STRE&M: LED Absorption Spectrometry

ECE 445 Design Document - Spring 2023

Project #52

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1 Introduction

1.1 Problem

Urine tests are critical tools used in medicine to detect and manage chronic diseases. These tests are often over the span of 24 hours and require a patient to collect their own sample and return it to a lab. With this inconvenience in current procedures, many patients do not get tested often, which makes it difficult for care providers to catch illnesses quickly. The tedious process of going to a lab for urinalysis creates a demand for an “all-in-one” automated system capable of performing this urinalysis, and this is where the STRE&M device comes in.

The current prototype is capable of collecting a sample and pushing it to a viewing window. However, once it gets to the viewing window there is currently no automated way to analyze the sample without manually looking through a microscope, which greatly reduces throughput. Our challenge is to find a way to automate the data collection from a sample and provide an interface for a medical professional to view the results.

1.2 Solution

Our solution is to build an absorption spectrometer that is capable of measuring and plotting the absorbance of casts, bacteria, and cells that may be present in the sample. Since each protein that we are trying to detect absorbs light at a particular wavelength, we need to emit this wavelength of light. Our approach is a low-cost, effective spectrometer that can emit these wavelengths of light corresponding to the proteins we desire to detect and measure the absorption at the wavelengths.

1.3 Visual Aid

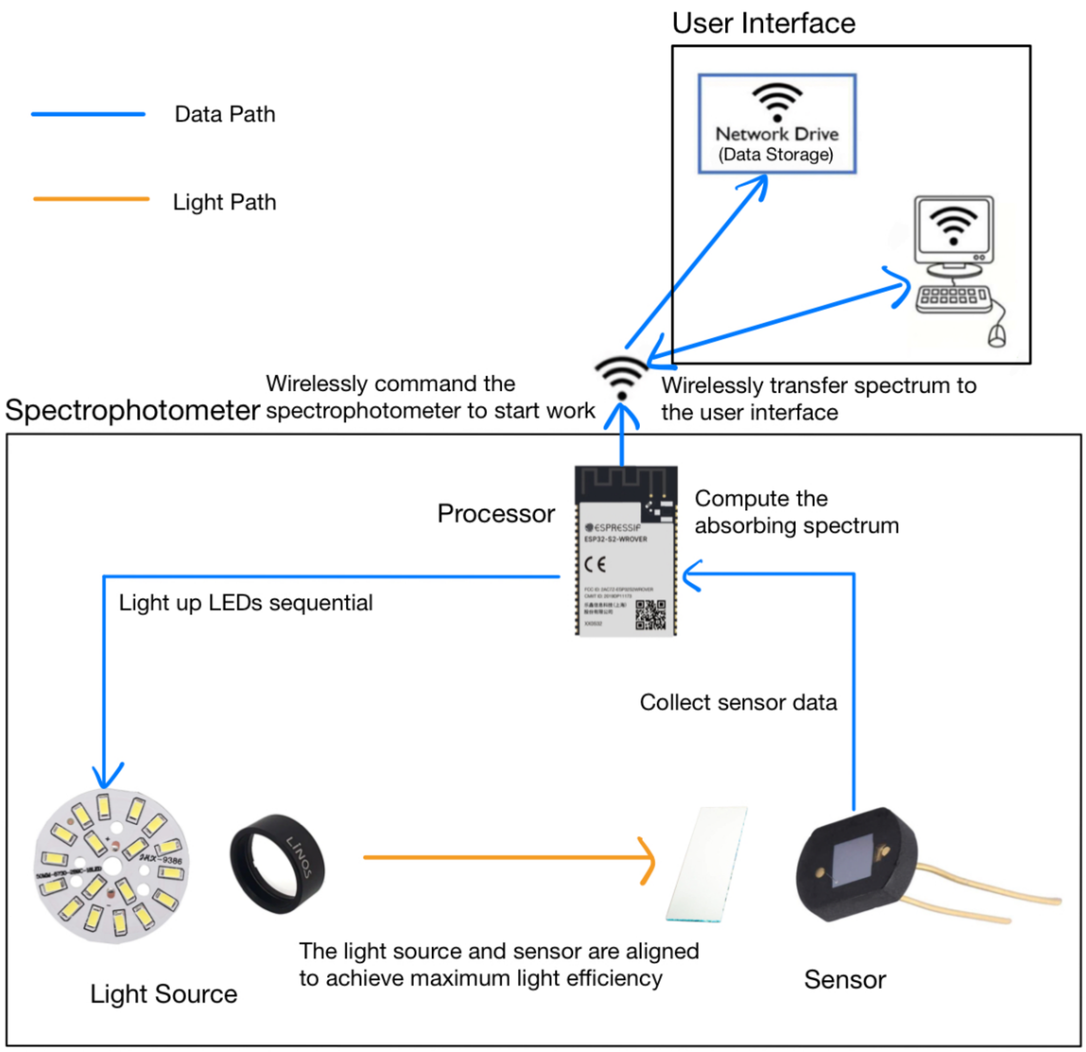

Figure 1: Visual Aid Representation of Our Project

1.4 High-Level Requirements List

To consider our project successful, our LED Spectrometer must fulfill the following requirements:

- The spectrum analysis and data transfer must be completed in less than 30 seconds
- Our system must be able to produce an absorbance spectrum for a sample with known absorbance in our desired range (380-480nm), and generates no response for a sample with known absorbance in range (600-800nm).
- The device must be capable of performing absorbance spectroscopy with a resolution rate of ~10 nm for the light source emitting lights ranging from 380 nm to 480 nm.

2 Design

2.1 Block Diagram

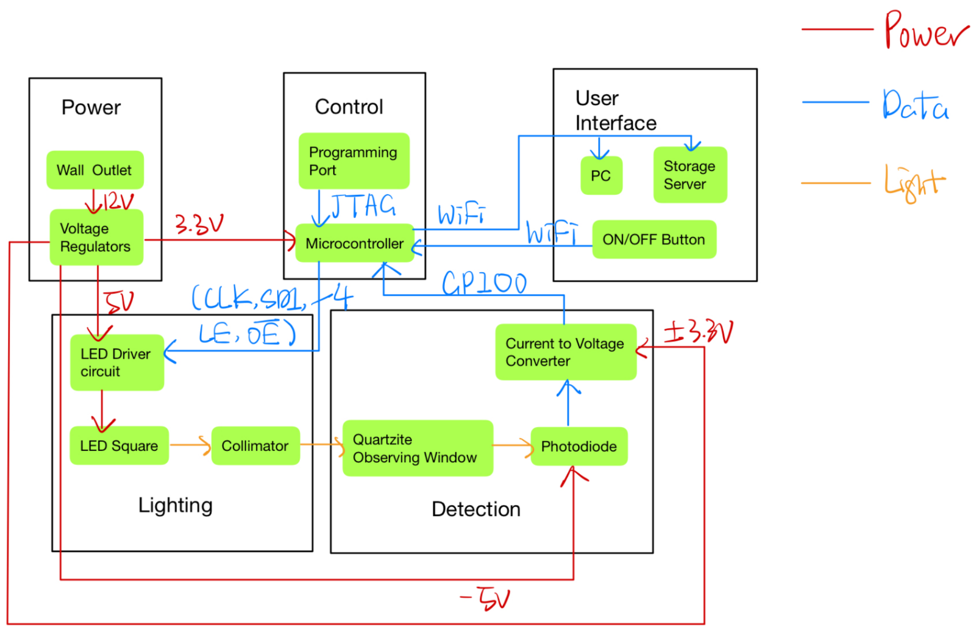

Figure 2: Block Diagram of Our Subsystems with Connection Specified

The lighting subsystem and the detection subsystem are crucial for our project. The lighting subsystem is composed of 8 different LEDs ranging from 380 nm to 480 nm with ~10 nm separation. When testing is started, the MCU will light the 8 LEDs up sequentially so that each LED could work as an impulse function centered at its peak wavelength. The detection subsystem contains the quartzite observing window and a photodiode. The photodiode will examine the passing spectrum of the sample at a certain wavelength per time.

