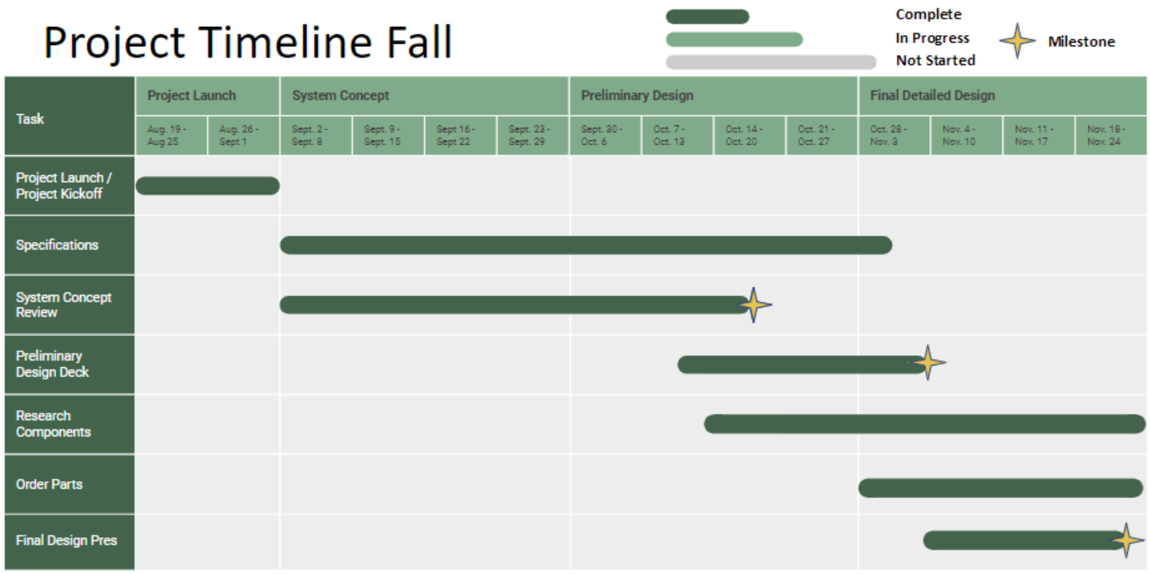

Figure 7: Fall Project Schedule

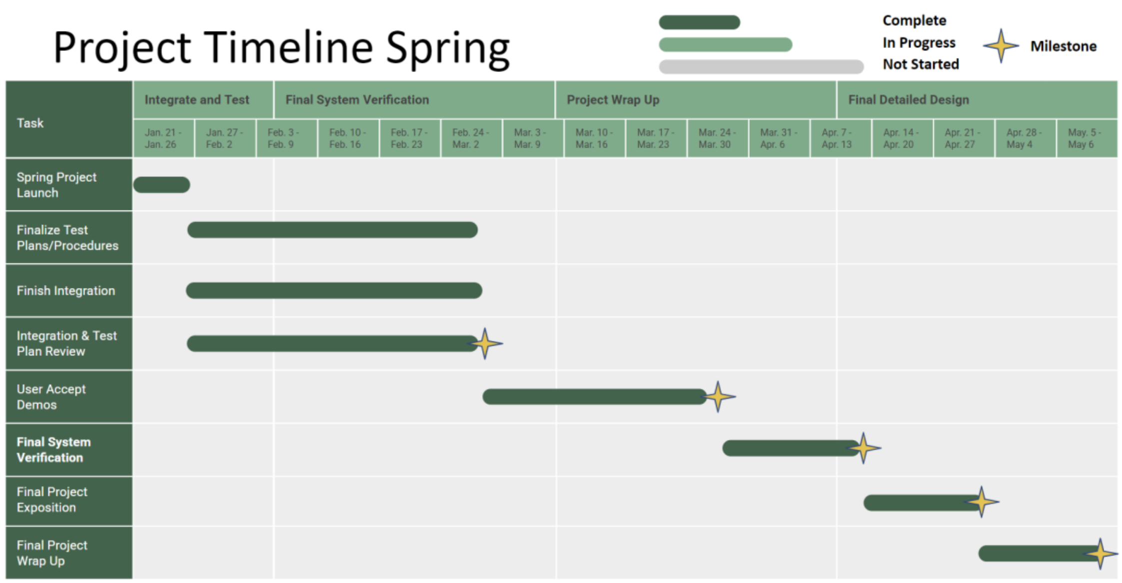

Figure 8: Spring Project Schedule

5.3 Project Finances

The budget for the Raman Spectrometer project was set at $1500, and the total expenditure over the year came to $725.99, well below the allocated amount. This financial flexibility allowed for the selection of high-quality components while staying cost-effective. Optical elements were the most significant expense, accounting for 74% of the total costs, reflecting the precision needed for accurate spectral analysis. Despite this focus on quality optics, strategic sourcing enabled us to maximize the impact of the budget.

