iSPY,
Image Surveillance and Protection Yielder

Group 5

Our Team

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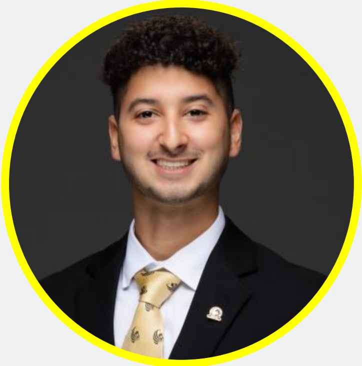
Introduction

- iSPY is a surveillance system that utilizes Free-Space-Optical (FSO) communication and body recognition.
- By transmitting data from a live video feed using FSO, iSPY minimizes the interception risks associated with most wireless surveillance systems.
- iSPY's body recognition allows for precise monitoring, making it perfect for urban and military security.

One could visualize the future of the system like this

Motivation and Background



- **Current surveillance and telecommunication systems are susceptible to hacking when not integrated within a secure network.**
  + Dangerous when considering proliferation of products like the Ring Doorbell Camera and peripherals.
  + If systems are not under a secure network, hardware is in danger of being tapped!
  + Private home and military installation surveillance systems are susceptible.
- **Electromagnetic carrying capacity is narrowing every day.**
  + Proliferation of RF tech uses up necessary EMF real estate.
  + The spectrum must expand towards optical frequencies to meet demand.
- **Optical wireless communication (OWC) is a solution.**
  + Has picked up momentum recently.
  + Common for TV controllers…but now also for LiFi and on satellites.

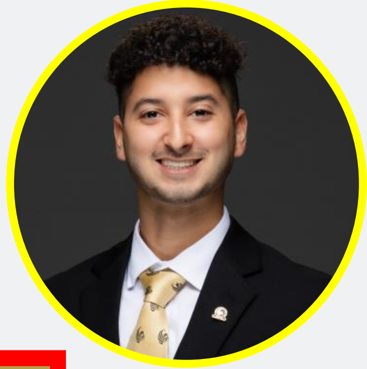
"iSPY addresses these needs and paves the way for other technologies benefiting from OWC."

– iSPY Team

Goals and Objectives

Basic Goals	Advanced Goals	Stretch Goals	Basic Objectives	Advanced Objectives	Stretch Objectives
Capture faint images of the environment.	Capture a clear image of the surrounding environment with 80 degrees FOV.	Aberration-corrected, high-resolution, 120° FOV images.	Create a two-lens imaging system.	Create a wide field of view imaging system to capture a continuous image feed.	Design a wide field of view lens system capable of resolving aberration-free and well-detailed images.
Transmit and receive a laser pulse.	**Transmit and receive usable optical signals using integrated circuits at 1Gbps.**	**Ultra-fast transmission speeds using high-speed FSO transceivers.**	**Turn laser on/off and measure pulse.**	**Utilize optical transceiver to transmit and receive laser pulses.**	**Create an ultra-fast laser/receiver system with adaptive optics capabilities.**
Designed PCB must effectively house a processing unit, electrical components, power systems, and the necessary connection pins.	The power systems must power the imaging acquisition system and an external processing board.	Optimize thermal management for extended operation.	Design a PCB with a voltage regulator, an MCU, and a sensor.	Integrate a working PCB with the necessary ports to support peripherals.	Integrate all transmitting and receiving components using external boards and PCBs to realize a video feed.
Able to detect objects with the use of computer vision algorithm in video feed.	**Capture recognition of people as well as count the number of individuals recognized from video feed.**	**Tracking movement of individuals in video feed with confidence scoring and enhancing recognition of people to determine gender and age.**	**Utilize an object detection algorithm.**	**Edit a body detection library to detect a human body with ≥75% confidence.**	**Write object tracking algorithms to enhance body detection algorithms' abilities with high confidence scores.**
Establish a stable method that can efficiently compress data for transmission and decompress data for viewing on display.	Achieve a high-quality video feed of 720p after compression and decompression.	Implement compression that is capable of dynamically adapting to video complexity which would allow much higher quality of video feed.	Effectively compress image data into bit stream to modulate laser.	Implement codecs for real-time compression to achieve low latency.	Develop an AI-driven algorithm to compress and decompress bit stream data depending on load for faster processing.

Engineering Specifications



Component(s)	Parameter	Specifications
Image acquisition system (Camera)	Field of view	80 degrees (horizontally) 50 degrees (vertically)
Computer vision algorithm (MCU)	Accuracy of detection	75%
Transceivers	Optical Link Length	0.25 meter
MCU	Clock Speed	16 MHz
Camera sensor	Framerate	30 frames per second
Power Supply (External)	Voltage Output	3.3V DC regulated
Display	Framerate	30 frames per second

Work Distribution

Armani

- PCB Design and Fabrication
- PSU Design and Implementation
- Interface Design for Data Transmission
- Signal Conditioning Processing

Alejandro

- FSO Lens Design and Implementation
- Laser and Detector Selection and Implementation
- Optoelectronics integration with PCB Housing

Gabryella

- Design and Align Lenses for Image Acquisition System
- Selection of Appropriate Image Sensor
- Integration of Image Acquisition System