Since the photodiode only examines the light intensity regardless of the wavelengths, we need to make sure that the MCU could light up the second LED only when the spectrum measurement for the first LED is done. Otherwise, light pollution will make our spectrophotometer inaccurate. Furthermore, the surface mount LEDs are not strong light sources. We have picked up our photodiode carefully to make sure it can detect the light producing our chosen LEDs. But as figure 1 mentioned, we need to carefully align our light subsystem (LED arrangement on the PCB) and detection subsystem to make sure that our project effectively uses the lights.

2.2 Subsystem Overview

2.2.1 Subsystem 1 (Lighting)

The lighting subsystem will serve to produce light at wavelengths that are of interest in the field of urinalysis. The light is needed so that we can detect the change in light intensity and determine how much absorbance there is at a given wavelength of light. To prove the design is functional, we will focus on emitting at wavelengths between 380-480 nm with intervals of ~10 nm. This is done to maintain a higher level of resolution compared to more dispersed values of wavelength. Our design will be scalable so that more LEDs can be added in the future without major design changes.

2.2.2 Subsystem 2 (Detection)

To detect the absorbance, we will use a photodiode to produce a current that corresponds to a given light intensity captured after passing through a sample. We will collect the light after passing through the sample. The design will focus the light on the sample, which then will absorb some light that the photodetector will be nearby to detect. The current produced will be converted into a voltage output and be inputted to our internal MCU ADC converter.

2.2.3 Subsystem 3 (Control Unit)

The control subsystem is programmable. The control subsystem is connected to the lighting subsystem, the detection subsystem, and the power subsystem. It will talk to the peripheral subsystems (the lighting system and detection subsystem) to get the measurement data and then calculate the final spectrum. After it gets the final spectrum, it will wirelessly send the result to the PC and a server using its built-in wifi capability. There’s also an ON/OFF button for us to start the system for testing. Since now, our system is detached from the urine collection system designed by another senior design team previously, the start-to-test signal should be sent by their microcontroller. For this design, we will use the ON/OFF button to launch the testing process.

