TSUNAMI

Hyperspectral Imaging Camera

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TABLE OF CONTENTS

Chapter 2 – Project Description

2.1 Project Background and Motivation

Traditionally, many imaging systems used in modern life are designed around the fact that our human perception of vision is enabled by three wavelength-selective cells in our eyes. Through natural evolution, we developed sensitivity to red, green, and blue light within the *visible* range of the electromagnetic spectrum. As a result, most cameras and displays we use for daily purposes are designed to both simultaneously capture and output these three wavelengths in varying strength, hence "RGB" colorspace. The pixel, or the most fundamental unit used in imaging, is thus a three-element vector within the color images and videos we use on a daily basis.

RGB spectral information can tell us a lot about the world around us and allows us to use wavelength as a factor in how we make decisions. Having only three spectral datapoints points on a given pixel is sufficient for such things, but imaging more than just three (multi-spectral), or even a full-spectrum of wavelengths per pixel (hyper-spectral) can provide professionals with images containing a vastly larger wealth of insight from the information it provides. In typical application, RGB (and sometimes multi-spectral) imaging is accomplished with the use of a spatially multiplexed filter array, assigning a different wavelength filter per pixel in a repeating array, sacrificing image resolution with the number of bands to be imaged. In RGB imaging, a square repeating pattern of two green, one red, and one blue filter is used, which is referred to as a "Bayer" filter, conceived by Bryce Bayer of Eastman Kodak [1].

Hyperspectral imaging is typically accomplished by either switching one axis of an image sensor from spatial to wavelength, or done with a variable and tight controllable filter for an incident image. These are referred to as spatial scanning and wavelength scanning techniques, respectively. We intend to use spatial-scanning via rotation of our instrument, as a large-aperture tuneable bandpass filter with very tight pass-band is prohibitively expensive and not possible for the spectral resolution we are interested in. In spatial scanning, the imaging field of view is left as a line, which diffracts internally to the spatial/wavelength dimensioned image. With composite processing of all images recorded at all scan positions, a final image "cube" is created, consisting of many monochromatic 2-D images, each centered at a different wavelength. This resulting dataset is extraordinarily useful for many remote-sensing applications, in fields such as agriculture, climatology, meteorology, geology, oceanography, and other sciences [2-5].

2.2 Current Technologies and Past Projects

2.2.1 Existing Commercial Product: *Resonon Pika L-F*

Resonon Inc. offers a hyperspectral camera geared toward the agricultural processing industry. The Pika L-F has an operating wavelength range of 420-980 nm with 224 spectral channels and a full-width-half-max (FWHM) spectral resolution of 3.1 nm. The camera has a maximum frame rate of 585 fps, which allows it to be placed above an agricultural processing belt and quickly identify different produce types and/or qualities for sorting. They are able to image at an f/# of 2.8 and in a small form factor of 115 mm x 104 mm x 66 mm. [2]

2.2.2 Existing Research Payload: *NASA JPL AVIRIS Imager*

The NASA Jet Propulsion Laboratory's Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS) is a 380-2500 nm hyperspectral imaging system located on an aircraft. This imaging system has been used to sweep wide areas of California to look for oceanic, botanical, geological, and atmospheric markers and patterns. The camera has a FWHM spectral resolution of 10 nm and a field of view (FOV) of 34 degrees x 1 mrad. Images are taken from 4-20 km of altitude. [3,4]

2.2.3 Previous Collegiate-Level Thesis: *J. Moorhouse of UARK*

As an example of what has been done at the university level, we found the work of Joshua Moorhouse at the University of Arkansas Fayetteville. Moorhouse designed and 3D printed an optical housing for a hyperspectral imaging system which was able to differentiate three different laser lines. No field images were taken in this work and FWHM spectral resolution wasn't specified, but the optical design of the set-up gives us confidence that our optical design will be functional. [5]