Luke

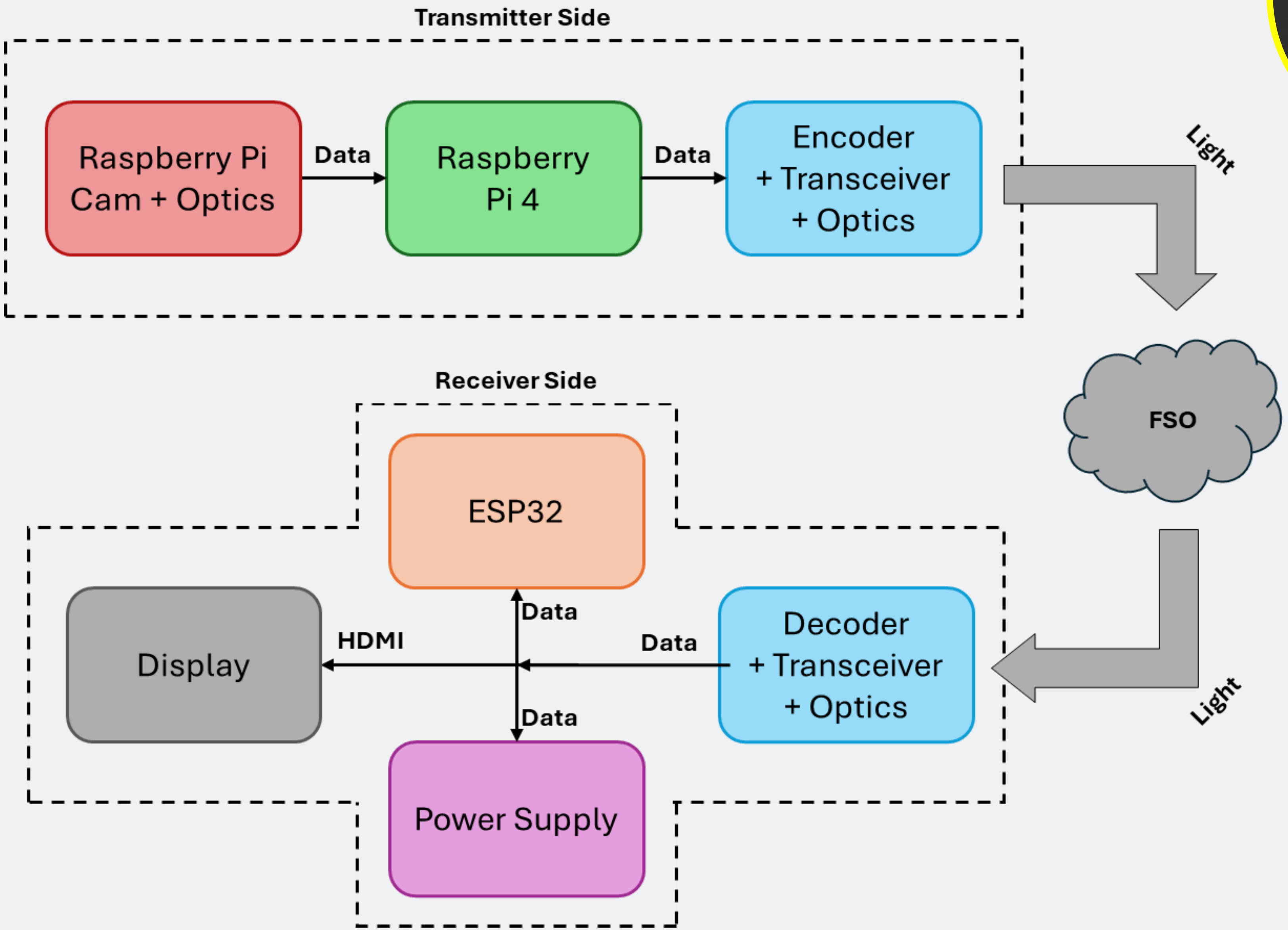
- Image Correctness
- Output Video Processing and Display
- Compression Software Design and Implementation
- Website management

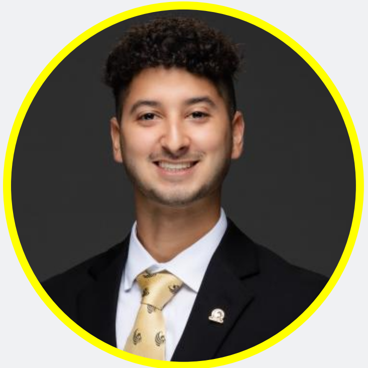
Robert

- Computer-Vision Software Design and Implementation
- Appropriate MCU Selection
- Machine Learning Algorithm Development