Optical components, including mirrors, filters, and lenses, drove the bulk of expenses, highlighting the need for accuracy in detecting and analyzing spectral data. However, by balancing these costs with affordable electronics like the power components and laser source, the project remained well within budget. This strategic choice ensured the spectrometer met both technical specifications and field requirements, supporting accurate, portable, and durable use in outdoor environments. Overall, the careful selection of components allowed us to maintain alignment with project goals while managing costs effectively, making the budget a non-issue throughout the project's completion.

Subtotal	$	680.65
Shipping	$	13.35
Total	$	694.00
Budget	$	1,500.00
Reserve	$	806.00

Item	Manufacturer	Part Number	Description	Qty	Cost/Unit	Subtotal	Shipping Cost
1	Mikikit	091158BRB2PONF	Cuvettes	1	$ 1.19	$ 11.89	$ -
2	SanDisk	SDSQUA4-032G-GN6MT	MicroSD card for Rasp Pi	1	$ 6.39	$ 12.77	$ -
3	TalentCell	LF8011	Talentcell 24V 6Ah LiFePO4 Battery Pack LF8011, 25.6V 153.6Wh Deep Cycle Rechargeable Lithium Iron Phosphate Batteries	1	$ 42.99	$ 42.99	$ -
4	Aitrip	LM2596	5 Pack LM2596 DC to DC Buck Converter 3.0-40V to 1.5-35V Power Supply Step Down Module	1	$ 1.60	$ 7.99	$ -
5	Laser Pointer Store	JD-851	532nm green laser 30 mW	1	$ 14.90	$ 14.90	$ -
6	Newport	20CGA-550	Longpass Filter, Colored-Glass Alternative, 2x2 in., 550 nm Cut-on	1	$ 102.00	$ 102.00	$ -
7	Thorlabs	CM127-050-E02	Ø1/2" Dielectric-Coated Concave Mirror, 400 - 750 nm, f = 50 mm	1	$ 65.63	$ 65.63	$ 13.35
8	Thorlabs	CM254-050-E0	Ø1" Dielectric-Coated Concave Mirror, 400 - 750 nm, f = 50 mm	1	$ 93.55	$ 93.55	$ -
9	Newport	33009FL01-29(	Ruled Diffraction Grating, 25 x 25 mm, 500 nm, 26.7° Blaze, 1800 g/mm	1	$ 139.00	$ 139.00	$ -
10	Thorlabs	LB1757	N-BK7 Bi-Convex Lens, Ø1", f = 30.0 mm, Uncoated	2	$ 29.36	$ 58.72	$ -
11	McKesson	70-101PMCK	McKesson Premium Microscope Slides, Plain, Float Glass, Beveled Edges, 25 mm x 75 mm x 1 mm, 72 Count	1	$ 0.13	$ 9.40	$ -
12	Thorlabs	P50K	Ø1" Mounted Pinhole, 50 ± 3 µm Pinhole Diameter, Stainless Steel	1	$ 78.62	$ 78.62	$ -
13	Toshiba	TCD1304DG(8Z,K)	CCD Linear Image Sensor	1	$ 37.90	$ 37.90	$ -
14	Kxable	KXU2A-Mic-2F	Micro-usb cable	1	$ 2.65	$ 5.29	$ -
15	YILUBAO	B0C5X7CY3X	Laser pointer	1	$ 20.00	$ 20.00	$ -
16	Fctoerg	B0CMX2CBQ9	Rubber Grommets	1	$ 2.00	$ 11.99	$ -

Shipping	$ 13.35
Total	$ 725.99
Budget	$ 1,500.00
Reserve	$ 774.01

Figure 9: Bill of Materials

6 System Implementation

The system implementation phase focused on integrating all individual parts that had been previously tested into the final design. This involved the physical construction of the box, software integration, and ensuring all parts functioned well together. Figure 10 below details the integration system diagram for the Raman spectrometer.

