TEAM SDDEC26-06 | SENIOR DESIGN

Portable VIS-NIR Spectrometer

Design Document

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Prepared for Iowa State University Electrical and Computer Engineering Senior Design

Executive Summary

Team SDDEC26-06 is developing a portable VIS-NIR spectrometer for Dr. Avishek Das and the Biomedical Imaging Lab at Iowa State University. The project addresses the need for a lower-cost, compact spectrometer that can support routine optical measurements without relying on expensive commercial instruments that are difficult to relocate or schedule around. The intended device operates across the 400 to 1000 nm wavelength range and is designed to support faster experimental iteration in biomedical imaging and biosensing workflows.

The primary design requirements are wavelength coverage from 400 to 1000 nm, real-time spectral acquisition, USB data transfer to a host computer, live display through a Python application, configurable integration time, portability, and a total cost significantly below comparable commercial VIS-NIR spectrometers. The project also targets approximately 5 nm FWHM spectral resolution and a frame rate suitable for live display and data capture.

The proposed design is organized into three main subsystems: optics, embedded acquisition, and desktop software. The optical subsystem uses a Czerny-Turner-style layout with a slit, collimating mirror, reflective diffraction grating, focusing mirror, and TCD1304DG linear CCD. The embedded subsystem uses an STM32F411CEU6 microcontroller to generate the CCD timing signals, acquire the CCD output through ADC and DMA, and transmit spectral frames over USB. The host-side Python/Kivy application receives the data, displays a live spectrum, supports CSV export, and provides the framework for calibration functions including dark and bias correction, pixel-to-wavelength mapping, and spectral response correction.

Current progress has established the core electronics and software pipeline. The CCD driver board has been fabricated and assembled, the STM32 firmware generates the required fM, SH, and ICG timing signals, and the CCD output can be captured and sent to the host computer over USB. The Python/Kivy application can display live data and supports early calibration workflows. Current performance is approximately 31 frames per second for on-screen plotting and approximately 80 frames per second when streaming to CSV, with additional optimization required to approach the target acquisition rate.

The design currently satisfies several major functional needs, including CCD timing, USB communication, host-side visualization, and early calibration capability. The remaining technical work is concentrated in the optical subsystem and final characterization. Next steps include finalizing the optical alignment, validating 400 to 1000 nm wavelength coverage, mitigating second-order diffraction, completing pixel-map calibration, implementing spectral response normalization, enclosing the optical path, and comparing system performance against reference sources or a commercial spectrometer in the BILab.

Learning Summary

Development Standards & Practices Used

The team implemented a variety of hardware, firmware, and software development practices to ensure the reliability and maintainability of the spectrometer:

- **Hardware & PCB Design:** Standard practices for PCB schematic design, fabrication, and assembly were followed, including the use of ground vias for isolation and decoupling capacitors to filter power traces.
- **Optical Assembly:** Components are initially mounted on standard optical breadboards using post-mount hardware to facilitate alignment before being placed in a permanent enclosure.
- **Embedded Systems:** The firmware utilizes hardware timers for precise CCD signal generation, DMA (Direct Memory Access) for high-speed ADC buffer transfers to minimize CPU overhead, and USB CDC (Communication Device Class) for data transmission.
- **Software Development:** The host application is developed in Python. This uses real-time plotting libraries and parallelization to prevent GUI lag during data acquisition as much as possible.
- **Project Management:** A hybrid Waterfall-Agile approach was adopted, utilizing weekly standup meetings and Gantt charts for schedule tracking, and GitLab for version control.

The following engineering standards were considered and applied as design references for safety, compatibility, and performance:

- **IEC 61010-1:** Safety requirements for laboratory electrical equipment, focusing on chassis grounding and heat dissipation.
- **IEC 61326-1:** Electromagnetic Compatibility (EMC) requirements, addressed through shielding and filtering to protect sensitive analog signals from noise.
- **ASTM E275:** Methodology for describing and measuring the performance of spectrophotometers, particularly wavelength accuracy and stray light.
- **CIE 233:2019:** Standards for the calibration and characterization of array spectroradiometers, guiding the software’s dark-frame subtraction and pixel-to-wavelength mapping.
- **NIST-Traceable Wavelength Standards:** Used for wavelength traceability and calibration accuracy.

These standards are discussed at length in Section 2.2.

Summary of Requirements

The project must adhere to several key requirements to satisfy the needs of the Biomedical Imaging Lab:

- **Functional:** Separate light into component wavelengths (400–1000 nm), capture data via TCD1304DG CCD, and transmit real-time spectral data over USB to a GUI.
- **Performance:** Achieve a spectral resolution of 5 nm FWHM and a data acquisition rate >100 fps.

- **Physical:** The device must be portable, compact enough for relocation by a single person, and enclosed to block ambient light.
- **Economic:** Total bill of materials and project costs must remain significantly below commercial alternatives and within the senior design budget.
- **User Experience:** Minimal setup/teardown time and a live, updating spectral plot for immediate analysis.

Applicable Courses from Iowa State University Curriculum

- CPRE 2880: Embedded Systems
- EE 4380: Optoelectronic Devices and Applications
- EE 4180: High Speed System Measurement and Testing
- EE 2300: Electronic Circuits and Systems
- EE 2240: Signals and Systems I

New Skills/Knowledge acquired that was not taught in courses

Beyond the standard curriculum, the team acquired several specialized technical skills:

- **Advanced Spectrometer Design:** Designing and simulating a reflective Czerny-Turner optical configuration.
- **CCD Timing Requirements:** Implementing the specific nanosecond-accurate timing signals required for linear CCD sensors.
- **Custom Thin-Film Fabrication:** Learning the process of linear edge-pass filter fabrication using thin-film deposition machines at the ASC.
- **Scientific Calibration:** Developing procedures for dark-signal correction, spectral response normalization, and pixel-to-wavelength mapping using known reference sources.

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1. Introduction

1.1. PROBLEM STATEMENT

Dr. Avishek Das needs a spectrometer that facilitates his routine experiments in the Biomedical Imaging Lab (BILab) at Iowa State University. In the research environment at the BILab, available spectrometers are expensive, bulky, and effectively fixed to a single location, which can introduce scheduling constraints and delays when an experiment requires measurements in a non-standard setup. These delays reduce iteration speed and limit the ability to validate results.

To address these needs, our project is developing a lower-cost, portable spectrometer that operates across the 400-1000 nm wavelength range. The device will operate as a complete package, combining three systems into a compact physical design with the core measurement functions needed for reliable use. First, the instrument will incorporate an optical system that separates incoming light into its component wavelengths, next a sensor and readout system will accurately capture the resulting spectrum, and finally a computer interface will display and record measurement data in a consistent, usable format. This structure will enable us to deliver a self-contained, practical tool that fits Dr. Das's workflows, supports use across the BILab, and remains more affordable than commercially available options.

1.2. INTENDED USERS

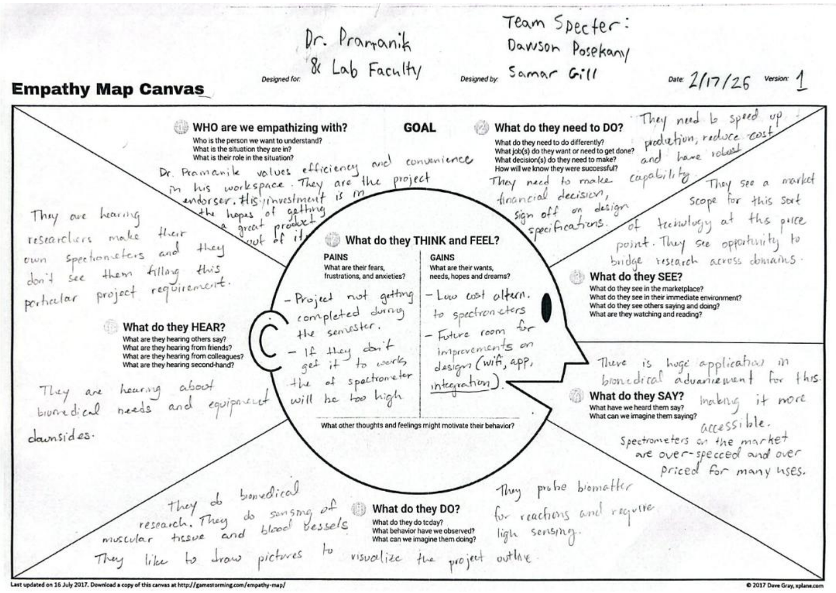
This project was proposed by Dr. Avishek Das under Prof. Manojit Pramanik through the Biomedical Imaging Lab at Iowa State University. Based on client discussions, Dr. Das is the only confirmed faculty user for the initial device. The design process therefore prioritizes his research workflow and laboratory constraints while recognizing that the completed device may also be useful to other researchers or educational users in the future.

Persona 1: Dr. Das

Dr. Das is a Postdoctoral Research Associate in the Biomedical Imaging Lab at Iowa State University. He is a highly technical user whose work involves biosensing and optical measurement. His workflow values portability, efficiency, and cost-effective instrumentation that can support research without sacrificing the core measurement capability needed for laboratory experimentation.

The device supports Dr. Das's biomedical research by enabling rapid, non-invasive optical measurements for embedded object imaging in multilayered biological tissues. His work specifically benefits from near-infrared wavelength behavior, so the spectrometer must capture and display spectral information across the required wavelength range. The system must also integrate with the existing laboratory workflow by sending measurement data to a computer for analysis and visualization, with future modularity potentially extending to a phone-based interface. These needs require a device that can measure wavelength-dependent intensity accurately, present results clearly, and avoid the cost and location constraints of larger commercial instruments.

With the proposed spectrometer, Dr. Das can conduct more frequent and flexible measurements. The design serves as a simplified and affordable substitute for higher-cost commercial instruments while focusing on the wavelength range and functionality needed for this research application. By limiting unnecessary features and emphasizing the required spectral range, the device is intended to improve laboratory throughput and reduce the delay between measurement setup, data collection, and analysis.



Empathy Map Canvas

Designed for: Dr. Pramanik & Lab Faculty

Designed by: Team Specter: Dawson Posekany Samar Gill

Date: 2/17/26 Version: 1

GOAL

WHO are we empathizing with?
Who is the person we want to understand?
What is the situation they are in?
What is their role in the situation?

Dr. Pramanik values efficiency and convenience in his workspace. They are the project endorser. His investment is in the hopes of getting a great product out of it.

What do they need to DO?
What do they need to do differently?
What job(s) do they want or need to get done?
What decision(s) do they need to make?
How will we know they were successful?

They need to speed up production, reduce cost and have robust capability. They need to make financial decision, sign off on design specifications.

What do they SEE?
What do they see in the marketplace?
What do they see in their immediate environment?
What do they see others saying and doing?
What are they watching and reading?

They see a market scope for this sort of technology at this price point. They see opportunity to bridge research across domains.

What do they SAY?
What have we heard them say?
What can we imagine them saying?

There is huge application in biomedical advancement for this. Making it more accessible.
Spectrometers on the market are over-specced and over priced for many uses.

What do they DO?
What do they do today?
What behavior have we observed?
What can we imagine them doing?

They do biomedical research. They do sensing of muscular tissue and blood vessels. They like to draw pictures to visualize the project outline.
They probe biomatter for reactions and require ligh sensing.

What do they HEAR?
What are they hearing others say?
What are they hearing from friends?
What are they hearing from colleagues?
What are they hearing second-hand?

They are hearing researchers make their own spectrometers and they don't see them filling this particular project requirement.
They are hearing about biomedical needs and equipment downsides.

What do they THINK and FEEL?

PAINS
What are their fears, frustrations, and anxieties?
- Project not getting completed during the semester.
- If they don't get it to work the of spectrometer will be too high

GAINS
What are their wants, needs, hopes and dreams?
- Low cost altern. to spectrometers
- Future room for improvements on design (wifi, app, integration).

What other thoughts and feelings might motivate their behavior?

Last updated on 16 July 2017. Download a copy of this canvas at http://gamestorming.com/empathy-map/

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Figure 1.2.1 Dr. Pramanik & Dr. Das empathy map

Note: Dr. Das encouraged publishing this device into scientific literature if the team feels the work warrants it. People outside Dr. Das's lab could then use the device for a variety of purposes. In the way that the team is approaching this project, only the needs of Dr. Avishek and the capabilities of our team are being considered when making design decisions. Due to this, documentation about the needs of external users were placed in the appendix.

2. Requirements, Constraints, And Standards

2.1. REQUIREMENTS & CONSTRAINTS

Functional Requirements

- The device shall separate incoming light into its component wavelengths and capture the resulting spectrum using the TCD1304DG linear CCD sensor.
- The device shall operate across a wavelength range of 400 to 1000 nm.
- The device shall transmit spectral data to a host computer in real-time via USB.
- A Python application shall display the captured spectrum visually on the host device.
- The device shall support a configurable integration time to accommodate varying light source intensities.
- The firmware shall drive all required timing signals for the TCD1304DG (master clock, integration clear pulse, shift gate) using the STM32F411CEU6 microcontroller.