2.3 Project Functionality

2.3.1 Overall System Functionality

Our objective is to design and fabricate a line-scanning hyperspectral imager. This instrument will be able to capture an image across a two-dimensional field of view, simultaneously recording an entire visible/NIR spectra per “pixel”. The camera will do this by limiting its field of view to a vertical line (parallel to z-axis, which is orthogonal to the mounting surface), and rotating the imaging optics along the θ-direction (rotation along z in cylindrical coordinates). A linear incident beam is used, as when it is passed through a diffractive grating, it will form a two-dimensional image on a given plane. This image, rather than containing two traditionally spatial dimensions, now includes only the z-axis dimension, with the other being wavelength. When illuminated onto an image sensor array, this image is now a per-pixel spectral representation of the incident beam into the imager. While the final image cannot be captured simultaneously, with a static target, a faithful hyperspectral image can be produced, where any selected (θ, z) pixel can have a full spectrum read off of it. The entire device will be powered via an external AC/DC wall-adapter, feeding in DC power and connecting to a computer (laptop) via USB interface to stream captured image “cubes” for PC processing.

2.3.2 Imager Optics

As we intend to use a commercially available CMOS image sensor for both cost and integration ease, we are limited to the spectral response of a typical commercial silicon pixel. For most CMOS image arrays (barring external NIR block filters), we can expect an effective wavelength bandwidth (above -10dB loss from peak) of roughly 350-1050nm. This depends on the image sensor used, but the optics described in this system will be designed to work across this visible/NIR target wavelength range. The imager subsystem will compose of five major components, which are as follows; the imaging slit, our focusing lens pair, the diffraction grating (in a transmissive mode), our CMOS image sensor (at m = +/-1 order, off axis), and the mechanical substructure specific to aligning and translating these particular parts. The focusing lens pair will be a translatable positive and negative focal length lens. Through translation on a threaded stage, the pair will vary effective focal length from infinite far field down to 2 meters. The object distance will determine the focal length of the pair and will be manually focused. The diffraction grating will be a visible-NIR transmissive grating which will operate efficiently for our wavelength range. The CMOS sensor will collect the first order diffracted light from the grating.

2.3.3 Laser Cursor

To aid with the user experience of working with the instrument, as well as act as a functionally useful indicator, we find it necessary to design a laser “cursor” subsystem. This subsystem will be based on a commercially available red laser diode, and will take the diode’s beam and expand it along the z-axis of the imager. The laser will be pulsed in such a fashion where the laser illuminates the target between successive captures along the imagers' θ-direction. With human persistence of vision, the imager would be able to display a scan-line as it images the objective, without appearing in the image. The laser will be intensity pulse modulated 180-degrees out-of-phase with the pulse signal for the CMOS sensor's global shutter. The laser driver will be designed in such a way where it can receive a TTL pulse signal from the master controller.

2.3.4 Mechanical Structures

Our structures will be designed to be able to accurately pan the camera while maintaining tolerance and strength of the system under motion. A stepper motor will be used to provide torque to the rotation stage with a measurable position via the use of a shaft encoder. The majority of the structural material will be 3D-printed PLA components. For mounts, cases, and support components this will give us the tolerance required while keeping cost down and iteration easy. Threaded components (i.e. lens translation) will be machined from stainless steel, as 3D-printed PLA does not have the tolerance or low-friction required. The baseplate will be a stainless steel plate in order to keep the system from being top heavy and to keep the baseplate from rotating underneath the motorized stage.

2.3.5 Processing and Control Electronics

While the electronics needed for this system will be working as a whole, the electronics subsystem can be generally divided into responsibilities of both data acquisition/processing, and system control. Overall, both portions will be controlled via a high-performance microcontroller (unit, MCU), simultaneously managing both motor control and image acquisition in both hardware and software computation. We will heavily leverage memory transfer and computational hardware outside the CPU such as direct-memory-access (DMA) controllers and filter math accelerators (FMACs) to take advantage of the offered modern MCU peripherals and save on CPU time.

