Spectral Guide

Spectrometry and Imaging Automation for Astronomy

The Orion Nebula: Photo taken by Addison Long

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BACKGROUND AND MOTIVATION

Spectroscopy began with Sir Isaac Newton's observations of the sun's spectrum. He made the first measurements by allowing sunlight to pass through a small hole around one-third of an inch broad from the shutter of his window in an otherwise dark room. Then Newton placed a prism in front of the small hole, allowing sunlight to pass through the prism, revealing a spectrum of colors akin to a rainbow. In his 1705 publication "Opticks or, a Treatise of the reflexions, refractions, inflexions and colors of light" he wrote "The blew was refracted more by the lens than the red, so as to converge sooner by an inch and a half, and therefore is more refrangible". Newton understood his discovery was a significant advancement in the study of light. But still, I wonder if he understood the full grandiosity of his discovery that the color of light is related to the angle of refraction. Besides this crucial conclusion, Newton noted anomalies in the solar spectrum: certain colors were missing. Unbeknownst to him, he had just created the first spectrometer, a tool in optics and photonics that would go on to revolutionize our understanding of the cosmos.

Only a short time after Newton's discoveries, Joseph von Fraunhofer, inspired by the potential of these discoveries, sought new applications and is credited as the first to combine a prism with a telescope. This simple combination of instruments enabled him to study the spectra of various celestial bodies. Fascinated by his findings, Fraunhofer experimented further and created one of the first diffraction gratings, a simple grating constructed from metal wire. With this new invention, Fraunhofer measured the wavelengths of the spectral lines he observed.

Since then, the analysis of stellar spectra has become a cornerstone in astronomical research. In today's modern world, spectrometry empowers us to search for life on distant exoplanets using cutting-edge instruments like the James Webb Space Telescope. However, despite the many advancements in spectroscopy and the creation of new manufacturing techniques such as photolithography and precision machining, spectroscopy remains a costly endeavor, often exceeding five thousand dollars, placing it out of reach for many aspiring astronomers.

Tracking systems for astro observation have become a cornerstone for creating clear and accurate images. Manual tracking mounts which can be dated back to the earliest of astronomers have been around for many years however as humans have gotten smarter so has this technology. Jim G. Astheimer as a pioneer guide was added to commercial mounts back in the mid 1980’s and was implemented via feedback loops. This technology rapidly gained traction due to its ease of use and exceptional results. With developments of more powerful microcontrollers and more open source cameras guiding systems have begun to play a crucial role in tracking mounts.

The autoguiding systems found today often allow for near perfect tracking of astral bodies and therefore allow for considerably higher resolution images due to the longer exposure time. The main issue however lies in the cost and portability. With the cheapest viable guiding mounts ranging at around a thousand plus dollars this places it outside the range of amateur photographers. The other issue we aim to bridge is the need for external equipment. Astro photography needs to remain as compact as possible due to the need to relocate or even transport this equipment to different sites. Due to the none all in one approach of these guiding systems at a low cost most of them require the use of an external computer to tap into the guiding system.

In our senior design project, we aim to bridge this gap. We plan to develop a spectrometer that is low-cost and adaptable to any amateur astronomer's telescope. To provide the lowest cost possible, we will open-source the project by providing 3D printing schematics and software while using affordable precision optics so that our project may be replicable without buying a completed kit. With this approach, any willing astronomer can adapt the project to their needs. This will significantly reduce the cost of the spectrometer since the construction will be handled on the consumer's end. This open-source initiative seeks to enable budding astronomers to explore the night sky and learn to interpret the spectra they observe while optimizing performance and price. It will also foster an interest in photonics and astronomy while gaining education on the analysis of spectrograms and the construction of a spectrometer.

GOALS

Project Star Spec should be able to classify stars by letter O, B, A, F, G, K, and M. These classes are well defined by spectroscopic analysis in the optical regime from about 450 nanometers to 700 nanometers. This commonly accepted method for classifying stars reveals information about elemental makeup, temperature, and a rough mass estimate. Having the capability to classify stars is the primary and most fundamental goal of Project Star Spec.