Resource Requirements

- The device shall use the STM32F411CEU6 as the primary microcontroller.
- The optical subsystem shall use the TCD1304DG linear CCD as the detector.

Physical Requirements

- The device shall be portable and compact enough to be relocated within a lab environment by a single person without specialized equipment.
- All optical components shall be mountable on a standard optical breadboard using post-mount hardware during the development and testing phase.
- The final device shall include an enclosure that protects internal optics and electronics from ambient light contamination and physical damage.

Performance Requirements

- The device shall achieve sufficient spectral resolution to distinguish features relevant to Dr. Das's biosensing research across the 400-1000 nm range.
- The signal-to-noise ratio of the captured spectrum shall be adequate for reliable identification of spectral peaks under lab lighting conditions.
- The device shall complete a full spectral acquisition and transmission cycle at a rate sufficient for real-time display on the host computer.

User Experience Requirements

- The Python interface shall display a live spectral plot that updates with each new acquisition.
- The device shall be operable by Dr. Das without requiring hardware reconfiguration or adjustments to the code between routine measurements.
- Setup and teardown time for a standard measurement shall be minimal, supporting the fast iteration speed that motivated this project.

Economic Requirements

- The total project cost shall remain within the allocated senior design budget.
- The final device cost shall be lower than commercially available VIS-NIR spectrometers with comparable wavelength coverage.

Environmental Requirements

- The device shall be designed for indoor laboratory use under standard temperature and humidity conditions.
- Component selection shall prefer parts with reasonable availability and lead times to avoid supply chain delays.
- Materials used shall not be hazardous to people or the environment, assuming proper operation and disposal.

2.2. ENGINEERING STANDARDS

Engineering standards provide a shared technical basis for safety, compatibility, performance evaluation, and calibration. For this project, the selected standards guide decisions related to laboratory electrical safety, electromagnetic compatibility, spectrometer performance characterization, and wavelength traceability. The standards below are used as design references rather than full certification targets for the senior design prototype.

1. IEC 61010-1: Safety Requirements for Electrical Equipment

- **Standard Type:** Safety
- **Description & Purpose:** This is a foundational safety standard for lab equipment. Its primary goal is to protect the user and environment from hazards like a shock or fire. Crucially, it discusses the single-fault condition which states that even if one component should fail, the device remains safe to touch.
- Relevance to VIS-NIR Project: This spectrometer has a light collecting device and a power supply, so the team must adhere to this guideline to ensure the chassis is properly grounded and that any heat generated is efficiently dissipated.
- **Design Modifications:**
  - **Isolation:** Including vias to ground and adequate spacing to reduce danger in the case of a current surge and EMI protection.
  - **Containment:** Making a metal layer between the outer device and the internal optics and electronics with the aim of protecting the user.

2. IEC 61326-1: Electromagnetic Compatibility (EMC) Requirements

- **Standard Type:** Compatibility and Immunity
- **Description & Purpose:** This standard regulates the electromagnetic emissions and immunity of laboratory equipment. It ensures the spectrometer does not interfere with other electronics. On the other hand, it also seeks to ensure that our device can operate accurately in a noisy electromagnetic environment.
- Relevance to VIS-NIR Project: Spectrometers rely on highly sensitive photodetectors. The signals that are then produced are relatively weak. Without EMC compliance, external electrical noise could easily distort spectral data, leading to high signal-to-noise ratios. This would ultimately interfere with the high data resolution that we seek to achieve with this device.
- **Design Modifications:**
  - **Shielding:** Including some sort of coating or metal around the analog front-end should protect from outside EM noise.
  - **Filtering:** Decoupling capacitors added to the power traces level out the incoming power and prevent noise from leaking out to other parts of the circuit or off the device as radiation.

3. ASTM E275: Describing and Measuring Performance of UV-Vis Spectrophotometers

- **Standard Type:** Performance and Metrology
- **Description & Purpose:** This standard provides a consistent methodology for verifying the technical performance of a spectrometer. It focuses on characterizing wavelength accuracy, stray light levels, and photometric precision to ensure the data collected is scientifically valid.
- Relevance to VIS-NIR Project: This is the benchmark for our project's success. It allows us to compare our "Senior Design" instrument against industry-standard benchmarks. It moves the project from being a "sensor" to a "scientific instrument."
- **Design Modifications:**
  - **Calibration Routine:** Developing a software module that executes a startup self-test, checking the dark current and the reference signal against a known baseline. A device that generates known, overlapping wavelengths will also be used to ensure precision of the sensor.

  - **Opto-mechanical Alignment:** Testing the slit and grating mounts to meet resolution requirements serves us with better data and is in line with this standard. The team will accomplish this by using a variable slit in earlier models for flexibility in the testing phase.

4. CIE 233:2019: Calibration, Characterization and Use of Array Spectroradiometers

- **Standard Type:** Spectroradiometer Calibration, Characterization, and Measurement Quality
- **Description & Purpose:** CIE 233:2019 is a technical report published by the International Commission on Illumination that focuses specifically on array spectroradiometers. The report explains the instrument characteristics that affect accurate spectral measurements, including calibration behavior, wavelength accuracy, detector response, stray light, linearity, bandwidth effects, and measurement uncertainty. It also proposes performance indices that allow array spectroradiometers to be evaluated according to the measurement properties most relevant to a given application.
- **Design Modifications:**
  - **Wavelength Calibration:** The software will include a pixel-to-wavelength calibration procedure using known reference wavelengths from laser diodes or other reference light sources. This calibration will map CCD pixel position to wavelength and correct for nonlinearity in the optical geometry.
  - **Dark Signal Correction:** The Python application will include dark-frame subtraction to reduce baseline offset, dark current, and fixed-pattern sensor contributions before displaying or exporting spectral data.
  - **Spectral Response Correction:** The calibration workflow will account for wavelength-dependent response from the CCD, mirrors, diffraction grating, filter, and optical path. This correction will help normalize the measured intensity so that changes in the displayed spectrum more closely represent the input light rather than the instrument's own response curve.
  - **Stray Light and Second-Order Diffraction Evaluation:** The team will evaluate stray light and second-order diffraction artifacts during calibration. A long-pass or custom thin-film filter will be tested to reduce higher-order spectral overlap, especially where shorter wavelengths can interfere with longer-wavelength measurements.
  - **Performance Characterization:** The device will be characterized using measurable performance indicators such as wavelength error, full width at half maximum, signal-to-noise ratio, repeatability, and usable wavelength range. These values will be used to determine whether the final spectrometer satisfies the project requirements and Dr. Das's intended laboratory use.

3 Project Plan

3.1 PROJECT MANAGEMENT/TRACKING PROCEDURES

The team initially adopted a waterfall-plus-agile management approach. Early work required careful sequencing because optical, PCB, and sensor components had to be selected and ordered before later integration tasks could proceed. During this phase, the team used a more deliberate process for component selection while still assigning weekly subsystem tasks to pairs of team members.

Later in the project lifecycle, the team shifted more strongly toward agile project management. Once the first prototype elements were functional, weekly work focused on improvements, and feature additions. This phase emphasized iterative progress, rapid issue identification, and prioritization of the next highest-value task.

Progress is tracked through weekly meetings with Dr. Das. Our weekly reports document completed tasks, active subtasks, unresolved issues, and planned work. Software development is tracked through GitLab so previous versions can be reviewed when debugging or integrating new features. Optical and hardware documentation, including manuals, datasheets, and design files, is stored in Microsoft Teams for shared access by the project team.

3.2 TASK DECOMPOSITION

The project is decomposed into four main task areas: optical setup, embedded firmware, host user interface, and subsystem integration. Testing, optimization, and calibration span all four areas because the final spectrometer performance depends on the combined behavior of the optics, CCD readout, USB data path, and software processing pipeline.

The optical task is divided into wavelength dispersion, second-order diffraction reduction, ambient-light rejection, and size restrictions. This work primarily involves selecting optical components, evaluating their placement, and verifying that the dispersed spectrum spans the detector in a usable way.

The microcontroller firmware must generate the required CCD timing signals, acquire analog data output from the CCD, and efficiently transfer full frames to the desktop interface. It must also respond to host commands for starting acquisition, stopping acquisition, and updating operating parameters such as integration time.

The desktop interface must display received spectral data and provide controls for measurement configuration. This requires USB communication, frame parsing, wavelength calibration, intensity processing, and real-time plotting of the resulting spectrum.

Subsystem integration also requires several supporting tasks, including enclosure design, CCD driver circuitry, power management, and physical packaging. These tasks determine whether the separate optical, embedded, and software components can operate as a stable portable instrument.

3.3 PROJECT PROPOSED MILESTONES, METRICS, AND EVALUATION CRITERIA

The project is organized into three physical subsystems: optics, microcontroller, and desktop interface. The milestones below are grouped by subsystem and mapped to quantitative performance targets derived from the project requirements.

1. **Subsystem 1: Optical System:** The optical subsystem is responsible for physically separating incoming light into its component wavelengths and directing the resulting spectrum onto the CCD detector.

1.1. **Optical Component Procurement and Bench Assembly:** All optical components (diffracting grating, focusing mirror, collimating mirror, slit aperture, and mounting hardware) are sourced and assembled on an optical breadboard.
- *Metric:* All components are physically mounted and aligned within the breadboard footprint, with no missing parts.
- *Evaluation:* Visual inspection and component checklist.

1.2. **Wavelength Coverage Verification:** The optical path successfully disperses light and covers the full 400-1000 nm operating range.
- Metric: When illuminated by a broadband light source, the CCD pixel array captures a continuous spectrum spanning at least 600 nm (400-1000 nm).
- Evaluation: Pixel-to wavelength mapping verified using at multiple known spectral emission lines at opposite ends of the range.

1.3. **Spectral Resolution:** The optical system resolves spectral features at a level sufficient for Dr. Das's biosensing work.
- Metric: The full-width at half-maximum (FWHM) of narrow emission line is ≤ 5 nm across the 400-1000 nm range.
- Evaluation: A narrow-linewidth source (e.g., laser diode or filtered lamp) is measured and its FWHM is extracted from the acquired spectrum.

2. **Subsystem 2: Microcontroller and Driver Board:** The microcontroller and driver board form the data capturing system of the spectrometer. The STM32F411CEU6 must generate precise timing signals to operate the TCD1304DG CCD, perform analog-to-digital conversion of the pixel data, and transmit results over USB.

2.1. **PCB Fabrication:** The custom driver PCB is fabricated, assembled, and passes electrical testing.
- *Metric:* No shorts or open connections are present, and the SH, ICG, f_M, and V_{os} output signal paths are correctly routed.
- *Evaluation:* Use continuity checks to verify board connections, then confirm SH, ICG, fM, and CCD output behavior with an oscilloscope.

2.2. **Firmware Timing Signals Verified:** The STM32 drives the three required timing signals: master clock (f_M), integration clear gate (ICG), and shift gate (SH).
- Metric: On an oscilloscope, f_M runs at 2 MHz (±0.1%), ICG period is 8ms and pulse width is 7.388ms, and SH features a set time of 10us, and a pulse aligns with the ICG off time.
- Evaluation: Oscilloscope captures compared against TCD1304DG timing diagram.

2.3. **ADC Acquisition of CCD Output:** The STM32 ADC acquires the full 3648-pixel CCD output waveform per integration cycle via DMA transfer.
- *Metric:* A complete frame of 3648 samples is read without dropped samples, confirmed by DMA transfer complete flag and buffer inspection.
- *Evaluation:* UART or USB debug dump of a single frame; sample count and waveform shape verified.

2.4. **USB Data Transmission:** The STM32 streams spectral frames to the host computer over USB at a rate sufficient for real-time display.
- *Metric:* Complete 3648-sample frames are transmitted at a rate of ≥10 frames per second at minimum integration time.
- *Evaluation:* USB packet timing measured on the host; frame rate computed from timestamps.

2.5. **Key Parameter Adjustments:** The STM32 shall receive commands from the desktop interface that allows modifying the key parameters for the spectrometer. i.e. integration time
- Metric: *The device properly adjusts integration time based from user command.*
- *Evaluation: Verify changes in the period of SH on an oscilloscope.*

3. **Subsystem 3: Desktop Interface:** The Python application serves as the human-facing layer of the spectrometer and the key data processing system: it receives raw pixel data from the STM32, applies the various calibrations, and presents a live spectral plot. The goal is for Dr. Das to plug in the device and immediately see a spectrum, with no reconfiguration required between routine measurements.

3.1. **USB Data Reception and Parsing:** The Python application successfully receives and parses a full spectral frame from the STM32 over USB.
- *Metric:* Application receives full frame data and logs it.
- *Evaluation:* Interface logs compared to debugger logs from the Cube IDE.

3.2. **Live Spectral Display:** The application displays a live, updating spectral plot of intensity vs. wavelength
- Metric: Plot updates at ≥10 Hz during continuous acquisition.
- Evaluation: Integrated performance data values; axis labels verified against calibrated emission line positions.