Within the data acquisition/processing side, the electronics must interface to an auxiliary PCB, hosting the desired CMOS image sensor connected via a parallel data interface (DCMI, VGA, etc). The MCU's parallel interface peripheral will read-off the image data captured per global shutter of the sensor, taking a new image per rotational increment of the overall system. The image data will be buffered via an external VRAM chip, giving the MCU adequate time budget to manage other systems while the DMA controllers shuffle this image data around. The DMA will pull image data from the camera interface peripheral into VRAM, and then out to our USB interface when ready.

For controls, pointing accuracy of the motor is paramount, and directly impacts our spatial resolution along the θ-axis. We want to develop motor control electronics to "micro-step" our stepper motor to reach our target spatial (angular) resolution for the imager. This controller/driver will need to accurately deliver and report time-varying current signals as produced by the MCU to meet this.

Real-time closed-loop control will be in-place within either hardware (FMAC) or software computation, and given priority to discipline the frame-capture speed of the CMOS sensor. Our laser diode in the cursor subsystem will be driven with a constant-current circuit, with on-off keying (OOK) input from the MCU. The MCU will also control and monitor on-board DC/DC converters that deliver power to itself and the motor and laser driver.

2.4 Goals and Objectives

In this section we outline our goals and objectives for the *Tsunami* imaging spectrometer instrument. **Goals** are defined through the project's overall purpose and *qualitative* motivation, while our **objectives** are written to detail *quantifiable* deliverables to lead our implementation. Within these, our team also details "stretch" goals and objectives. While we may not necessarily adhere to these in our final product, we will guide our design in such a way that these are possible without significant extra development. Basic goals/objectives MUST be met, with advanced goals/objectives being attempted with absolute, full effort.

2.4.1 Project Goals

Basic Goals:

- The instrument shall be able to faithfully capture spatial and wavelength data simultaneously
- The instrument shall be able to produce fully human-resolvable hyperspectral images of target objects
- The instrument shall allow for easy adjustment of entry lens focus
- The laser cursor shall be able to accurately represent the imager's linear field of view, discernable to any operator
- The control portion of the electronics shall be able to maintain closed-loop control over the imager's rotation mount
- The instrument's collected data shall be able to be streamed to the user PC via a USB full-speed interface

Advanced Goals:

- The instrument's imaging path shall keep stray light to an absolute minimum
- The instrument shall keep the spatial imaging axis achromatic
- The laser cursor shall be able to deliver enough optical power to be viewable outdoors in a reasonably well-lit environment
- The laser cursor shall be able to pulse its output between frames with reasonable accuracy and dead-time for imager exposure

Stretch Goals:

- The instrument may potentially be able to switch between a 2D view and a spatial / wavelength view for easy focusing
- The laser cursor may potentially be able to display multiple colors, beyond just the target red (650nm) wavelength.

- The instrument may potentially be able to auto-calibrate its spectral response and spatial/pointing accuracy

2.4.2 Project Objectives

Basic Objectives:

- The instrument optics shall maintain a large vertical depth of field and avoid image aberrations as much as possible
- The instrument shall be able to vary the entry focus for different object distances
- The instrument's rotational mount shall be able to pan the imager and cursor accurately around a scene
- The instrument's mechanical structures shall be designed to be non-cost prohibitive to manufacture

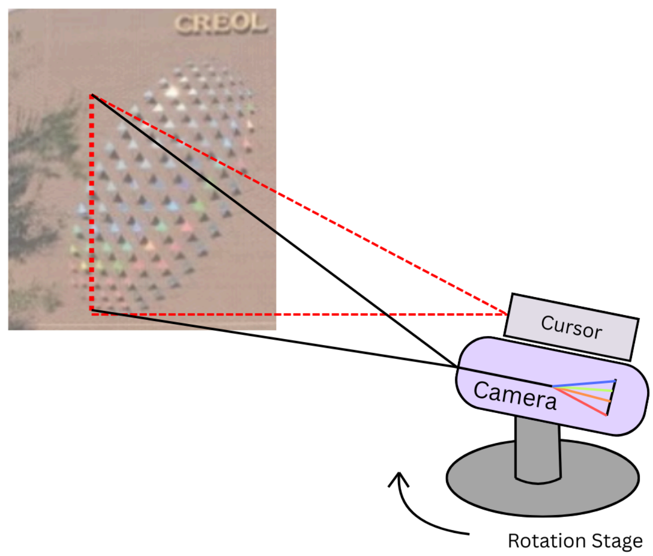
Advanced Objectives:

- The laser cursor's intensity distribution over the system z-axis shall be made flatter than a pure Gaussian distribution
- The instrument's rotational stage shall be capable of maintaining a very high pointing accuracy for lateral spatial resolution
- The laser cursor shall point as close to the camera's linear field of view as possible (maximum overlap)
- The control portion of the electronics shall maintain a fast control loop bandwidth

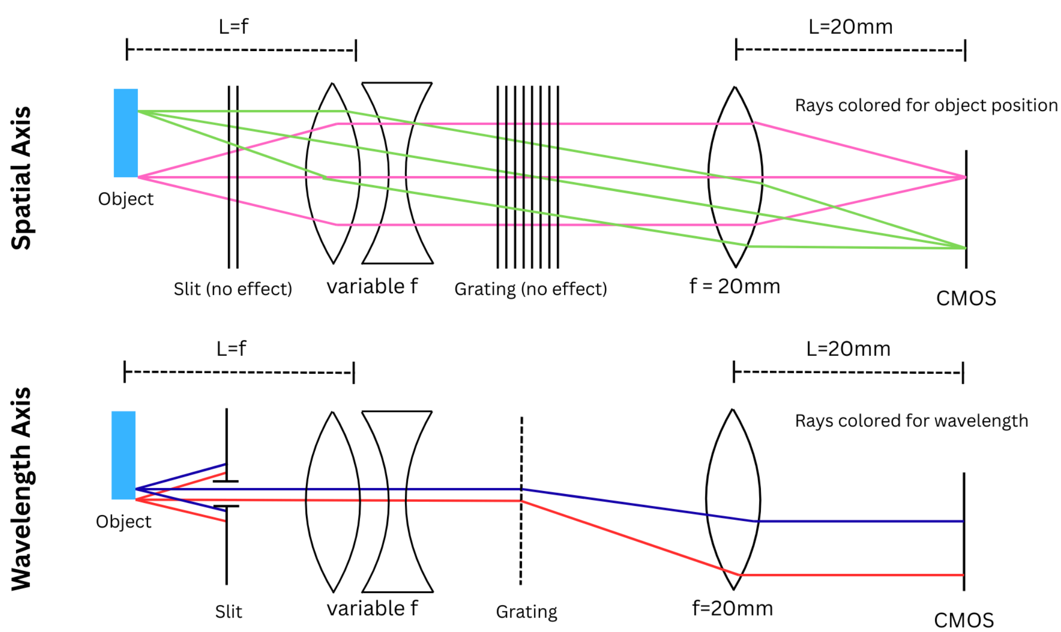
Stretch Objectives:

- The instrument's rotational stage may potentially be able to pan across the scene with equal or better resolution to the directly-imaged spatial axis
- The processing electronics may potentially be able to support USB high-speed interfacing (480Mbps max baud. rate) to enable for much faster frame streaming
- The processing electronics may potentially be able to support local mass storage to avoid streaming to user PC (SD card or likewise)