Tracking and guiding will play a major role in allowing for clear and high accuracy spectrographs. We will be taking advantage of the wifi technology readily available in many entry and mid level DLSRs to be able to view the image live without the need of an external computer. This will allow for a more lightweight solution which relies less on additional peripheral software and hardware. With the advantages provided by the Raspberry Pi Compute Module we will use the available SDK to process the image, make guiding adjustments to reduce any error developed over time due to tracking error and communicate this adjustments to a central microcontroller that will then direct the motor movement to reduce or eliminate this error.

With the advantages provided by an onboard computer running in the linux environment we will be able to interphase other technology such as smart analysis of stars for identification based on their spectrographs by being able to communicate to the open source nature of astrophotography. Many databases exist such as the BeSS database which will work as an ample way of comparing spectrograms in order to determine the observed star. In addition we would like to use the available systems on board the mount to allow for an easy interface to an app as a way to gain more information about the current star being observed. This will be a mixture of open source information available as well as the results from the spectrograph analysis.

Our advanced goal is to identify binary stars by spectroscopy. Very few binary star systems have orbits with eccentricity great enough that the stars are resolvable by observation independently. However, it's well-studied that the spectrum of these binary star systems shows a clear combination of spectra indicating the presence of a binary system. A notable binary star in the sky currently is Procyon. It is known as a spectroscopic binary star system because the two stars, Procyon A and B, are easily distinguishable due to their different classifications. While Procyon B is a white dwarf star, Procyon A is an F-type star. This difference makes it easy to determine that we are looking at a combination of spectrums. The main challenge of analyzing the spectrum for a spectroscopic binary star system is that our system must have enough resolution to differentiate the absorption lines of each star.

Despite our current design utilizing a wall outlet as our power source, and by extension power not being a significant restraint, we intend to make our design as power efficient as possible for several reasons. The first being that we desire to practice principles of good design, and efficiency is a strong component of good design. Secondly, and more practically important, if we achieve a low enough level of power consumption we could advance the design to a battery based power source. This would allow for a more mobile design, enabling end users to use this product in places where power outlets are not readily available or where extension cords are impractical, not to mention making the entire design more compact due to the removal of the wall outlet cord.

The main motivation for choosing a tracking and guide system which will be at more entry level price is that after market analysis it is evident that guide systems greatly improve the ability to take clearer images and therefore more accurate spectrographs and allow for smart technology to be implemented due to the live image processing. This combined with the high entry point for systems such as this make this an interesting addition to Project Star Spec. It is critical that the cost remains accessible and low, without compromising on functionality. Acquiring images of distant stars is a delicate task and we must be able to keep the stability and accuracy requirements of this task intact, while reducing the cost.

Finally, our stretch goal is observing emission lines from bright nebulae such as the Orion Nebula. The main challenge of observing the nebula's emission spectra is signal-to-noise. Nebulas are very dim compared to stars, but unlike stars with a primarily continuous spectrum, nebulas have individual emission lines. Astrophotographers have long since used narrow band optical filters to block as much surrounding light as possible. Should project star spec be able to resolve the emission lines of a bright nebula, it could be used to determine the correct narrow band filter for best viewing as well as provide descriptive information on the nebula's composition.

OBJECTIVES

Spectroscopic resolution is a critical factor and is typically classified into three distinct categories: low, intermediate, and high resolution. Low resolution is characterized by $R < 1000$, intermediate resolution falls within the range of $1000 < R < 10000$, while high resolution is defined as $R > 10000$. We aim to attain a resolution greater than 1000 ($R > 1000$). This resolution positions us right at the low end of the intermediate resolution spectrum. Intermediate resolution strikes an optimal balance, providing sufficiently detailed spectral data for effective star classification. By targeting this level of resolution, Project Star Spec ensures the acquisition of high-quality, usable stellar spectra without the prohibitive expense associated with high-resolution spectroscopy.