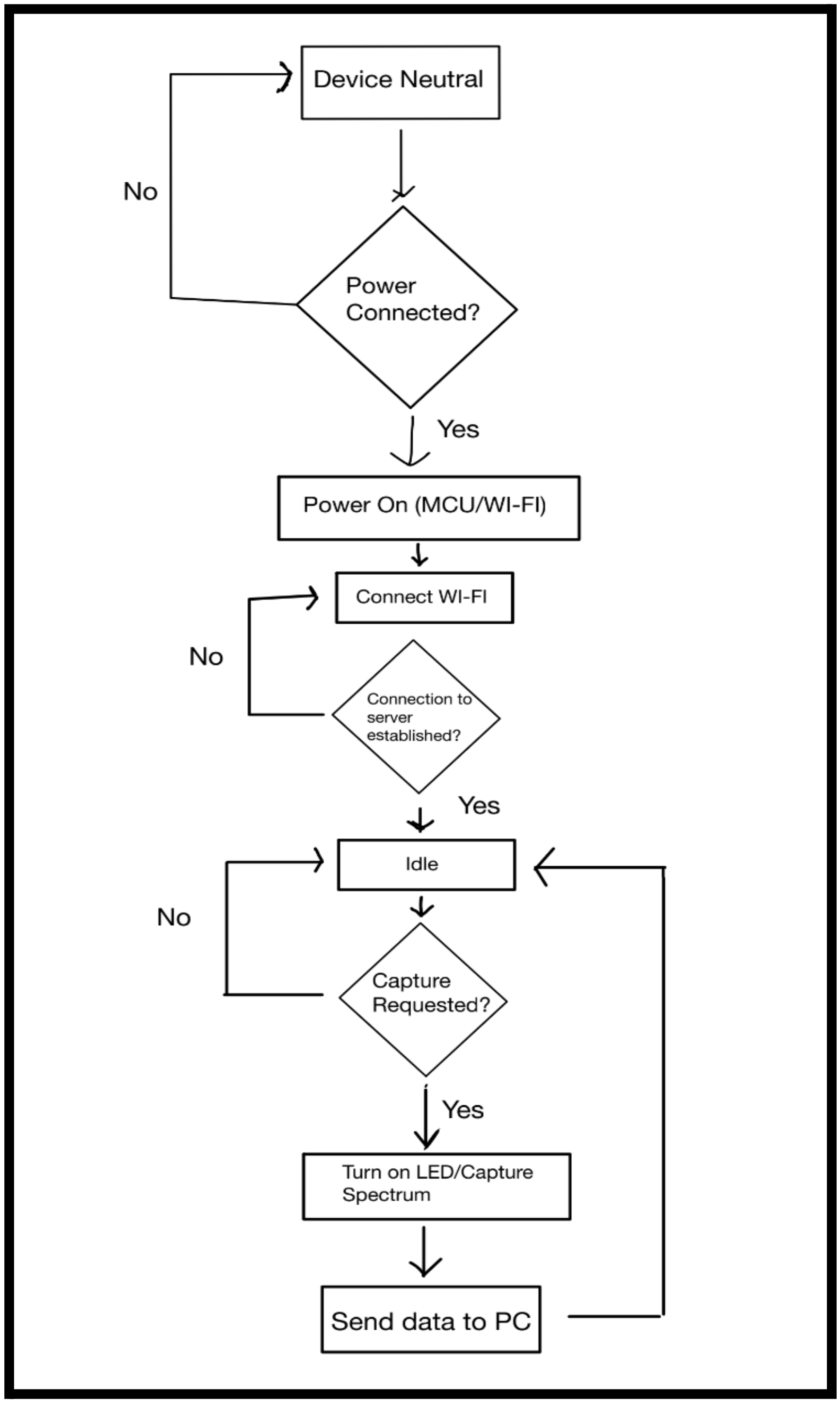

Figure 3: Software Flowchart

2.2.4 Subsystem 4 (Power system)

The power subsystem will provide power to all the subsystems. It will convert AC power from the wall outlet to DC power and then adjust the DC power to different voltage levels due to the demands that different components need different drive voltages. The power subsystem needs to connect to all subsystems. The power subsystem will begin with a 12V wall-connected power supply that will connect to our PCB via a standard power jack. The 12V must also be reduced to 3.3V for our microcontroller, for which we will use a linear voltage regulator to achieve this task.

2.3 Subsystem Requirements

2.3.1 Subsystem 1 (Lighting)

The lighting subsystem will include an array of LEDs with peak wavelengths at values corresponding to the proteins we are trying to detect. These LEDs will be laid out and can be turned on and off from our MCU. A LED driver will be used here to assist the microcontroller to control the LEDs since the microcontroller cannot provide sufficient power to the LEDs. The LED driver will provide a very steady current to drive the LEDs. To make the LED driver work, we need to provide a 5V voltage supply. Additionally, the LEDs will need to be focused by a lens so that the light can be directed across the sample as directly and focused as possible. Note that our first stage goal is to make the spectrophotometer function correctly as proof of concept. We will focus on the wavelength range from 380 nm - 480 nm with a wavelength spacing of ~10 nm first.

Requirement	Verification
The LED Driver will sequentially light LEDs starting with the lowest wavelength (1) and ending with the highest wavelength (8).	Remove LED. Connect DMM across LED pads. Record current with LED activated.
The circuit will supply 20mA of current for the LEDs to be emitted.	Code slow sequential lighting of the LEDs. Validate that LEDs light in order from LED 1-8.

2.3.2 Subsystem 2 (Detection)

The observing window is used to examine the sample. Note that the observing window is made of quartzite since quartzite won't block UV lights. The photodiode needs a -5 voltage supply to reverse bias it. Depending on the bias voltage, it will produce a current based on the light intensity in a nearly linear relationship. Note that due to quantum efficiency, the photodiode absorbs light with different wavelengths differently. We need to take that into account when we compute the spectrum produced by the photodiode. The current value will then be converted to an analog voltage value that our MCU can discern through a current-to-voltage converter. This current-to-voltage converter is composed of an op-amp, a high pass filter, and a buffer. Figure 4 below shows our design idea. The op-amp converts the current signal into voltage. The high pass filter filters out the DC biasing voltage. The buffer circuit takes advantage of the high input impedance of op-amp to make the input voltage to the microcontroller precise. The buffer will also serve as an amplifier. The biasing voltage for the photodiode is -5V. The op-amps are biased at -3.3V to 3.3V. These values will ultimately (after ADC) be interpreted by our MCU as absorbance at a given wavelength (McClain, 2002).

