Mars Rover Spectrometer

Jay Szekely, Michael Rusinko
UCF Optica chapter, in collaboration with RCCF

Abstract
This paper serves as a collection and reference for the work done to create a low-cost high performance spectrometer for absorption spectra analysis. This spectrometer is done under the "Science" arm of Project S.T.O.R.M., a collaboration with Robotics Club of Central Florida (RCCF), Students for Exploration and Development of Space (SEDS), and Optica UCF CREOL. Project S.T.O.R.M. was initiated by RCCF and aims to create, test, and deliver a working autonomous rover capable of operating in the Utah desert as a test for a Martian environment. One of the mission objectives requires analysis of samples to determine of the environment is capable of supporting life. This analysis has been decided to be best done through a spectrometer, and thus this paper has been created to serve as a collection of the work.

Contents

1 Introduction

A spectrometer is an optical tool used to detect the specific colors of light which make up some input beam of light. A diffraction grating is used to decompose chromatic light into its composite wavelengths as a continuous spectrum. For this project wavelengths between 250 nanometer and 800 nanometer would ideally be detected.

This give us a design requirement of a minimum 550 nm detectable range spanning the entire visible spectrum and going slightly UV. We also need a high resolution, ideally sub 0.5 nm so we need more than a 1100 pixel wide sensor. This spectrometer will also be placed inside a moving rover operating in the Utah desert. There will be a lot of vibration present as well as a lot of heat and plenty of thermal fluctuation.

We plan to use a simple series of lenses, 1000+ lines/mm transmissive grating, and a

HD CMOS sensor from a webcam.

1.1 Sponorship

This portion of the project will be funded by RCCF.

2 Notes

These notes were created during winter break of 2024.

2.1 Beginning

We should look at industry standard spectrometers to draw inspiration and follow good design practices. Stellarnet and OceanOptics are two companies which make high quality spectrometers which sell for thousands of dollars. They have specification sheets and education videos explaining how spectrometers work. They may not go in depth into how they are made exactly, but that is why we are optical engineers!

We did more research into the previous spectrometer I recommended: The "Little Garden" spectrometer on AliExpress. It does not have a high enough resolution to resolve the double peak of a potassium lamp. Thus, it is not high quality enough for the project or the analysis we need. It also consistently had errors in detection, being off by 2 nm, as well as detecting the output from higher order modes. This is not wanted, and as such, we will build our own spectrometer.

2.2 Theory

Our spectrometer needs several considerations that would ensure its performance in the field. These challenges will be detailed here, and discussed as they're addressed in each component of the spectrometer.

2.2.1 Material Thermal Expansion

Mars (and, perhaps more relevantly, the Utah desert) has violent thermal swings which can make portable optical design more complex. It poses a danger of, at the very least, causing the components to de-align, and at most, the material will begin to crack and deform, causing all sorts of issues. The vast range of temperature which can be reached within the month of the rover's assessment would have to be accounted for to ensure the unit continues to function. This means many cost-cutting strategies we could employ in other settings, like 3D printing with cost-effective material, are unable to be employed here. More expensive components, such as diffraction gratings and hardware, have ranges of temperatures at which they could be rated to be effective, but this could easily eat a non-insignificant part of the budget for the entire rover, which we wanted to avoid.

2.2.2 Shock resistance

In addition to the thermal resistance it needs, part of the challenge is the rover undergoing more and more formidable terrain to get to the testing sites. This means more sturdy enclosures, and ensuring optical components are secured within the enclosure and that they do not loosen or detach as the rover traverses the terrain.

2.2.3 Spatial limitations

While the spectrometer can theoretically be as small or large as we need it, other details of the science team are designing other components of the assembly—namely, the carousel which will house the cuvettes. Thus, it may prove prudent to separate the part of the spectroscope which would have the cuvette holder from the actual part which actually reads absorption peaks.

2.3 Background Info

1 - An Introduction to a Spectrometer - The Slit - Describes how standard spectrometers take in light. Includes a useful equation.

2.4 Sample Spectrometers

1 - OceanOptics
2 - StellarNet

3 The Sensor

Creation and implementation of the spectrometer's sensor

3.1 Industry Standards

Both OceanOptics and StellarNet seem to commonly use similar types of sensors: CMOS or CCD line sensors. The issue with this is that both of these are quite expensive standalone, and even more difficult to implement as we are simply undergraduate students.

We have taken the approach of using a design that uses high-quality components while also being more cost-effective than pre-assembled spectrometers.

We chose optics and components which are detailed in subsequent sections, however, for the sensor, we opted for a ThorLabs CS165MU. This was primarily chosen because of ubiquitous pre-written tools made to work with the hardware already, thus lightening the load on our software team.

3.2 Testing

Over winter break 2024, we ripped a webcam out of a broken laptop for testing. We stripped the wires and tested each connection with components on the PCB to determine the power, ground, and data wires to get the camera minimally operating.