Tracking and guiding are determined by their accuracy in arcminutes as our goal is to produce high quality deep-sky spectrographs. We need our guiding system to operate at or under 1 arcminute of accuracy. This is the main factor for the guiding system and we expect to be able to reach this by implementing both an equatorial tracking approach which will allow us to follow the earth's rotation and after calibration and then adjusting for any error created using a guiding system onboard the mount. With this approach we hope to be able to reach exposure times of around 1-2 minutes which would meet standards for tracking and guiding mounts.

To minimize noise and motion blur across the 1-2 minute exposure time, our physical implementation of the tracking of the star requires a significant level of accuracy. To achieve this accuracy, we will need to continuously move the motors by manipulating not the position of the motors every time a new frame is analyzed, but the velocity. This velocity will be governed to adjust both the speed and direction required for both the X and Y axis. To achieve this level of accuracy, we need to have a strongly responsive system with very low latency and accurate voltage monitoring on the motors. This could likely be done with a Raspberry Pi, or with a mid range MCU, but for our design we are interested in using an FPGA. We would like to use an FPGA for this control, alongside the Raspberry Pi, for two main reasons. First, FPGA’s are wicked and Sebastian loves to use them. Second, and more importantly, we believe that the parallelization and low level control available to FPGA's will allow for the processing and response to the tracking data to be more timely and accurate than if this task were to be offloaded onto the Raspberry Pi.

ENGINEERING SPECIFICATIONS

These engineering specifications are not comprehensive and are very much preliminary estimates. Some requirements may be tweaked and more requirements will be added as research continues and part selections are solidified.

Spectral Resolution	R>1000
Grating period	600 lines/mm
Slit width	3mm
Pixel size	3.72um
Position Accuracy	< 3 arcminute
Weight	< 5lbs
Motor Input Power	12VDC
PCB Input Power	5VDC
Frame Refresh Rate	.25s
Clock Speed	~3 GHz

EXISTING PRODUCTS

The following is a selection of a few existing products in the field that are used in the field of space photography. Though these are each different in nature and have different capabilities, these are all considered "entry level" space photography tools by those within the community.

HEQ5 PRO

[Sky-Watcher HEQ5 Pro GoTo Equatorial Mount]

HEQ5 PRO is a guiding equatorial mount and is an entry level autoguiding and tracking mount for astrophotography. This mount follows the principle that by moving as the earth rotates and then using software to make small adjustments you can increase the exposure time of the image allowing you to see deeper into the astros. This mount's selling point is its accuracy which is claimed to be at 1 arc minute and its ability to detect 42900+ objects via its smart guide system which is connected via a rs-232 to be able to take advantage of the autoguiding system.

The main areas we are looking at improving are reducing the price from its 1,335$ dollar price to something more entry level and accessible. The goal would also be to eliminate the need for an additional computer instead of offloading the guiding system to an on-board system with a bluetooth interphase. We hope to be able to keep similar arc minute precision while reducing the price and reducing the required hardware.

Star Analyzer 100/200

The Star Analyser SA-100, SA-200

The star analyzer 100/200 is a transmissive diffraction grating filter and is the simplest way to create a spectrogram. However, because it is a transmissive grating, you have a lot of signal loss. It comes in two varieties: 100 lines/mm and 200 lines/mm. The primary difference between these two varieties is the distance it must be mounted from the detector. Should you be limited by space, the 200 enables you to capture the same spectrum at a shorter distance at the trade-off of luminosity.

The benefit of transmissive gratings is the ease of use and price. This filter can be mounted to any camera and only costs $200. The performance may not be the best, but it is currently the most affordable way to do amateur stellar spectroscopy, assuming you have a camera and tracking mount.

SX-Spectrograph reflective

SX-SPECTROGRAPH PRO

Despite still being considered an amateur spectrograph, it costs $4660. However, this product uses a concave reflective grating that cuts down on the optical design portion by combining one of the focusing mirrors with the diffraction grating. This approach also preserves signal since the spectrum doesn't have to transmit through an optic and is instead reflected, avoiding absorption. At 550 lines/mm this spectrometer has plenty of resolution and is more than sufficient for producing sharp spectrographs. Along with a solid optical design, this product also integrates a guide camera to ensure the accuracy of the tracking to make the best quality spectrum.