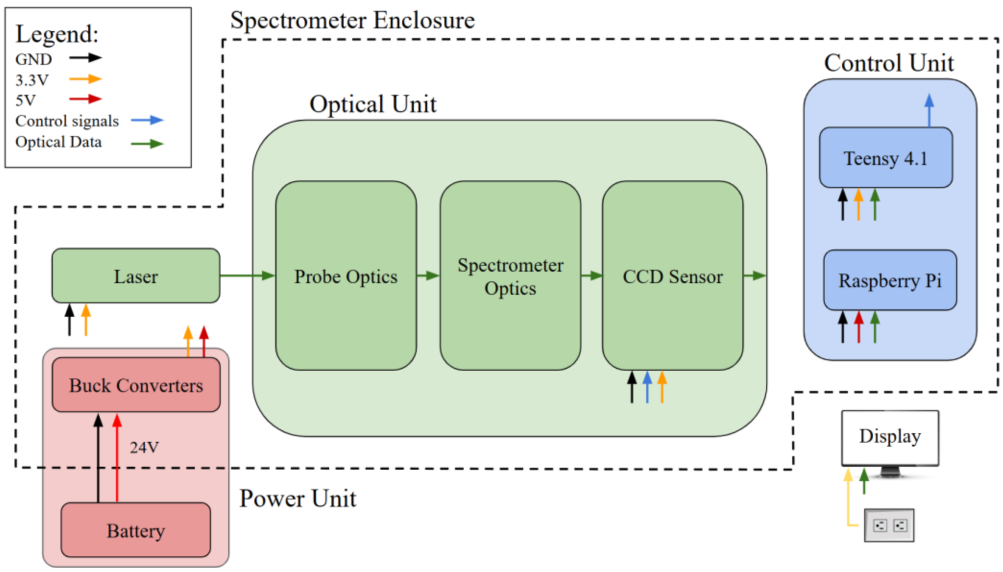

Figure 10: Integration System Diagram

- 6.1 Hardware Implementation

The hardware subsystem was assembled by mounting optical components, including the 532 nm laser, lenses, mirrors, diffraction grating, CCD, Pico 2, and a sample holder within a custom-made enclosure designed to meet the required dimensions of 300 mm × 200 mm × 100 mm. Electrical components such as the microcontroller and power regulation circuit were installed and replicated as if it was on the rover. This entailed using a 24V battery, as well as connecting the Pico 2 and Pi 4 over USB.

The power system was implemented to operate from a regulated 24V DC source, with onboard voltage regulation supplying the necessary 5V, 3.3V, and 3.7V for the Raspberry Pi, CCD, and the laser respectively.

6.2 Software Implementation

The system's firmware was developed in C, intended to be used within a bare-metal environment and implemented on a Pico 2 microcontroller to control the CCD and help manage the data. The software, written in Python and implemented on a Pi 4, handles the Raman spectrometer readings, signal filtering, and communication with the Pico 2 and display screen. The implemented GUI allows for real-time visualization of the Raman spectra, allowing for easy testing and analysis for the BURT.

- 6.3 Optical Alignment

Implementation also included carefully aligning the optical path to ensure efficient excitation and collection of Raman-scattered light. The enclosure was designed based on precise measurements to ensure the laser has a clear path to the CCD. During integration, slight changes were needed to ensure optical alignment, such as adjusting angles and distances, as well as adding a light-blocking wall between the probe and spectrometer optics. Calibration was performed using a known sample, water, to test if the output was correct. Figure 11 shows the final implementation of the optical enclosure used during final testing and validation.

Figure 11: Final Optical Enclosure Implementation

- 6.4 Testing and Troubleshooting

During implementation, each subsystem was tested alone and was then integrated. Issues faced during this process include alignment issues, CCD stability, and laser stability. The alignment issues were solved by adjusting the positions of various components, such as the second focusing lens and diffraction grating. CCD readings were improved by securing the laser, as well as blocking ambient light through the added wall and black construction paper. Finally, the laser was stabilized in its mount by adding additional padding, and was controlled through a physical power switch for improved ease of use. The final system tested a compatible dirt sample, and consistently resulted in a unique spectra distinguishable from water. The spectras of a pure water sample and an aqueous soil sample can be seen below in Figure 12.

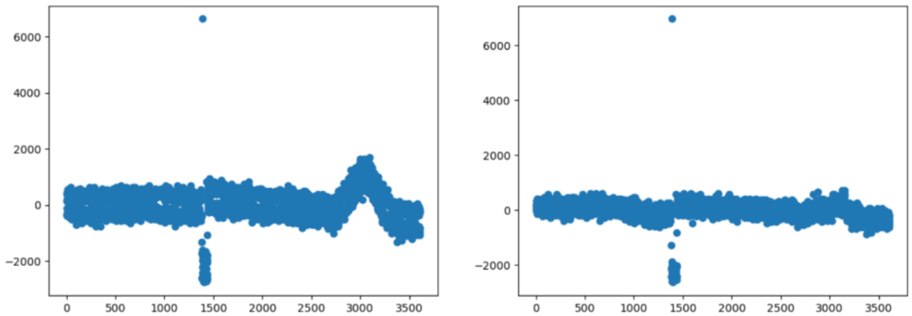

Figure 12: (left) Raman Spectra of Water (right) Raman Spectra of Aqueous Soil Sample

7 Project Evaluation

7.1 Overview

To fully evaluate and test the designed Raman Spectrometer, a series of tests were conducted to validate the completion of the project's requirements and stretch goals. To do this, the team created an Integration and Test Plan, which consisted of 11 tests to thoroughly validate the system and all requirements. More details on the results of these tests and their procedures can be found in Appendix D: Test Results and Procedures.

