Multispectral Imaging Camera
ECE 445 Design Document

Project #6

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Table of Contents

1. Introduction

1.1 Problem

What humans can see is subjective, inconsistent, and, most importantly, limited. In several fields, we rely solely on human vision to determine problems and solutions; however, some areas require higher resolution, wider spectral ranges, and consistent data. In a medical context, the ability to capture a variety of spectra, including those invisible to the naked eye, at a consistently accurate level can improve the assessment abilities of a medical professional, especially in surgical tasks. According to SpectralMD, limited tools are currently available to determine tissue health[1]. Multispectral imaging (MSI) can help alleviate this issue as doctors will be able to use light emitted in UV/NIR spectrums to accelerate tissue diagnosis'. Additionally, combining color imaging with NIR bands can help to locate and distinguish between tumors and surrounding tissues.

Existing endoscope technology typically uses RGB endoscopes, which are confined to the visible spectrum, thus limiting the number of tissue layers it can show as visible light cannot "penetrate through the surface of the skin" [2]. A multispectral camera will allow "the physician to extract intrinsic properties and structures of specific tissues which are not visible to a human eye"[2]. MSI will allow for improved real-time diagnosis rather than invasive, time-consuming procedures. As a direct result, patient care can be expedited with a faster diagnosis. MSI enhances inspection capabilities for various applications and fields but can potentially be a very beneficial tool in the medical field.

1.2 Solution

Our solution will be a handheld device with an integrated camera sensor capable of multispectral imaging across the UV, visible, and NIR spectra with real-time visualization. NIR wavelengths go much further into tissue, so the ability to capture that data is crucial. A user will be able to hold the sensor above any object for which light can pass through and see any of the three different spectra displayed on a monitor. The device will be wired for power and contain a MIPI CSI-2 compatible image sensor and microcontroller that is USB compatible for data transfer. The image will be processed to show three different spectra (UV, NIR, and visible) on a real-time video display. Our solution is novel compared to other medical handheld imaging devices, such as endoscopy cameras, due to the ability to capture multiple spectra in such a small device. It will enable physicians to use the MSI technology in closer proximity than before, making diagnosis a more straightforward and less painless process. More information when imaging will empower medical staff to make more informed clinical decisions.

1.3 Visual Aid

The image below shows a very general description of how multispectral imaging works. A multispectral camera takes in images from a sample illuminated by a light source. These images are then processed to show the different spectrums captured.

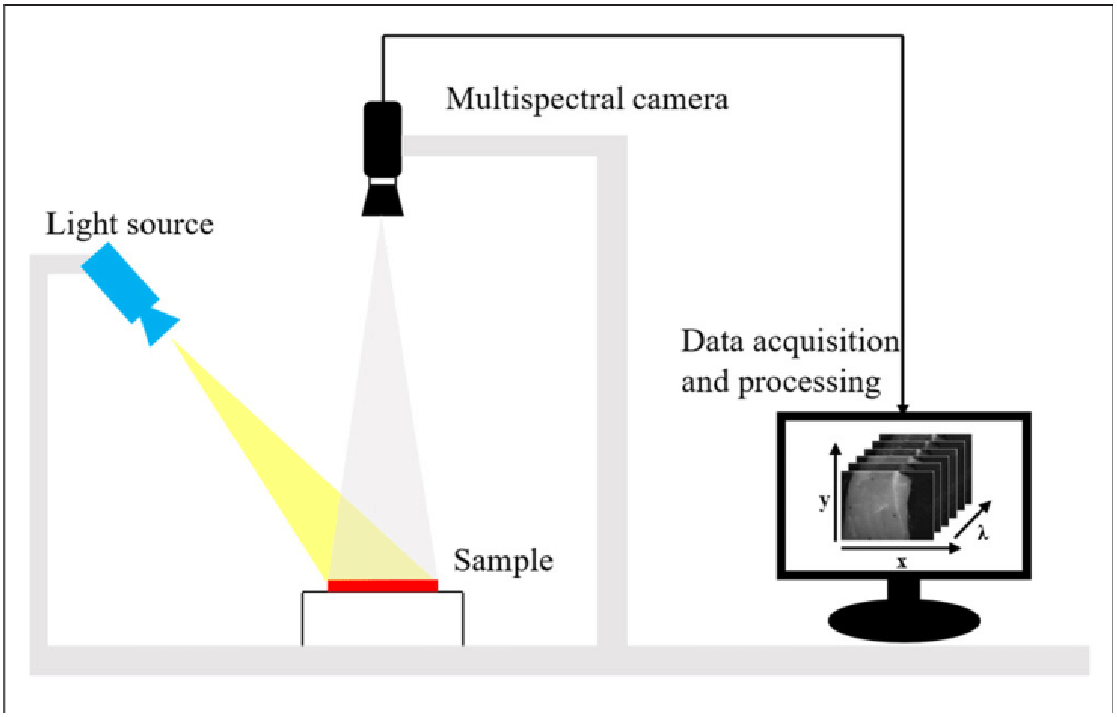

Figure 1: Multispectral imaging general design

The visual aid below is a slightly more specific image of what our project will look like. One can see that the pen-shaped device has an image sensor on one end, a microcontroller within the enclosure, and a USB connection on the other end, which will go straight into a computer where the three different spectra: UV, Visible, and NIR will be displayed. In our use case, the sample will likely be cells that are being imaged to identify a tumorous mass.

