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Construction of a Hyperspectral Camera using Off-the-Shelf Parts and 3D-Printed Parts

A thesis submitted in partial fulfillment
of the requirements for the
Mechanical Engineering Honor's College

by

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1. Introduction

1.1 Background

Spectrograms allow for the contents of a subject to be determined by observing how the light emitting off the subject splits into different wavelengths. These images are distinctive, characterized by solid lines of color stretching vertically across a black background. The most commonly seen spectrograms are those of atomic spectra, often seen in chemistry textbooks. Differing atomic structures produce a different set of lines, allowing scientists to identify the elements in the subject. As valuable as this information is, there is always room for improving this system, as spectrograms have a limited range of applications.

Hyperspectral imaging identifies the spectrum for individual pixels in an image, allowing for a much more thorough analysis of the subject, transforming a 2-dimensional image into a 3-dimensional image (if not more!). Hyperspectral images have been used to identify the health of crop yields and forests, by allowing for at least one extra dimension of information to be gleaned from the camera [1]. However, due to the specialized nature of hyperspectral imaging, it is a relatively expensive technology. The Specim IQ, for example, starts at a price of around \$20,000 [9]. This is partly due to it being able to detect visible AND near-infrared wavelengths, which is an extremely useful, albeit novel, function. A cursory search yields similar results from other manufacturers. It is clear that as useful as the technology is and can be, it is still relatively fresh on the market, leading to high prices.

1.2 Goal of the Project

The Arkansas Center for Space and Planetary Sciences (ACSPS) is working together with the Mechanical Engineering Department to build a modifiable camera with 3D-printed parts and off-the-shelf parts (sourced from Edmund Optics and Amazon). The design is to be readily changeable, primarily with the 3D printed parts, as to accommodate new ideas and functionalities in the future. Ultimately, the camera should be relatively cheap while maintaining functionality for proposed use cases. Earlier versions of the design will be tested extensively and rapidly updated in the ACSPS labs with benchtop testing. This will involve subjects with both visible and infrared emissions, with specific use in the ACSPS' Mars and Titan simulation chambers. Later down the road, field testing will help develop the automation and scanning abilities of the design, either by hand or attached to a drone. This will help develop the methods for compositing wavelength data with a given image, producing a hyperspectral image. The end goal for all of this testing and development is to build a camera to place in a cube satellite in order to make characterizations of planetary surfaces.

The first run of the camera was designed for reading visible light wavelengths and producing a useable, simple spectrogram. This is only a preliminary step to future versions that will incorporate new wavelength ranges (infrared, near-infrared) and functions (automation, hyperspectral imaging). It was deemed important from the beginning to build a working model so that adjustments and changes could be made rapidly. Subsequent models will be able to take in infrared and near-infrared wavelengths to be read

by a detector and stored to a computer for further analysis. Even further down the road, the device will be able to composite a spectral image with the original image, in order to create the desired hyperspectral image, where wavelength data is stored at each pixel. However, again, the goal of this preliminary construction project was to build a working prototype from which improvements can be made and to build a deeper understanding of the device.

The camera design is inspired by a design conceived by a research team in Norway [2]. Their goal with the design was to use rapid prototyping, enabled by 3D-printing, in order to produce a camera for use in handheld and airborne applications, with the goal of producing push-broom spectral imaging. The goals of our project align with the team from Norway, in that we are aiming to minimize costs on the path to producing a hyperspectral image. To be more specific, our design is based on their very first design, as it uses cheap parts and achieves the desired simple functionality.

1.3 Theory

By focusing light emitted off of a subject through a grating, the light can be split into distinct lines of color, as Figure 1 shows:

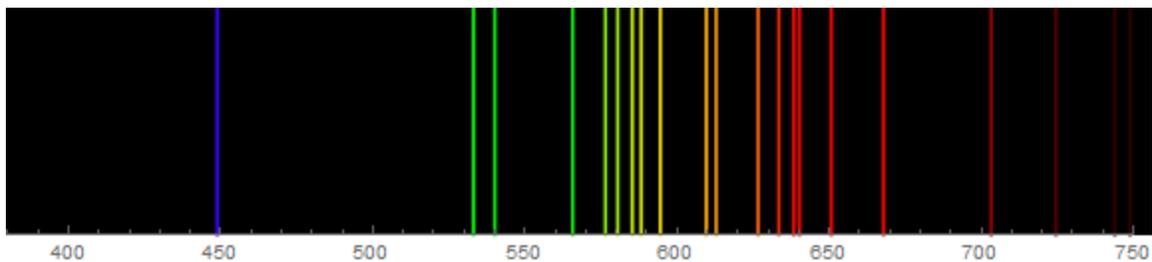


Figure 1. A basic spectrogram (mathematica.stackexchange.com)