These tests were conducted throughout March and early April, with the most critical being completed several times. This ensured the system remained reliable and consistent, as small system changes were implemented throughout the process. Overall, all but one test were successfully completed, resulting in the system meeting all seven requirements and five of six stretch goals. The stretch goal that was missed required the system to automatically provide analysis into the spectral results. Due to inconsistency of results late in the project timeline, this stretch goal was unable to be completed, and the ramifications of this were discussed with the BURT.

7.2 Testing and Results

Detailed testing and validation of the Raman Spectrometer began early on in the integration process, with the validation of several small, but key requirements. These included tests related to component specifications and the spectrometer's size and weight. Requirements ECD512-R-004 and ECD512-R-005, which required the use of standard cuvettes and electrical components respectively, were among the first to be tested and validated, as these were specifically related to the spectrometer's physical design. The last test to be completed, the Raman Spectra Analysis Test, which validated the requirement ECD512-R-003, related to the validity of the spectral results, and as such had a much more complex testing process.

Due to the precision necessary for the optical components, the validation of the spectral results was very time-consuming. Issues such as alignment and the presence of ambient light resulted in extremely noisy signals. Steps were taken to eliminate these issues, both physically and with data processing software, however, it did prevent the completion of stretch goal ECD512-G-003. This stretch goal stated that the device should provide insight into the chemical composition of samples. Since this was not met, an impact assessment was completed and discussions were had with the BURT. Ultimately, the rover team communicated that having accurate and relatively noise-free signals was more important than being provided analysis, and as such this is where the focus of the project shifted to. Further information on the project's requirements and stretch goals can be seen in Appendix A, and the results of the impact assessment can be found in Appendix G.

7.3 Assessment

Overall, this project successfully meets all core requirements, and all but one of the stretch goals. The primary drawback of the design was related to the optical alignment. Due to changes in the optical setup late in the project timeline, not all components are properly secured. The enclosure, and some mounts, need to be reprinted to ensure stability on the rover. Due to the precision necessary for accurate spectral results, this is critical to fix and maintain, as realigning the optics requires a great amount of time and effort.

The requirements for this design were split into two categories: hardware and software. On the hardware side, the system used a 24V battery and standard electrical components, including cuvettes for holding samples. The entire setup was also designed to be self-contained as required. The software components of this design were required to graphically display spectra results, specifically Raman spectra suitable for status of life analysis. This was met using water and an aqueous soil sample as the tested samples, where very clear spectral differences could be seen. These spectras can be seen above in Figure 12.

The system's stretch goals were split into the same two categories. For the hardware we ensured that the system fit within a 300mm x 200mm x 100mm volume, it weighed no more than 2kg and the current draw was no more than 1A. The design was made with future implementation onto the 2025 rover in mind. The firmware was written in C to ensure a smoother implementation as well.

The only stretch goal unable to be met was that the results display should provide insight into the chemicals found in the solution. Due to timeline constraints, this portion of the software was unable to be implemented, so instead the focus shifted onto improving all other aspects of the design to ensure consistent and accurate results.

7.4 Future Potential

This project has a lot of future potential especially because of the BURT. We plan on providing them with the design developed here, along with a bill of materials and user guide to help them implement and maintain the spectrometer on the Rover. There are several key changes needed to fully integrate the spectrometer onto the rover, such as more advanced chemical testing, integration of software, and automated sample placement. This project will serve as a good proof of concept and the rover team will be able to take our design and build upon it. This design can be used as a table top version of a custom spectrometer in order to collect the data for BURT’s chosen chemical tests. By providing the team with a proof of concept design, the testing conducted in the actual URC events will be much more streamlined and efficient.

8 Notes

8.1 Acronyms and Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ARM	Advanced RISC Machine
BURT	Binghamton University Rover Team
CCD	Charge-coupled device
ECD	ECE Capstone Design
ECE	Electrical and Computer Engineering
EHS	Environmental, Health, and Safety
GUI	Graphical User Interface
HDMI	High–Definition Multimedia Interface
IDE	Integrated Development Environment
I/O	Inputs and Outputs
PLA	Polylactic Acid
RAM	Random-Access Memory
SDK	Software Development Kit
USB	Universal Serial Bus
URC	University Rover Challenge
VOC	Volatile Organic Compound

8.2 Bibliography

Not applicable.