3.3. **Dark Frame Subtraction:** The application applies a dark frame subtraction to reduce baseline noise.
- *Metric:* After dark subtractions, the RMS noise floor across a baseline (no-light) acquisition is reduced by at least 50% compared to uncorrected data.
- *Evaluation:* Statistical comparison of raw vs. dark-corrected frames under identical conditions.

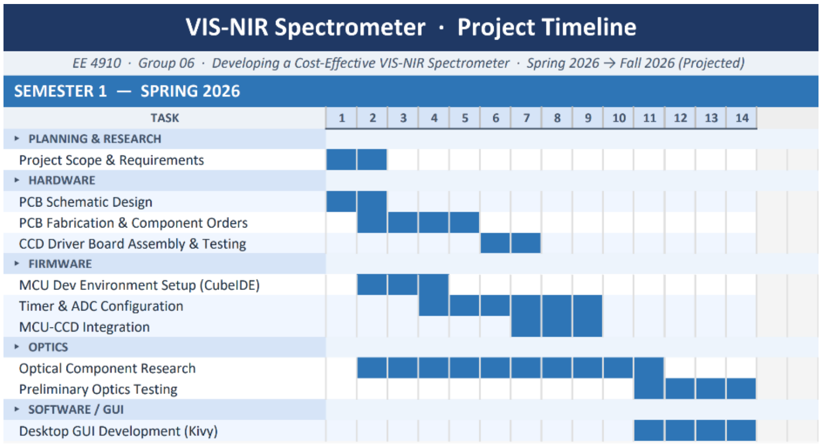
3.4. **Pixel Map Calibration:** The application applies a pixel to wavelength map to show the proper spectrum of incident light.
- Metric: Known reference wavelengths appear at the correct mapped wavelength locations in the displayed spectrum.
- Evaluation: Post calibration measure know wavelength laser diodes, compare the displayed and expected peak values.

3.5. **Quantum Efficiency Calibration:** The application applies the multiplicative factors of CCD, Grating, and mirror efficiencies.
- Metric: Light sources with similar optical power produce approximately equal normalized intensity values after correction.
- Evaluation: Measure reference sources with similar known power levels, compare the normalized displayed intensities, and adjust the wavelength-dependent correction factors until the response is consistent across the tested wavelengths.

3.6. **Data Export** The application can save an acquired spectrum to a file for downstream analysis.
- *Metric:* A spectrum is exportable as a csv with all information with a single button press or command.
- *Evaluation:* Exported file opened in a spreadsheet and columns verified.

3.4 PROJECT TIMELINE/SCHEDULE

The team used Gantt charts to coordinate long-term planning, track progress, and identify schedule risks as subsystem dependencies changed. The first-semester schedule focused on establishing the project scope, fabricating and assembling the CCD driver board, configuring the microcontroller firmware, beginning optical component evaluation, and developing the initial Python-based GUI. The original target was a functioning first-semester prototype capable of demonstrating spectral dispersion and live data acquisition. The project fell slightly behind schedule midway through the spring semester because the diffraction grating and filtering approach required design changes.



VIS-NIR Spectrometer · Project Timeline

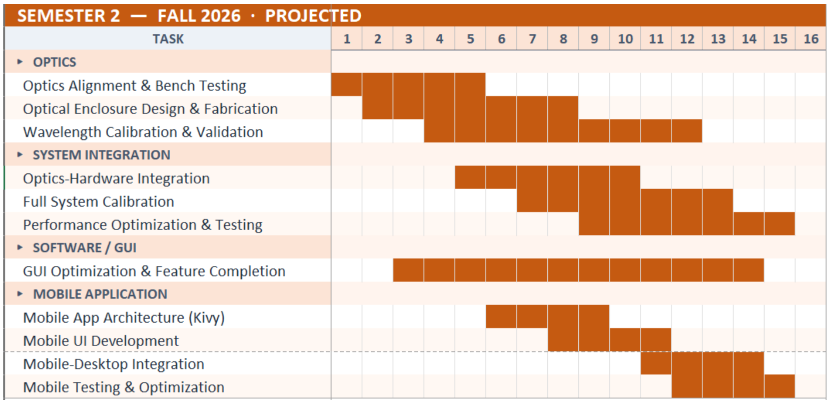
EE 4910 · Group 06 · Developing a Cost-Effective VIS-NIR Spectrometer · Spring 2026 → Fall 2026 (Projected)

SEMESTER 1 — SPRING 2026

TASK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
‣ **PLANNING & RESEARCH**														
Project Scope & Requirements	■	■												
‣ **HARDWARE**														
PCB Schematic Design	■	■												
PCB Fabrication & Component Orders		■	■	■	■									
CCD Driver Board Assembly & Testing						■	■							
‣ **FIRMWARE**														
MCU Dev Environment Setup (CubeIDE)		■	■	■										
Timer & ADC Configuration				■	■	■	■	■	■					
MCU-CCD Integration							■	■	■					
‣ **OPTICS**														
Optical Component Research		■	■	■	■	■	■	■	■	■	■			
Preliminary Optics Testing											■	■	■	■
‣ **SOFTWARE / GUI**														
Desktop GUI Development (Kivy)											■	■	■	■

Figure 3.4.1: Semester 1 Gantt Chart

The second-semester schedule shifts from subsystem development to full-system integration, calibration, and performance validation. Major planned tasks include final optical design, enclosure fabrication, wavelength calibration, optics-hardware integration, full-system calibration, GUI optimization, and final performance testing. The projected schedule also includes mobile application development as an extension goal, with work focused on adapting the Kivy-based architecture for future mobile compatibility. This phase is intended to move the project from a functional prototype toward a calibrated, usable VIS-NIR spectrometer that can be evaluated against the project requirements and demonstrated to the client.



SEMESTER 2 — FALL 2026 · PROJECTED

TASK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
‣ **OPTICS**																
Optics Alignment & Bench Testing	■	■	■	■	■											
Optical Enclosure Design & Fabrication		■	■	■	■	■	■	■								
Wavelength Calibration & Validation				■	■	■	■	■	■	■	■	■				
‣ **SYSTEM INTEGRATION**																
Optics-Hardware Integration					■	■	■	■	■	■						
Full System Calibration							■	■	■	■	■	■	■			
Performance Optimization & Testing									■	■	■	■	■	■	■	
‣ **SOFTWARE / GUI**																
GUI Optimization & Feature Completion			■	■	■	■	■	■	■	■	■	■	■	■		
‣ **MOBILE APPLICATION**																
Mobile App Architecture (Kivy)						■	■	■	■							
Mobile UI Development								■	■	■	■					
Mobile-Desktop Integration											■	■	■	■		
Mobile Testing & Optimization												■	■	■	■	

Figure 3.4.2: Semester 2 Gantt Chart

3.5 Risks and Risk Management/Mitigation

Identified Risk	Probability	Severity	Mitigation strategy
Second-order Reflections	1.0	Very High	Add linear edge pass filter and validate wavelength mapping experimentally across spectral range. Potential software fixes.
Order Delays	0.5	Medium	Have multiple tasks queued to allow switching tasks while waiting for the other to progress.
Damaging Delicate Optics Components	0.3	High	Wear gloves and handle all optics components according to BILab standards.
Low signal-to-noise ratio at higher wavelengths (800-1000 nm)	0.8	High	Adjustable integration time range, optimize analog front-end gain, and select optics with NIR-optimized coatings.
Limited dynamic range during bright measurements	0.4	Medium	Support adjustable integration timing and optional neutral density filtering.
Optical alignment sensitivity	0.7	High	Use adjustable mounts inside the enclosure.
Enclosure light leakage	0.3	Medium	Add sealing features and verify dark-condition performance during system testing.
Calibration drift over time	0.5	Low	Perform periodic recalibration using known spectral reference sources and store correction tables.
Thermal variation affecting measurements	0.4	Low	Characterize temperature dependence and allow recalibration or compensation in firmware if required.

Figure 3.5.1: Risk Management Chart

3.6 PERSONNEL EFFORT REQUIREMENTS

Subsystem/Task	Description	Man-hours
Optics		
Overall design	Base-level optics selection including slit, grating, lenses, and mirrors.	10
Second-order light filtering	Evaluating various methods to suppress spectral overlap	20
Component selection	Selection of grating, mirrors, slit, lenses, and optical filter options	12
Testing/Positioning	Alignment testing, wavelength spread verification, and focus optimization	14
Enclosure Design	Designing an enclosure that provides stable mounts between optical components and CCD board	20
Total		**76**
Microcontroller		
MCU IDE Bring up	Familiarizing ourselves with the IDE and building the basic code for the CCD driver timers.	12
CCD driver timer implementation	Generating SH, ICG, and master clock timing signals for TCD1304 operation	16
ADC acquisition configuration	Configuring ADC sampling timing synchronization and buffering	10
Testing Basic Code	Verifying CCD waveform timing and signal capture stability	4
Code Improvements	Improve the baseline code to enable inputs from the host PC for calibration modes and selectable integration times.	18
Noise reduction	Implementation of noise reduction processes.	8
Total		**68**
User interface		
Scoping Data Transmission/Features	Validating waveform timing throughput and transfer reliability	8
PC visualization interface	Developing plotting pipeline for spectral display and storage	10
Designing device or selecting filters	Adding selectable integration control, gain selection, and capture triggers	10
Calibration Procedure for pixel map	Mapping pixel index to wavelength using reference emission source	12
Spectral correction workflow	Implementing intensity normalization and dark-frame subtraction	8
Total		**48**

Subsystem/Task	Description	Man-hours
Assembly and Testing		
PCB Design and Assembly	Fabrication of CCD driver PCB and others.	12
Mechanical enclosure assembly	Integrating optics, electronics, and housing into portable structure.	8
System-level integration testing	End-to-end spectrum capture validation across wavelength range and tuning of response.	30
Performance validation	Resolution, SNR, repeatability, and wavelength accuracy testing.	12
Documentation and handoff preparation	Preparing calibration instructions, wiring diagrams, and usage procedures.	8
Total		**70**
Grand Total		**262**

Figure 3.6.1: Personnel Hours Chart

3.7 OTHER RESOURCE REQUIREMENTS

Additional resources needed to complete this project are as follows:

1. Thin film deposition machines available at the ASC will be used to fabricate a linear edge pass filter that will be used to filter second-order reflections.
2. ISU spectrometer to verify device characteristics to certified testing equipment.

4 Design

This section presents the full design of the portable VIS-NIR spectrometer, from broader context and prior work through design exploration to the proposed architecture. The instrument uses a Czerny-Turner reflective grating configuration, a TCD1304DG linear CCD, and an STM32F411-based embedded acquisition system to capture spectra across 400–1000 nm, all within a target cost of under $500. Key design decisions—reflective grating over transmission for compactness, Python over MATLAB for an open-source host application, and a custom thin-film filter for second-order diffraction suppression—are documented with trade-off analyses. The section also details the three integrated subsystems (optical, embedded, and host software), outlines current areas of concern including optical alignment and long-wavelength SNR, and summarizes the technology considerations and design analysis that confirm feasibility based on progress to date.

4.1 DESIGN CONTEXT

4.1.1 Broader Context

Area	Description	Our Project
Public health, safety, and welfare	How does your project affect the general well-being of various stakeholder groups? These groups may be direct users or may be indirectly affected (e.g., solution is implemented in their communities)	Increases access to spectrometers, allowing more research. Also allows a more customizable experience for different scenarios
Global, cultural, and social	How well does your project reflect the values, practices, and aims of the cultural groups it affects? Groups may include but are not limited to specific communities, nations, professions, workplaces, and ethnic cultures.	Makes methods and information about our design publicly available, with the goal of scientific advancement rather than profit

Area	Description	Our Project
Environmental	What environmental impact might your project have? This can include indirect effects, such as deforestation or unsustainable practices related to materials manufacture or procurement.	Design decisions such as ease of replacing parts and using sustainable materials can reduce overall waste and environmental impact
Economic	What economic impact might your project have? This can include the financial viability of your product within your team or company, cost to consumers, or broader economic effects on communities, markets, nations, and other groups.	Depending on the demand for a cheaper alternative, the overall market for spectrometers and similar devices may shift to accommodate users with lower budgets

Figure 4.1.1: Design Ethics Chart

4.1.2 Prior Work/Solutions

Several commercial spectrometers cover the VIS-NIR range relevant to this project. Ocean Optics has the most similar products to our design, offering instruments such as the STS-VIS and the USB2000+. These devices are well-characterized, compact, and support USB connectivity, but carry a price point that places them out of reach for routine, flexible lab use. The following comparison highlights the differences between our proposed design and representative commercial products.

Feature	This Project	Ocean Optics ST VIS	Ocean Optics SR-2VN500-25
Link	N/A	Edmund Optics	Edmund Optics
Wavelength Range	400-1000 nm	350-810 nm	350-1040nm
Detector	TCD1304DG (3648 px)	Unknown	Proprietary (2098)
Interface	USB	USB/RS-232	USB/RS-232
Approximate Cost	< $500	$1820.00	$3859.00
Portability	High	High	High
Opensource / Customizable	Yes (open firmware/software)	No	No

Figure 4.1.2: Commercial Solutions Chart

The primary advantage of this project over commercial solutions is cost and customizability. The primary disadvantage is that commercial instruments have been thoroughly validated and characterized, while this device requires the team to develop and verify calibration procedures from scratch.