Such a grating, usually called a diffraction grating, works by allowing different wavelengths of light to react uniquely based on their wavelengths, thus splitting the source light into its component wavelengths. The simplest type of grating consists of parallel slits and allows different wavelengths to “bounce” through these slits according to their wavelengths, thus creating a spectral image as seen above. Figure 2 is a basic representation of this phenomena, provided by Shimadzu:

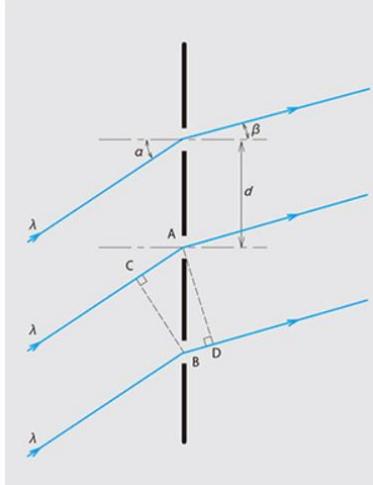


Figure 2. A grating diffusing light, i.e. the same input angle results in the same output angle (shimadzu.com)

The grating in our camera assembly is a transmission grating, with the light needing to enter the grating at an angle perpendicular to the reverse side [8].

The image from the camera will need to be calibrated, a process that requires a test setup and known wavelengths (usually achieved with lasers) to make a simple linear extrapolation for intermediate wavelengths. All this was done with Excel, in a process that will be described in the experimental setup section. For reference, the shown “ r^2 ” value on the curve fit describes how accurate the curve fit was.

2. Experiment

2.1 Construction of Camera

Aside from the detector and the 3D-printed parts, all components of the camera were sourced from Edmund Optics. These were all off-the-shelf parts and were built into two main assemblies: the front mount assembly and the detector assembly. The front mount assembly consists of (note that the number in parentheses refers to the item's number on the parts list):



Figure 3. S-Mount Thin Lens Mount (5)



Figure 4. Collimator Lens (FL = 30 mm) (7)



Figure 5. S-Mount Focus Tube (6)

The remaining parts of the front mount assembly consist of some delicate parts, so we did not disassemble for pictures once assembled. The remaining parts consist of:



Figure 6. Front Lens (1), M12 Lock Nut (2), S-Mount Thin Lens Mount (5), Precision Air Slit (3), Field Lens (4)

The detector assembly consists of just three parts:

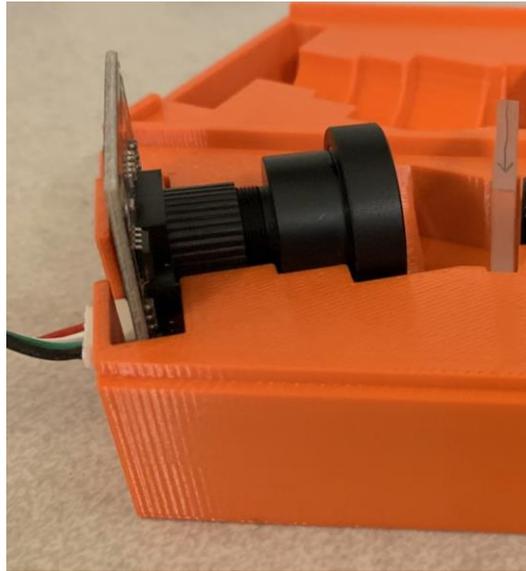


Figure 7. Detector (12), S-Mount Brass Spacer (10), Detector Lens (9)

The detector/camera bought off of Amazon required no extra adapters to connect with the detector lens, as it has native USB connectivity. Note that the grating sits between the two halves of the camera assembly. The entire assembly is laid out in Figure 8:

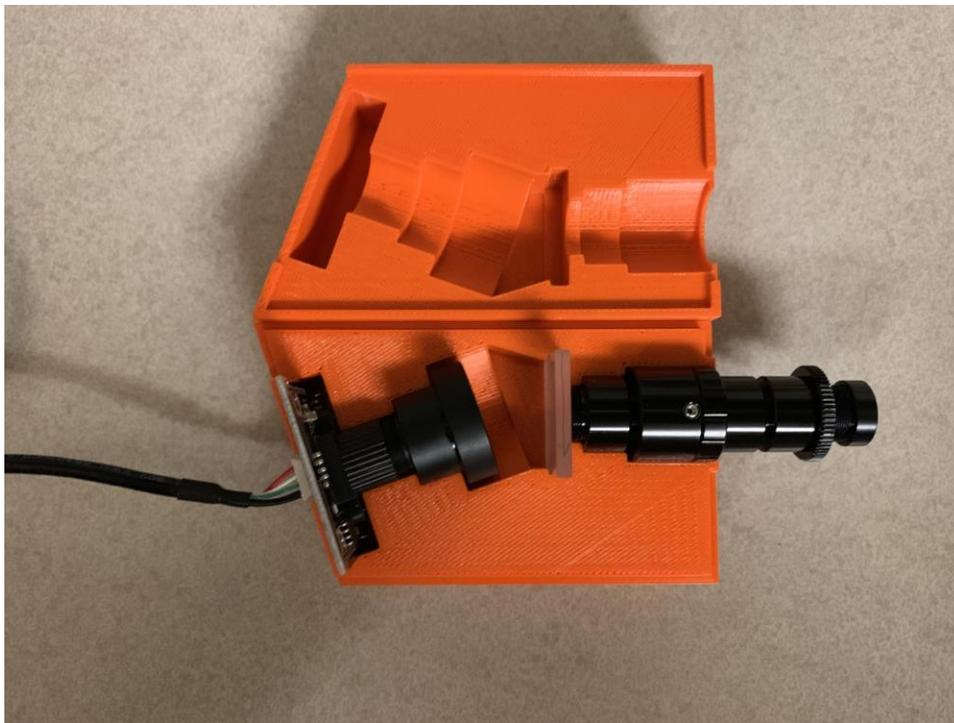


Figure 8. Overall layout of camera

Again, the slit and the grating are especially delicate, requiring a careful hand during movement and disassembly/assembly. A small arrow was drawn onto the edge of the grating to help orient it. The arrow should point to the right in the direction of the subject. The slit also needs to be aligned properly. This is a simple job, as you can use the S-mounts to rotate the parts as need be without disassembling the camera but needs to be done before spectrograms are taken to ensure proper operation. Simply looking through the front assembly while pointing it at a light source should help ensure the slit is aligned properly.

The grating used in the camera assembly is a transmission grating supplied by Edmund Optics, with 600 grooves/mm, 25 mm by 25 mm size, and a 28.7° blaze angle grating. The choice of grating was due to its size, which matched the size of the other parts well (not too big, not too small), its relatively low price (~\$100), and its efficiency at diffusing visible light. Edmund Optics provides a graph (Figure 9) that shows the efficiency of different gratings for different wavelengths:

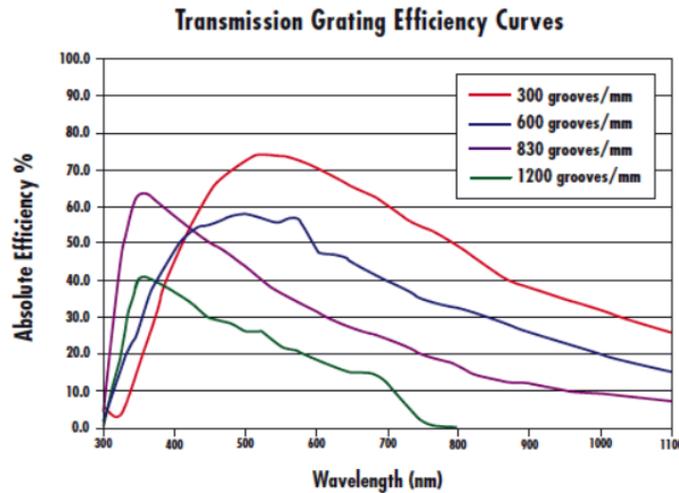


Figure 9. Transmission Grating Efficiency (*edmundoptics.com*)

The graph shows that a grating with 600 grooves/mm (the blue line) has an efficiency between around 45 and 60 percent between the wavelengths 400 nm and 700 nm, which is perfect for the visible spectrum. The aforementioned blaze angle refers to the angle of the sawtooth pattern etched onto the surface of the grating, which provides heightened efficiency for a range of wavelengths. Other components of the camera were selected for their low cost and small form factor, and were mostly general optics parts, aside from the slit, which helps focus the light through the grating and provides the y-axis range for the spectrogram, i.e., the slit height is the height of the images taken.

The 3D-printed part was originally designed by the research team from the paper mentioned above [2]. However, no dimensions besides the characteristic angle were given, necessitating trial and error, along with the measurement of the camera components to achieve a functional housing. They calculated the characteristic angle of the part with the equation:

$$\lambda = (a/k) * \sin\beta \tag{1}$$

Where λ is the dead-center wavelength, k is equal to 1 (to account for the first spectral order), β is the characteristic angle, and a is the groove spacing, which is calculated by dividing 1 by the number of lines per mm in the grating and converted to nm, as the wavelengths are also in nanometers. For the grating in this design, there are 600 grooves per mm, making the groove spacing a equal to 1666.67 nm.