8.3 References

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- 9 Appendices

- Appendix A: ECD Project Specifications Document

ECD Project Specification Document

ECD512 Raman Spectrometer for Soil Classification

Project Description

Summary: Our project involves the design and development of a custom-made Raman Spectrometer for the Binghamton University Rover Team. This portable device will assist in the classification of soil samples, specifically analyzing aqueous soil solutions for the status of life. The spectrometer will utilize a 24V power source, standard electrical components, and display the resulting spectra graphically on a screen. It will be compact, self-contained, and capable of being mounted on the rover, with a user guide and technical documentation included. The system's firmware should be written in C/C++, and the budget for the project is $1,500.

Sponsor: Avangrid
Project Advisor: Dr. Summerville
Team: Rebecca Carpenter, Christian McCormack, Devan Bade, James Plummer

Requirements

This document lists all essential project requirements for this project. A requirement is identified by "shall", a good practice by "should", permission by "may" or "can", expected outcome or action by "will", and descriptive material by "is" or "are" (or another verb form of "to be").

The following Qualification Method (QM) is to be used:

- Demonstration (D): The operation of the system, or a part of the system, that relies on observable functional operation not requiring the use of instrumentation, special test equipment, or subsequent analysis.
- Test (T): The operation of the system, or a part of the system, that uses instrumentation or other special test equipment to collect data for analysis.
- Analysis (A): The processing of data obtained from another qualification method. For example, reduction, interpolation, or extrapolation of test results.
- Inspection (I): The visual examination of system components, documentation, etc.

The following Requirement Categories (RC) are to be used:

- System Capability Requirements (SC): Requirements pertaining to the functionality and behavior of the system.

· System External Interface Requirements (EI): Requirements based on the external interfaces of the system. Interfaces with input power, user input, or any other outside source

· Project Business Requirements (PB): Requirements pertaining to business objectives set by a sponsor such as installation requirements, requirements pertaining to specific lab access or lab equipment needs etc.

· Other Requirements (O): Safety, Security and Privacy, System Environment concerns etc.

2.1 Derived Requirement Specification

ID	QM	RC	Derived Requirement
ECD512-R-001	T	EI	The device shall be powered using a 24V source
ECD512-R-002	I	SC	The device's resulting spectra shall be displayed graphically on a screen
ECD512-R-003	A	SC	The device shall be able to produce a Raman spectra suitable for status of life analysis of a selected aqueous soil solution
ECD512-R-004	D	SC	The device shall process samples contained in standard cuvettes
ECD512-R-005	I	O	The device shall use standard electrical components
ECD512-R-006	I	EI	The device shall be a self-contained unit
ECD512-R-007	I	PB	The project shall include a comprehensive user guide describing the device's functionality with a bill of materials

2.2 Derived Stretch Goals

ID	QM	RC	Derived Requirement
ECD512-G-001	D	EI	The device should measure no more than 300mm x 200mm x 100mm (LxWxH)
ECD512-G-002	I	SC	The device's firmware should be written in C/C++
ECD512-G-003	D	SC	The results display should include insight into the chemicals found in the solution through analysis of the resulting spectra within 5-10 minutes
ECD512-G-004	D	EI	The device should be capable of integration onto the 2025 Rover
ECD512-G-005	T	EI	The device should not draw more than one amp from the 24-volt source
ECD512-G-006	T	O	The device should not weigh more than 2 kilograms

2.3 Original Proposed Requirements

1. The device shall be powered using a 24V source
2. The device's resulting spectra shall be displayed graphically on a computer
3. The device shall be able to analyze aqueous soil solutions to determine the presence or absence of life
4. The device shall analyze samples contained in standard cuvettes
5. The device shall use standard electrical components
6. The device shall be a self-contained unit suitable for mounting and use upon the Binghamton University Rover Team's rover
7. The project shall include a comprehensive user guide describing the device's functionality
8. The project shall include documentation for all parts describing purchase and/or manufacturing details
9. The device should measure no more than 300mm x 200mm x 100mm (LxWxH)
10. The device's firmware should be written in C/C++
11. The results display should include insight into the chemicals found in the solution through analysis of the resulting spectra

- Appendix B: ECD512 Final Parts List

Part Description	**Link**	**Quantity**
Cuvette	Amazon	1
MicroSD card for Rasp Pi	Amazon	1
24V 6Ah LiFePO battery	Amazon	1
LM2596 DC to DC Buck Converter	Amazon	2
532nm Laser Pointer	Amazon	1
Longpass Filter	Newport	1
1/2" diameter concave mirror	Thorlabs	1
1" diameter concave mirror	Thorlabs	1
Ruled Diffraction Grating	Newport	1
1" diameter Biconvex Lens	Thorlabs	2
Microscope Slide	Amazon	1
CCD Sensor	Digikey	1
Micro USB cable	Amazon	1
3D printed Enclosure	N/A	1
3D printed Lid	N/A	1
From rover team:		
Raspberry Pi 4	N/A	1
Pi Pico 2	N/A	1
5V buck converter	N/A	1