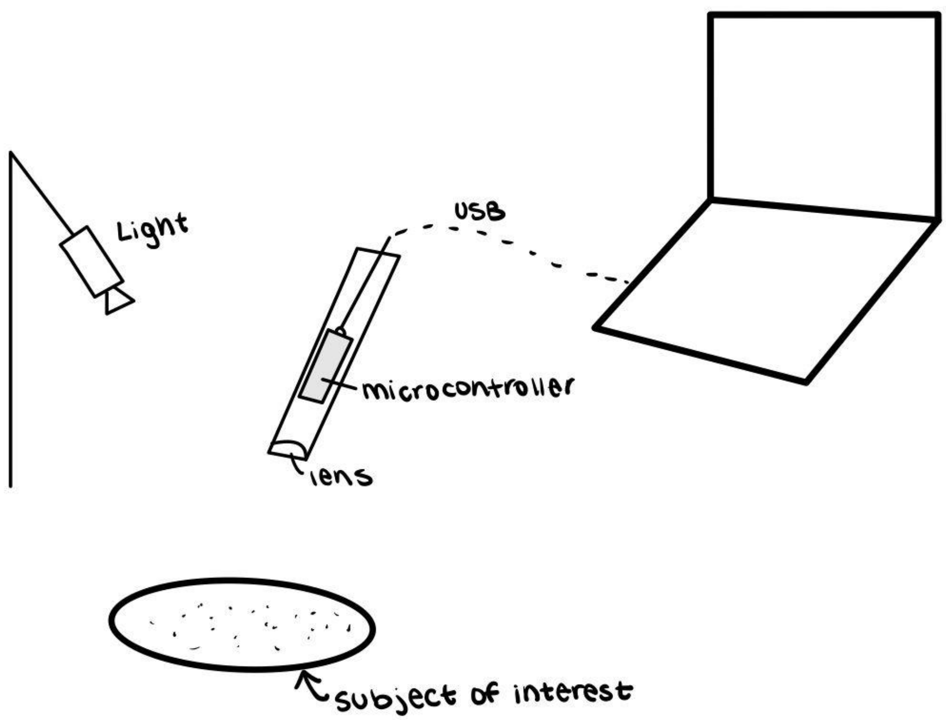

Figure 2: Multispectral Imaging Project Design

1.4 High-Level Requirements

To consider our project successful, our device must:

1. Display real-time video at a rate above 20 frames per second so that the image on the screen is accurate to the location that the device is hovering over.

2. Have the ability to capture signals across the UV, visible, and NIR spectrums to achieve multi-spectral imaging.

3. Have the maximum dimensions of a 2” by 2” by ~7” handheld enclosure in order to be compact enough to be able to be used in a variety of different medical applications.

2. Design

2.1 Block Diagram

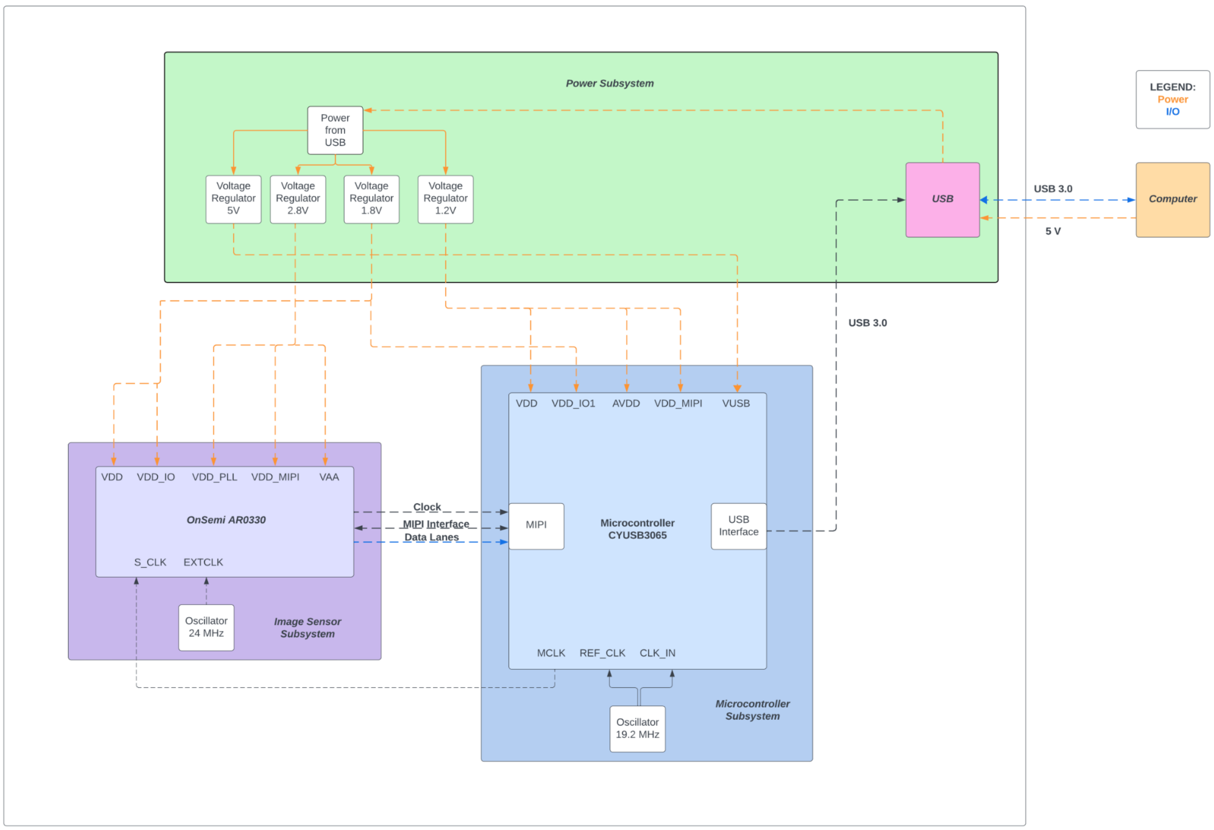

Figure 3: Block Diagram

Our project has three critical subsystems: Power, Image Sensor, and Microcontroller. The power subsystem supplies power at the appropriate levels to the rest of the board through the use of voltage regulators. The image sensor subsystem captures the incoming light to the pixels and sends it to the microcontroller subsystem, where the data will be processed and sent to the computer via USB that will display the video.