This characteristic angle was calculated with a wavelength of 552.5 nm produced from a green light source. This resulted in an angle of 19.36 degrees off center axis and the wavelength of 552.5 nm being dead center in the image produced. In other words, if the subject of the image consists of light of wavelength 552.5 nm, it will appear in the center of the captured image, making for a solid calibration point. If need be, this angle can be adjusted based on the desired dead-center wavelength. Also, with the transition to infrared and near-infrared wavelengths, an appropriately “middle” source can be used to design the angle of the housing. The two halves of the 3D printed clamshell assembly were joined by friction alone, and the camera components were almost all held in a similar fashion. However, it is recommended that the grating is fixed using glue or tight tolerances, as to eliminate any motion with the grating, as that will necessitate re-calibration.

The detector was found on Amazon and was chosen due to its low price and native USB functionality, allowing for easy set up and testing, along with real-time feedback from a connected laptop. Once the camera assembly was assembled, it was tested to see if a spectrogram was produced. The preliminary images taken showed that the camera can indeed produce the desired image, as seen in figure 5, which is an image taken with the camera assembly pointed at a fluorescent light. Something of note is that normally, spectrograms are displayed left to right, with the shorter wavelengths (i.e. blue wavelengths) on the left and the longer wavelengths (i.e. red wavelengths) on the right. Figure 1 is an example of this. However, the image in Figure 5 has red on the left and blue on the right, indicating that the image is flipped. This will need to be accounted for when identifying wavelengths in the future.

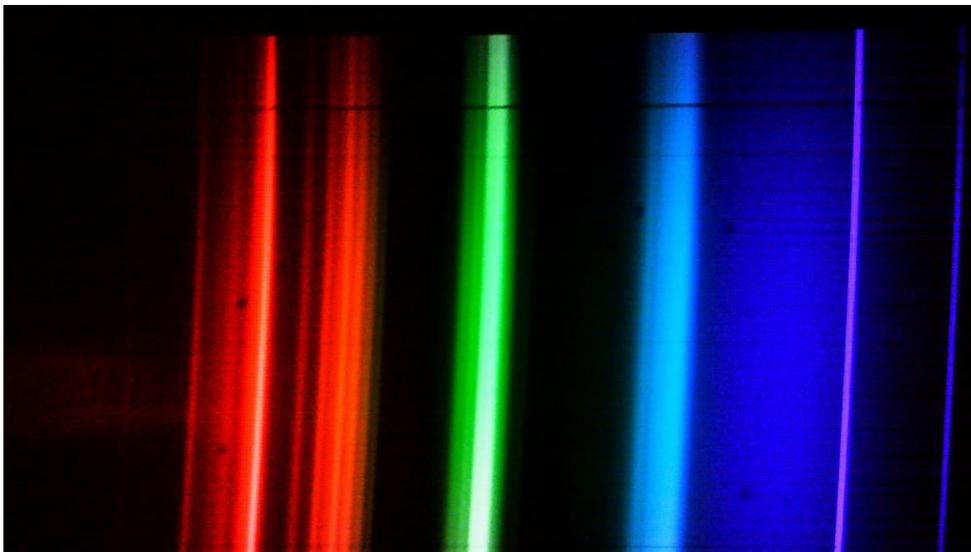


Figure 10. Spectrogram of fluorescent light. Note the reversal of the position of blue and red.

More work will need to be done to produce a hyperspectral image, i.e. a combination of an RGB image and the wavelength data at each pixel. Such a hyperspectral camera will require more complex methods of gathering information in order to produce the desired image. One common method of creating a three-dimensional (X, Y, wavelength) image from a two-dimensional (X, Y) detector is point scanning, in which an image is divided into a grid and the wavelength data is taken at each square in the grid, one by one. This produces an accurate, high resolution hyperspectral image. However, it is exhaustive and therefore slow. The design of the camera will be tuned and updated in order to accommodate this function. The methods and theory required to achieve this will be included in the discussion section.