Hardware Design

- Luke
- Alejandro
- Armani
- Gaby
- Robert

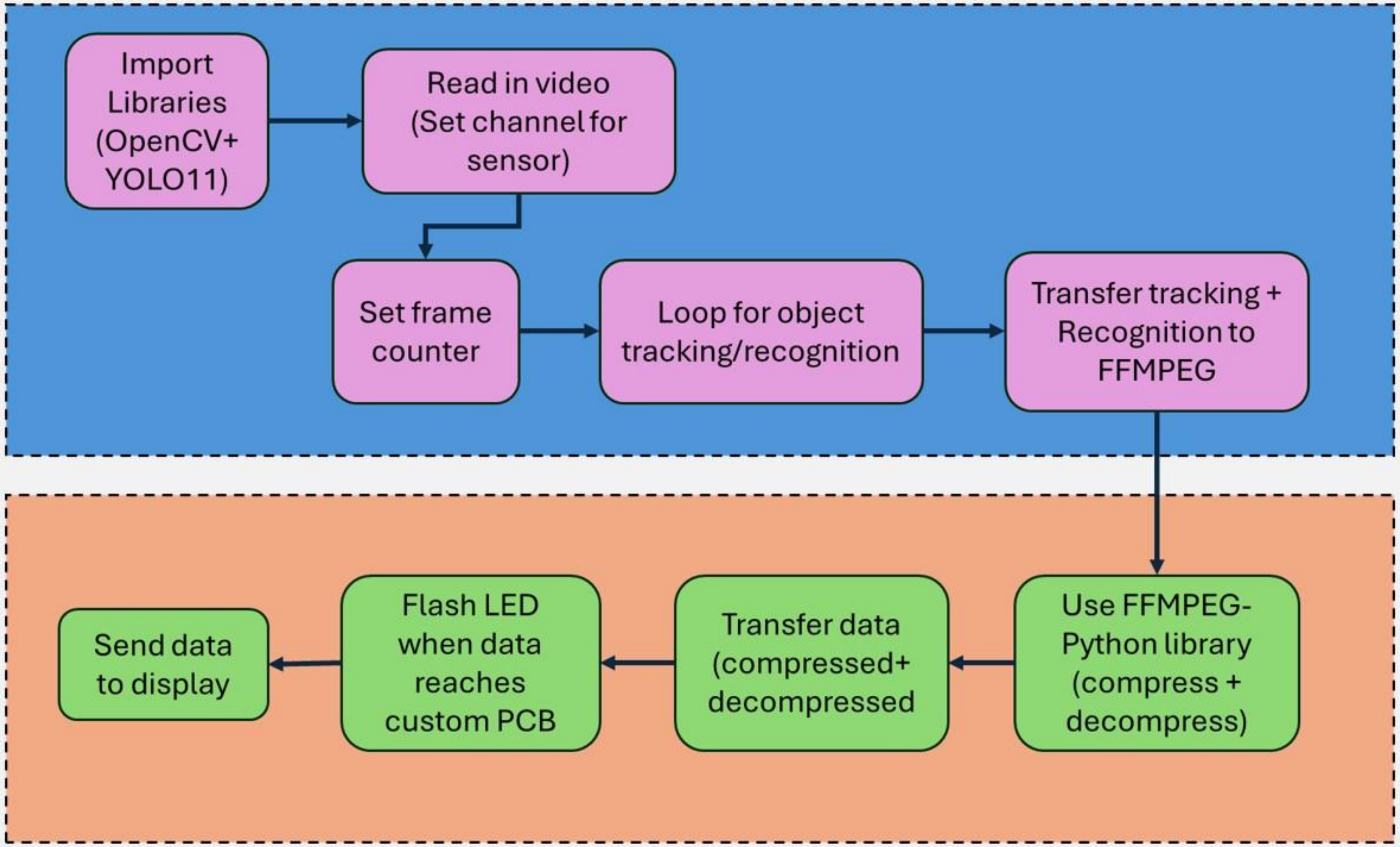




Software Design

Robert

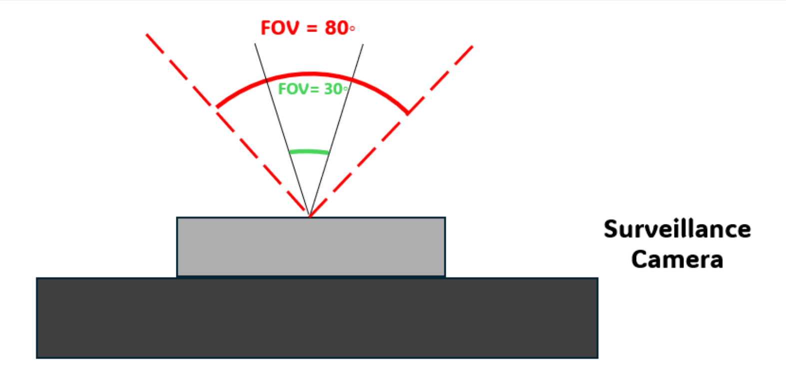
Luke



Comparison and Selection of Hardware

Image Acquisition System - Overall

- For our surveillance system we wanted a camera with a wide field of view.
- Field of view (FOV) is an angle measurement of how much of a scene one can see.
- A wide field of view give us a “big picture” of a scenario rather than a detailed focus in one part.
- Our plan is to build our own camera with the goal of reducing size and cost.
- Off-the-shelf cameras have around 4 lenses. We want to reduce that number.



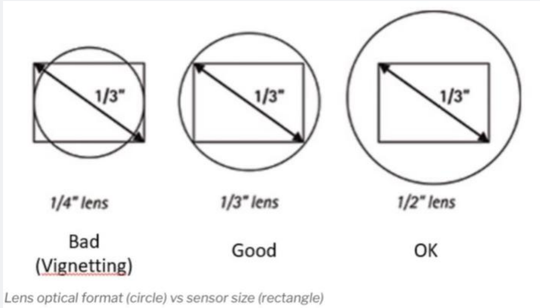
FOV (field of view) representation

Lenses from an off-the-shelf surveillance camera

Comparison and Selection of Hardware

Image Acquisition System - Sensor

- The optical design of the image acquisition system starts with the choice of the sensor.
- The sensor size dictates the size of the lenses.
- Failure in matching sensor size with the lenses will cause vignetting.



Lens optical format (circle) vs sensor size (rectangle)

- Size and price of the sensor and lenses increase proportionally.
- FPS (frames per second)
- CMOS vs. CCD
- Shutter type
- Connection to PCB / Interface

Camera Module A

Model	Frame rate (fps)	Sensor size	Interface	Shutter Type
daA3840-45uc	45	1/1.8’’	USB 3.0	Rolling
Brand	**Pixel size (H x V)**	**Resolution**	**Weight**	**Price**
Basler	2.0 x 2.0 µm	8.3 MP	< 15g	$199

Camera Module B

Model	Frame rate (fps)	Sensor size	Interface	Shutter Type
Pi Camera Module 3	30	1/2.43’’	MIPI CSI-2	Rolling
Brand	**Pixel size (H x V)**	**Resolution**	**Weight**	**Price**
Raspberry Pi	1.4 x 1.4 µm	11.9 MP	4g	$25

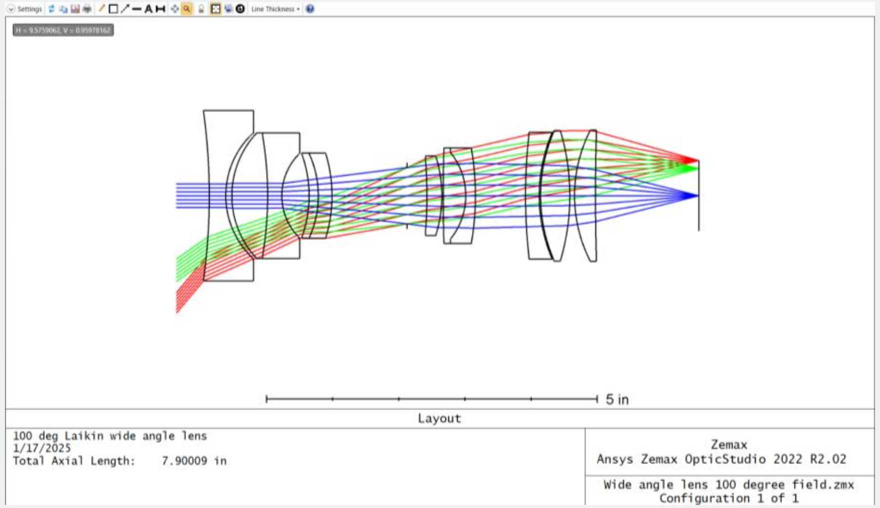
Camera Module C

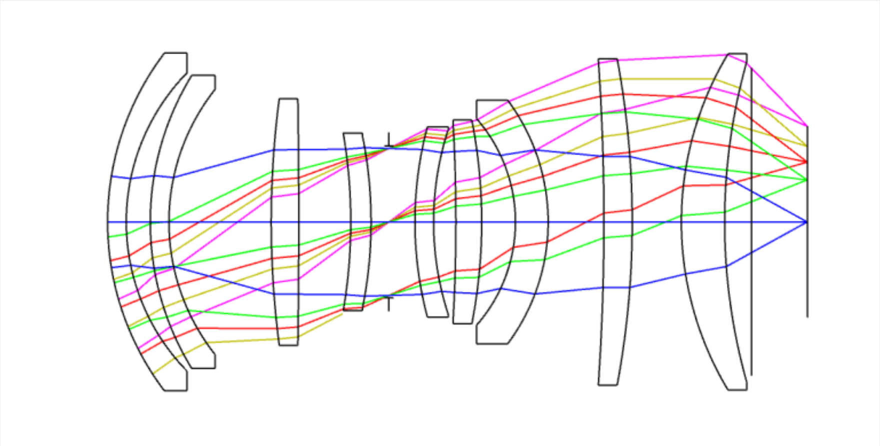
Model	Frame rate (fps)	Sensor size	Interface	Shutter Type
IMX519	30	1/2.53’’	-	Rolling
Brand	**Pixel size (H x V)**	**Resolution**	**Weight**	**Price**
ArduCam	1.22 x 1.22 µm	16 MP	8.5g	$37.99

Comparison and Selection of Hardware

Image Acquisition System

Lens Design for Wide FOV





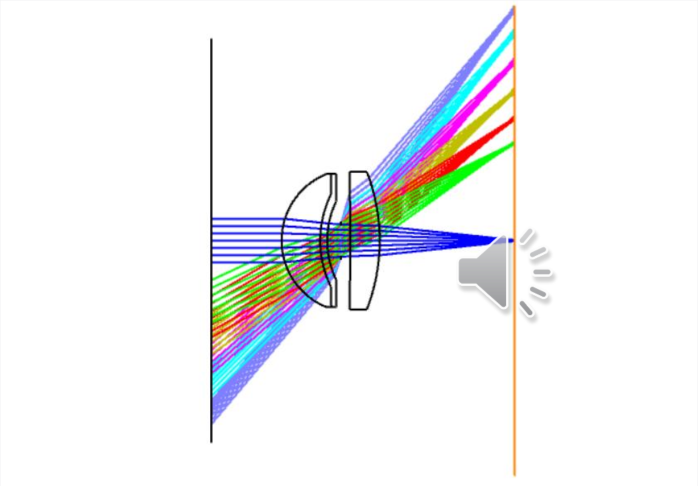
Challenges

- Complexity of the lens system for wide field of view.
- Aberrations/Distortion.
- Budget and time.