COST AND BUDGET

Several of these components, and by extension their costs are not solidified. What is listed is a non-comprehensive estimate of the major components in the design. Some components may be tweaked and more components will be added as research continues and part selections are solidified.

Component	Quantity	Unit cost	Total
Orion EQ-13	1	$179.99	$179.99
FPGA	1	$30	$30.00
Low power MC	2	$30	$60.00
Motors	2	$100	$200.00
Raspberry Pi	1	$80	$80.00
Reflective Diffraction Grating	1	$80	$80.00
First surface concave mirrors	2	$30	$60.00
Total Cost			$690

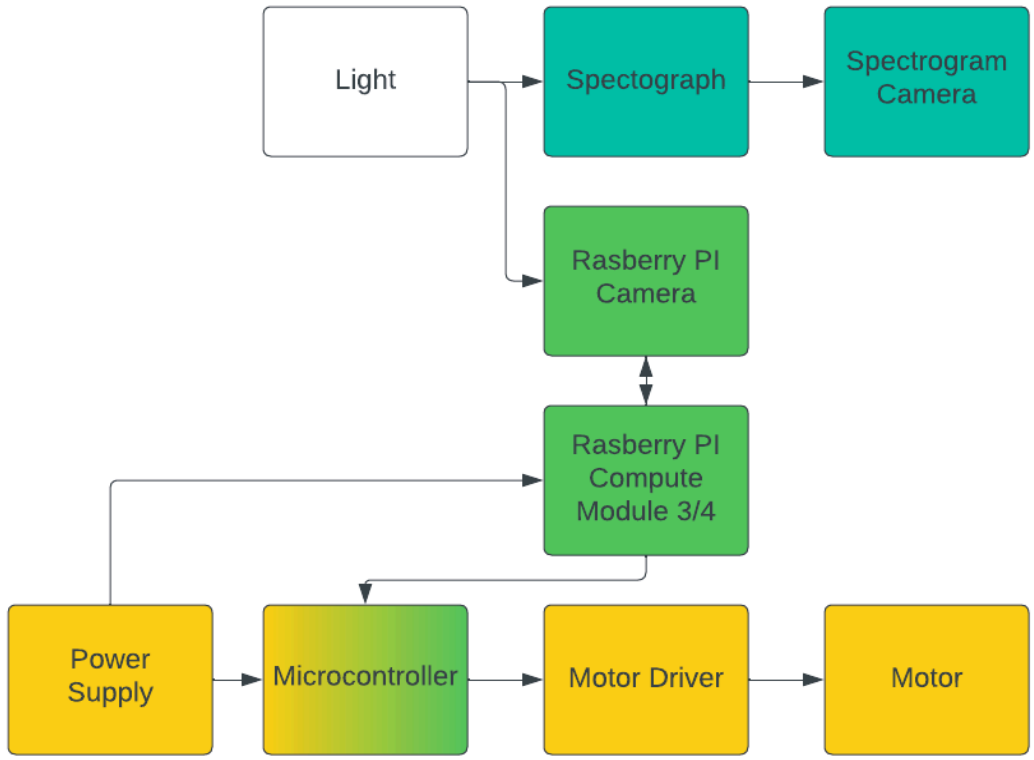
MILESTONES

As the Senior Design lectures continue, there may be adjustments to these milestones if and as additional deadlines and requirements are announced.

Task	Start date	End date	Duration
Brainstorming	January 11th	January 14th	3 days
Division of work	January 18th	January 18th	0 days
Research	January 18th	Ongoing	
Conceptual test with transmissive grating	January 28th	January 28th	0 day
Divide and conquer	January 18th	February 2nd	15 days
Acquire Raspberry pi and connect with	February 2nd	February 8th	6 days

camera			
Website	February 2nd	February 10th	8 days
Initial Motor Test	February 4th	February 10th	6 days
Spectrogram Initial Software Test	February 10th	February 20th	10 days
FPGA communication Research	February 20th	March 5th	15 days
60 page draft	January 18th	March 22nd	63 days
Initial Prototype Design	March 22nd	April 22nd	31 days
120 Page Paper	January 18th	May 1st	120 days