No prior Iowa State senior design project was identified that directly replicates this work, though open-source spectrometer designs such as the "Public Lab Spectrometer" and projects based on the TCD1304 CCD on hobbyist forums informed the team's component selection and strategy.

4.1.3 Technical Complexity

This project satisfies the technical complexity requirement in two major areas:

- Multiple distinct subsystems using different engineering disciplines: the optical subsystem applies geometric optics and diffraction theory; the microcontroller subsystem applies real-time embedded firmware, ADC timing, and DMA transfers; the analog front-end applies precision analog circuit design; and the Python interface applies signal processing and GUI development.
- Several challenging requirements that meet or exceed industry norms: achieving FWHM ≤ 5 nm spectral resolution across a 600 nm span with a linear CCD, generating microsecond-accurate CCD timing signals from a custom STM32 firmware, suppressing second-order diffraction artifacts with a custom-fabricated thin-film optical filter, and streaming calibrated spectral frames at ≥10 fps over USB all constitute non-trivial engineering problems.

4.2 DESIGN EXPLORATION

The project scope was well defined at the start, which reduced the number of early architecture decisions because several components and constraints had already been identified. The main design uncertainty has been how to integrate those components into a product that satisfies the client's wavelength, cost, portability, and usability requirements. Additional features beyond the minimum client expectations remain possible, but they are evaluated only after the core spectrometer functionality is protected.

4.2.1 Design Decisions

Three primary areas where specific technical choices were required are summarized below:

1. **Optical Grating Type:** Selection between transmission and reflective diffraction gratings to disperse incoming light across the CCD.
2. **Data Processing Language:** Selection of a programming language for the host-side spectral acquisition and visualization application.
3. **Second-order Diffraction Mitigation Strategy:** Selection of a method to suppress second-order diffraction artifacts that corrupt the lower portion of the target spectrum.

4.2.2 Ideation

The team explored several options for each design decision based on technical requirements and budget.

Optical Grating Type Options:

- Transmission grating with a linear layout: simple alignment but requires a longer optical path that may not fit within the 10 cm × 10 cm enclosure footprint.
- Reflective (blazed) diffraction grating in a Czerny-Turner configuration: more compact, commonly used in commercial instruments, but introduces alignment complexity.
- Volume phase holographic (VPH) grating: high efficiency and low stray light, but expensive and too narrowband for this project.

Data Processing Language Options:

- Python: open-source, large ecosystem, good USB serial libraries, support cross-platform deployment and potential mobile integration via frameworks such as Kivy.
- MATLAB: team is highly familiar, excellent for real-time plotting and matrix operations, but requires a paid license and is not well-suited for standalone deployment.
- LabVIEW: strong in instrumentation contexts, but proprietary, expensive, and not maintainable by most future users.

Second-Order Diffraction Mitigation Options:

- Two modes of operation with different filters: Simple and cost effective, however this would degrade user experience and limit testing capabilities.

- Commercial thin-film linear variable filter: directly addresses the problem with a graded cutoff matched to the CCD pixel array, no mechanical switching required. The primary tradeoff is cost at ~$1700.

- Custom thin-film linear variable filter fabricated at the ISU ASC: directly addresses the problem with a graded cutoff matched to the CCD pixel array, no mechanical switching required; fabrication feasibility is the primary uncertainty.

- Software correction only: no physical filter; post-process the spectrum to subtract modeled second-order contributions; simplest mechanically but unreliable for research data.

4.2.3 Decision-Making and Trade-Off

In this section, each of the design decisions mentioned will be expanded upon, giving particular focus to what steps the team took to make the choice and what information was researched or tested to aid in the decision-making process.

Optical Grating Type:

Ray-tracing simulations showed that a transmission grating in a linear layout cannot fit within the 10 cm × 10 cm target enclosure footprint. The reflective grating was therefore selected despite the added alignment complexity. A weighted decision matrix was used, scoring each option against criteria including compactness, alignment complexity, cost, and calibration linearity. The reflective grating score was highest overall. The tradeoff accepted is a more time-intensive optical alignment process, which contributed to schedule delays in the first semester. Adjustable mounts are being used to manage this risk.

Data Processing Language:

The team selected Python using a weighted wwdecision matrix based on software accessibility, plotting capability, deployment potential, and long-term maintainability. MATLAB was considered because the team has more experience with it and because it is strong for real-time data visualization and matrix operations. Python was selected because it is open source, supports USB communication and plotting libraries, and provides a better path toward future cross-platform or mobile integration. The accepted tradeoff is the team's lower initial familiarity with Python compared with MATLAB.

Optical Noise Mitigation Strategy:

Second-order diffraction from shorter wavelengths overlap the desired long-wavelength portion of the spectrum and produce artifacts that are difficult to remove reliably in software. The team is therefore evaluating a custom filter approach because commercial filters with the desired behavior are expensive relative to the project budget. The final mitigation strategy will depend on fabrication feasibility, validation of a two-filter alternative, and the remaining time available for prototype procurement and testing.

4.3 PROPOSED DESIGN

4.3.1 Overview

The proposed design is a self-contained, portable spectrometer that measures the spectrum of light across visible and near-infrared wavelengths (400-1000 nm). Light entering the device through a narrow slit is spread out by a diffraction grating into its component colors and focused onto a linear image sensor. A small circuit board reads the sensor and sends the data to a desktop via USB. A Python application on the laptop displays the spectrum in real-time as a plot of intensity versus wavelength.

The device is designed to be compact enough to carry between benches in a research lab, affordable enough to build on a senior design budget, and accurate enough to support biosensing experiments in the BILab. It does not require any specialized training to operate: the user plugs it into their computer, opens the Python application, and begins acquiring spectra.

4.3.2 Detailed Design and Visual(s)

System Architecture Overview:

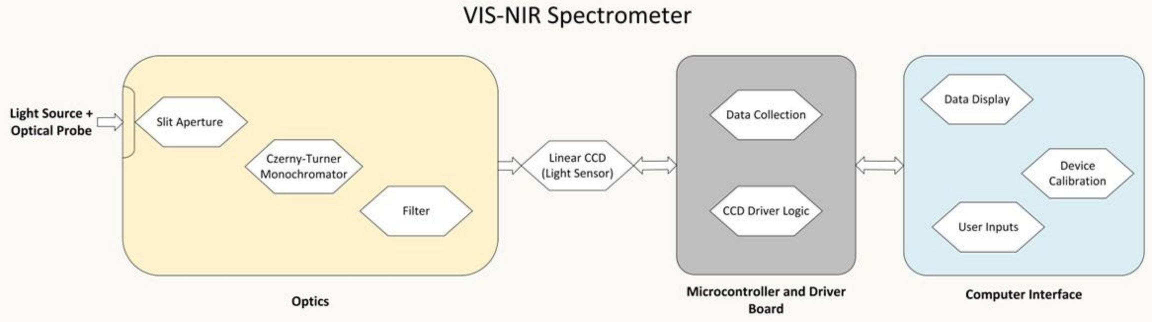


Figure 4.3.2.1 High level Systems Overview

The proposed portable spectrometer is organized into three tightly integrated subsystems: the optical subsystem, the embedded acquisition subsystem, and the computer interface subsystem. Together, these blocks convert incident light over the 400-1000 nm range into calibrated spectral data that can be displayed and stored on a host computer.

Subsystem 1: Optical System

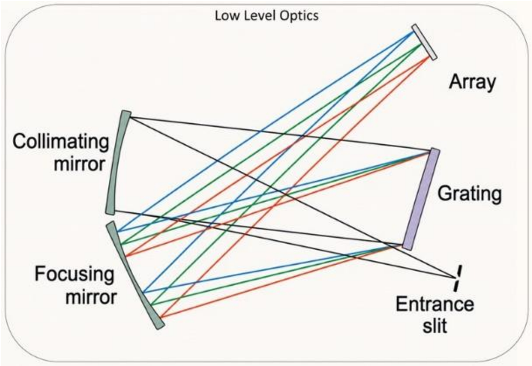


Figure 4.3.2.2 Low Level Optics Overview

The optical subsystem separates incoming light by wavelength and images the dispersed spectrum onto the detector. In the updated design, this subsystem uses a Czerny-Turner configuration rather than a lens-based geometry. Light first enters through the slit aperture, which defines the spatial width of the source presented to the spectrometer. Slit width directly affects the optical tradeoff between spectral resolution and optical throughput. After the slit, the light is directed toward a collimating mirror, which forms a collimated beam and sends it to the reflective diffraction grating. The grating disperses the light angularly as a function of wavelength across the target 400-1000 nm operating range. A focusing mirror then images the dispersed spectrum onto the TCD1304DG linear CCD.

This reflective Czerny-Turner layout is better aligned with the project goals because it supports a compact optical path and avoids lens-driven chromatic effects across the wide visible-to-near-infrared range. The grating geometry and mirror placement are selected so that the first-order spectrum spans the useful 3648-pixel active width of the TCD1304DG. A long-pass filter will also be included in the optical path to reduce second-order overlap from shorter wavelengths. Without this filter, 2nd order short-wavelength light diffracts into long-wavelength first-order light, producing inaccurate spectral content.

The TCD1304DG serves as the terminal sensing element in the optical chain. It converts the focused spectrum into a sequential analog signal, where each pixel corresponds to a narrow wavelength band. Its sensitivity from approximately 350 to 1000 nm makes it suitable for the required measurement range.

Subsystem 2: Microcontroller and Driver Board:

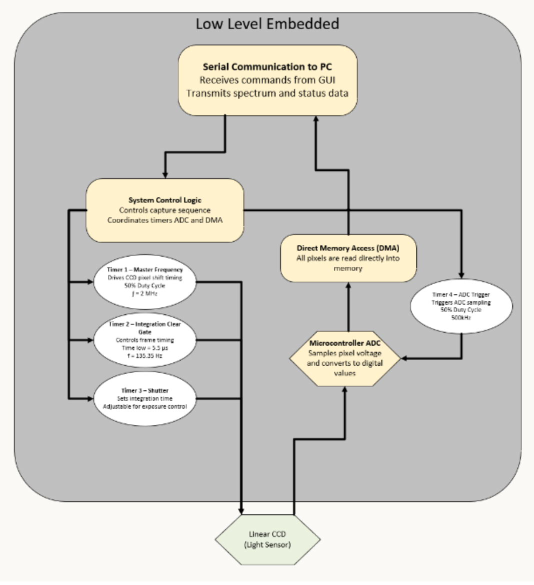


Figure 4.3.2.3 Low Level Embedded Structure

The embedded subsystem controls the CCD, digitizes the sensor output, and transfers spectral frames to the computer. This subsystem is built around the STM32F411CEU6 microcontroller, which acts as the timing and acquisition controller for the TCD1304DG. The microcontroller generates the three required CCD timing signals using hardware timers: the 2 MHz master clock (fM), the shift gate (SH), and the integration clear gate (ICG). These timing signals define pixel shift timing, frame timing, and the effective integration period used for exposure control.

During operation, the system control logic coordinates the capture sequence. It receives commands from the host computer over USB serial, updates integration timing as requested by the user, initiates frame capture, and manages the transfer of each completed spectrum. The CCD analog output is sampled by the STM32 ADC using timer-triggered conversions so that each pixel is captured at a controlled point in the readout cycle. Direct Memory Access (DMA) is used to move the sampled data directly into memory as a full frame buffer with minimal CPU overhead. This preserves timing consistency and reduces the chance of dropped samples or software-induced jitters.

Once a full 3648-sample frame has been acquired, the embedded system packages the raw spectral data and sends it to the host computer over USB CDC. The custom driver PCB supports this process by providing regulated power, local decoupling, and analog filtering for the CCD signal path.