Solutions

- Scale down project as per advisor’s input.
- Work with off the shelf lenses.
- Aspheric lenses.

Distortion example



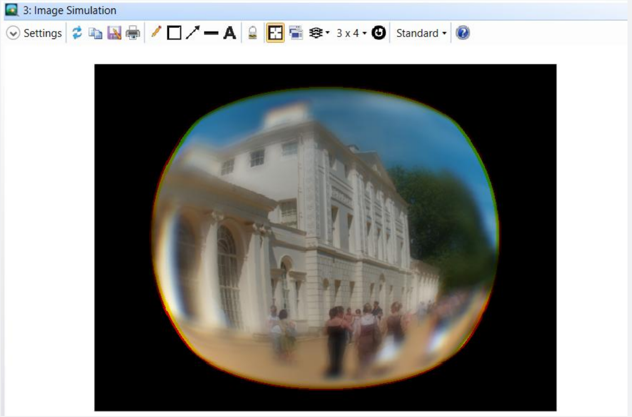
Lens Design for a FOV of 80 degrees

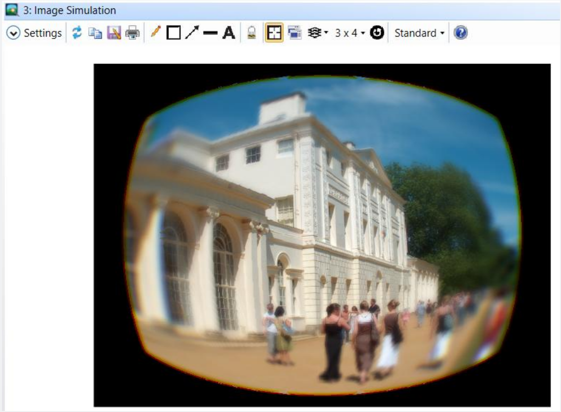
Comparison and Selection of Hardware

Image Acquisition System – Lens Design

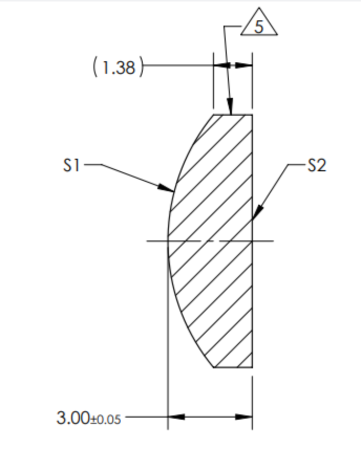
- Short focal length
- Wide FOV and aberrations
- Coating
- Aspheric lenses
- Fixed focal length/focus
- Illumination
- F# and Aperture stop

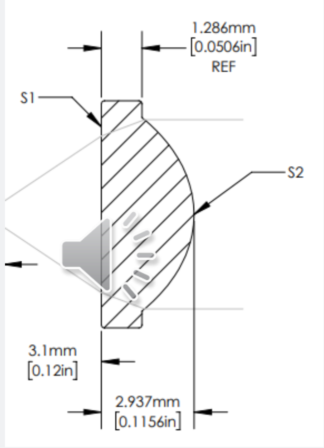
Aberration examples





Regular lens vs. Aspheric lens





$$\tan(\mathrm{FoV}/2) = (D/2)/\mathrm{EFL},$$

$$\mathrm{EFL} = D/[2\tan(\mathrm{FoV}/2)].$$

EFL = 4.41 mm for 80° FOV

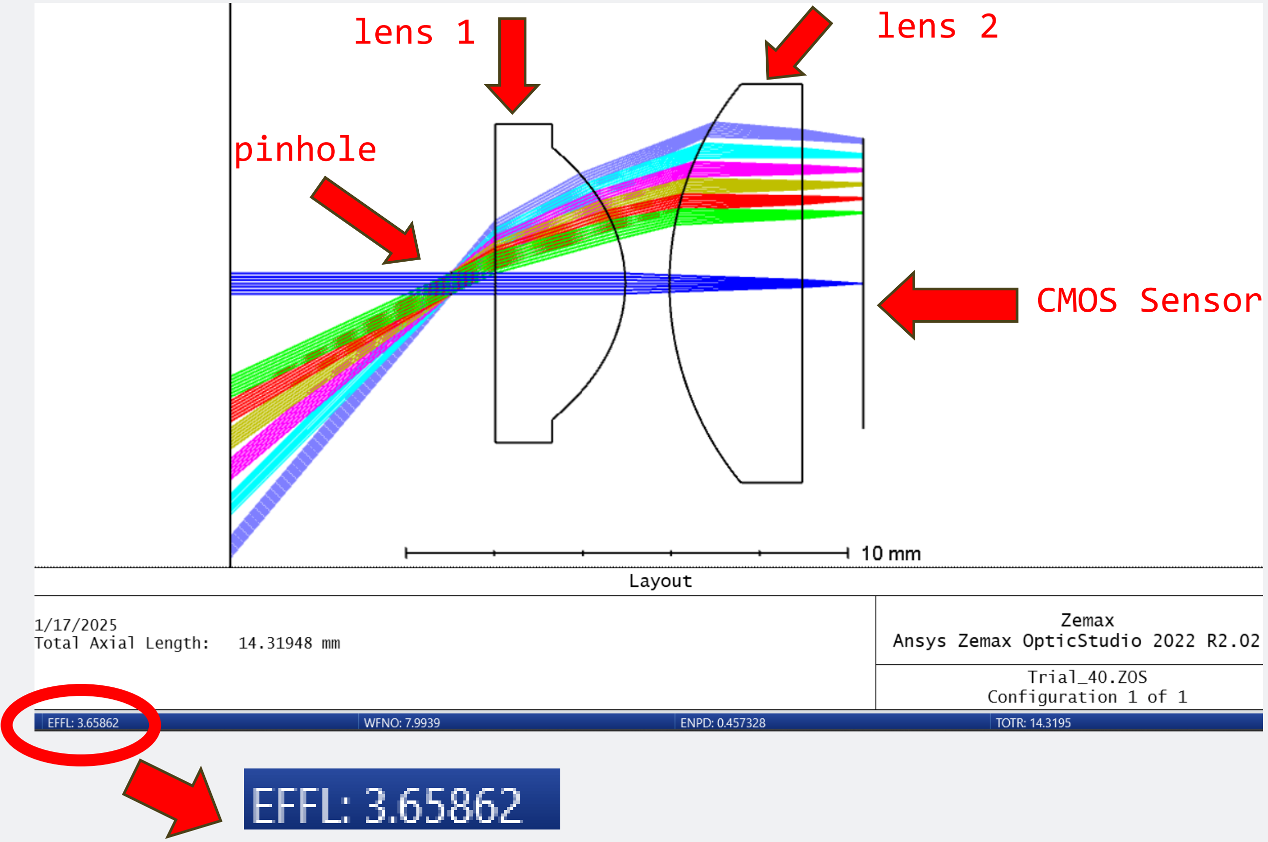
EFL = 3.14 mm for 100° FOV

$$F\# = \frac{\text{focal length}}{\text{entrance pupil diameter}} \Rightarrow \frac{4.41\text{ mm}}{6 \text{ to } 8} \Rightarrow 0.735\text{ mm to } 0.55\text{ mm}$$