Block Diagram



OPERATIONAL FLOW DIAGRAM

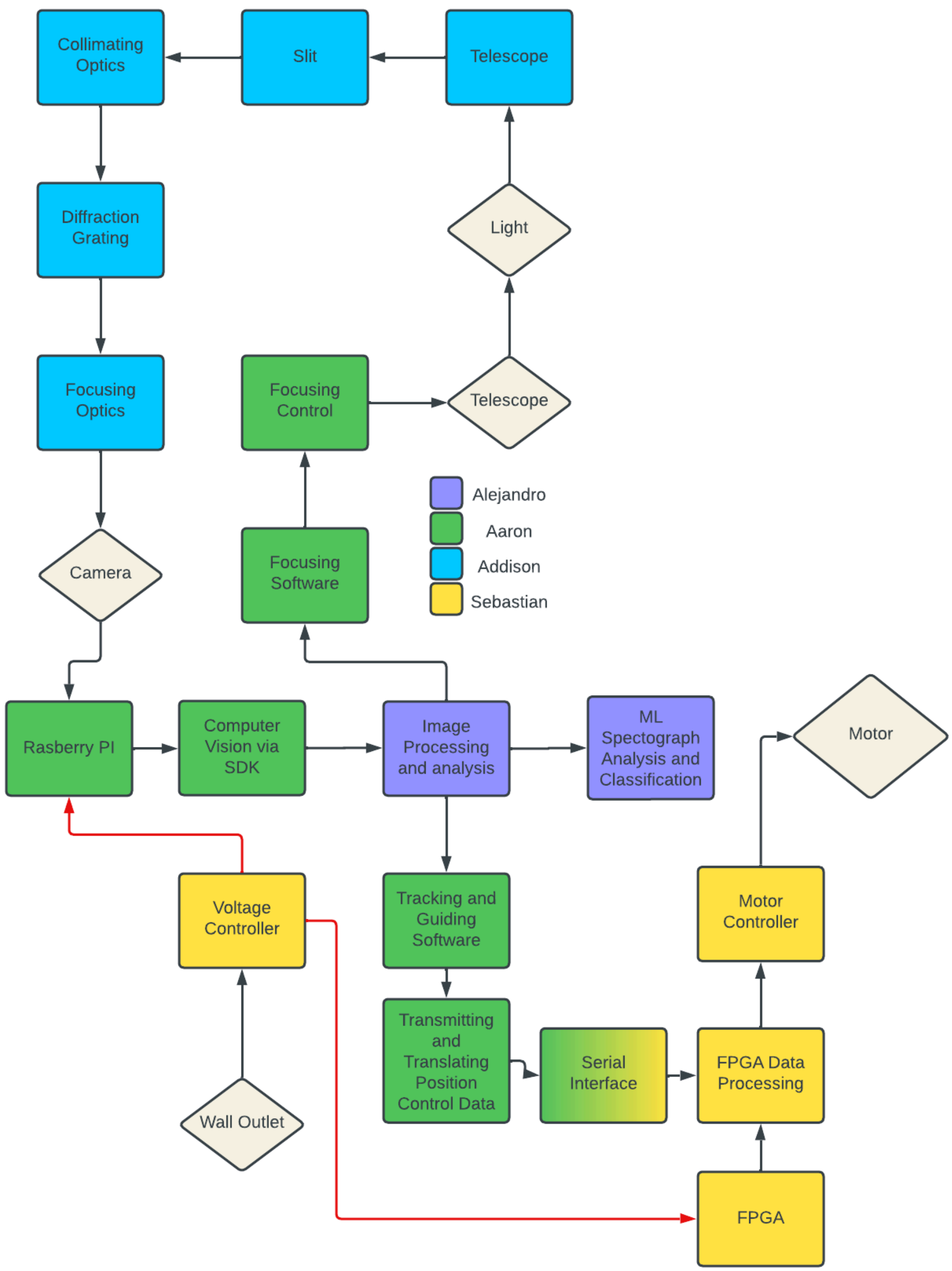