Subsystem 3: Python Host Application:

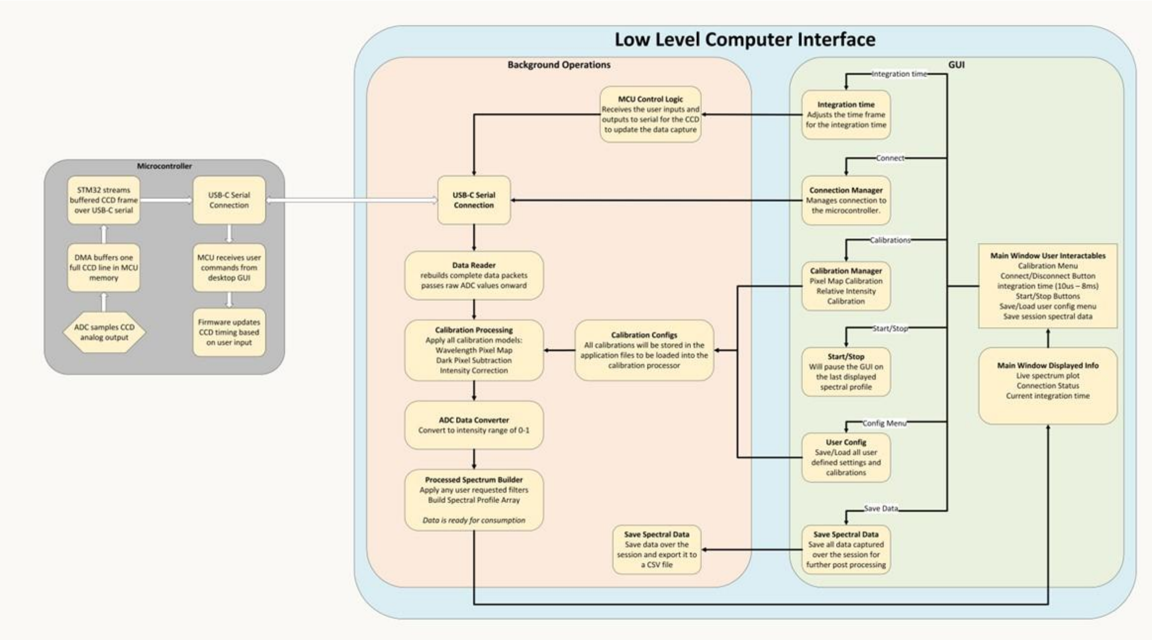


Figure 4.3.2.4 Low Level Desktop Interface

The host application receives raw frame data from the embedded system, applies calibration and correction steps, and presents the spectrum to the user in a usable form. Communication with the hardware is handled over USB CDC. Each incoming frame is reconstructed into a complete 3648-sample spectral array before post-processing is applied.

The application then performs the main data-conditioning steps needed for meaningful spectral output. First, it converts the received ADC samples into an intensity array. It then applies dark-frame subtraction to reduce baseline offset and fixed-pattern contributions. A stored pixel-to-wavelength calibration is applied so that detector position is mapped into physical wavelength units. Additional intensity correction or relative-response calibration can also be applied if required by the final calibration procedure. The processed result is then displayed as a live plot of intensity versus wavelength, with continuous updates during acquisition.

The GUI also serves as the main operator interface for the instrument. It manages connection and disconnection from the spectrometer, allows the user to set integration time, provides controls for starting and stopping live acquisition, opens the calibration tools, and supports saving both user settings and acquired spectra. Captured spectra can be exported as CSV data for downstream analysis, typically as wavelength and intensity columns.

4.3.3 Functionality

A typical measurement session proceeds as follows:

- The user connects the optical slit to a SMA fiber optic probe and positions the probe in the desired measurement location.
- The user connects the spectrometer to their laptop via USB. The Python application is launched.
- The application begins streaming spectral frames from the device and displays a live intensity-versus-wavelength plot.
- The user adjusts the integration time via the application interface if the signal is saturated or too weak.

Once a satisfactory spectrum is acquired, the user saves it to a CSV file with a single button press for additional downstream analysis.

4.3.4 Areas of Concern and Development

The current design meets the core functional requirements as specified, with the following primary concerns identified for the remaining development period:

- **Second-order diffraction suppression:** This is the highest-severity risk in the project. Without adequate filtering, spectral data above approximately 800 nm will be corrupted by second-order artifacts from shorter wavelengths. The team is actively evaluating both commercial longpass filters and a custom thin-film filter fabricated at the ASC.
- **Optical alignment:** The reflective grating geometry is sensitive to component positioning. Achieving FWHM ≤ 5 nm across the full 600 nm operating range requires careful alignment of the slit, grating, and CCD. Adjustable kinematic mounts are being used to manage this during the development phase before the enclosure is finalized.
- **SNR at longer wavelengths:** The TCD1304DG has decreasing quantum efficiency above ~850 nm. Achieving adequate SNR in the 850-1000 nm range may require longer integration times and careful management of dark current, which itself increases with integration time. Characterization testing is planned to determine the practical sensitivity limit.
- **Enclosure design:** The final enclosure must block all ambient light while providing stable, repeatable mounting for the optical components. This remains in early design and will be developed following successful optical alignment on the open breadboard.

4.4 TECHNOLOGY CONSIDERATIONS

The design uses four distinct technology domains, each with specific strengths and tradeoffs:

Optical Components (slit, grating, lenses/mirrors, filter):

- Strengths: Passive, no power consumption, highly reliable, mature commercial availability.
- Weaknesses: Sensitive to physical alignment; performance depends on component quality and coatings. Reflective grating geometry complicates alignment compared to a transmission grating.
- Tradeoff: A reflective grating was selected over a transmission grating to satisfy the enclosure size constraint, accepting increased alignment complexity.

TCD1304DG Linear CCD Sensor:

- Strengths: 3648-pixel resolution, good sensitivity across 350-1000 nm, well-documented timing requirements, low dark current at short integration times.
- Weaknesses: Analog output requires a precise, noise-sensitive analog front-end; quantum efficiency drops significantly above 850 nm; requires three precisely timed control signals; product is discontinued commercially.
- Tradeoff: Chosen by the client as a constraint. Its 3648-pixel array provides high spectral sampling density given the 600 nm operating range, and its sensitivity profile covers the target range acceptably.

STM32F411CEU6 Microcontroller:

- Strengths: High clock speed (up to 100 MHz), hardware timers suitable for CCD timing generation, built-in ADC, DMA, and USB full-speed peripheral, large community and documentation base.
- Weaknesses: Limited 12-bit ADC resolution (4096 counts); Too slow for higher speed detectors which is a possible upgrade to be done in semester 2; USB CDC implementation requires careful driver configuration on the host side.
- Tradeoff: Chosen by the client as a constraint. The STM32F411 provides sufficient peripheral capability for all timing, ADC, and USB requirements within the project's scope.

Python Host Application:

- Strengths: Open source, cross-platform, large library ecosystem, no licensing cost, extensible for future features such as mobile integration.
- Weaknesses: Interpreted language introduces some latency; real-time plotting at high frame rates can cause GUI lag if not carefully implemented using background threading or non-blocking update patterns.
- Tradeoff: Selected over MATLAB and LabView for long-term maintainability and accessibility. Performance concerns are manageable.

4.5 DESIGN ANALYSIS

As of the current project state, the microcontroller and driver board subsystem is functional. The STM32F411CEU6 firmware successfully generates the three required CCD timing signals (fM, SH, ICG) and reads out the full 3648-pixel CCD output frame via ADC with DMA. Initial verification on an oscilloscope confirmed that the timing signals match the TCD1304DG datasheet specifications. The custom driver PCB has been fabricated and assembled, with all power rails verified within tolerance and the STM32 booting successfully from flash.

A preliminary functionality test was conducted by illuminating the CCD with a light source and observing the output. The readout correctly showed elevated signal in illuminated pixels and returned to baseline when light was blocked, confirming that the sensor and readout chain are operating as expected.

The optical subsystem is currently in the component selection and alignment phase. Optical components have been sourced and are being evaluated for placement on the optical breadboard. The diffraction grating geometry is being finalized, and first measurements of spectral spread across the CCD are planned as the next milestone.

The Python application framework has been scoped and initial USB communication and frame parsing have been prototyped. Live plotting infrastructure is being set up in parallel with the optical work.

The proposed design is feasible based on progress to date. The primary remaining technical uncertainties are second-order diffraction suppression and achieving the target spectral resolution through optical alignment. Both are being actively addressed. Cost constraints continue to require careful component evaluation before ordering, which is an accepted tradeoff given the project's budget requirements.

Immediate next steps include finalizing the optical layout and grating positioning, acquiring and testing a long pass filter for second-order suppression, completing the pixel-to-wavelength calibration using a known reference source, and integrating all three subsystems for end-to-end spectral acquisition.

5 Testing

Testing is central to this project because the final measurement quality depends on the combined behavior of the optical path, CCD timing, analog acquisition, USB transfer, and host-side calibration software. The spectrometer will be evaluated as a complete system, where the input optics, diffraction grating, focusing optics, TCD1304DG linear CCD, embedded acquisition system, and host-side calibration software all contribute to the accuracy and repeatability of the final spectral measurement.

The testing strategy follows the calibration and characterization approach described in CIE 233:2019, Calibration, Characterization and Use of Array Spectroradiometers. For this project, testing will verify that the instrument can produce repeatable wavelength and intensity measurements across the intended 400 to 1000 nm operating range. The major test categories are CCD timing verification, readout validation, dark and baseline characterization, wavelength calibration, spectral response correction, stray-light and second-order diffraction evaluation, linearity testing, repeatability testing, and comparison against known reference sources.

Testing will be performed iteratively throughout development. Each subsystem will first be verified independently, then tested at its interfaces, then evaluated as part of the full spectrometer. This is necessary because several measurement errors come from subsystem interaction. Wavelength error depends on optical alignment, grating position, CCD placement, and the pixel-to-wavelength calibration curve. Intensity error depends on the CCD response, grating efficiency, mirror reflectivity, filter transmission, integration time, analog acquisition chain, and software correction factors. For this reason, calibration and characterization are treated as core parts of the testing plan.

5.1 UNIT TESTING

Unit testing verifies that each individual subsystem performs its intended function before it is integrated into the full spectrometer.

1. **CCD Driver Board:** The custom CCD driver board will be tested to verify that it correctly interfaces the STM32 control signals with the TCD1304DG linear CCD. Continuity checks will confirm that no shorts or open connections are present on the SH, ICG, f_M, and CCD output signal paths. After basic electrical checks, an oscilloscope will be used to verify that the master clock, shift gate, and integration clear gate signals reach the CCD with the expected timing behavior. The driver board passes this test when it reliably delivers the required CCD timing signals and returns a stable CCD output waveform.
2. **Microcontroller Timers:** The STM32 firmware will be tested to confirm that the hardware timers generate clean and repeatable CCD timing cycles. The master clock, SH pulse, and ICG pulse will be measured using an oscilloscope. The timing will be compared against the TCD1304DG datasheet requirements and the project's selected integration-time scheme. This test verifies that the firmware can support fixed integration measurements, adjustable integration time, and repeatable frame acquisition without timing drift.
3. **CCD Output and ADC Capture Testing:** The analog CCD output will be observed directly on an oscilloscope before the team relies on digitized data. This confirms that the sensor produces the expected waveform structure, including dummy pixels, light-shielded pixels, and effective image pixels. The STM32 ADC and DMA capture will then be tested by verifying that one full frame is captured with the expected number of samples. The output buffer will be checked for dropped samples, clipping, abnormal offsets, and timing-related sampling errors.
4. **Python GUI Module Testing:** The Python/Kivy application will be tested known test patterns. The test patterns will verify that the GUI can parse a complete frame, detect frame boundaries, plot the intensity array, apply a stored pixel-to-wavelength map, and export data to a CSV file. Performance monitors will be used to verify display update rate, dropped-frame count, and USB packet parsing reliability.
5. **Dark Frame and Baseline Correction Testing:** The dark correction routine will be tested using covered or blocked-light measurements. Several dark frames will be collected at each supported integration time. The software will average the dark frames and subtract the resulting dark spectrum from later light measurements. The main metric is the reduction in baseline offset and fixed-pattern noise after subtraction. Dark behavior can depend on integration time and temperature, so dark correction will be characterized across the operating conditions used by the device.

5.2 INTERFACE TESTING

Interface testing verifies that signals and data pass correctly between connected subsystems. For this project, the most important interfaces are the CCD-to-driver-board interface, the driver-board-to-microcontroller interface, the microcontroller-to-host USB interface, and the calibration-software interface:

- **CCD-to-Driver Board Interface:** The connection between the TCD1304DG and the driver board will be tested by verifying that SH, ICG, and f_M reach the CCD pins correctly and that the CCD output signal appears at the expected output node. This test will use continuity checks, oscilloscope probing, and comparison against the expected waveform structure. The interface passes if the CCD responds predictably to changes in integration time and light exposure.

- **Driver Board-to-MCU Interface:** The interface between the driver board and STM32 will be tested by measuring timing signals at both the STM32 output pins and the CCD-side signal paths. This verifies that the routing, inversion stages, and signal conditioning preserve the timing behavior required by the CCD. The CCD output routed back to the STM32 ADC input will also be checked for continuity, expected voltage range, and noise pickup.

- **MCU-to-Host USB Interface:** The USB CDC interface will be tested by sending known frame patterns from the STM32 to the Python application. The host software will verify frame length, frame order, packet boundaries, and data integrity. The main success criterion is that complete frames are received without corruption during continuous acquisition. Frame timestamps will be used to identify dropped frames, inconsistent timing, or USB bottlenecks.
- **Calibration Software Interface:** The calibration interface connects raw CCD data to corrected spectral output. This interface will be tested by applying stored calibration files to known test data. The software must correctly load the dark frame, pixel-to-wavelength map, and wavelength-dependent correction factors. The output spectrum should preserve the expected peak locations and apply intensity normalization consistently.