-
-

Table 1: Final Parts List for Spectrometer Design

- Appendix C: Financial Summary

ProjectID	Order Num	Order Date	Total Order Cost	Project Budget	Available Funds	Order Requested By	Contact
ECD512	1	13-Nov-2024	$ 694.00	$1,500	$806	Devan Bade	dbade1@binghamton.edu
ECD512	2	03-Feb-2025	$20.00	$1,500	$786	Devan Bade	dbade1@binghamton.edu
ECD512	3	04-April-2025	$11.99	$1,500	$774.01	Devan Bade	dbade1@binghamton.edu

Table 2: Project Order Summary

- Appendix D: Test Results and Procedures

- 1.1 Test Results

Test ID	Test Name	QM	RC	Requirements Addressed	Test Completion Date
ECD512-T-001	Physical Dimensions Test	D	EI	ECD512-G-001 ECD512-G-006	03/26/25
ECD512-T-002	Self Containment Test	I	EI	ECD512-R-006	03/26/25
ECD512-T-003	Cuvette Compatibility Test	D	SC	ECD512-R-004	03/06/25
ECD512-T-004	Electrical Components Compliance Test	I	O	ECD512-R-005	03/20/25
ECD512-T-005	Firmware Functionality Test	I	SC	ECD512-G-002	03/24/25
ECD512-T-006	Power Management Test	T	EI	ECD512-R-001 ECD512-G-005	03/27/25
ECD512-T-007	Spectra Display Test	I, A	SC	ECD512-R-002	03/25/25
ECD512-T-008	Raman Spectra Analysis Test	A, D	SC	ECD512-R-003	04/09/25
ECD512-T-009	Chemical Analysis Insight Test	D	SC	ECD512-G-003	Not completed
ECD512-T-010	User Guide and Documentation Review	I	PB	ECD512-R-007	03/25/25
ECD512-T-011	Rover Integration Test	D	EI	ECD512-G-004	04/04/25

Table 3: Test Results Summary

- ## 1.2 Test Procedures

- ### *ECD512-T-001: Physical Dimensions Test*
- ### *Overview*

Objective: The Physical Dimensions Test is intended to show that the spectrometer's main enclosure box fits within the size and weight requirements requested by the Rover Team.

Requirements Addressed: ECD512-G-001, ECD512-G-006

Step #	Step-by-Step Operations	Expected Results
1	Measure the spectrometer enclosure's length, width, and height	The dimensions should be no more than 300x200x100mm
2	Weigh the spectrometer enclosure box	The weight should be no more than 2kg

-
- ### *ECD512-T-002: Self Containment Test*
- ### *Overview*

Objective: This test ensures that the spectrometer is a self-contained unit

Requirements Addressed: ECD512-R-006

Step #	Step-by-Step Operations	Expected Results
1	Verify that all spectrometer components are contained in the enclosure. Power and display components are excluded.	The device is self-contained.
2	Operate the spectrometer without any external dependencies other than display and power	The device functions without any external devices
3	Ensure that there are no additional components required for operation	The system fully functions independently

-

- ***ECD512-T-003: Cuvette Compatibility Test***
- ***Overview***

Objective: This test is intended to show that the cuvettes used are easily accessible and compatible with the overall system.

Requirements Addressed: ECD512-R-004

Step #	Step-by-Step Operations	Expected Results
1	Google search cuvettes and compare results with chosen cuvettes	Our cuvettes match those easily found on the internet
2	Measure the cuvettes being used. Compare dimensions both to system design and those found online	The cuvettes are of standard dimensions and easily fit within our system
3	View product descriptions to compare use cases	The cuvettes are suitable for use in spectrometers

-
- ***ECD512-T-004: Electrical Components Compliance Test***
- ***Overview***

Objective: The Electrical Component Compliance Test will show the electronics used in this design are easily accessible and suitable for integration into the Rover Team.

Requirements Addressed: ECD512-R-005

Step #	Step-by-Step Operations	Expected Results
1	List all electrical components used in the device	Components are documented
2	Check the current and expected future availability of components from suppliers	Components are currently, and will continue to be commercially available
3	Ensure that all components are functioning while running a test	Components are functioning as intended

-

- ***ECD512-T-005: Firmware Functionality Test***
- ***Overview***

Objective: This test is intended to show that the firmware code used in this design is written in either C or C++, which improves the Rover integration process

Requirements Addressed: ECD512-G-002

Step #	Step-by-Step Operations	Expected Results
1	Show evaluators firmware code	Firmware code is written using C
2	Describe how the code is being used to interact with the hardware	Show that the firmware code is functional and suitable for this application

-
- ***ECD512-T-006: Power Management Test***
- ***Overview***

Objective: The Power Management Test is intended to show how the spectrometer meets the necessary limits on the voltage and current levels.