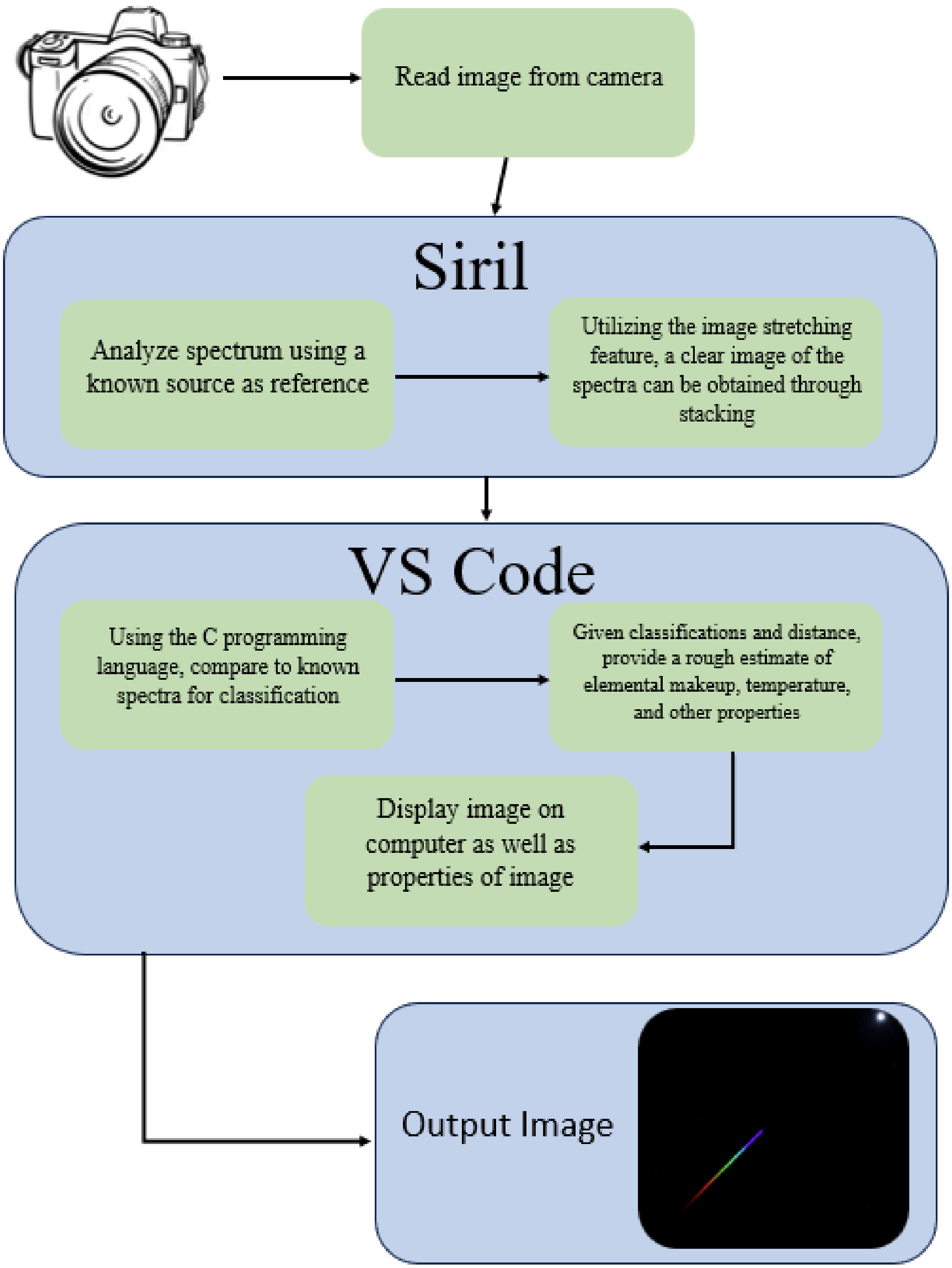