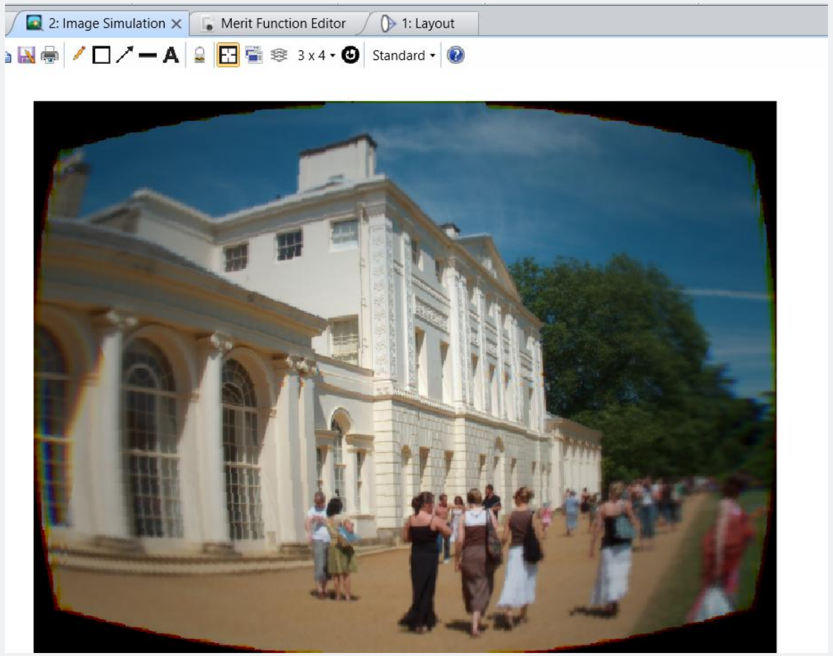
$$\Rightarrow \frac{3.14\text{ mm}}{6 \text{ to } 8} \Rightarrow 0.523\text{ mm to } 0.3925\text{ mm}$$

Comparison and Selection of Hardware

Image Acquisition System – Simulation



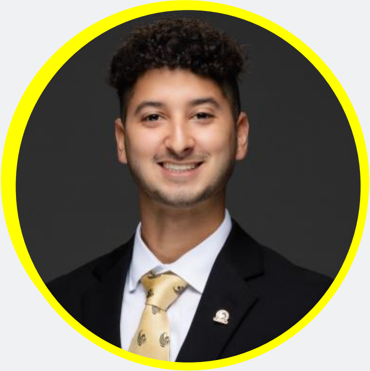
Effective Focal Length



Further image enhancement will come from post-processing.

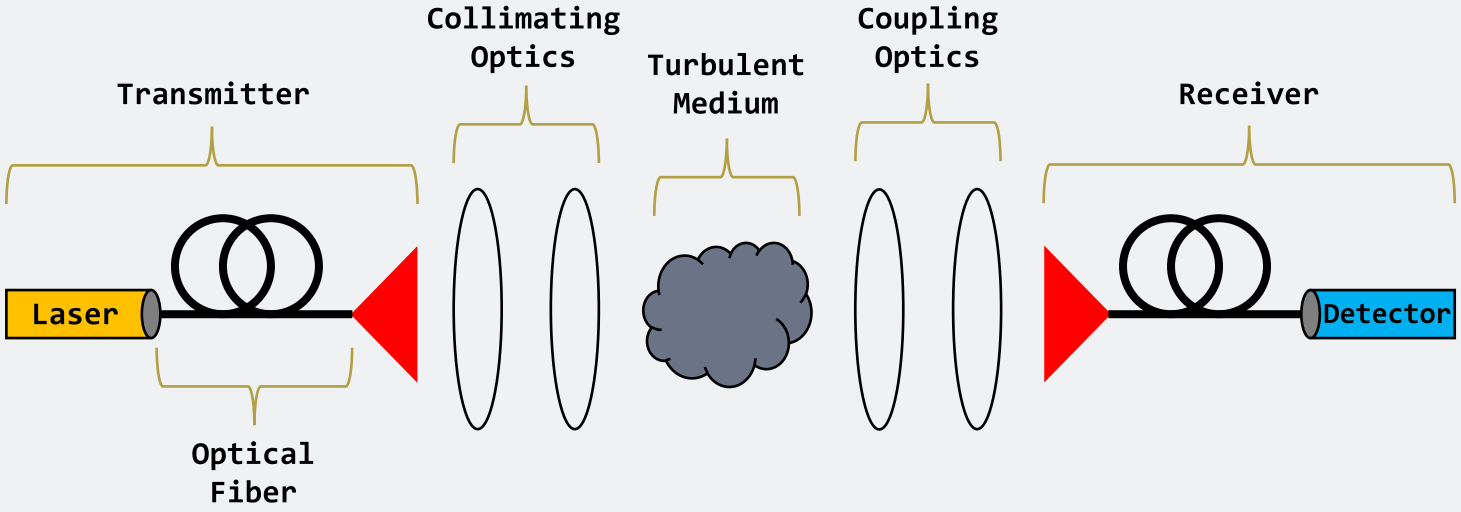
- 400 microns pinhole – entrance pupil / aperture stop
- Aspheric (lens 1)
- Convex-plano (lens 2)
- CMOS sensor

Comparison and Selection of Hardware



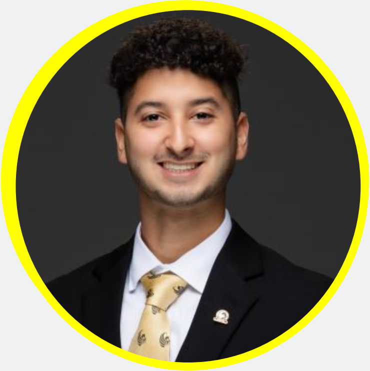
Free-Space Optical Communications System - Overall

General Design:



- To facilitate OWC, the transmitter and receiver are housed inside optical transceivers.
- Optical transceivers necessitate optical fibers to deliver light signals.
- To send optical signals, twin collimating/coupling optics are also necessary.