Requirements Addressed: ECD512-R-001, ECD512-G-005

Step #	Step-by-Step Operations	Expected Results
1	Connect the 24v source to the spectrometer	Device successfully powers, indicated by lights on the Raspberry Pi and buck converters
2	Measure current and voltage using a multimeter	The voltage will be at least 24v and the current will be less than 1A
3	Run the device for 2 tests and monitor the current	The device should be stable and not exceed the current limit

-

- ***ECD512-T-007: Spectra Display Test***
- ***Overview***

Objective: This test is to see if the spectrometer will display the produced spectra graphically on the screen.

Requirements Addressed: ECD512-R-002

Step #	Step-by-Step Operations	Expected Results
1	Power the spectrometer and connect the Raspberry Pi to the screen via HDMI	The device will connect successfully
2	Run a test sample and observe the output	The spectra will be generated and displayed graphically on the screen

- ***ECD512-T-008: Raman Spectra Analysis Test***
- ***Overview***

Objective: This test verifies that the spectrometer produces accurate raman spectra suitable for signs of life.

Requirements Addressed: ECD512-R-003

Step #	Step-by-Step Operations	Expected Results
1	Prepare a known sample indicating presence of life in a cuvette	The sample is ready for analysis
2	Insert the cuvette in the device and begin testing	The device processes the sample and begins the analysis
3	Visually compare the output spectra with reference data of the expected spectra	Spectra aligns with the expected Raman signature for current sample
4	Repeat process for a known sample that does not indicate life	The analysis process should follow the previous steps, with successful visual

		matching of the spectra

ECD512-T-009: Chemical Analysis Insight Test

- ***Overview***

Objective: The Chemical Analysis Insight Test will be used to evaluate whether the GUI can display accurate and informative insights into the chemical composition of soil samples.

Requirements Addressed: ECD512-G-003

Step #	Step-by-Step Operations	Expected Results
1	Use the GUI to start the testing process. Start a timer.	The GUI can correctly transmit information to start the testing sequence
2	Wait for the results to appear on the GUI display	The system will test a sample and process the results
3	Stop the timer once both the graph and the chemical analysis boxes are filled.	The timer will be less than 5 minutes (ideal) or 10 minutes (acceptable)
4	Compare both the spectra and chemical analysis with the documented expected results for the given sample	The results should visually match, indicating successful analysis

-
- ***ECD512-T-010: User Guide and Documentation Review***
- ***Overview***

Objective: The User Guide and Documentation Review will show that the Rover Team will be provided the necessary information in order to easily operate and integrate the Raman spectrometer design.

Requirements Addressed: ECD512-R-007

Step #	Step-by-Step Operations	Expected Results
1	Show the written user guide and BOM	The user guide and BOM exist and provide information about the system

2	Check that the BOM matches the components used in the system	The BOM should be a complete and accurate list of materials used in this design
3	Step through a testing sequence using only the instructions in the user guide	A successful test should be run by only using the given instructions

- ***ECD512-T-011: Rover Integration Test***
- ***Overview***

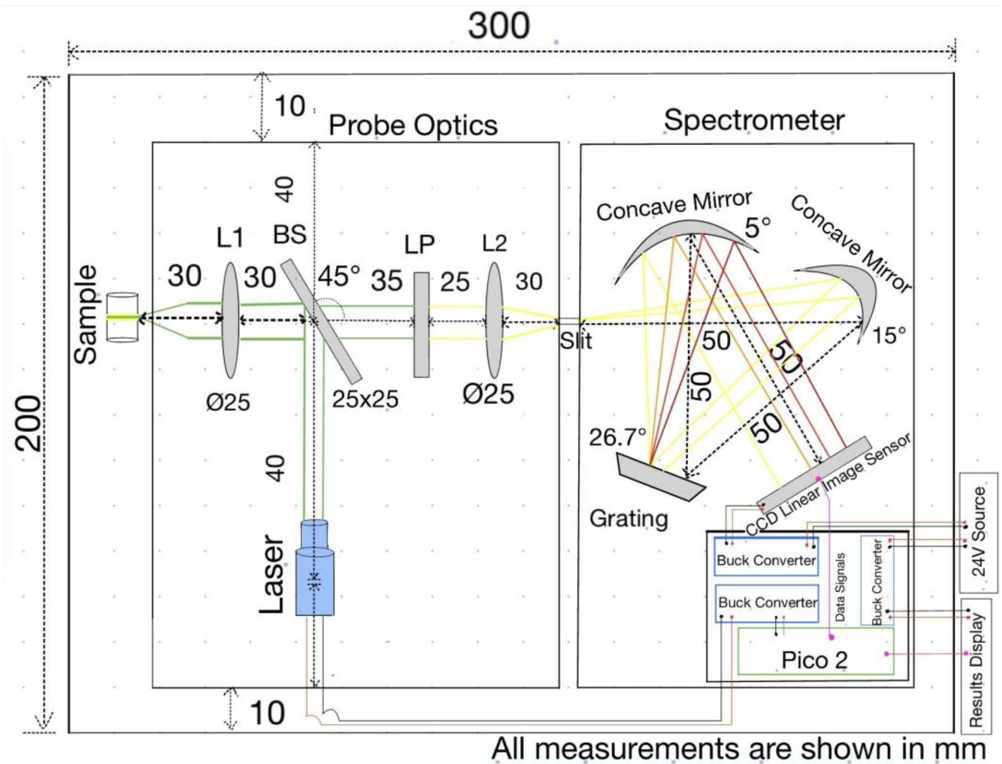
Objective: This test ensures that the device is capable of integration on to the 2025 rover