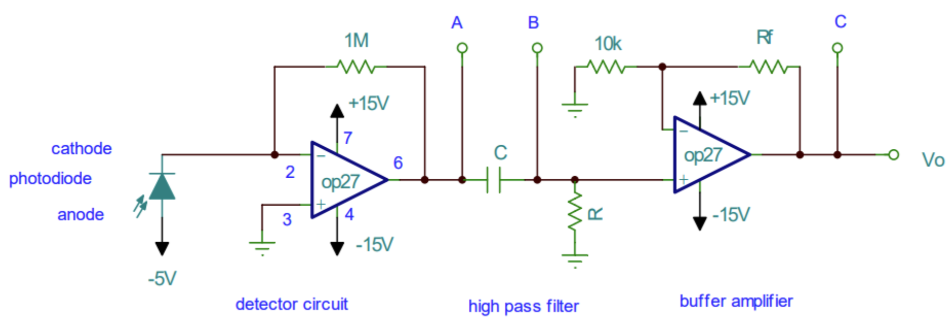

Figure 4: Detection circuit (McClain, 2002)

Note that we will change the values of the components and also the biasing voltages for our design, but the overall design will be very similar to the design above

Requirements	Verification
The photodiode buffer circuit will convert any producible current into a voltage value not to exceed the MCU pin rating of 3.3V.	Turn on each LED individually. For each LED, measure the voltage output of the Photodiode Buffer Circuit. If any value is above 3.3V, add a current limiting resistor.
Voltage connecting to MCU can be measured continuously with less than 5% variance for 10 seconds.	Set up a photodiode buffer circuit on a benchtop. Connect DMM to the output of the buffer circuit and set it to measure voltage. Fix a light source in front of the photodiode. Collect data points for 10 seconds. Calculate the variance in measured voltage values.
There is no response when we flow water into our calibrated system.	We flow water through the device repeatedly and record the response of the photodiode circuit to calibrate. We then flow a sample through the device with absorption within our range of detection and record response. Finally, we reflow water again and confirm there is less than a 10% response from our previous water baseline.

2.3.3 Subsystem 3 (Control Unit)

The microcontroller will indirectly get data (analog output) from the detector (photodiode) and compute the corresponding absorbing spectrum of the sample. Note that to get the absorption spectrum of the sample, we need to know the passing spectrum (How much light could pass through the observing window) of the blank observing window first. This blank passing spectrum will serve as the control spectrum. When we get the passing spectrum of our sample later on, we then take the difference between the passing spectrum of the blank observing window and the passing spectrum of the sample to get the absorption spectrum of the sample. Furthermore, due to the effect that the photodiode will have different quantum efficiency on different wavelengths and the effect that LEDs on the edge of the LED arrays may not be able to transmit all its output light to the sample, we need to somehow normalize the result.

The microcontroller will send the result to the server and PC through the WiFi transceiver module (built-in) once the result is available. The microcontroller is programmable through a JTAG port. ESP32-S2-WROVER will be used as our microcontroller for its built-in WIFI module.

Additionally, our spectrum is not continuous yet. It only contains several points on the spectrum. Since every LED will peak at some wavelength, they serve as impulse functions. They can only be used to examine absorbance for certain wavelengths. We will first get the discrete spectrum down and then work on the continuous spectrum based on some machine-learning models if we have extra time.

Requirements	Verification
The data must be transferred to the computer within 2 seconds of sending data.	Initiate time capture in code at a point right before data send. Then capture the second point when the data transfer is complete to the PC. Find the time difference and confirm the Δt is less than 2 seconds.
The data must be displayed in a graph that resembles the output of a standard spectrometer.	Analyze the graph for at least 2 different samples with known wavelength absorbance spectrum. Compare the wavelength value of max response for our design and known. Must be within +-15nm of the known spectrum peak.