2.2 Physical Design

Figure 4: Mock Enclosure Design

Our design will use a custom 3D printed enclosure with an ergonomic/handheld design. It will be printed with an ABS filament, a commonly available filament used for 3D Printing that is durable and highly functional for everyday handling. The design will include interior threaded PCB mounting bosses for easy mounting. The USB port, along with part of the wire, will be contained within the enclosure and will thread out to a computer to interface with the PCB. Since the motivation is to use this device as a medical grade electronic, usage of this device in a clinical setting will require a sterile equipment cover that meets FDA Title 21 (21CFR820) & ISO 13485 standards (See Ethics and Safety for more details).

2.3 Image Sensor Subsystem

2.3.1 Overview

The image sensor subsystem is responsible for capturing image data across the UV, VIS, and NIR spectra and then sending this data to the microcontroller over MIPI (Mobile Industry Power Interface) CSI2 (Camera Serial Interface 2) to be processed. The image sensor chosen is the OnSemi AR0330CM.

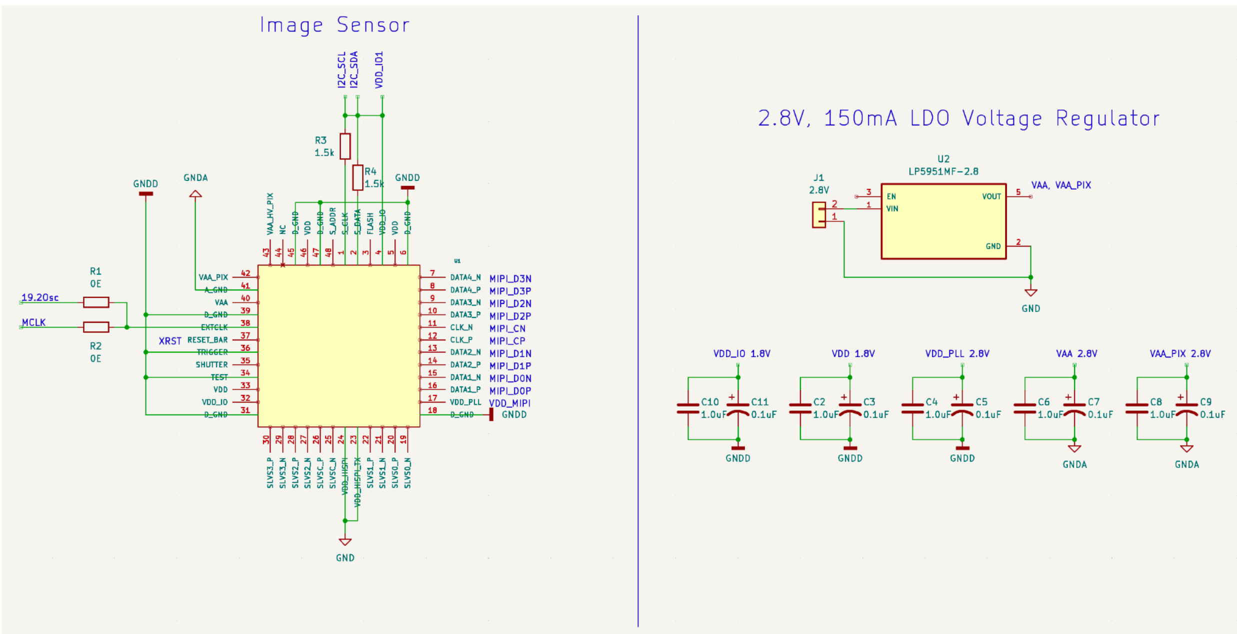

Figure 5: Current Image Sensor Subsystem Schematic

2.3.2 Interfaces

- Power Subsystem
  - The subsystem receives 1.8V +/- 0.1 V and 2.8V +/- 0.1V from the power subsystem
- Microcontroller Subsystem
  - Sends data and clock information to the microcontroller
  - Sends and receives the MIPI interface for compatibility

2.3.3 Requirements and Verification

Requirement	***Verification***
Must have a minimum quantum efficiency of	1. Program the board so that real-time video can be read. Display it out to a

10% at 380 nm and 10% at 780 nm.	screen. 2. Attach a lens that filters out wavelengths outside of the ranges of interest (ex. 200nm - 380nm, 380nm - 780nm, 780 - 1100nm) onto the camera in front of the image sensor 3. Obtain a sample of fluorophores that will be excited by light/signals in that particular wavelength. 4. Apply a an light/excitation source to the fluorophores 5. Observe light and signals being read on the display. The fluorophores will light up and show up on the display a. By doing some image processing, one can obtain the pixel intensities and calculate the percentage of pixels being excited. This will correspond to the QE of the camera and our device. 6. Results will be presented in a table.
Must support and sustain real-time video at a rate above 20 frames per second for at least 5 seconds.	1. Program the board to read in real time video 2. There are two options to calculate framerate. a. Using a performance analysis tool such as FRAPS on Windows or Quartz Debug on MacOS b. While grabbing frames, instantiate a variable in your program to increment each time a frame is grabbed. Program a timer that will restart every time the number of frames grabbed reaches 20. At this point, divide the number of frames (20 in this