2.2 Experimental Setup

The testing apparatus was designed to hold the camera assembly close enough to a target board covered with a white, diffusing surface, such that the camera's distance from the target was kept constant, and the light diffused off of the target was bright enough for the detector to pick up. For initial testing and calibration attempts, the camera was kept at a distance of 15 cm from the target, measuring from where the light first enters the device to the surface of the board. This was an adequately close enough distance that the picture wouldn't extend beyond the sides of the target. Figure 11 is an image of the testing apparatus with one of the light sources being shone on the target:



Figure 11. Basic experimental setup for the capture of preliminary test spectrograms

The light source was adjusted so that enough light penetrated the slit and reached the detector, as opposed to aiming at a central target. This is because during the experiment, it was observed that as long as enough light was able to reach the detector, moving the source a small amount had no effect on the

position of the spectral bands. Several different lasers and light sources were tested to confirm the functionality of the camera. 3 low-power laser pointers (red, green, and blue), 1 high-power green laser, and one multi-function laser (with red, UV, and flashlight modes) were used. The low powered laser pointers did not produce enough light for the detector to pick up. The high-power green laser produced a very vibrant band, as did the multi-function laser pointer on its flashlight mode. Neither the low-power red laser or the multi-function's red laser function were able to produce a strong band, but a smaller band was still captured by the camera, providing the most likely source of inaccuracy. The red bands were difficult to capture and required much more time than the other two sources. Refer to the appendix (figures i, ii, and iii) for the images.

2.3 Post-Experiment Processing

Once the images were taken, the camera needed to be calibrated. For the purposes of troubleshooting basic functional errors with the camera, calibration was done manually with a relatively simple process in order to produce a simple linear curve fit by which other subjects could be judged. Down the road, automated calibration, along with a process by which to adapt to different targets will be developed. This will require calculating the effective focal length of the lens setup, the field of view of the camera, and the distance to the target in order to adapt the taken image.

Knowing that the detector takes images at 1080p resolution, we created an x-axis for each image taken, from which we could compare to other images and then identify the wavelengths given off by the subject. For example, if a laser of wavelength 550 nm produced an image with a band at some pixel x in the image, we could then say pixel x corresponds to 550 nm, which will allow us to identify the wavelengths in other subject images. By adding other known points, the linear extrapolation can be more accurate. Different colored lasers allow for more calibration points, and lasers specifically are chosen as they can produce a single, consistent wavelength. The lasers used in the preliminary experiment had a deviance in wavelength of less than 2% (plus or minus 10 nm, to be exact) so their accuracy provided no significant amount of error.

The images were placed into Microsoft Paint, as Paint has a built-in pixel coordinate function. By estimating the center of each spectral band and drawing a line through it, each band was placed on the x-coordinate pixel. The images with lines added are in the appendix in figures iv, v, and vi. The wavelengths and their corresponding pixel values are tabulated in Table 1.

	Wavelength (nm)	Pixel Value (out of 1920)
Blue Laser	405	1538
Green Laser	532	922
Red Laser	650	38

Table 1. Wavelengths and pixel values for each laser

In Excel, a scatter plot was made using the wavelengths listed on the lasers for the x-axis and the pixel value of each band on the y-axis. Then, a linear curve fit was created in order to calibrate the

camera. Using this curve fit, the wavelengths of any subject emitting visible light 15 cm away can be identified.

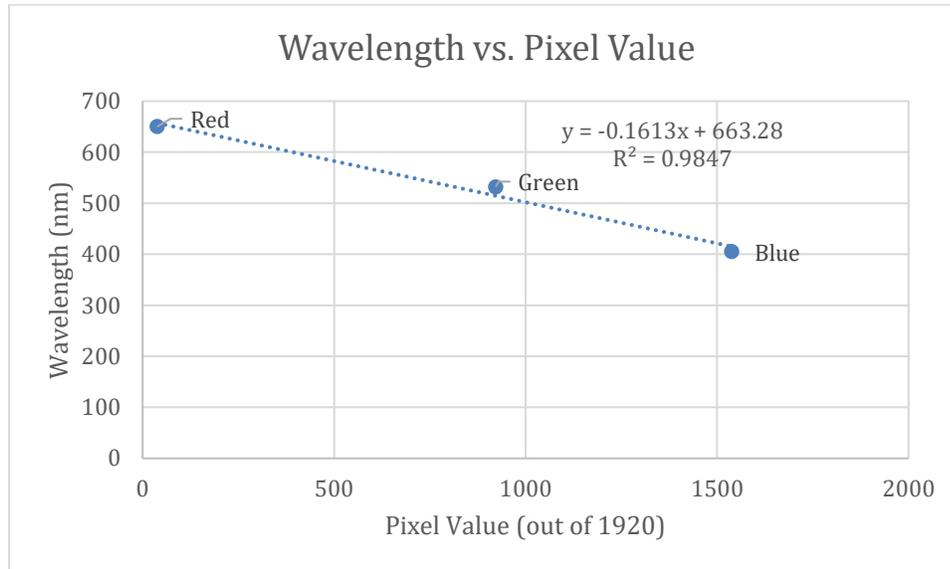


Figure 12. Scatter plot of wavelength vs. pixel value with curve fit

The r^2 value is 0.985, meaning that within the range of wavelengths, the curve fit is very accurate. All these calculations will be done with Excel for testing in the near future. Further down the road, this process will be automated and added along with the processing required to create the hyperspectral images.