Image Processing/ Spectrum Analysis

Alejandro Olivo



HOUSE OF QUALITY

Project: Project Star Spec

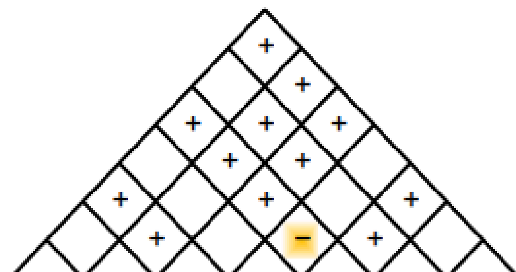
Revision: 1

Date: 1/28/2024

Correlations	
Positive	+
Negative	−
No Correlation	

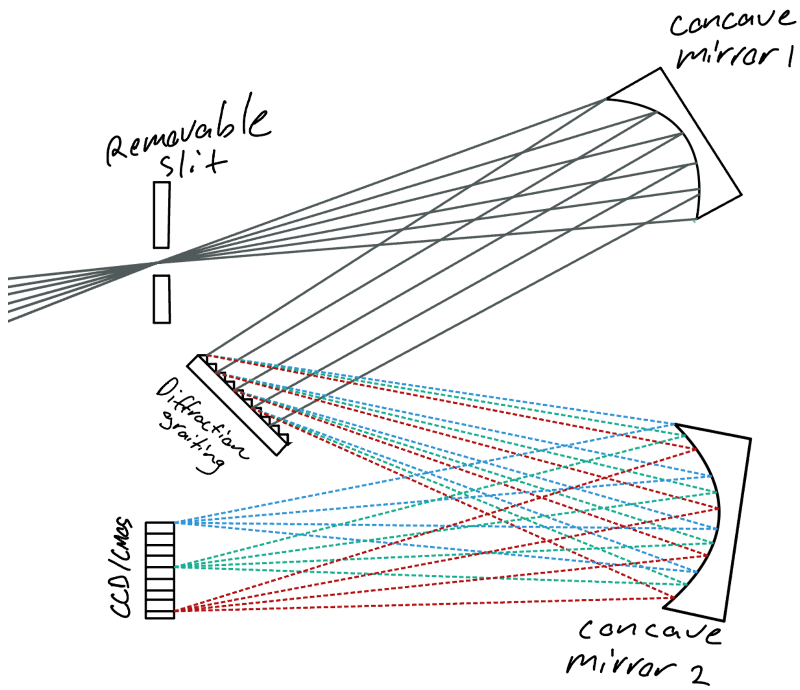
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Category	Weight	Customer Requirements (Explicit and Implicit) / Engineering Requirements	Spectral resolution	processing speed	Tracking accuracy	weight	Power	respose time	signal quality
		Column #	5	6	7	8	9	10	11
		Direction of Improvement	▲	▲	▼	▼	▼	▼	▲
	▲	User interface	▲	▲	◇	◇	◇	◇	▲
	▼	price	◇	◇	▼	▼	▼	▼	◇
	▲	ease of use	▲	▲	◇	◇	◇	◇	▲
	▲	ease of instalation	▲	▲	◇	◇	◇	◇	▲
	▲	educational	▲	▲	◇	◇	◇	◇	▲
		Target	r > 1000	~1.2GHZ	<1 arcmin	<5 pounds	Wall outlet ~120w	<1second	SNR>150

OPTICAL DESIGN



When devising the optical design to fulfill our requirements, we must consider these three core tenets: cost-efficiency, performance, and adaptability. Most importantly, we need to minimize expenses as much as possible to make stellar spectroscopy accessible to the amateur astronomer. The best way to accomplish this is by limiting the number of optical components used in the system.

Next, we need to ensure that we avoid refractive optical elements. The nature of our application—spectral analysis of starlight—demands signal integrity throughout our system. Refractive elements, by their very nature, introduce signal attenuation. This constraint is especially pertinent given the inherently weak signals involved in astronomical observations, where every photon counts.

Moreover, the system must afford us the flexibility to adjust the spectral resolution according to specific observational needs. This adaptability is crucial for tailoring our apparatus to various scientific inquiries.