5.3 INTEGRATION TESTING

Integration testing verifies that multiple subsystems operate together as a functional measurement chain. The critical integration path is optical input to dispersed spectrum, dispersed spectrum to CCD output, CCD output to STM32 acquisition, STM32 acquisition to USB transfer, and USB transfer to GUI display and calibration:

- **Optical Path Alignment Testing:** The optical subsystem will be aligned using known-wavelength sources. A narrow-band source such as a 532 nm laser will be used to create a clear peak on the CCD. Additional sources across the VIS-NIR range will be used to confirm that the dispersed first-order spectrum falls across the usable 3648-pixel CCD width. The primary metric is that known wavelengths appear in the expected pixel regions and remain stable after repeated measurements.
- **Pixel-to-Wavelength Calibration Integration:** The pixel map calibration will be tested by measuring multiple known wavelengths and fitting a calibration curve that maps CCD pixel position to wavelength. The application will then display intensity versus wavelength rather than intensity versus pixel number. The calibration passes if known reference peaks appear at their expected wavelength locations within the project’s error target.
- **Quantum Efficiency and Spectral Response Integration:** The spectral response correction workflow will be integrated after basic wavelength calibration is complete. The correction factors will account for wavelength-dependent response from the CCD, grating, mirrors, and filters. Testing will compare light sources with similar known optical power at different wavelengths. After correction, the normalized displayed intensity values should be approximately equal for sources with similar power. This test verifies that the software is compensating for the instrument response.

5.4 SYSTEM TESTING

System testing evaluates whether the complete spectrometer satisfies the functional and performance requirements. These tests are based on the final use case: Dr. Das should be able to connect the device, acquire a spectrum, adjust integration time, view the calibrated result, and save data for analysis:

- **Wavelength Range Verification:** The spectrometer will be tested with multiple reference wavelengths across the 400 to 1000 nm target range. The purpose is to confirm that the optical layout and CCD placement provide usable response across the intended VIS-NIR band. The system passes this test if the known sources appear within the calibrated wavelength range and are not clipped, saturated, or outside the detector span.
- **Wavelength Accuracy Testing:** Wavelength accuracy will be tested by measuring known reference peaks and comparing their displayed wavelength locations to their expected values. The primary target is a peak-location

error within approximately 2 nm after calibration. Any systematic offset will be corrected through the pixel-to-wavelength calibration curve.

- **Spectral Resolution Testing:** Spectral resolution will be tested by measuring narrow-linewidth sources and calculating the full width at half maximum of the measured peak. The goal is to achieve approximately 5 nm FWHM or better for narrow spectral features. This test will also reveal whether the slit width, optical focus, grating alignment, or CCD sampling is limiting the measured resolution.
- **Signal-to-Noise Ratio and Noise Floor Testing:** Noise performance will be characterized using dark measurements and stable light-source measurements. For dark tests, the optical input will be blocked and repeated frames will be collected at multiple integration times. The RMS noise floor, baseline offset, and fixed-pattern structure will be calculated. For light-source tests, the mean signal and standard deviation near a peak will be used to estimate SNR. This verifies whether the instrument can produce stable spectra for the expected lab use.
- **Linearity Testing at Fixed Integration Time:** A stable light source will be measured while input intensity is changed using neutral density filters or controlled source current. With integration time held constant, the measured CCD counts should scale with input intensity over the usable dynamic range. This test identifies saturation, low-end noise limits, and nonlinear behavior in the CCD output or acquisition chain.
- **Thermal and Repeatability Testing:** The system will acquire repeated measurements from a stable source over an extended operating period. Peak position, peak height, baseline offset, and noise floor will be tracked over time. This test characterizes drift caused by temperature changes, optical alignment shifts, CCD behavior, or electronics warm-up. The result will determine whether the system needs a warm-up period, periodic dark recalibration, or repeated wavelength checks.

5.5 REGRESSION TESTING

Regression testing ensures that design changes preserve previously verified functions. This is important because changes to firmware timing, USB packet structure, GUI plotting, optical alignment, or calibration files can affect the entire measurement pipeline:

- **Firmware Regression:** After firmware changes, the team will re-check SH, ICG, and fM timing with an oscilloscope or logic analyzer. The team will also confirm that a full CCD frame is still captured without dropped samples. Any change to timer configuration, ADC trigger timing, DMA setup, or integration-time control requires this test.
- **USB and Data Parsing Regression:** After communication or GUI changes, the team will transmit known test frames and verify that the Python application still receives complete frames correctly. Frame length, frame order, packet boundary detection, and dropped-frame count will be checked.
- **Calibration Regression:** After optical adjustments, enclosure changes, grating movement, or CCD repositioning, the pixel-to-wavelength calibration must be repeated. The system will re-measure known reference wavelengths and compare peak positions to the saved calibration curve. If the error exceeds the target tolerance, the calibration file will be updated.

5.6 ACCEPTANCE TESTING

Acceptance testing will demonstrate that the spectrometer meets the client's needs and the project requirements. Dr. Das will be involved in evaluating the device as both the project client and intended primary user:

- **Client Demonstration:** The team will demonstrate a complete measurement workflow to Dr. Das. The workflow will include connecting the spectrometer, launching the Python application, acquiring a live spectrum, adjusting integration time, applying calibration, and exporting the measured data. The goal is to show that the device can be operated as a practical research tool without requiring code changes or hardware reconfiguration during routine use.

- **Reference Instrument Comparison:** When available, the device will be compared against a commercial spectrometer in the BILab. Both instruments will measure the same source under similar conditions. The comparison will focus on peak location, relative spectral shape, repeatability, and normalized intensity behavior. This test provides practical evidence that the device is producing useful spectral data for the intended research context.

5.7 SECURITY TESTING (IF APPLICABLE)

Security testing is not applicable to this project. The spectrometer is a localized research tool operating over a direct USB or point-to-point wireless connection for data acquisition. It does not handle sensitive user data, process financial transactions, or connect to external public networks, making traditional cybersecurity testing unnecessary.

The limited security testing that applies will focus on safe and reliable operation. The Python application should reject malformed or incomplete USB frames, avoid crashing during disconnect events, and prevent invalid integration-time settings from being sent to the microcontroller. If wireless functionality or mobile integration is added later, additional security testing will be required for pairing, data transfer, and access control.

5.8 USER TESTING

User testing will evaluate whether the spectrometer can be operated effectively by the intended user in a real laboratory workflow. Since Dr. Das is the primary intended user, testing will focus on his ability to set up the device, collect data, adjust measurement settings, and interpret the displayed spectrum.

The user testing process will include a guided demonstration followed by a short independent-use session. During the guided demonstration, the team will explain the setup procedure, GUI controls, calibration options, integration-time control, and data export process. During the independent-use session, Dr. Das will operate the spectrometer while the team observes where confusion, delay, or repeated explanation occurs.

Feedback will be collected in three areas. First, the team will evaluate setup usability, including whether the device is easy to connect, align, and prepare for measurement. Second, the team will evaluate software usability, including whether the live plot, buttons, calibration tools, and export options are clear. Third, the team will evaluate measurement usefulness, including whether the displayed spectrum provides the information needed for BILab experiments.

The results of user testing will be used to refine the GUI layout, labels, calibration workflow, physical enclosure, and user documentation. Since the project is intended to support faster and more flexible laboratory measurements, the final device should reduce setup time and make spectral data collection easier than relying only on shared commercial equipment.

5.9 RESULTS

Testing completed so far has focused primarily on subsystem bring-up and early functionality. The team has verified that the CCD driver and microcontroller can generate the timing behavior needed to operate the TCD1304DG. Initial oscilloscope measurements confirmed that the control signals are being generated and that the CCD output changes when the sensor is exposed to light. This indicates that the basic CCD timing and readout chain are functional.

The team has also begun validating the data path from the microcontroller to the host computer. The current Python/Kivy application can receive streamed data, display a live plot, and support early calibration development. Current performance has demonstrated approximately 31 frames per second for on-screen display and approximately 80 frames per second when streaming data to a CSV file. The target performance remains approximately 125 frames per second, so GUI optimization and data-handling improvements are still required.

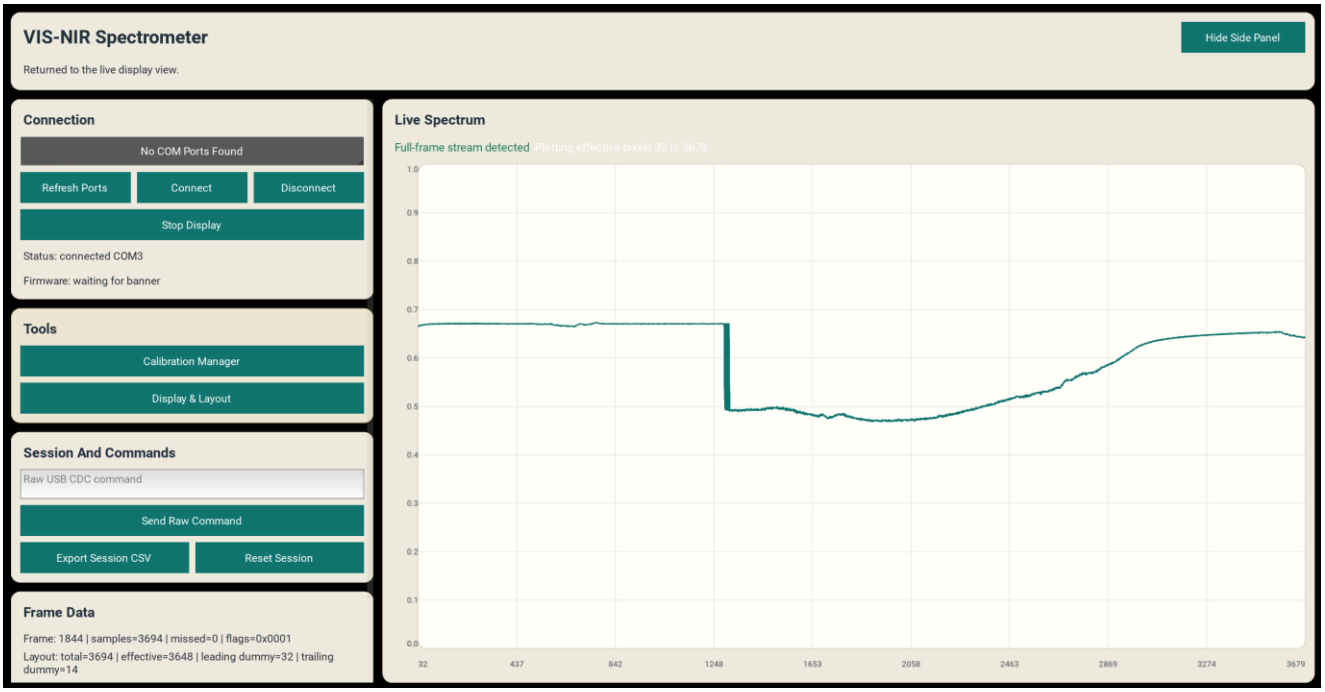
Early calibration work has focused on dark and bias correction and pixel-to-wavelength mapping. Dark-frame correction has been implemented as an initial software feature, and the team has started building a calibration source using multiple laser diodes. The purpose of this calibration device is to provide known wavelength points that can be used to generate and verify the pixel map. Additional calibration work is still needed for wavelength accuracy, spectral response correction, and normalized intensity calibration.

The main testing conclusion so far is that the electronics and software pipeline are functional enough to support continued calibration and optical validation. The remaining uncertainty is concentrated in the optical subsystem. The team must still complete final grating alignment, verify full 400 to 1000 nm wavelength coverage, characterize second-order diffraction, and confirm that the final system can achieve the required wavelength accuracy, resolution, and signal-to-noise ratio. The next testing phase will therefore focus on CIE-style characterization of the complete spectrometer, including dark baseline behavior, linearity, wavelength calibration, spectral response correction, stray-light control, repeatability, and comparison against known reference sources.

6 Implementation

Our Preliminary implementation has focused on bringing up the electrical readout system, host-side software, and early calibration workflow. The custom CCD Driver Board has been fabricated and assembled, and the STM32F411 firmware has been developed to generate the required TCD1304DG timing signals, including the master clock, SH, and ICG. The CCD output is being captured and sent to the host computer over USB, where the Python/Kivy application receives the data, displays a live spectrum, and supports early calibration functions. Current software work includes live plotting, CSV export, dark and bias correction, and the initial framework for pixel-to-wavelength mapping. In parallel, the team has begun assembling the optical and calibration hardware, including the use of known-wavelength laser diodes for calibration testing. The remaining implementation work will focus on final optical alignment, enclosure integration, full calibration, and performance validation of the complete VIS-NIR spectrometer.

Figure 6.1 Populated CCD Driver Board



Returned to the live display view.