	case) by the time elapsed to calculate the frame rate. 3. Using either method, display the frame rate as a numerical value to see if it is within a range. 4. Start a timer for 5 seconds and see if the sustained frame rate is for 5s. 5. Results will be presented in a table.
Must interface with the controller over MIPI CSI2.	1. Validate the sensor's MIPI CSI2 compliance by checking its conformance to the MIPI CSI2 standard specifications using the MIPI Alliance Transmitter Conformance Test Suite. 2. Perform hardware-software co-simulation using an emulation platform such as Palladium from Analog Devices. 3. Design a test to ensure the communication between sensor and controller over MIPI CSI2. 4. Results will be presented in a pass/fail format.
Must operate within the temperature range of -30°C to +70°C.	1. Place the sensor in a temperature-controlled chamber. 2. Test the sensor's performance at -30°C, +70°C, and a few points in between. 3. Confirm that the sensor operates as expected within this temperature range. 4. Results will be presented in a table.

Table 1: Image Sensor Subsystem RV Table

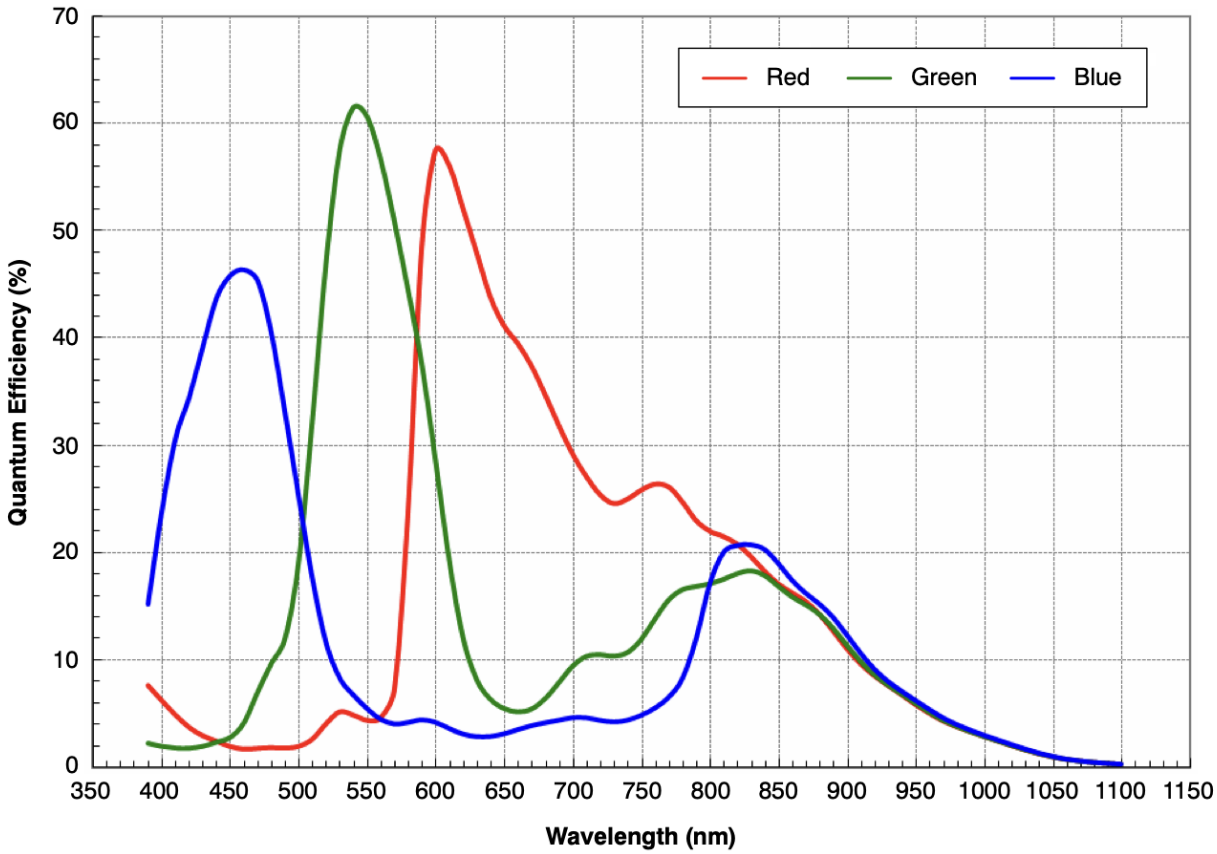

Figure 6: Quantum Efficiency table of AR0330CM Image Sensor

2.3.4 Design Decisions

Due to the nature of the pitched project, MIPI CSI 2 compatibility was an uncommon requirement needed for this project. Since it is a relatively new protocol, few image sensors and microcontrollers had the proper compatibility within our desired size and QE range.

2.4 Microcontroller Subsystem

2.4.1 Overview

The microcontroller subsystem processes the image data from the imaging subsystem and prepares the video data to be sent to the monitor over the USB (Universal Serial Bus) 3.0 interface. The microcontroller used in this project will be the Infineon CYUSB306X.