3.3 Sensor Resources

1 - Repurpose a laptop webcam

3.4 Parts Used

1 - ThorLabs CS165MU

4 The Diffraction Grating

Shedding light on the scattering of the light

4.1 Background

The theory behind the spectrometer tells us that after certain wavelengths are absorbed by the media we are reading, the light is transported to a diffraction grating which essentially organizes the light by wavelength. There is a rather elegant way to illustrate this: a diffraction grating is pretty much a sheet of prisms! The light behaves very much the same as a ray of light going through a prism, which each wavelength interacting minutely differently. Each prism-like structure on the diffraction grating is known as a groove, and the more grooves are on a grating of identical size, the more **dense** the grating is, the **more** spectra it will throw, and the **smaller** each spectrum will be. This allows one to control the size of thrown spectra by increasing or decreasing the number of ridges, and thus to control the image distance by controlling

Grating Density	Distance to Card (cm)	Spectrum Length (cm)
300	5	2.5
	8.5	3.5
	10.5	4.0
	14	5.6
	19.7	7.4
	33	8.0
	44	9.5

Table 1: The diameter of a complete cycle of the visible spectrum through a diffraction grating, at different distances.

the ridge density.

4.2 Approach

Determining what ridge densities was required for the rover spectrometer required a series of tests for different ridge densities, and measuring the length of each spectrum at different distances. The data gained during this process has been presented in Table 1. Doing this allowed us to further compare the size of the spectrum to the size of the CMOS sensor.

4.3 Parts Used

1 - 300 Grooves, 12.7mm Sq, 17.5° Groove Angle Grating

5 Lens System

Small description

5.1 Approach

Lenses will be the backbone of the spectrometer. The assembly of the spectrometer will be split into two different parts - the first part, which will read the soil sample, and a second, which will actually read the light and its absorption peaks. This allows us to have degrees of freedom in our arrangement of the spectrometer and allow us to work it "around" other people's work.

First, will be the lens/carousel assembly. This contains two planoconvex lenses as well as the carousel assembly. The exact dimensions are not super important, as the rays will be parallel throughout the entire carousel apparatus. This is because the first lens takes the point light source located at the lens's focal point, and creates parallel rays from them. These parallel rays then hit a second lens to collimate the rays toward its focal point.

After this, the light will hit a multi-modal fiber optic cable. The fiber cable will be attached to the casing and have a GRIN collimator tip to direct the rays into the fiber cable. This allows the highest proportion of the rays to reach the second part of the spectrometer and, by proxy, the sensor reading the absorption spectra.

Then, we hit the second part of the spectroscope. We now have two lenses and our chosen diffraction grating. The first lens, before the diffraction grating, will be a cylindrical lens to create parallel rays from the tip of the fiber cable. It then hits the diffraction grating, which casts the spectra. The spherical lens then acts as a collimating lens, focusing the spectra on the CMOS sensor.

5.2 Parts Used

1 - 12.0mm Dia. x 25mm FL, Uncoated, Plano-Convex Lens
2 - 12.7mm Dia x 100mm FL, Uncoated Imaging Grade PCX Cylinder Lens
3 - 12.5mm Dia. x 25mm FL, Uncoated, Best Form Spherical Lens

5.3 References

1 - Design inspiration - Starting point from which the spectrometer was built

6 Construction

Components and Materials

6.1 Challenges

With a dry climate like that of Mars and Utah, the temperature will fluctuate over quite a wide range from day-to-day. Thus, the primary challenge we needed to account for was the repeated thermal expansion the rover would experience during these thermal fluctuations. This ruled out the ability to use most plastic materials (due to their high CTE), including 3D printer resin and filament. Additionally, we needed a material that was (relatively) shock resistant, as the rover goes over more and more tumultuous terrain. We couldn't have any of our pieces becoming dislodged as the rover traveled. This was another thing which had prevented us from using many more cost-effective materials for the enclosures for the spectrometer.

6.2 Approach

As research continued, a relatively low-cost material revealed itself: that of 6061-T6 Aluminum. This material is already time-tested in environments where lightweight yet strong materials are needed, a few examples of these being smartphone casings, frameworks of some buildings, secondary firearm chambers, and the hulls of ships. This material seemed ideal for our spectrometer, with its ability to withstand and, in the worst-case scenario, absorb most shocks that the rover could put the spectrometer through. Additionally, the CTE is much lower than plastics, at 23.6 microns per degree Celsius, meaning in an average May day in Utah, with fluctuations in temp of about 20 degrees Celsius, we would see an expansion in the apparatus of about half a milimeter - well within an allowable expansion for a metal. As a bonus, with an operating temp of -200 to 180 C, this enclosure would also be entirely usable on the surface of Mars as well, from the equator to the poles.

7 Conclusions

Overall, this plan for the Project S.T.O.R.M. spectrometer achieves comparable results and data similar to a pre-assembled spectrometer, at a fraction of the price. The spectroscope would be able to pick up accurate absorption down to the nanometer and allow us to adopt a clear picture of the existence of proteins of the soil samples collected by Project S.T.O.R.M. in the field by dipping into the red, UV and IR light spectra to allow us to establish a confidence interval of a composition based on the chemical reactions of each test.

The process starts with a point source, with negatively focused light beams emerging from it. These beams hit a lens, which focuses them into parallel rays. These rays end up passing through a cuvette and being focused be an identical lens on a fiber collimator, which passes a light beam into a fiber cable and sends it through to the second part. Emerging from the fiber optic cable, the rays hit a cylindrical lens, being focused once again into rays passing through space. These rays hit the diffraction grating, are bent at about 15.5 degrees, then hit a spherical lens, which collimates the rays onto a CMOS sensor, manufactured by ThorLabs.
To build the entire assembly, it would cost somewhere between $1600-1800 to acquire the parts at retail price, roughly reducing the cost of the spectrometer by half. This was a more practical and cost-effective way to build and implement a spectrometer instead of buying a completely ready-made product.

References