Status: connected COM3

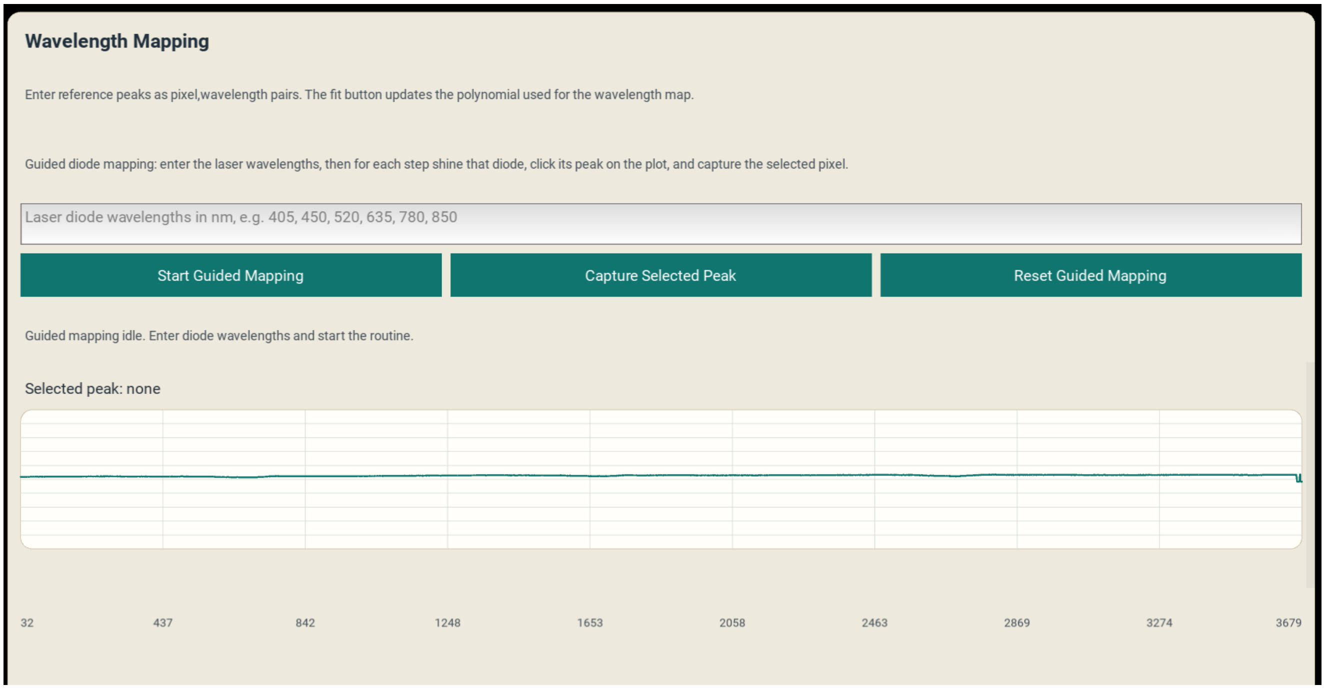
Firmware: waiting for banner

Frame: 1844 | samples=3694 | missed=0 | flags=0x0001

Layout: total=3694 | effective=3648 | leading dummy=32 | trailing dummy=14

Full-frame stream detected Plotting effective pixels 32 to 3679.

Figure 6.2 CySpectra App



Enter reference peaks as pixel,wavelength pairs. The fit button updates the polynomial used for the wavelength map.

Guided diode mapping: enter the laser wavelengths, then for each step shine that diode, click its peak on the plot, and capture the selected pixel.

Guided mapping idle. Enter diode wavelengths and start the routine.

Selected peak: none

Figure 6.3 Wavelength Map Calibration

7 Ethics and Professional Responsibility

This section examines the ethical and professional responsibility dimensions of the portable spectrometer project. It maps the seven ideals of professional responsibility to the IEEE Code of Ethics, documenting how the team has practiced work competence through peer review of schematics and firmware, financial responsibility by tracking spending against the sub-$500 BOM target, communication honesty through transparent status reporting, health and safety via IEC 61010-1/61326-1 compliance and enclosed optics, intellectual-property stewardship using open-source libraries and proper citations, sustainability through USB-powered and reusable design choices, and social responsibility by targeting an affordable, openly publishable instrument. The section then applies the four bioethics principles (beneficence, nonmaleficence, autonomy, justice) to each broader-context area from §4.1.1, identifying Global/Social and Justice as the project's strongest ethical contribution. Environmental and Nonmaleficence is the area most needing improvement. It concludes with team and individual virtue reflections centered on honesty, accountability, and humility.

7.1 AREAS OF PROFESSIONAL RESPONSIBILITY/CODES OF ETHICS

The following table maps each of the seven ideals of professional responsibility (McCormack et al., 2012) to a relevant item from the IEEE Code of Ethics, with a description of how Team SDDEC26-06 has engaged with that area during the project so far.

Area of Responsibility	Definition (in our words)	Relevant Item from IEEE Code of Ethics	How our team has engaged with this area
Work Competence	Performing engineering work at a professional level of skill and care.	I.5 — "to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, to be honest and realistic in stating claims or estimates based on available data…"	We pair-review each other's PCB schematics and firmware before committing, document component selections in a shared decision log, and revise our wavelength-resolution and cost targets as bench data comes in rather than defending earlier estimates.
Financial Responsibility	Delivering quality work within budget and managing project resources honestly.	I.4 — "to avoid unlawful conduct in professional activities, and to reject bribery in all its forms"; II.9 — "to avoid injuring others, their property, reputation, or employment by false or malicious actions, rumors or any other verbal or physical abuses."	We track parts spending against the < $500 BOM target in a shared sheet and request quotes from multiple vendors for the CCD, optical components, and PCB fabrication before purchasing.
Communication Honesty	Communicating truthfully and accurately with clients, advisors, and teammates.	I.5 — "to be honest and realistic in stating claims or estimates based on available data."	We give weekly status updates to Prof. Pramanik and Dr. Das that report blockers and missed milestones plainly rather than overstating progress, and our weekly standups follow the same standard internally.

Health, Safety, and Well-Being	Protecting the safety and well-being of users, the public, and team members.	I.1 — "to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment."	We selected IEC 61010-1 and IEC 61326-1 as governing safety and EMC standards (§2.2), enclose the optical bench to prevent stray-light exposure, and use current-limited bench supplies during all breadboard testing.
Property Ownership	Respecting intellectual property, licenses, and the property of others.	I.7 — "to support colleagues and co-workers in following this code of ethics"; III.10 — broader respect for ownership of work.	We use only open-source firmware libraries with compatible licenses, cite datasheets and reference designs (TCD1304, STM32) in the design document, and keep our own source under a team-controlled repository.
Sustainability	Considering the environmental impact of design decisions across the product lifecycle.	I.1 — "to strive to comply with ethical design and sustainable development practices…"	We selected a USB-powered design that avoids disposable batteries and chose a reusable enclosure approach; sustainability remains an area we revisit in §7.2 since material choice for the optical housing is still open.
Social Responsibility	Considering how the design serves and affects the broader community.	I.2 — "to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies, including intelligent systems."	By targeting a < $500 open spectrometer for a research lab, we aim to make VIS-NIR measurement accessible to groups that cannot afford commercial instruments; Dr. Das has indicated the design may be published openly to extend that benefit.

An area in which our team is performing well is Communication Honesty. We hold weekly internal standups, biweekly virtual meetings with Prof. Pramanik, and weekly hands-on meetings with Dr. Das in the ASC lab, and we report blockers and missed milestones plainly rather than smoothing over them. This signifies strong performance because both faculty contacts have a continuously accurate picture of project state, which in turn lets them redirect our effort early when an approach is not working rather than after a milestone slips.

An area in which our team needs to improve is Sustainability. To date we have considered sustainability mainly in the choice of a USB-powered, non-disposable design, but we have not yet evaluated the environmental footprint of the optical housing, the PCB substrate, or end-of-life disposal of the CCD assembly. Going forward, the team will document material choices for the enclosure and PCB in the BOM with a short sustainability note for each, and prefer recyclable or commonly available materials where the optical and mechanical requirements allow.

7.2 FOUR PRINCIPLES

The following table applies the four principles of bioethics (beneficence, nonmaleficence, respect for autonomy, and justice; Beauchamp, 2007) to each broader-context area identified in §4.1.1.

Broader Context	Beneficence	Nonmaleficence	Respect for Autonomy	Justice
Public health, safety, and welfare	Enables faster, more flexible optical measurements that support biomedical research with potential downstream patient-care benefit through Dr. Das's tissue-imaging work.	Enclosed optical bench and compliance with IEC 61010-1 and IEC 61326-1 prevent stray-light exposure, electrical hazards, and EMC interference with nearby lab equipment.	Open firmware and Python interface let researchers inspect and adapt the measurement pipeline rather than treating it as a closed instrument they must trust blindly.	Lower price point makes a capable VIS-NIR spectrometer reachable for labs and programs that cannot justify a commercial unit, broadening access to the underlying measurement capability.
Global, cultural, and social	Open documentation and a publishable design support knowledge sharing across the broader research community, including institutions outside well-funded labs.	Avoids contributing to a closed-instrument culture in which measurement methods are opaque; we cite reference designs and datasheets rather than obscuring component choices.	Users can modify, extend, or fork the design for their own workflows; the device is not locked to a single vendor's software stack.	Targeting an under-$500 cost reduces the equipment gap between well-resourced and under-resourced research environments, which is the area where this project most directly advances justice.
Environmental	USB-powered operation avoids	Material and disposal impact	Open design lets users repair or	The environmental

	disposable batteries, and a reusable enclosure approach avoids single-use packaging during normal lab use.	of the optical housing, PCB substrate, and CCD assembly is not yet fully characterized; this is an area where the design is currently neutral at best.	replace individual subsystems instead of discarding the whole instrument, which extends usable lifetime.	burden of low-volume prototyping falls on our team and the lab; we have not externalized manufacturing costs onto communities elsewhere, but we also have not formally assessed lifecycle impact.
Economic	Reduces the cost barrier to VIS-NIR measurement for the BILab and similar labs, freeing budget for other research needs.	Open licensing and clear documentation reduce the risk of users being locked into proprietary software or forced into expensive recalibration services.	Users can choose their own host software, calibration procedure, and integration path rather than being constrained to a vendor's ecosystem.	By publishing the design, the economic benefit of a capable spectrometer extends beyond a single lab, with the strongest impact on groups that are currently priced out of commercial instruments.

The most important broader-context–principle pair for this project is Global, cultural, and social × Justice. Commercial VIS-NIR spectrometers in this wavelength range cost roughly $1,800–$3,900, which puts capable optical measurement out of reach for many academic and educational settings. By delivering an open, sub-$500 design that is documented well enough to reproduce, we are working toward a more equitable distribution of measurement capability across labs. We will ensure this benefit by publishing the firmware, host software, and BOM under permissive terms, and by writing the design document so that the calibration and assembly procedure is reproducible by a reader who does not have access to our team.

The pair where the project is currently weakest is Environmental × Nonmaleficence. The optical housing, PCB substrate, and CCD assembly all carry material and end-of-life impacts that we have not yet characterized, and prototyping inherently produces some scrap. This negative is partly offset by other strengths in the same row, including USB power instead of disposable batteries, repairability of individual subsystems, and a reusable enclosure, and by the broader benefit that a single shared instrument displaces the manufacturing footprint of multiple commercial units. To improve, the team will document material choices for the enclosure and PCB in the BOM with a short sustainability note, prefer recyclable or commonly available materials where the optical and mechanical requirements allow, and record an end-of-life disposal procedure for the CCD assembly in the final user documentation.

7.3 VIRTUES

Team Virtues:

Three virtues that are important to Team SDDEC26-06 are honesty, accountability, and humility.

Honesty means giving accurate status updates to teammates, advisors, and our client even when progress is behind schedule. We support this virtue by reporting blockers plainly in weekly standups, by documenting failed approaches in the project log alongside successful ones, and by stating realistic estimates rather than the most optimistic ones.

Accountability means owning the work each member commits to and following through on shared decisions. We support this virtue through written meeting notes that capture task ownership, two-person sub-teams that distribute responsibility for each subsystem, and an expectation that members who miss a meeting catch up on the notes and report status the following week.

Humility means recognizing the limits of our individual knowledge and seeking input from teammates, advisors, and our client. We support this virtue by reviewing each other's PCB schematics and firmware before integration, by bringing open questions to Dr. Das during weekly ASC lab visits, and by treating revisions to earlier design choices as expected rather than as failures.

Individual Virtues:

Ryan Majstorovic

One virtue I have demonstrated so far is integrity. Integrity is important to me because in embedded design and team organization, honest communication about what is working and what is not prevents small issues from compounding into larger failures. A team can only make sound decisions when every member reports the ground truth. When I discovered an error in one of my optics design contributions, I flagged it to the team immediately rather than quietly trying to patch it. Owning the mistake allowed us to correct course early and reinforced the team's culture of honest self-assessment.

A virtue I want to grow into is confidence, particularly when it comes to presentations. Confidence matters because clearly communicating our work is just as critical as the technical execution itself. If I cannot convey our design decisions convincingly, the quality of the underlying engineering does not come through. To build confidence before the end-of-semester faculty presentation, I plan to rehearse my sections in front of teammates, practice fielding likely questions from Prof. Pramanik and the evaluators, and prepare concise backup material so I can trust that I am ready for follow-up questions rather than second-guessing myself at the podium.