Given these considerations, the Czerny-Turner spectrograph is a great model for our optical design. This configuration starts with light entering through a slit. The light is then collimated and directed onto a diffraction grating that disperses the light incident onto a concave mirror, which subsequently focuses the dispersed light into our camera. This arrangement satisfies our criteria for minimal optical components and non-reliance on refractive elements while providing flexibility in tuning spectral resolution. Leveraging the Czerny-Turner design facilitates high-quality spectral analysis while adhering to our project's stringent cost and performance specifications.

When determining the spectral resolution of our system we will use the commonly accepted metric of spectral resolution. As seen in the following equation.

$$R = \frac{\lambda}{\Delta\lambda}$$

Where λ is our central wavelength and Δλ is equal to:

$$\Delta\lambda = \frac{RF(\delta\lambda)Ws}{n(Wp)}$$

RF stands for the resolution factor, a dimensionless number that quantifies the system's inherent resolution capability and is dependent on the slit width and pixel size of our system. We approximate to around RF = 1.5. **Ws** is the width of the slit, **n** refers to the number of illuminated pixels on the detector that the dispersed light covers, and Wp is the pixel size. The easiest quantities to tune for spectral resolution will be the slit width and number of illuminated pixels.

Optical Design Part selection

In the optical design of the Czerny-Turner Spectrograph, the selection of components is paramount to preserving signal quality while balancing cost and adaptability. A critical component in this regard is the diffraction grating, which significantly influences the system's overall performance. After careful consideration, we have opted for a holographic diffraction grating with 600 lines per millimeter, prioritizing a reflective over a transmissive approach for several reasons.

Despite their higher cost, reflective diffraction gratings offer superior signal quality compared to their transmissive counterparts. Transmissive gratings attenuate the signal and are rarely optically flat, leading to potential aberrations and a compromised output spectrum. The signal's integrity is crucial for our system, making the reflective option the clear choice despite its cost.

The line count per millimeter directly affects the spectral resolution, with a higher count dispersing light over a larger area, thus enhancing resolution. We balance cost and performance by selecting a 600 lines/mm grating, achieving ample separation between the spectral range's low end (450nm) and high end (700nm). This choice provides a desirable angular dispersion while sitting at the low end of line counts for holographic gratings, saving money.

While ruled diffraction gratings offer efficiency and an advantageous blaze angle, their production costs are significantly higher due to complex manufacturing requirements. Conversely, holographic gratings present a cost-effective alternative, sacrificing only a marginal amount of signal efficiency (approximately 10%). This trade-off is acceptable for our application, allowing us to maintain budget constraints without severely impacting performance.

Given the decision to use reflective optics, selecting mirrors is the next crucial step, with considerations including spectral range, surface curvature, and numerical aperture.

Our mirrors must support the visible spectral range (450-700nm), necessitating a dielectric coating that maximizes reflectivity within this range.

The trade-off between spherical aberration and alignment complexity influences the choice between parabolic and spherical mirrors. Parabolic mirrors, while eliminating spherical aberration, are challenging to align precisely, with minor errors causing significant coma. Therefore, we will use spherically ground mirrors with a slow numerical aperture. This choice simplifies alignment and collimation at the expense of a larger assembly size but avoids the significant aberrations associated with misaligned parabolic mirrors.

Tracking and Guiding Image Processing Research

Computer Vision plays a key role in our autonomous guiding and tracking system for autonomous spectral analyses. Computer Vision is the idea of interfacing with some kind of camera over some integrated circuit in order to detect and compute information about the image being seen by the camera. The main considerations for Computer Vision image processing speed as well as image detection accuracy and mapping. Due to the limitation presented by standard microcontroller based approaches. Raspberry PI's have entered the scene as a reliable and efficient solution to embedded Computer Vision based systems.

Explained Below are the Pro’s and Con’s of using Raspberry PI based architecture within the Tracking and Guiding System.

Pros

Parallel Processing Capabilities:

The

Linux Environment:

Built-In Camera Support:

Expandable Storage:

Cons