Requirements Addressed: ECD512-G-004

Step #	Step-by-Step Operations	Expected Results
1	Show that we've met our size and weight requirements from test ECD512-T-001	The device is of adequate size and weight to be included on the rover
2	Show that the device is capable of being placed and used on the rover, from meeting requirements ECD512-R-001 and ECD512-R-006	The device, with exception of the power and display components, is self-contained and able to run independently of other power sources
3	Show that the device's firmware and GUI are written in Rover's standard languages (C/C++ and Flutter respectively)	The spectrometer utilizes the same programming languages as the rover team, making the software compatible

- Appendix E: Miscellaneous

- **Proposed Optical Configuration**



- Appendix F: Project Standards

Hardware Standards:

To mitigate risks such as electrical shock and fire hazards, we have followed IEC 61010, which specifies safety requirements for electrical equipment in laboratories. This standard ensures that our Raman spectrometer incorporates safety features such as proper grounding and overcurrent protection. Additionally, this standard helps prevent hazardous conditions by defining testing procedures for electrical safety, minimizing risks to users, and ensuring the reliability of our system.

We also adhered to IEEE 1100, which provides recommended practices for grounding and powering sensitive electronic equipment. This ensures that our spectrometer's power supply design minimizes electrical noise, prevents voltage fluctuations, and protects sensitive components such as the CCD sensor and microcontroller from power-related failures. Proper grounding and surge protection were incorporated to enhance system reliability.

Laser Safety Standard:

To ensure the safe operation of our laser setup in our project, we adhered to ANSI Z136.1, the American National Standard for Safe Use of Lasers. This provides guidelines for laser classification, exposure limits and control measures to mitigate risks. Since this project involves a laser as the primary light source for the Raman spectrometer, appropriate safety measures were implemented. This included the use of safety glasses, adherence to exposure limits, and using a less powerful laser when doing initial testing.

Software Standards:

The firmware code written for this project utilized the C11 programming language standard. This was chosen to ensure compatibility with the device's microcontroller, a Raspberry Pi Pico and the Binghamton University Rover Team. The code directly interacts with the microcontroller and CCD sensor, and sends the data received to the Raspberry Pi 4 for further processing. Additionally, to improve code reusability and readability, individual driver files are used for each major task, and then combined in the main() function.

In addition to the C11 standard, this project also utilizes the USB protocol. While not officially a standard, understanding and implementing this protocol was essential to the project, as this is the primary form of communication between the microcontroller and GUI. Both the Raspberry Pi Pico and Pi 4 utilized drivers and libraries in order to easily implement this protocol.

Project Design Standard:

For the project design timeline, we followed the W-model, introduced to the team during class lectures. This model allows for testing throughout the design process, ensuring individual components meet all requirements. By testing throughout the process, rather than just at the end as in a V model, issues are caught early in the design process and can be remedied. This was applied when developing our requirements, as well as all hardware and software components.

- Appendix G: Requirement Impact Assessment

Requirements ID	Test Status	Pass/Fail	Project Impact	Impact Assessment (Must fill out for all requirements not tested, or that failed testing)
ECD512-R-001	Completed	Pass	Medium	
ECD512-R-002	Completed	Pass	High	
ECD512-R-003	Completed	Pass	High	
ECD512-R-004	Completed	Pass	Low	
ECD512-R-005	Completed	Pass	Low	
ECD512-R-006	Completed	Pass	Medium	
ECD512-R-007	Completed	Pass	Medium	
ECD512-G-001	Completed	Pass	Low	
ECD512-G-002	Completed	Pass	Medium	
ECD512-G-003	Delayed	Fail	Medium	Automatic analysis into spectra was not implemented due to inaccurate signals late in the project timeline. Work was completed to improve the signal quality, but not enough time was left to implement analysis.
ECD512-G-004	Completed	Pass	Low	
ECD512-G-005	Completed	Pass	Low	
ECD512-G-006	Completed	Pass	Low	

Table 4: Impact Assessment for Failed Requirements/Stretch Goals