2.3.4 Subsystem 4 (Power system)

We will use the wall outlet to power the whole system. The plugin can convert 120V AC power to 12V DC power. Then, several voltage regulators will turn the 12V DC voltage to 3.3V and 5V DC voltage. The microcontroller requires a power voltage of 3.3V, and we will need a steady voltage supply for our LEDs, so a very stable regulator will be necessary.

Requirements	Verification
The output voltage of the 3.3V voltage regulators should be (3.3±0.2)V	When we use the voltage regulator to drive the LEDs, we could use a voltmeter to measure the voltage across the voltage regulator
The output voltage of the 5V voltage regulators should be (5±0.2)V	When we use the voltage regulator to bias the op-amp, we could use a voltmeter to measure the voltage across the voltage regulator

2.4 Tolerance Analysis

For our tolerance analysis, we demoed our photodiode and amplifier circuit in LTSpice. We wanted to confirm that our output would not reach the 3.3V max threshold of our microcontroller.

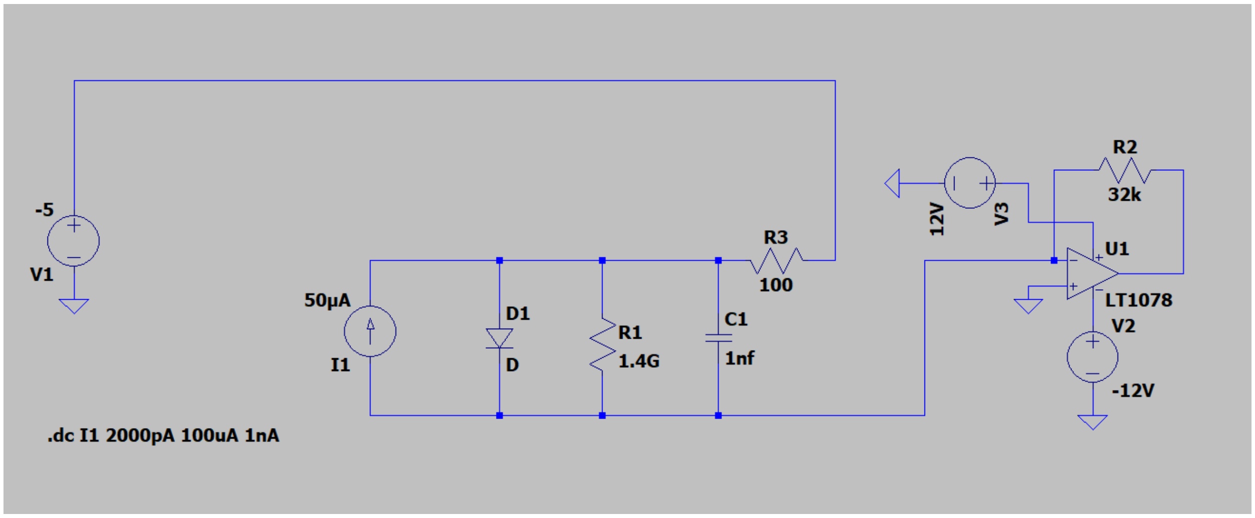

Figure 5: LTSpice Photodiode

Our LED will generate a photodiode current in the low microampere range. To calculate the gain resistor necessary for our circuit we took the Voltage max minus the Voltage min divided by the max current (Teja, 2021). (3.3V - 0.1V)/100uA = 32kΩ. We then swept the current over the range of possible current values the photodiode could generate to confirm the voltage range we would be outputting.