Comparison and Selection of Hardware



Free-Space Optical Communications System - Overall

Challenges

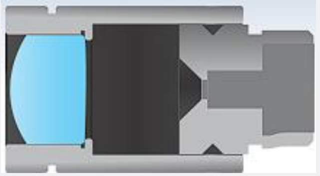
1. Encode bitstream to optical signals
2. Deliver optical signal to FSO channel
3. Effectively convert optical signals back to bitstream signals
4. Account for the optical loss of each component (absorption + misalignment)

Solutions

[Transceiver]

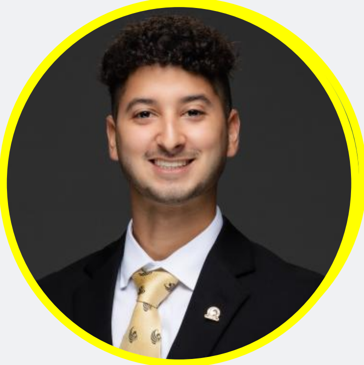
[Open-SFP to RJ45]

[SMF28e]



[Singlet]

Free-Space Optical Communications System - Transceivers

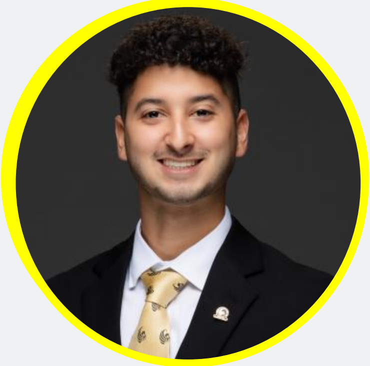


Transceiver	Cisco GLC-SX-MMD	Cisco GLC-EX-SMD	Brocade E1MG-EZX-100
Fiber Type	Multimode	Single Mode	Single Mode
Power Budget (dB)	8	17	27
Wavelength (nm)	850	1310	1550
Cost	$12.00	$28.00	$48.00

- Why design a Tx/Rx system when an optical transceiver does the job?
- Transmitting high quality video in near real-time necessitates fast speeds.
- Optical components are lossy. Larger power budgets give more optical wiggle room.

[Transceiver]

Free-Space Optical Communications System - Media Converters



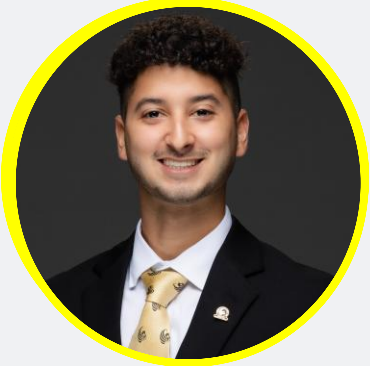
Converter Type	SFP to RJ45	Integrated SFP to RJ45
Swappable SFP? (Yes/No)	Yes	No
Power Consumption	4.3 W	5 W
Cost	$18.99	$19.99

- Optical (SFP) to Ethernet (RJ45) media converters are ubiquitous.
- Open-SFP formats enable different SFP modules to be used on the same converter.
- Integrated-SFP formats have built-in Tx/Rx systems.

[Open-SFP to RJ45]

[Integrated-SFP to RJ45]

Free-Space Optical Communications System - Fiber



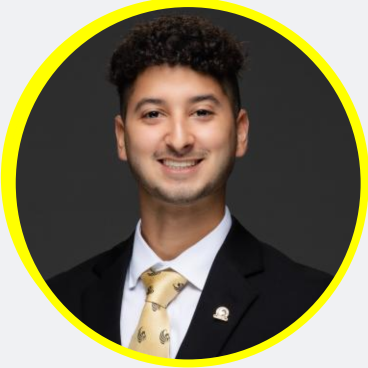
Fiber Name	Corning ClearCurve (OM3)	Corning SMF-28e (OS2)
Fiber Type	Multimode	Single Mode
Numerical Aperture	0.215	0.14
Modal Bandwidth (MHz·km)	2000	N/A
Wavelength (nm)	850	1550
Loss (dB/km)	2.3	0.20
Cost	$10.79	$5.93

- Optical fibers are optical waveguides.
- Transceivers are built for and used with optical fibers.
- Optical fibers are very low loss. Choice comes down to other parameters like numerical aperture, loss, and wavelength.

[ClearCuve]

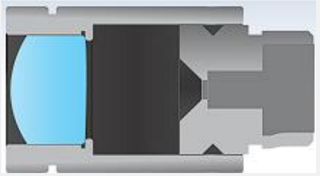
[SMF28e]

Free-Space Optical Communications System - Lenses

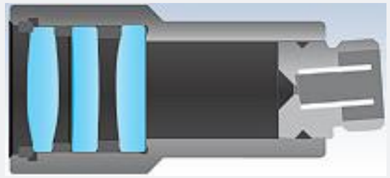


Collimating Lens Type	Achromatic Doublet	Pigtailed Fiber	Single Lens	Air-space Triplet
Numerical Aperture	0.54	0.125	0.15	0.28
Losses	N/A	< 1 dB/km (fiber loss)	N/A	N/A
Spot Size (mm)	0.17	5	3.6	3.3
Coated Type	B	C	C	C
Cost	$240.98	$226.14	$181.00	$488.23

- Lenses enable effective free-space optical links for communications.
- Lenses must match the fiber NA and coated according to working λ.
- The more lenses, the more divergence is controlled…but the more it costs.
- Chosen lens yields low loss.



[Singlet]



[Triplet]

[Doublet]

Comparison and Selection of Hardware

MCU - Overall

- Adequate Performance
- Low Power Consumption
- Cost Effective
- Compact Design
- Flexibility for system integration

Parameters	MCUs		
Model	ESP32-S3-WROOM-1-N16R8	STM32H753VIT6	Raspberry Pi CM4
Clock	240MHz	480MHz	1.5GHz
RAM	512KB of SRAM + 8MB PSRAM	1MB SRAM	Up to 8GB LPDDR4 SRAM
Operating Voltage	3.3V	1.7 - 3.6V	5V
Operating Temp.	-40°C to 85°C	-40°C to 125°C	0°C to 80°C
Cost	~$4	~$17	~$30