To adapt the design for infrared or near-infrared wavelengths, again, the entire assembly will have to undergo a few changes. For one, a desired dead-center wavelength will need to be chosen that is appropriate for the type of light. This will determine the characteristic angle of the 3D-printed assembly. Then, a proper detector has to be chosen. This will be the main source of cost for the camera, as specialized detectors can be very expensive. Finally, once the camera is assembled, the new detector will need to be calibrated again, ideally with some known subjects with predicted/known wavelengths.

3. Final Remarks

3.1 Discussion

The preliminary tests of the camera showed that it can indeed produce a useable spectrogram, as long as the subject provided sufficient light to reach the detector through the assembly. While the blue and green calibration bands were strong and vibrant, it was much more difficult to capture the red band, as both red lasers were lower powered, and generally speaking longer wavelengths have a harder time penetrating than shorter wavelengths. More complicated functions (infrared detection, hyperspectral imaging) have yet to be implemented, but the design of the camera is easily adaptable to accommodate a different range of wavelengths. Calibration is still not automated, as the image data needs to be manually

processed in Excel to identify the wavelengths. Future designs may include a small program to read the images and output the pixel values automatically for calculation and identification of the wavelength values.

As mentioned above, the basic assembly of the camera need not change for different types of electro-magnetic waves. The two parts that would need to be replaced in this case are the detector and the grating, as they both have specific wavelength ranges of function. For infrared wavelengths, the goal of keeping costs low is still achievable, as infrared detectors are relatively inexpensive and widely available. However, as near-infrared detectors are still niche and rare, the cost of the camera assembly will increase, posing a problem for the primary goal of the experiment. The 3D-printed assembly will also need to change, with the model's angle changing based on the desired dead-center wavelength.

There are a few common methods for creating a hyperspectral image, and depending on the method chosen, the optics of the assembly change. One of the most common as mentioned above is point scanning. The basic principle, as mentioned above, requires taking the wavelength data at each point in a grid, usually the pixels of the image. One way to achieve this is to send the incoming light to two detectors, such that one reads the wavelengths through a grating, and the other takes the image. Then, the detectors are instructed to take images at each point along a grid, thus creating a set of data that can be then compiled into a hyperspectral image. Other methods, such as line scanning and snapshot scanning, require different optics and different setups.

3.2 Conclusions

- Assembly and testing were successful for the first prototype of the camera
- Spectrograms can be produced; hyperspectral images will require more time/research along with a more complicated assembly and interface to produce
- Difficulties in capturing the spectrograms were due to insufficient source strength and inherent difficulties at higher wavelengths.

4. Recommendations for Future Iterations

To recap, the ultimate goal for this project is to develop a device capable of producing a hyperspectral image, which requires the synthesis of both wavelength data and a source image (usually RGB). To achieve this, it is recommended to implement a point scanning method. This will require the camera to assign a grid to its subject, then take the wavelength data of each square in the grid, one by one, until it can finally be composited with the final image. Other methods, such as line scanning and snapshot scanning, sacrifice resolution or require much more expensive/complicated parts.

Dr. Chevrier noted that while the camera should work first with visible light, it will need to later be adapted to infrared and near-infrared wavelengths. As mentioned above, this will require the following changes:

- Edit the characteristic angle of the 3D-printed housing using equation 1 and a desired dead-center wavelength
- Change the detector to one that can read infrared/near-infrared wavelengths
 - Note that this is going to be the main source of cost
- Change the grating out for one with the proper wavelength range (the one used in this model has a range of 400-700 nm, for example)
- Develop a program (perhaps using Visual Basic for Excel compatibility) that can help calibrate, process, and composite all the data from the spectrogram and the source image, such that the process can be automated

For the near future, the fit of the 3D-printed assembly should be improved, as there are still some light leaking into the assembly. The testing apparatus should also be improved upon to keep the camera more still and to help maintain consistency during operation. More diffused light sources should also be purchased/developed, as a small point subject, such as a small laser pointer, cannot provide enough light for the detector to pick up. Finally, there are two directions to choose from for the next step: automation or infrared. I believe that developing a way to automate the image taking, calibration, and processing is key to enabling future rapid prototyping, as it will be less time-consuming to capture usable images and turn it into data.