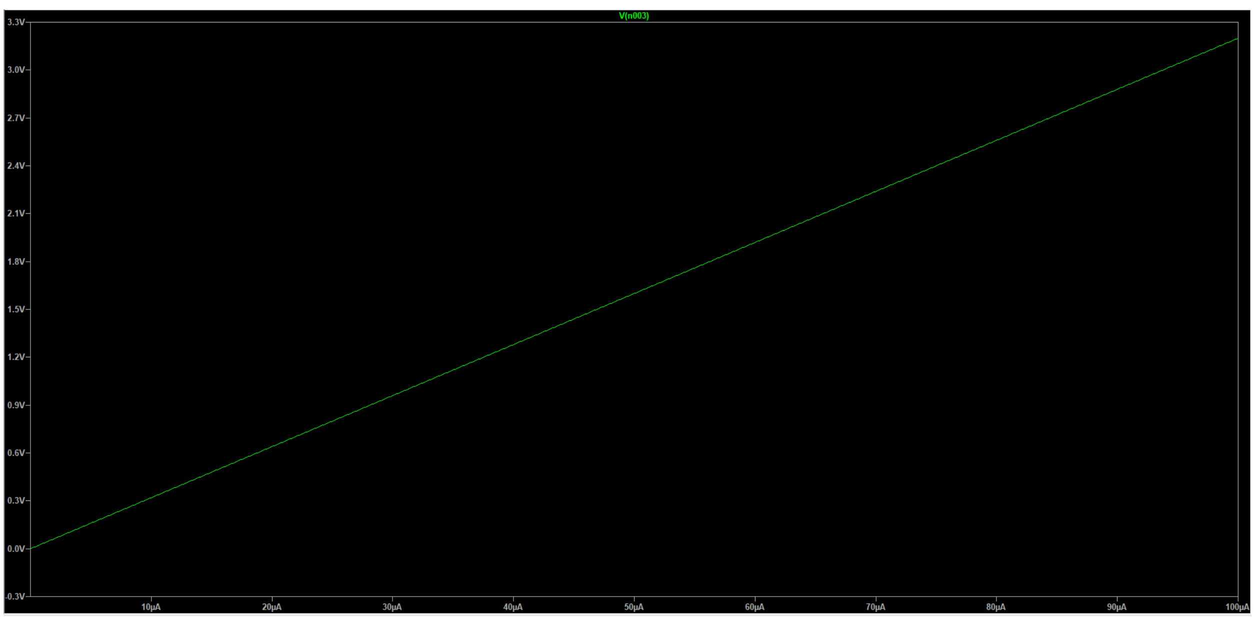

Figure 6: Photodiode Output Voltage

This has confirmed the functionality of our photodiode and amplifier circuit. It also has confirmed the values of components we will need to have a usable output voltage range for our microcontroller.

2.5 Cost

2.5.1 Labor Cost

The average salary of an Electrical Engineer graduate from Illinois is $80,000, which is approximately equivalent to $38.00/hr (Grainger Engineering Office of Marketing and Communications, 2023). We estimate that we will meet weekly, averaging 4 times a week spending on average 4 hours per meeting, for a total of 16 hours per week. Over 12 weeks, this is about 16*12 = 192 hours per person. When multiplied by 2.5 we get 480, and this multiplied by 3 (since there are three group members) is 1440. To get the total labor cost, we multiply this adjusted 1440 hours total by $38/hr to get an estimate of $54,720 for labor cost.

2.5.2 Total Cost

Our total cost including parts and estimated labor would be $54833.55 with the labor cost being based on the average salary of an Illinois EE graduate. After adding smaller components like resistors, capacitors, viewing window material, and other auxiliary components, we can expect this amount to grow slightly, but certainly not to exceed an additional $500. Even with some price variation, this total project cost would be very small compared to how expensive commercial spectrometers can cost. Spectrometers can range from anywhere from $500-$10000+, which makes our design considerably more cost-effective.