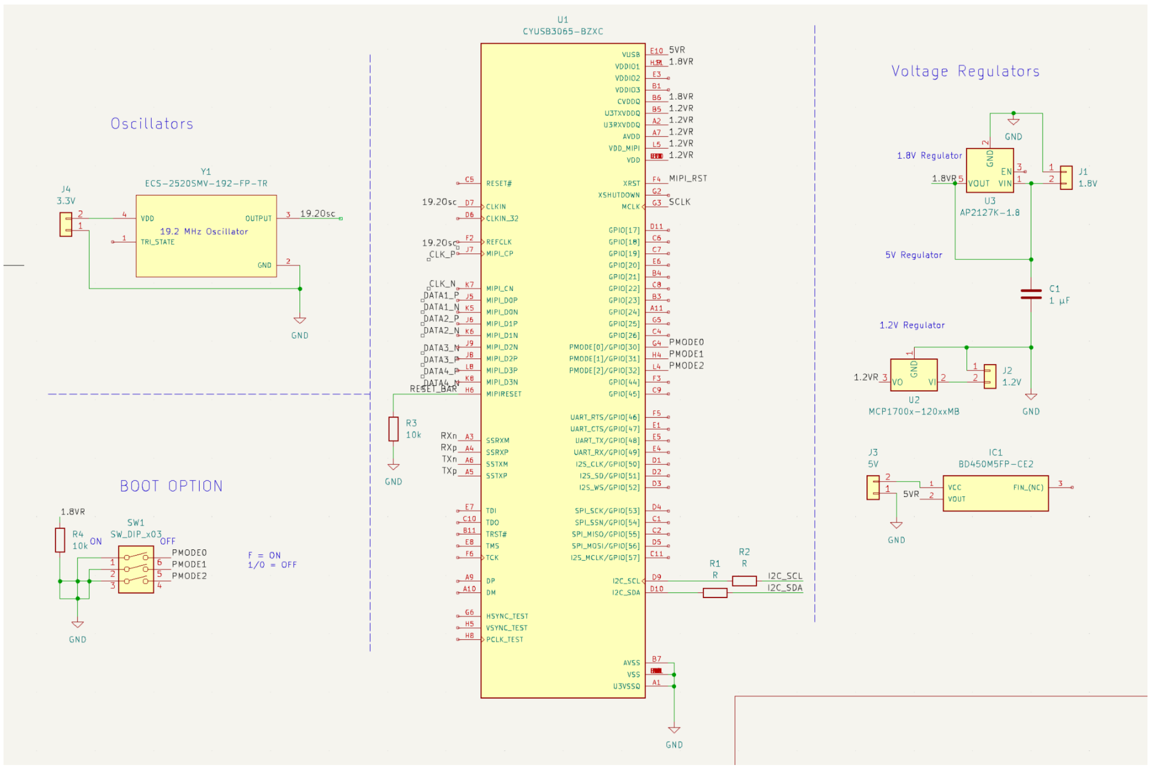

Figure 7: Current MCU Subsystem Schematic

2.4.2 Interfaces

- Image Sensor Subsystem
  - Receives image data and clock information from the image sensor subsystem
- USB Subsystem
  - Sends processed data to USB subsystem via USB 3.0 protocol
- Power Subsystem:
  - The subsystem receives 1.8V +/- 0.1V, 5 V +/- 1V , and 1.2V +/- 0.1V from the power subsystem

2.4.3 Requirements & Verification

Requirement	***Verification***

Transmit Data to the computer under USB 3.0 Specification	Signal Integrity/HSEYE Test 1. Either using a breakout board or the pins on the pcb, find the Tx +/- or Rx +/- pins and use a differential probe to connect them. 2. Configure an EYE diagram using the oscilloscope, make sure that the scope is at least 6GHz and has DSP capability 3. Based on the eye diagram, make sure the height of eye is no more than 1200mV and no less than 100 mV [3] Low Frequency Periodic Signaling TX test 1. Connect the PCB to a test fixture for USB 3.0 testing 2. Power on the device under test and let it pass through the Rx. Detect state to the Polling.LFPS substate. 3. Trigger on the initial burst sent by the PCB and capture the first five bursts 4. Measure the following LFPS parameters and compare against the USB 3.1 specification requirements : tburst, trepeat, tperiod, tRiseFall2080, Duty cycle, VCM-AC-LFPS, and VTX-DIFF-PP-LFPS. [4]
Communicate with Image Sensor under CSI-2 specification 1. MIPI data to clock Timing a. Dual Data Rate of the clock 2 ns $< T_{CLK} <$ 25ns 2. Low power AC Characteristics a. Peak Interference amplitude $V_{INT} <$ 200mV at a max of 148 uA	1. The CSI-2 specification has multiple receiver, transmitter, and clock lanes to communicate with. 2. Prior to testing, to ensure that the firmware programmed to the microcontroller to interface with the Image sensor is correct, one can use the code provided by Infineon's CX3 AppNote. 3. Using an oscilloscope use a differential probe to read from the CS-2 Receiver pins as well as the Clock.

	4. Set a trigger condition to read when these pins are active 5. Clock should be within resemble the range specified, while accounting from some noise since the oscilloscope will not be a perfect measurement 6. Setting the MCU to lower power mode, use an oscilloscope to probe an output data pin on the microcontroller. Make sure that you can set a trigger condition to read one of the pins before applying an interfering voltage. 7. Apply a small voltage V_{INT} as interference to an input data pin using a signal generator. To verify that you did apply an interfering voltage, use the oscilloscope to probe an input data pin to see the interference voltage. Save a snapshot of this 8. Observe a snapshot of the probed output data pins on the oscilloscope. There should be no irregularities in the output (See figure 7 in [5] for further clarification)

Table 2: Microcontroller Subsystem RV Table

2.4.4 Design Decisions

The microcontroller must be MIPI CSI-2 compatible to interface with the image sensor and USB 3.0 compatible to interface with the USB subsystem at the desired speed. Within the microcontroller subsystem are the REF_CLK and CLK_IN pins, which operate under a different range of frequencies; however, we chose to provide both pins with the output of a 19.2MHz oscillator to reduce design complexity.