Dawson Posekany

A virtue that I have been mindful to demonstrate is inclusion. I think it is important in a professional engineering environment for everyone's voice to be heard so that the best possible solution can be found. This also aids in preventing anyone from falling behind in the project. I have shown this by prompting teammates for their opinions. For example, when creating our end-of-semester faculty presentation, I asked each of my team members to give feedback on if the Gantt Chart created was accurate and professional looking.

A virtue I would like to focus more on is consistency. In many aspects of my life, professional and otherwise, I don’t follow through on my promises as much as I would like. My excuse is that I get distracted and busy, but the truth is that you can find the time for anything as long as you make it a true priority and living by that is important to me. Going forward, I will create an environment that promotes sticking to my promises by writing them down and putting in protocols so that they get done.

Evan Tamer

One virtue that I have demonstrated so far is curiosity. This virtue is important because there is always more to learn about a subject. By seeking more knowledge, mistakes can be avoided and improvements can be made without needing to figure out everything on your own. One way I have demonstrated this is by looking into calibration methods. It was suggested that I use laser diodes, but rather than just purchase them immediately, I made sure to do some research on the topic. By doing this, I learned more about standards for spectrometry and potential ways to improve our accuracy. Something I have not demonstrated as much as I would like to is showing more initiative in my work. This is important because no progress can be made without taking action, and I would have been able to contribute more if I had better embodied this virtue. One way I could demonstrate this in the upcoming semester is to more clearly define what I want to get done and set aside a time to work on it.

Samar Gill

The virtue I find most important to demonstrate is humility. Why it is important to me: This virtue is important to me because I don’t think that the way I solve a problem is the same for everyone nor do I think that it is the best way to solve a problem. I leave myself open to constructive criticism and allow for feedback to improve my skills. An early example came when we discussed who would own the optics subsystem. Even though I was actively taking an optics course, I drew on my partners' input rather than assuming my perspective was sufficient, which led to more informed decisions.

The virtue I want to develop further is orderliness. I value structure, and orderliness is becoming increasingly important to me as the project grows in scope. I want each task to have a defined time, place, and level of effort. I plan to build personal tracking systems that connect my individual progress to the team's broader goals, making it easier to see at a glance what has been completed and what remains.

8 Closing Material

8.1 CONCLUSION

At this stage, the team has developed a design capable of displaying CCD output on a computer. Current progress includes a CCD driver board, microcontroller code for CCD timing and computer communication, and a functional GUI. The team has also researched the optical setup, purchased an interim housing for development use, purchased optical and calibration components, and begun building the calibration device.

The main goal for this phase was to demonstrate basic device functionality. That goal has been partially achieved through the electronics, firmware, and GUI work, but the optics subsystem remains incomplete. The primary limiting factors have been cost constraints and unresolved second-order diffraction mitigation, which prevented the team from finalizing the optical design during this phase.

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8.3 APPENDICES

The following is an incomplete list of personas that the team considered during the design and testing phases.

Persona 1: Biomedical/Electrical Engineering Researcher

- **Demographic:** Adult, Researcher, PhD
- **Hobbies:** Learning
- **Motivation:** Money, Scientific advancement
- **Personality:** Passionate, Curious
- **Values:** Accuracy, understanding of the world

This user is a professional in their respective field of study. They are driven by a desire for scientific advancement. They are well versed in each of the fields of work used to make this device, including optics, embedded systems, and analog circuitry. They are highly technical and value precision and efficiency. The researcher needs access to an accurate yet affordable spectrometer that can be used in various applications. This tool offers a way to streamline testing, ultimately speeding up the researchers' contribution to the scientific community.

Persona 2: Medical Staff

- **Demographic:** Specialized Staff in bio-sensing
- **Hobbies/Interests:** Passionate workers care and keep up to date with new bio-sensing technology.
- **Work Motivations:** Making testing and data collection intuitive and usable for more people.
- **Values:** They value efficiency and reliability to draw quick, accurate conclusions.
- **Personality/Emotions:** They want the best for their clients and fellow faculty

This user is a specialized medical staff member with a focus on bio-sensing technology. Staying current with the latest developments in the field is both a professional priority and a personal interest. This user is deeply motivated by making testing and data collection more intuitive and accessible, not just for specialists but for a wider range of clinical staff.

Efficiency and reliability are central to how this user works. In a medical setting, quick and accurate conclusions are not a luxury; they directly impact the quality of care. This user wants tools that are dependable and easy to interpret and genuinely care about the wellbeing of both clients and colleagues.

A portable, accessible spectrometer aligns well with this user's goals. The ability to perform non-invasive optical measurements quickly and reliably could streamline workflows that currently require more complex or time-consuming methods. For this user, the value lies in a tool that brings meaningful sensing capability into everyday clinical use without demanding deep technical expertise to operate.

Persona 3: Educational Institutions

- **Demographic:** High school or University Lab Instructor.
- **Hobbies/Interests:** Science Communication, niche design projects.
- **Work Motivations:** Bridging theory and hands on learning for students.
- Values: They need cheap and portable devices so that they can supply a classroom. The devices must be durable and "student-proof". Encapsulation is crucial.
- **Personality/Emotions:** They are encouraging and patient, wanting to share the natural world with their students.

9 Team

9.1 TEAM MEMBERS

The team consists of four senior Electrical Engineering students, each leading one or more subsystems of the spectrometer:

Ryan Majstorovic — Embedded systems and team organization

Dawson Posekany — PCB design, simulation, and testing; progress documentation

Evan Tamer — Embedded systems and device calibration

Samar Gill — Embedded systems and project presentation

9.2 REQUIRED SKILL SETS FOR YOUR PROJECT

Delivering the portable VIS-NIR spectrometer requires the following skill sets, each tied directly to the system's subsystems and requirements:

Embedded firmware development (C/C++, STM32, hardware timers, DMA, USB CDC) for CCD timing generation, high-speed ADC buffering, and host communication.

PCB design and simulation for the CCD driver board and analog signal conditioning, including layout practices that satisfy the IEC 61326-1 EMC requirements.

Optical system design covering wavelength dispersion, second-order diffraction reduction, stray-light control, and calibration against NIST-traceable references.

Host-side software development in Python, including real-time plotting and parallelized data acquisition, for a responsive desktop GUI.

9.3 SKILL SETS COVERED BY THE TEAM

The required skill sets are distributed across the team as follows:

Dawson Posekany — Prior experience with spectroscopy devices and familiarity with PCB design, covering the optical subsystem context and PCB development.

Evan Tamer — Embedded systems background, supporting firmware development and breadboard-level circuit work.

Ryan Majstorovic — Embedded systems and PCB design, contributing to firmware and board-level signal integrity.

Samar Gill — Embedded systems and integration of AI tooling into the development workflow, supporting firmware and software productivity.

9.4 PROJECT MANAGEMENT STYLE ADOPTED BY THE TEAM

The team uses a hybrid Waterfall-Agile project management style, as described in §3.1. Early in the project, a Waterfall-leaning approach was necessary because optical, PCB, and CCD components had to be specified and ordered before later integration work could begin; component selection followed a deliberate, sequential process while weekly subsystem tasks were assigned to two-person pairs.

Once the first prototype elements were functional, the team shifted toward an Agile cadence. Weekly work now centers on iterative improvements and feature additions, with the next highest-value task prioritized at each weekly standup. Progress is tracked through weekly meetings with Dr. Das, weekly status reports, Gantt charts for schedule tracking, GitLab for software version control, and Microsoft Teams for shared optical and hardware documentation.

9.5 INITIAL PROJECT MANAGEMENT ROLES

Each team member holds a primary project management role aligned with their subsystem ownership:

Ryan Majstorovic — Team Organization Lead: schedules weekly standups, tracks action items, and coordinates cross-subsystem dependencies.

Dawson Posekany — Documentation Lead: maintains progress documentation, the shared decision log, and PCB design records.

Evan Tamer — Records Lead: captures meeting minutes and notes in the shared Excel tracker.

Samar Gill — Presentation Lead: prepares project presentations and client-facing updates for Prof. Pramanik and Dr. Das.

9.6 TEAM CONTRACT TEAM MEMBERS:

Team Members:

1) Ryan Majstorovic

2) Dawson Posekany

3) Evan Tamer

4) Samar Gill

Team Procedures

Prof. Pramanik, our advisor, will be virtual every other Thursday to briefly provide a status update. More meeting can be scheduled as necessary. As for Dr. Das, since he is an active member in this project, we meet in his ASC lab during our weekly Monday trip to the ASC for hands on work and progress evaluation.

As for meetings strictly within the Senior Design team, all agreed that Monday, Tuesday, and weekends when needed are adequate to complete group work. The TLA and SIC are common meeting areas.

Our methods of communication involve the following:

a. Microsoft Teams for File Sharing and interaction with project contact
b. Discord for quick discussions and assistance for the Senior Design team.
2. Decision-making policy (e.g., consensus, majority vote):
a. Decisions will be made via consensus. Team members will use best judgement to decide if something needs to be brought up to the group.
3. Procedures for record keeping (i.e., who will keep meeting minutes, how will minutes be shared/archived):
a. Minutes will be recorded in an Excel spreadsheet along with current and future tasks pertaining to the week. This document will be discussed with the team and recorded at that time.

Participation Expectations

1. Expected individual attendance, punctuality, and participation at all team meetings:
- Try to show up to all meetings on time, but missing some occasionally is fine.
- If you will not be there on time, let the group know beforehand and review the meeting notes afterwards.
- Team members have the duty of keeping up to date when they must miss a meeting. This involves giving status reports and staying up to date on their assignments.
- In meetings all members should participate by giving status updates, adding feedback, and asking questions about the system.

2. Expected level of responsibility for fulfilling team assignments, timelines, and deadlines:
   1. Everyone should make their best effort to put in a reasonable amount of time, ideally averaging four to seven hours per week.
   2. Be honest with expectations for deadlines. If a deadline needs to be pushed bring it up in the weekly standup.
3. Expected level of communication with other team members:
- Should let the group know if there are any issues, such as being unavailable for a meeting or having difficulties with tasks
- Should be responsive and helpful in group chats

4. Expected level of commitment to team decisions and tasks:
- Work with the team and speak up/ask questions.
- Impart expertise whenever available.

Leadership

1. Leadership roles for each team member (e.g., team organization, client interaction, individual component design, testing, etc.):
   - Dawson Posekany - PCB Design/Simulation/Testing, Progress Documentation
   - Evan Tamer - Breadboard circuit design, Note taking
   - Samar Gill - Embedded design, project presentation
   - Ryan Majstorovic - Embedded design, Team Organization

2. Strategies for supporting and guiding the work of all team members:
   - Weekly standups to discuss progress and overall direction of project

- Breaking into teams as needed to accomplish tasks.

3. Strategies for recognizing the contributions of all team members:
    - Members will document their individual accomplishments in Weekly Reports.
    - Insights and Progress will be discussed during Weekly standups and documented in the corresponding Excel sheet.

Collaboration and Inclusion

To ensure each team member is actively involved in the project, we discussed what expertise each member has that will be used in this project so that we can better segment off tasks.

Dawson Posekany - Experience with Spectroscopy devices, familiarity with PCB design

Evan Tamer - Embedded systems

Ryan Majstorovic - Embedded systems, PCB design

Samar Gill - Embedded system, integrating AI tool use

The team will maintain open communication when issues arise and will encourage members to ask for clarification when additional information is needed. Working in two-person sub teams will also help distribute knowledge across the project rather than isolating expertise within one team member. If there are issues in this aspect of the project, team members know to either tell someone in the group or bring it up with faculty if it keeps being an issue

Goal-Setting, Planning, and Execution

1. Team goals for this semester:
    - Get a functioning and documented branching framework for our project, breaking down the project into actionable tasks.
    - Stage 1: Breadboard circuit, LabVIEW integration, basic light sensing.
    - Stage 2: Wi-Fi Capability, Optics integration, circuit optimization, and device powering.

2. Strategies for planning and assigning individual and team work:
    - Work will be assigned during our weekly standup. Depending on the nature and difficulty of tasks, the team will be split amongst two-man teams.

3. Strategies for keeping on task:
    - Working as groups and having weekly tasks. Kindly holding each other accountable in our designated groups.

Consequences for Not Adhering to Team Contract

If our advisor or the team believe that the rules of the contract aren't being upheld, it will first be addressed through a team discussion focused on what needs to change. If infractions become egregious, issues will be discussed with the Project Faculty (Contact and/or Advisor) or Class Instructors depending on the nature of the issue. Upon consideration of all feedback, the team will make a decision on what must be done.

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a) *I participated in formulating the standards, roles, and procedures as stated in this contract.*

b) *I understand that I am obligated to abide by these terms and conditions.*

c) *I understand that if I do not abide by these terms and conditions, I will suffer the consequences as stated in this contract.*

1) Ryan Majstorovic DATE 2/8/2026

3) Dawson Posekany DATE 2/8/2026

4) Evan Tamer DATE 2/8/2026

4) Samar Gill DATE 2/8/2026