5. Appendix

5.1 References

1. https://www.nasa.gov/mission_pages/station/research/experiments/864.html
 - a. Uses of hyperspectral imaging
2. <https://www.osapublishing.org/oe/abstract.cfm?uri=oe-26-5-6021#articleBody>
 - a. Original Paper
3. <https://www.edmundoptics.com/resources/application-notes/imaging/understanding-focal-length-and-field-of-view/>
 - a. Optics Calcs if need be
4. <https://www.olympus-lifescience.com/en/microscope-resource/primer/java/components/perfectlens/>
 - a. Combining lenses
5. <https://www.shimadzu.com/opt/guide/diffraction/02.html>
 - a. Basics about diffraction grating
6. <http://www.cbrnetechindex.com/Print/6128/specim/specim-iq>
 - a. Production hyperspectral camera
7. <https://mathematica.stackexchange.com/questions/85990/how-to-plot-an-emission-spectrum>
 - a. Image of spectrogram
8. <https://www.shimadzu.com/opt/guide/diffraction/14.html>
 - a. Transmission Grating basics
9. <http://www.cbrnetechindex.com/Print/6128/specim/specim-iq>
 - a. Specim IQ spec sheet
10. <https://mathematica.stackexchange.com/questions/85990/how-to-plot-an-emission-spectrum>
 - a. Emission spectrum image (first answer)

5.2 Parts List

1. Front lens f/4 FL 16 mm
 - a. <https://www.edmundoptics.com/p/160mm-fl-no-ir-cut-filter-f4-micro-video-lens/26288/>
2. M12 lock nut for μ -video lenses
 - a. <https://www.edmundoptics.com/p/M12-Lock-Nut-for-Micro-Video-Lenses/18813/>
3. Precision air slit 25 μ m x 3mm
 - a. <https://www.edmundoptics.com/p/25mum-x-3mm-unmounted-precision-air-slit/4370/>
4. Field lens FL = 10 mm
 - a. <https://www.edmundoptics.com/p/100mm-Dia-x-100mm-FL-VIS-NIR-Coated-Plano-Convex-Lens/18147/>
5. 3 x S-Mount thin lens mounts
 - a. <https://www.edmundoptics.com/p/10mm-diameter-s-mount-thin-lens-mount/18655/>
6. S-mount focus tube

- a. <https://www.edmundoptics.com/p/175mm-25mm-s-mount-fine-focus-tube/18665/>
7. Collimator lens FL = 30 mm
 - a. <https://www.edmundoptics.com/p/100mm-Dia-x-300mm-FL-VIS-NIR-Coated-Plano-Convex-Lens/18155/>
8. 600 grooves/mm transmission grating 25×25 mm²
 - a. <https://www.edmundoptics.com/p/600-grooves-25mm-sq-287deg-blaze-angle-grating/10093/>
9. Detector lens f/2.5 FL = 25 mm
 - a. <https://www.edmundoptics.com/p/250mm-fl-no-ir-cut-filter-f25-micro-video-lens/13716/>
10. S-Mount brass spacer rings
 - a. <https://www.edmundoptics.com/p/brass-spacer-ring-kit-2-of-each-size/11201/>
11. C-mount to μ -video lens adapter
 - a. <https://www.edmundoptics.com/p/c-mount-to-mu-video-lens-adapter/10767/>
12. Detector
 - a. https://www.amazon.com/Spinel-Non-Distortion-3265x2448-Adjustable-UC80MPA-ND/dp/B0716RKLYM/ref=sr_1_2?keywords=imx179&qid=1551113855&s=gateway&sr=8-2
13. Low-power Laser Pack (Red, Green, Blue)
 - a. https://www.amazon.com/gp/product/B07PDFNKDB/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1
14. High-power Green Laser
 - a. https://www.amazon.com/gp/product/B07K8RXJFR/ref=ppx_yo_dt_b_asin_title_o00_s01?ie=UTF8&psc=1
15. Multi-Function Laser
 - a. https://www.amazon.com/gp/product/B076CFXP4C/ref=ppx_yo_dt_b_asin_title_o00_s01?ie=UTF8&psc=1
16. Diffusing Sheet
 - a. https://www.amazon.com/gp/product/B06XSBDWXX/ref=ppx_yo_dt_b_asin_title_o00_s01?ie=UTF8&psc=1