2.5.3 Component List

Part #	***Manufacture***	***Description***	***System***	***$/Each***	***QTY***	***Total***
ESP32-S3-WROOM-1-N16	*Espressif Systems*	Microcontroller 32-bit, 36 GPIOs	*Control*	*$3.83*	*1*	*$3.83*
L6R06H-120	Tri-Mag Inc	12V Power Supply	Power	$6.05	1	$6.05
PJ-036AH-SMT-TR	CUI Devices	Male Connector-12V Power	Power	$1.45	1	$1.45
MIC5219-3.3YM5-TR	Microchip Technology	12 to 3.3V Regulator	Power	$1.20	1	$1.20
VTB8441BH	Excelitas Technology	Photodiode 330-720nm	Detect	$3.41	1	$3.41
G063097000	Excelitas Technologies	Condensing Lense-21.4mm	Lighting	$79.00	1	$79.00
TLC5917IN	Texas Instruments	LED Driver, 8 Output	Lighting	$1.76	1	$1.76
ATS2012UV365	Kingbright	SMD LED, 365nm	Lighting	$3.50	1	$3.50
ATS2012UV385	Kingbright	385nm SMD LED	Lighting	$2.90	1	$2.90
ATS2012UV395	Kingbright	395nm LED	Lighting	$2.01	1	$2.01
ATS2012UV415	Kingbright	415nm LED	Lighting	$2.01	1	$2.01
CMD15-21UBC/TR8	VCC	430nm LED	Lighting	$4.58	1	$4.58
L234QBC-TR	American Opto Plus	455nm LED	Lighting	$0.75	1	$0.75
AA3528QBS/D	Kingbright	465nm LED	Lighting	$0.46	1	$0.46
AA3528VBS/D	Kingbright	470nm LED	Lighting	$0.64	1	$0.64
				Total		**$113.55**

2.6 Schedule

Week	Weekly Schedule
2/27	Design Schematics for Each Subsystem, Finalize PCB Design, Finalize Initial Physical Design (Talk with machine shop) Gage: Photodiode Circuit, MCU Schematic Adrian: Power System Schematic, Physical Design Model Ethan: LED Driving Schematic, PCB Design (together)
3/6	Submit PCB Order, Submit Revisions to Machine Shop, Write microcontroller code Gage: Continue spice simulations for the photodiode circuit Adrian: Begin writing MCU code, continue simulations for power/ LED circuits Ethan: Writing MCU code, simulations for power/LED
3/13	Spring Break (Possibly 1 meeting to work on current issues) No Assignments
3/20	Solder Components, Begin testing of design, make revisions to PCB based on feedback and test results Gage: Solder Photodiode System, Solder Microcontroller Adrian: Solder Power System, Solder Microcontroller Ethan: Solder LED Driver, Adjust PCB Design, Solder Microcontroller
3/27	Submit second PCB order (If needed), Setup LED control with MCU Gage: Test functionality/sensitivity of the photodiode Adrian: Assist in testing and writing code for LED Control Ethan: LED Control Algorithm

4/3	Focus on the function of the photodiode, work on data transfer to PC, Time Permitting: make sure the sample, lens, and photodetector align perfectly Gage: Establish wireless server connection Adrian: Align photodetector, power verification Ethan: Align LEDs, LED Requirements verification
4/10	Run calibration on design, Make sure results are displayed clearly Gage: Transfer data to PC, write the about process in paper Adrian: Calibration Tests, Line of best fit over data, detailed findings in paper Ethan: Calibration Tests, Error Analysis, record error analysis in paper
4/17	Mock Demo, Design gets fully integrated this week, Test system with samples with known expected values Gage: Mount photodiode into casing, testing continues Adrian: Mount power/pcb into casing, testing continues Ethan: Mount LED array, testing continues
4/24	Final Testing, Final Demo, Prepare for final presentation and paper due Gage: Slides for photodiode Adrian: Slides for power/some MCU Ethan: Slides for LEDs/MCU
5/1	Final Presentation, Submit Final Paper Gage: Work on presentation slides, Review Paper Adrian: Work on presentation slides, Review Paper Ethan: Work on presentation slides, Review Paper

Lab Notebook will be updated continuously

3 Ethics and Safety

Safety concerns will arise as we build our device to work with liquid samples. Some of the LEDs we are working with for the spectroscopy are in the UV range of wavelength. UV light can be extremely dangerous, causing damage to one's skin and/or eyes. We will need to avoid direct exposure to this light source as well as direct viewing to avoid any injuries. We have completed the DRS Laser Safety training so that we are adequately educated on the procedures of handling UV lights. Anytime that UV LEDs are lit, we will be wearing protective equipment for our eyes, as well as placing an acrylic shield between us and the light. We will uphold IEEE Code of Ethics #9 to assure we are not harming ourselves or the school and the labs they provide us. Since we are working with a team for our pitched project as well as the class TAs, the IEEE Code of Ethics #5 will be crucial in working on our project as we make sure to receive feedback from and credit the others working on this project (IEEE Board of Directors, 2020).

4 References

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