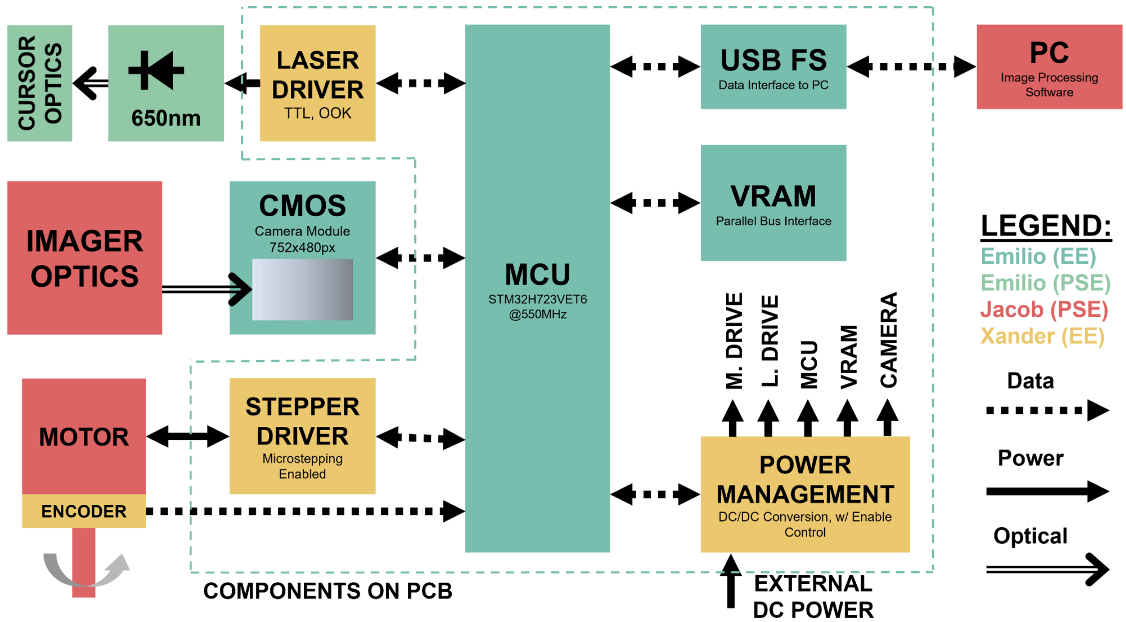
2.4.3 Overall Application Diagram



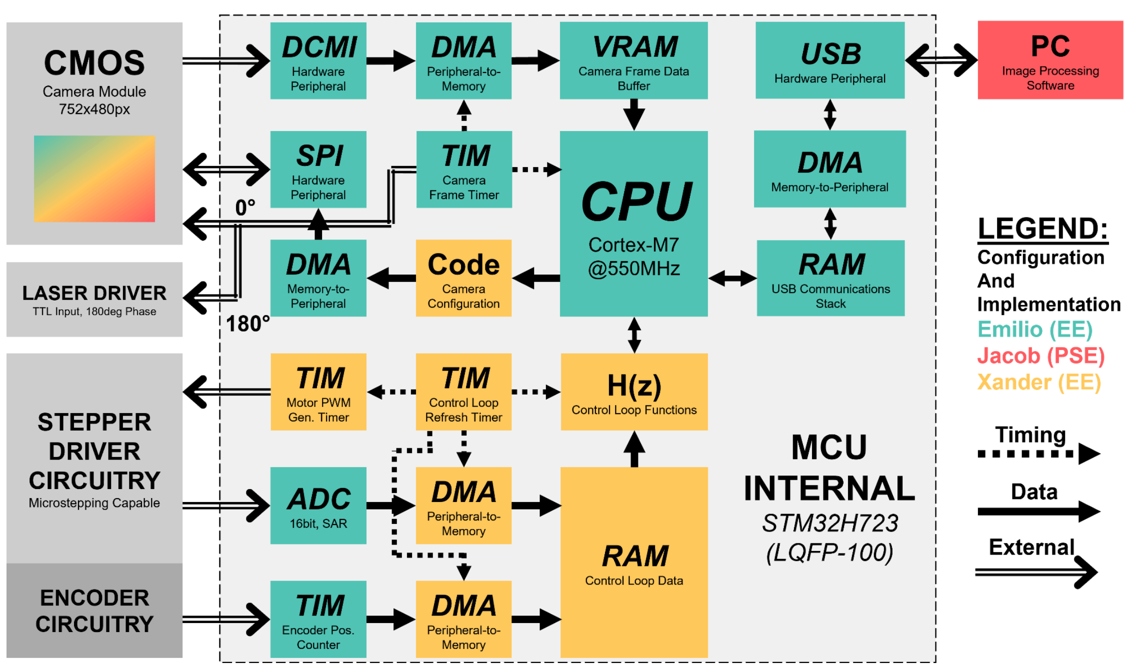
2.4.4 Imager Optical Diagram



2.4.5 Hardware Block Diagram



2.4.6 Software/Firmware Block Diagram

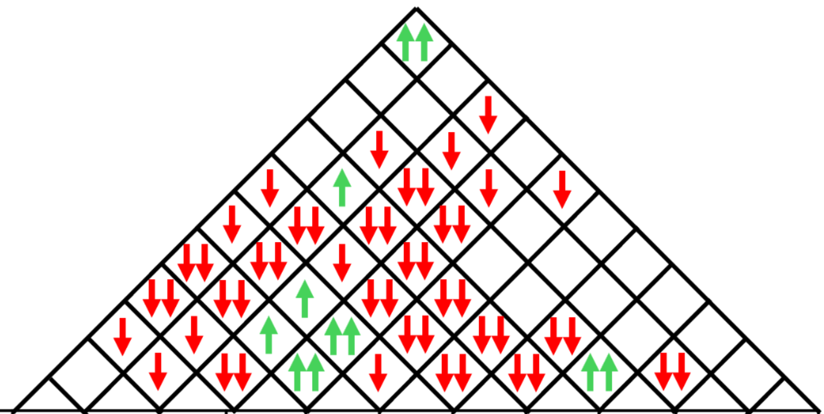


2.5 Required Specifications

2.5.1 Specification Value Table

Subsystem	Specification	Value
Imager Optics	CMOS image sensor resolution **(MT9V034)**	**≥ 752x480px**
	Spatial resolution (z-axis, vertical, on sensor)	**≥ 480px**
	Focused spot size (pixel size is 6μm)	**3 - 12μm**
	Detection wavelength range	**400 - 950nm**
	Entry focal-length range	**2.0m - ∞ (ff)**
Laser Cursor	Laser output power	**5 - 100mW**
	Laser spot aspect ratio (vertical/horizontal)	**≥ 20:1**
	Laser on/off rise/fall time (10% - 90%)	**≤ 10μs**
Mechanical Structures	Spatial resolution (θ-axis, pointing accuracy)	**≤ 1.0°**
	Total weight of instrument	**≤ 5kg**
	Compressive/tensile forces vs shear per part	**≤ 10x**
Processing & Control Electronics	Circuit protection (per power rail)	**OVP & OCP**
	Control-loop sample rate	**≥ 100Hz**
	Maximum power consumption (total, system)	**≤ 50W**
	Image sensor frame-transfer rate	**≥ 30Hz**
	ADC sampling resolution	**12 - 16bit** (≥ 12bit ENOB)
	USB communications transfer rate	**1 - 12MBps**
	Input DC voltage range	**12 - 45V**
	Motor encoder points-per-revolution	**≥ 1000ppr**