5.3 Spectrograms Taken with Camera

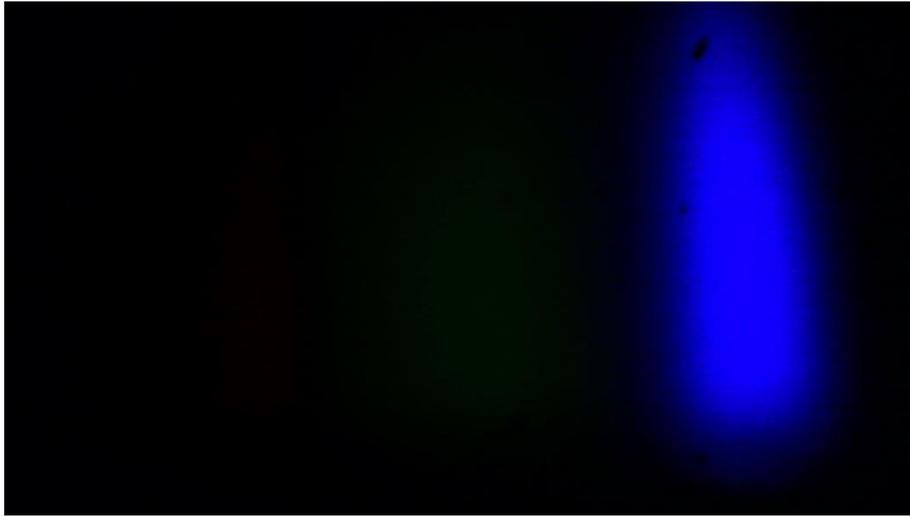


Figure i, Spectrogram of multi-function laser flashlight mode

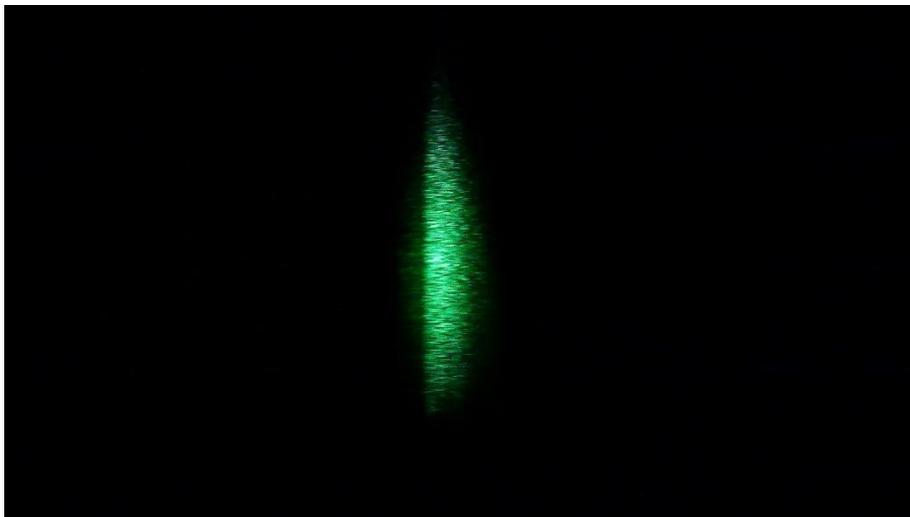


Figure ii, Spectrogram of high-power green laser



Figure iii, Spectrogram of low-power red laser



Figure iv, Spectrogram of multi-function laser flashlight mode with line

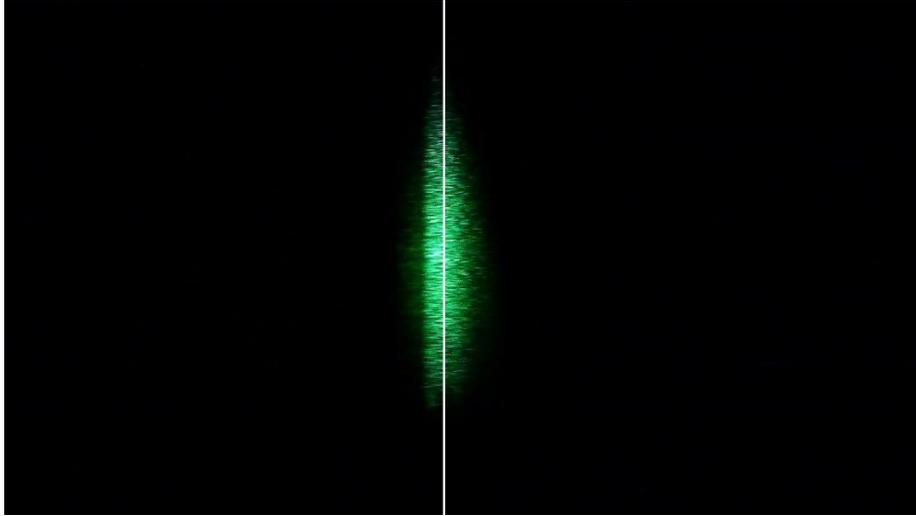


Figure v, Spectrogram of high-power green laser with line



Figure vi, Spectrogram of low-power red laser with line