Comparison and Selection of Hardware

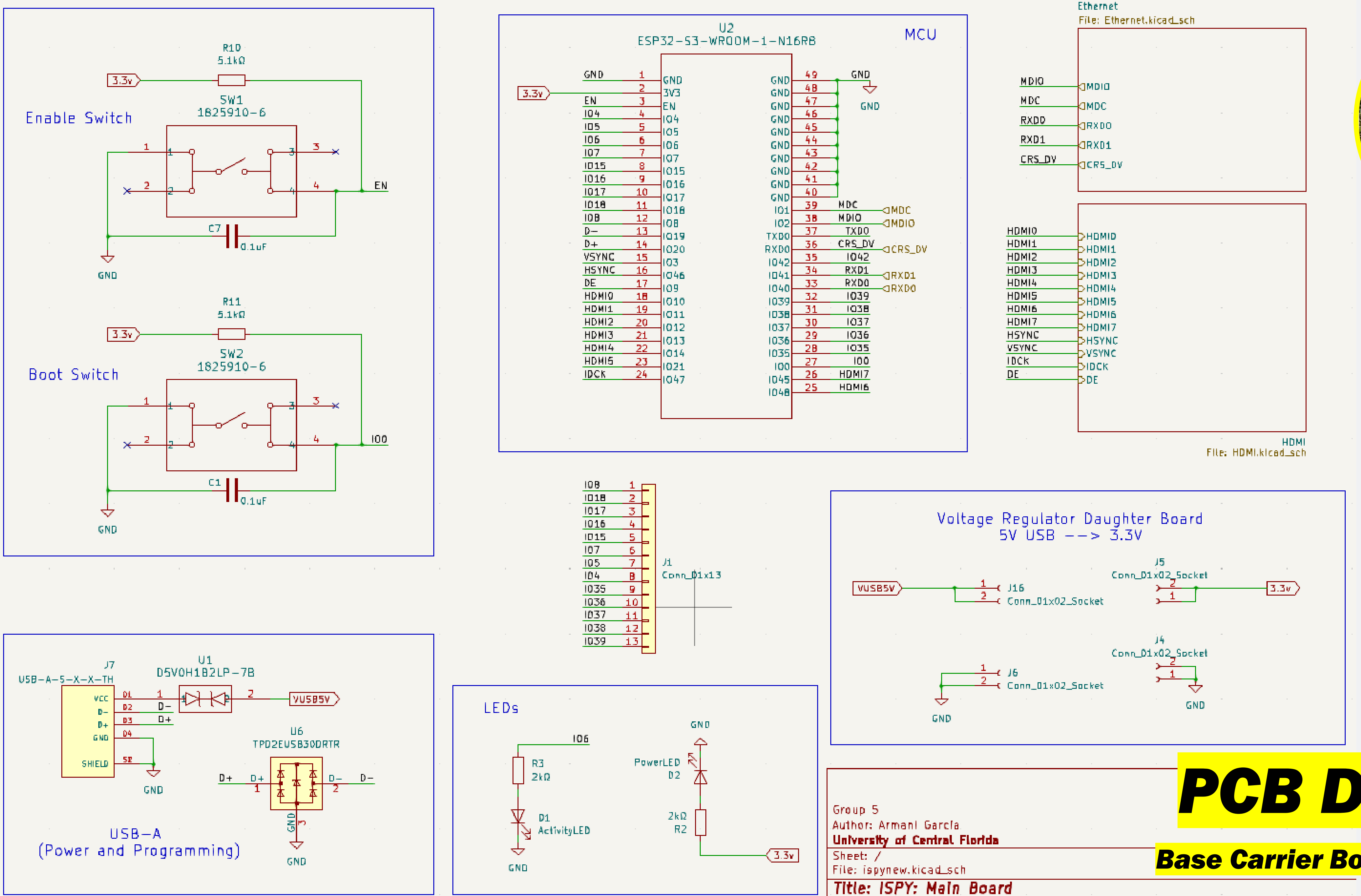
Power Supply

Based on the comparisons, the Mean Well LRS-50-5 meets the requirements set by the project:

- Reliable 5V Output
- Sufficient Current Capacity
- Compact and Efficient
- Protection Features

[Mean Well LRS-50-5]

Parameters	Power Supply Units			
Brand	Mean Well	RS Pro	CUI Inc.	Mean Well
MFG. P/N	LRS-50-5	777-6171	SWI5-5-N-P5	RS-15-5
Output Voltage	5V DC	5V DC	5V DC	5V DC
Output Current	10A	7A	1A	3A
Output Power	50W	35W	5W	15W
Efficiency	Up to 90%	Up to 82%	Up to 85%	~77%
Operating Temperature	-30°C to +70°C	0°C to +45°C	0°C to 40°C	-20°C to +70°C
Form Factor	Enclosed	Enclosed	Wall Plug Mount Adaptor	Enclosed
Size	99x82x30mm	99x82x30mm	22.6x36x47.7mm 1.5m Cord	62.5x51x28mm
MTBF Min. (Hrs)	645K	N/A	50K	108.8K
Price	~$15-$20	~$10-15	~$10	~$10-15