2.5.2 House of Quality Diagram



Legend:
(+) : Maximize
(-) : Minimize
↓ Works against
↑ Works with

Engineering Requirements:		Overall Cost	Power Consumption	CMOS Array Resolution	CMOS Array Max Framerate	Stepper Motor Pointing Precision	Stepper Motor Max Speed	Control Loop Sampling Speed	CPU Computation Time	Connection Bandwidth (USB)	Image Processing Software Complexity	Optical Component Cost
Marketing Requirements:		-	-	+	+	+	+	+	-	+	-	-
Overall Cost	-	↑↑		↓	↓↓	↓↓	↓	↓				↑↑
Spatial Resolution	+	↓↓	↓↓	↑	↑↑	↑↑	↑	↑	↓↓	↓↓	↓	↓↓
Spectral Resolution	+	↓↓	↓	↑↑					↓↓	↓↓	↓	↓↓
Wavelength Range	+	↓↓		↑					↓	↓	↓	↓↓
Vertical Field of View	+	↓		↑					↓		↓	↓↓
Ease of Use	+	↓								↓	↓↓	↓
Overall Size	-	↓	↓↓			↓↓	↓↓	↓↓	↓↓			↑
Acquisition/ Scan Time	-	↓↓	↓↓		↑↑	↑↑	↑↑	↑↑	↓↓	↓↓	↓	
Parameter Target Specifications		**≤ $1500**	**≤ 50W**	**≥ 752x480px**	**≥ 60fps @ Full Resolution**	**≥ 0.1875°**	**≥ 3° /sec**	**≥ 100Hz**	**≤ 62.5ms per scan**	**≤ 12Mbit/s**	**≤ Three weeks development**	**≤ $1000**

*Parameter target specifications above are provided **better** than basic objective specifications*

2.5.3 Utilized Standards/Conventions

Our team recognizes that for this project to be possible (and without re-inventing the wheel many times), relevant existing standards can be followed to aid external interfacing/development. Many regulatory bodies and other agencies collaborate to produce these. We will be incorporating those set by larger organizational bodies, such as IEEE among others. These are as follows:

- SPI communication (Motorola standard frame, MCU to camera module)
- DCMI camera connector interface and protocol (MCU to camera module)
- C programming language (modern dialects, controller firmware)
- CMake build system (controller firmware)
- MATLAB (Standard libraries/toolkits, used for image processing)
- Linux/Unix USB device management/driver endpoint (TinyUSB)

2.5.4 Project Constraints

Time Constraints:

- 32 weeks to ensure the prototype device works as intended
- 10 minutes to demo our uses of the prototype device
- Time taken to purchase parts
- Time taken to assemble/receive the device and PCB
- Time taken to test components and optimize performance in software/hardware

Cost Constraints:

- $1500 is the maximum estimated total cost for manufacturing the prototype (without any future sponsorship)
- Optic parts may be less readily available than typical electronic parts, causing the price to vary

Resource Constraints:

- $1500 is the maximum estimated total cost for manufacturing as a whole
- Only 3 group members (currently) without an external sponsor, including a double major
- Since limited time is an issue, the project must not include too many demanding features due to the deadline
- Gap in knowledge for certain group members in certain areas, such as optics or hardware

Health and Safety Constraints:

- Safety standards accepted by professionals and relevant equipment/PPE must be used when testing and constructing the prototype, where necessary
- Electronics handling high power or voltages must be designed not to fail under higher-than-normal loads or other fault conditions, also limiting user exposure

- Laser cursor output power must be very carefully considered for eye-safe operation

Legal Constraints:

- Intellectual Property Rights: Inspiration must be properly sourced and can't infringe on any pre-existing patents to claim as our own; however, we may use them on a case-by-case basis if we obtain permission from the rights holders for the use of certain trademarked materials
- If we obtain a future sponsorship, we may be subject to IP transfer from our group's endeavors to the sponsor's legally owned IP

Chapter 10 – Administrative Content

10.1 Senior Design 1 Administrative Milestones

#	*Milestone Description*	*Start Date*	*Anticipated End Date*	*Duration*
1	Finalize Project Idea	08/19/25	08/26/25	1 week
2	Finalize General Design Choices (Crucial Hardware)	08/19/25	09/05/25	2 weeks
3	D&C Finalization	08/28/25	09/05/25	1 week
4	D&C Meeting	09/09/25 11:30am	09/09/25	1 day
5	Committee Formation/Meeting	08/28/25	09/05/25	1 week
6	30-Page Draft	09/05/25	09/26/26	3 weeks
7	60-Page Draft	09/26/25	10/17/25	3 weeks
8	Midterm Milestone Report	10/17/25	10/31/25	1 week
9	Midterm Milestone Revision	10/31/25	11/07/25	1 week
10	90-Page Draft	10/17/25	11/07/25	3 weeks
11	Final Report	11/07/25	11/25/25	3 weeks
12	Mini Demo Video	11/07/25	11/25/25	3 weeks