2.5 Power Subsystem

2.5.1 Overview

The power subsystem is responsible for supplying the various voltages required across all subsystems. Power is provided over USB 3.0 in the USB-C connection and distributed to the rest of the system through individual voltage regulators per power pin. The USB-C connection will provide 5V; however, this is higher than what is necessary for the image sensor and certain microcontroller pins. Regulators will be used to ensure the correct voltage requirements for each component.

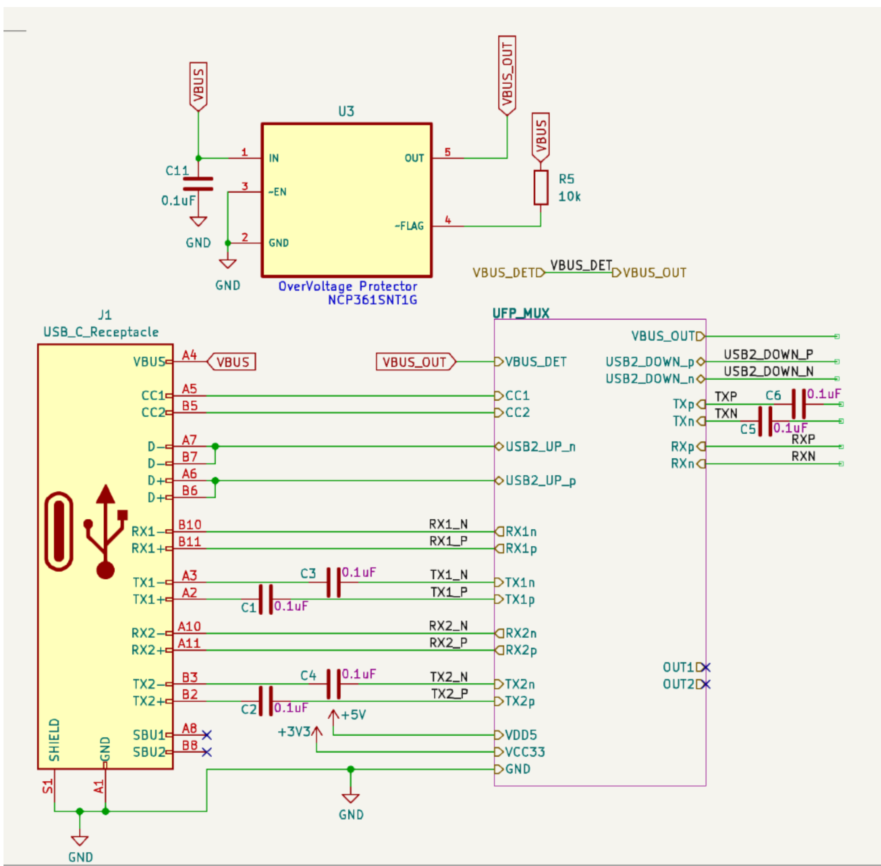

Figure 8: Current Power Subsystem Schematic

2.5.2 Interfaces

- Image Sensor
    - Voltage Requirements:
        - V_{DD}, V_{DD_IO} = 1.8 +/- 0.1 V
        - V_{AA} , $V_{AA\text{-}PIX}$, $V_{DD\text{-}PLL}$,, $V_{DD\text{-}MIPI}$, = 2.8 +/- 0.1 V
- Microcontroller Subsystem
    - Voltage Requirements

- V_{USB} = 5 +/- 1V
- Voltage sent to V_{USB} must pass through an overvoltage protection (OVP) device to ensure no more than 6V is delivered to the pin
- V_{DD_MIPI}, V_{DD}, U3TX$_{VDD,}$ U3RX$_{VDD}$, A_{DD} = 1.2 +/- 0.05 V
- 1.7 V < V_{DDIO} and C_{VDDQ} < 3.6 V

- Provides mux with 3.3 V +/- and 5V +/- for USB-C functionality

2.5.3 Requirements & Verification

Requirement	***Verification***
Image Sensors Power Delivery: The power subsystem must be able to supply at (2.8 +/- 0.1)V for Analog, PLL, Pixel, and MIPI supply voltages. It must also provide (1.8 +/- 0.1) V for core voltage and I/O digital voltage. 1. V_{AA} , V_{AA-PIX}, V_{DD-PLL} ,, $V_{DD-MIPI}$, = 2.8 +/- 0.1V 2. V_{DD}, V_{DD_IO} = 1.8 +/- 0.1V The power subsystem must be able to supply the following currents for the aforementioned pins: - Digital Operating Current: 114 - 136 mA - I/O Digital Operating Current: 0 mA - Analog Operating Current: 41 - 53 mA - Pixel Supply Current: 9.9 - 12 mA - PLL Supply Current: 15 - 27 mA - MIPI Digital Operating Current: 35 - 49 mA	1. Measure the output voltage of the regulator of interest (1.8V, 2.8V) using an oscilloscope or multimeter across the linear regulators, check to see if the potential difference is within tolerance.
Microcontroller Power Delivery: The power subsystem must be able to supply at (5 +/- 1) V for USB operation, (1.2 +/- 0.05) V for USB 3.0 supply, digital power, and MIPI operations, and 1.8 to 3.3 V for I/O and Clock operations. 1. USB Over Voltage Protector a. $4\,V < V_{USB} < 6\,V$ with at most 60 mA 2. 1.15V < V_{DD_MIPI}, V_{DD}, U3TX$_{VDD,}$ U3RX$_{VDD}$, A_{DD} < 1.25 V with at most 190 mA	1. Using a signal generator or voltage source, apply 15V to the IN pin on the OVP. Using an Oscilloscope, read the potential difference across pin 2 and pin 5, which corresponds to GND and OUT, respectively. There should be no difference since 10V exceeds overvoltage protection. 2. The pin V_{USB} must be 5 +/- 1V to function, connect an oscilloscope across the linear regulator feeding into the pin to measure the correct potential difference.

3. 1.7 V < V_{DDIO} and C_{VDDQ} < 3.6 V with at least 4.58 uA	3. Measure the output voltage of the regulator of interest (1.8V, 2.8V) using an oscilloscope and multimeter across the linear regulators, check to see if the potential difference is within tolerance
USB-C 2:1 Mux: 1. Mux requires @ 0.7 mA a. V_{CC33} = 3.3 +/- 0.3V b. V_{DD5} = 5V +/- 0.5 V	1. Measure the output voltage of the 3.3V and 5V using an oscilloscope and multimeter across the linear regulators of interest, check to see if the potential difference is within tolerance

Table 3: Power Subsystem RV Table

2.5.4 Design Decisions

A USB-C connection was chosen due to meet the system requirements for flexibility of data transfer as well as power delivery. USB 3.0 was necessary for the data transfer speeds and it met the power requirements for the project.

Albeit a USB B and USB A could have been used instead, the USB-C connection is more future proof for subsequent iterations of this project. Support for various protocols such as USB 3.1 Gen 2, Thunderbolt 3 and 4, etc., are made possible through the USB-C connections.

2.6 Tolerance Analysis

One of the constraints for our project from Professor Gruev is for the device to detect no more than 3 cm in any direction from a distance of 2 cm away; as a result, the “field of view angle” for the image sensor has to be 74 degrees. Anything less than or greater than this field of view angle would provide a larger/smaller field of view, which, in turn, would go against the goals of this project. Below is the mathematical analysis that supports the angle chosen.

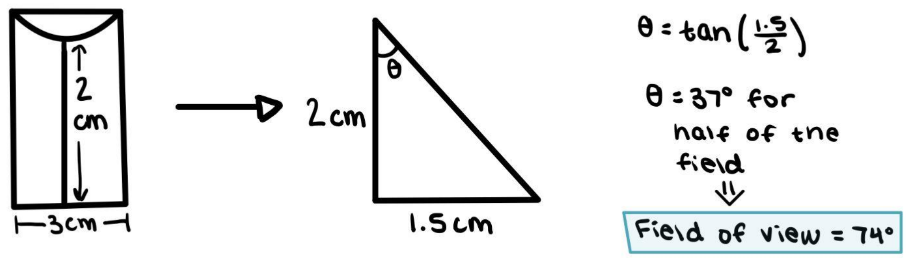

Figure 9: Mathematical Support for Field of View Angle

Additionally, the image sensor must be able to process 2.99 megapixels * 12 bits per pixel * 20 frames per second = 85.43 MBytes per second at the very least.

USB 3.0 can support a bandwidth of 5.0 Gb/s * 1 byte per 8 bits * 1000 Mb per Gb = 600MBytes per second, which is more than enough for the image sensor, and if we want to obtain a higher framerate, which we can, it is possible through this protocol.

Furthermore, the 4 lane MIPI CSI-2 protocol in the image sensor can support ~384 Mb/s, each lane contributing up to ~96Mb/s. In the microcontroller, the CSI-2 implemented protocol can support 1200 Mb/s, which is more than enough bandwidth required to meet our requirements for frame rate and resolution.

3. Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

The average salary for an electrical engineering graduate at Illinois is $87,769 and the average salary for a computer engineering graduate at Illinois is $109,176 [6]. Since we have a mix of both electrical and computer engineering majors, we will be using the average of the two, which is $98,472.5. For 50 work weeks at 40 hours per week, this comes out to $49.24/hour.

Once the design and assembly of the project begins, the project is estimated to take 8 hours of work per person per week, keeping in mind that a lot of work will be done in pairs or as a group. Designing began in week 5 of this class, and accounting for breaks and the due date of the project, we have roughly 9 weeks to complete the project resulting in 8 * 9= 72 total hours per person. We will not be utilizing the machine shop for our project. We will also multiply our costs by 2.5 to account for any overhead for the development of this project.

$49.24/hour * 2.5 * 72 = $8,863.2 per person * 3 = $26,589.6 in labor costs for the project.

3.1.2 Parts

Part Expenses					
Part	**Manufacturer**	**Model**	**Quantity**	**Per Unit Cost**	**Total Cost**
Microcontroller	Cypress	CYUSB3065	1	$25.95	$25.95
Image Sensor	OnSemi	AR0330	1	$19.02	$19.02
Voltage Regulator	Texas Instruments	LP5951MFX-1.8/NOPB	1	$0.68	$0.68
Voltage Regulator	Texas Instruments	LP5951MFX-3.3/NOPB	1	$0.74	$0.74
Voltage Regulator	Texas Instruments	LP5907MFX-1.2	1	$0.63	$0.63
Voltage Regulator	Rohm Semiconductor	5 V	1	$1.01	$1.01
Connector	Molex	USB-C	1	$1.46	$1.46
Over Voltage Protector	ONSEMI	NCP361	1	$0.75	$0.75
Mux for USB-C	Texas Instruments	HD3SS3220	1	$3.39	$3.39

Oscillators	ECS	ECS-2520SMV-192-FP-TR	2	$1.14	$2.28
32 kHz WD Clock	Micro Crystal Switzerland	OV-7604-C7-32.768KHZ	1	$2.11	$2.11
ABS FIlament (1kg)	PolyMaker	ABS FIlament	0.2	$19.00	$3.80
Capacitors	ECEB Shop	22uF	2	$0.17	$0.34
	ECEB Shop	1uF	10	$0.54	$5.40
			Total	$58.02	

Table 4: Parts Expenses

3.1.3 Sum of Costs

The total cost for the project is the Labor Cost for all three members + the parts total = $26,589.60 + $56.60 = $26,646.20.