10.2 Senior Design 1 Project Milestones

#	Milestone Description	Start Date	Anticipated End Date	Duration
1	Individual System Design	09/04/25	10/02/25	4 weeks
2	Individual System Testing	10/02/25	10/30/25	4 weeks
3	Breadboard Prototyping	10/30/25	11/20/25	3 weeks
4	PCB Design/Ordering	11/20/25	12/11/25	3 weeks

10.3 Senior Design 2 Project Milestones

#	Milestone Description	Start Date	Anticipated End Date	Duration
1	PCB Testing	01/05/26	01/16/25	2 weeks
2	System Testing	01/16/25	02/13/26	4 weeks
3	Project Demo	02/13/26	02/27/26	2 weeks
4	Final Documentation	02/27/26	03/13/26	2 weeks
5	Final Presentation Practice	03/13/26	03/20/26	1 week
6	Final Presentation	TBD	TBD	TBD

10.4 Work Distribution Table

Below is a table detailing the assigned tasks to the group members. Each system is entrusted to specific members, with some blending due to how they must work together. Collaboration is set at every level allowing these systems to fit with other system requirements. This allows all members to be aware of and involved in the design and implementation of the systems, whether they were directly or indirectly responsible for it.

<table>
<tr><th>Electrical Engineering</th><th>Responsibilities</th></tr>
<tr><td rowspan="6">Emilio Armas</td><td>Project Lead</td></tr>
<tr><td>MCU Integration and Implementation</td></tr>
<tr><td>USB Data Interface to PC</td></tr>
<tr><td>VRAM Parallel Bus Interface</td></tr>
<tr><td>CMOS Sensor to MCU Interface</td></tr>
<tr><td>PCB design and assembly</td></tr>
<tr><td rowspan="4">Xander Kin</td><td>Power Management System</td></tr>
<tr><td>Stepper Driver Implementation</td></tr>
<tr><td>Motor Encoder Readback Electronics</td></tr>
<tr><td>Laser Cursor Driver Electronics</td></tr>
<tr><th>Photonics Science and Engineering</th><th>Responsibilities</th></tr>
<tr><td rowspan="3">Jacob Silver</td><td>PC Image Processing Software</td></tr>
<tr><td>Imaging System Optical Design</td></tr>
<tr><td>Motor Mechanical Implementation</td></tr>
<tr><td>Emilio Armas</td><td>Laser Cursor Optical Design</td></tr>
</table>

10.5 Project Budget

Our project budget will be capped at $1500, agreed upon by each member for financial feasibility. This budget encompasses many aspects of the project including the PCB, microcontroller, optics, and motors. The bulk of our budget goes towards the high-cost items in the optics section. We also account for any replacements or last-minute changes that we might go through in unexpected circumstances. A detailed (tentative) breakdown of costs and distribution to each of us is detailed below in the bill of materials.

Component	Subsystem	Quantity	Unit Cost	Total
PLA Filament, 1kg	Mechincal Structures	3	$22.76	$68.28
Stepper Motor	Mechanical Structures	1	$14.00	$14.00
Transmissive Grating	Hyperspectral Camera	1	$17.76	$17.76
Achromatic Lens Doublet	Hyperspectral Camera	2	$135.09	$270.18
Positive/Negative Focal Le	Hyperspectral Camera	2	$120.00	$240.00
650 nm 7mW Laser Diode	Cursor	1	$20.17	$20.17
MCU	Electronics	1	$4.87	$4.87
CMOS Camera	Hyperspectral Camera	1	$25.00	$25.00
Miscellaneous	All	1	$100.00	$100.00
			Total	$760.26

Appendix A – Bibliography

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[4] Thompson, D. R., J. W. Boardman, M. L. Eastwood, R. O. Green (2017), A Large airborne survey of Earth’s visible-infrared spectral dimensionality. Optics Express (in press).

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