3.2 Schedule

Month	Week	Tasks/Goals	Person Assigned
September			
	Week of 9/18		
		Start Design Document	All
		Order and Finalize Components: Get Clarification on how PCB assembly works and payment process	All
		Expenses Chart	Amartya Bhattacharya
		Visual Aids	Isha Akella
		Physical Diagrams	Jason Jung
		Start PCB Design Once Finalized Components. PCB Design : KiCAD	Jason Jung
	Week of 9/25		
		Get TA to look over design document	All
		Order/Finalize components: FINAL Notice	All
		Find Code that Works with Dev Board	All
		PCB Design : MCU	Isha Akella
		PCB Design : Image Sensor	Amartya Bhattacharya
		PCB Design : USB Connection	Jason Jung
		Design Document is Due	
		Get Professor to Review PCB Designs	All
		Cross verify each others PCB designs	All
October		Prepare for Design Review (Power Point)	All
	Week of 10/2	**Design Reviews**	All
		Cross verify each others PCB designs	All
		Dev Board Programming (If Arrived)	Amartya Bhattacharya
		Start looking into 3D Enclosures to print out	Isha Akella
	Week of 10/9	**Order PCB way (First round of PCB Design**	All

		Finished)	
		PCB Design Feedback and Assemble PCB Board (ASAP)	All
		3D Printing First Round	Jason Jung
		Teamwork Evaluation I	All
	Week of 10/13 to November		
		Individual Progress Reports Due	All
		Assemble PCB Board (Final Round of Design)	All
		Test PCB Design and functionality,	All
		Integrate PCB into Enclosure, 3D print Enclosure (2nd Round)	All
November		Prepare for Mock Demo and Presentation	All
	Week of 11/13	**Mock Demo**	
		Get Feedback from Demo and Implement Changes	All
	Week of 11/27	**Final Demo**	
December			
	Week of 12/4	**Final Presentation**	All
	Week of 12/7 (Reading Day)	**Lab Notebook**	All

Table 5: Project Schedule

4. Discussion of Ethics and Safety

4.1 Development

Faulty development can lead to complications in the operating room. (e.g., misdiagnosis or incorrect incisions) which will be a detriment to patient health and safety. To avoid harm, before a potential clinical usage, a well-documented and thorough review of the fidelity and technical quality of the project by various experts within the field will be performed. Areas where the team's developers are not competent will seek consultancy from appropriate experts.

4.2 Misuse

We envision accidental misuse as the result of not knowing the product's limitations when used in a clinical setting. This is an imperative factor to consider when we are concerned about patient safety. Aspects such as the device's longevity and where it can be used in a patient setting will need to be standardized to avoid any potential complications. Additionally, the attributes necessary to determine diagnosis must be tested with the device so patients are not misdiagnosed.

4.3 Safety and Regulatory Standards Industry Standards

Within the medical device industry, regulations will be determined by the intended use case of the technology. For instance, if the desire is to use it as a preliminary tool for a patient diagnosis of skin cancer, it could potentially qualify as a Class II device and follow the FDA's guidelines for further development in a clinical setting. However, if there were a demand to use such a product as a small surgical tool, the product would undergo a stringent regulatory review known as Premarket Approval as it likely qualifies as a class III device. Furthermore, since it is a medical device, we need to ensure a degree of sterility during application. According to FDA guidelines, usage of medical devices should be done in a manner that will "prevent contamination of equipment or product by substances that could reasonably be expected to have an adverse effect on product quality" [7]. Therefore, in clinical applications, it is imperative that the device is used while wrapped in a sterile plastic bag, which is a common practice for medical electronics.

5. Citations

[1] "Multispectral Imaging: Artificial intellingence in medical imaging," SpectralAI, https://www.spectralmd.com/wound-healing-technologies/multispectral-imaging/#:~:text=Multispectral%20Imaging%20in%20Diagnostic%20Medicine,visible%20to%20the%20human%20eye. (accessed Sep. 28, 2023).

[2] "Multispectral Imaging in Healthcare – a convolution of machine vision and Spectroscopy," Jai, https://news.jai.com/blog/multispectral-imaging-in-healthcare-a-convolution-of-machine-vision-and-spectroscopy (accessed Sep. 28, 2023).

[3] Tektronix, https://download.tek.com/document/55W_23452_3_MR_Letter.pdf (accessed Sep. 29, 2023).

[4] Hewlett-Packard Company, Intel Corporation, Microsoft Corporation, Renesas Corporation, STEricsson, and Texas Instruments., *Universal Serial Bus 3.1 Specification*.

[5] CYUSB306X, EZ-USBTM CX3 MIPI CSI-2 to superspeed USB bridge controller, https://www.infineon.com/dgdl/Infineon-CYUSB306X_EZ-USB_TM_CX3_MIPI_CSI-2_to_SuperSpeed_USB_bridge_controller-DataSheet-v17_00-EN.pdf?fileId=8ac78c8c7d0d8da4017d0ecbbb354559 (accessed Sep. 29, 2023).

[6] Grainger Engineering Office of Marketing and Communications, "Salary averages," Electrical & Computer Engineering | UIUC, https://ece.illinois.edu/admissions/why-ece/salary-averages (accessed Sep. 28, 2023).

[7] "The code affirms an obligation of computing professionals to use their skills for the benefit of society.," Code of Ethics, https://www.acm.org/code-of-ethics (accessed Sep. 28, 2023).

[8] "University code of conduct," University Code of Conduct - University of Illinois Ethics ..., https://www.ethics.uillinois.edu/compliance/university_code_of_conduct (accessed Sep. 28, 2023).