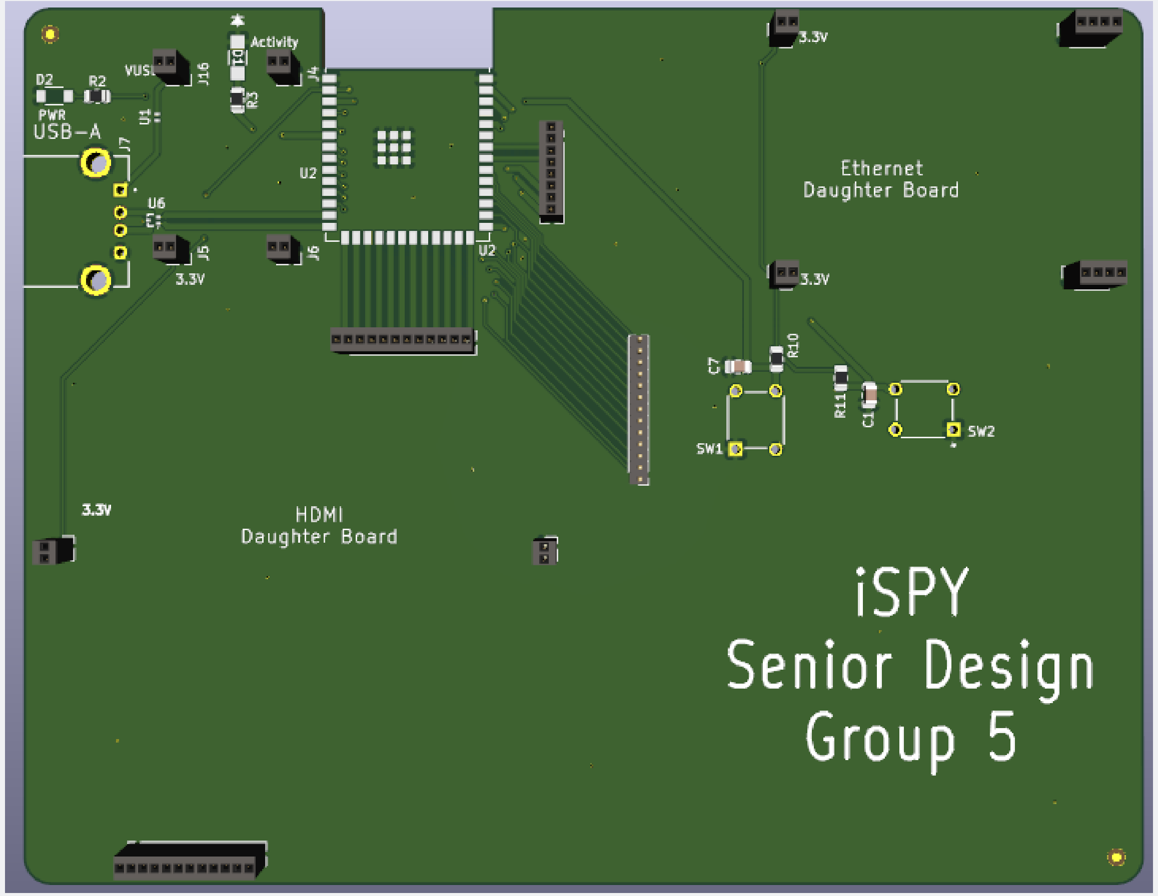


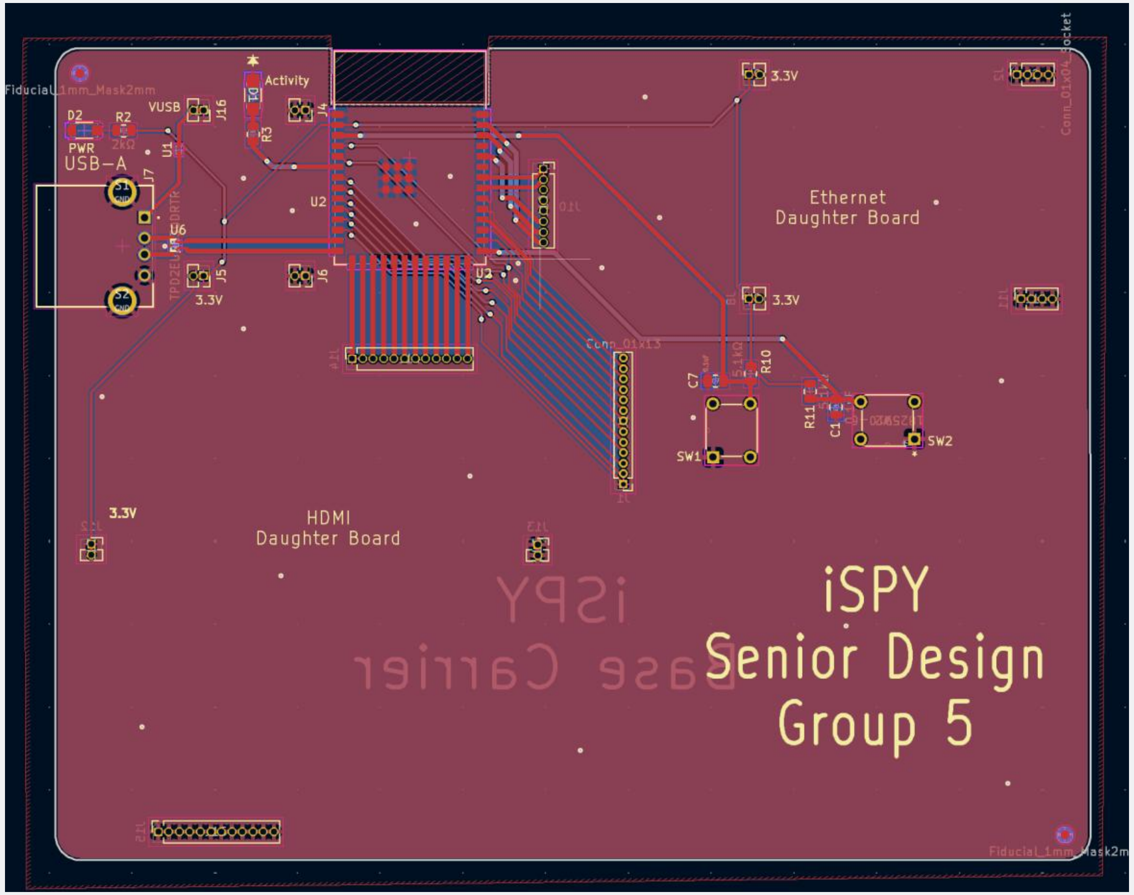
PCB Design

Base Carrier Board Schematic

PCB Design

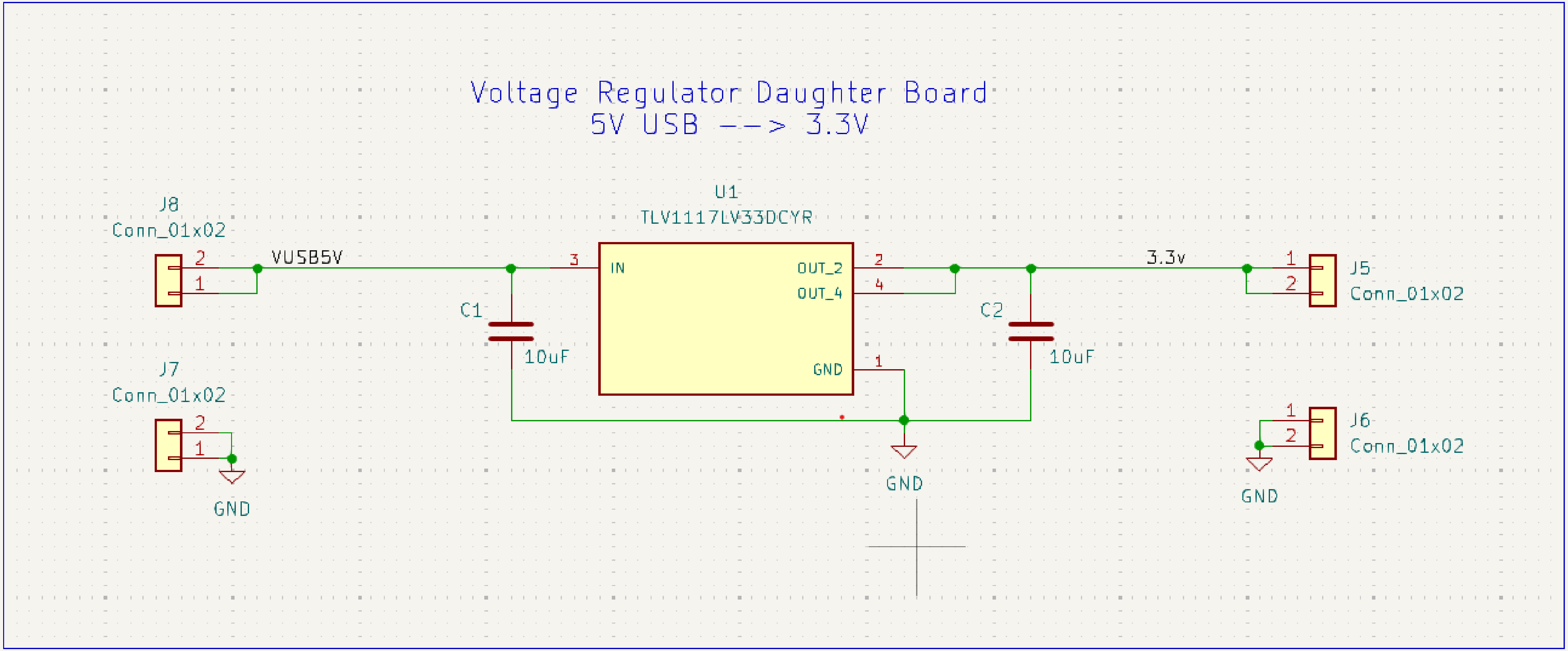
Base Carrier Board





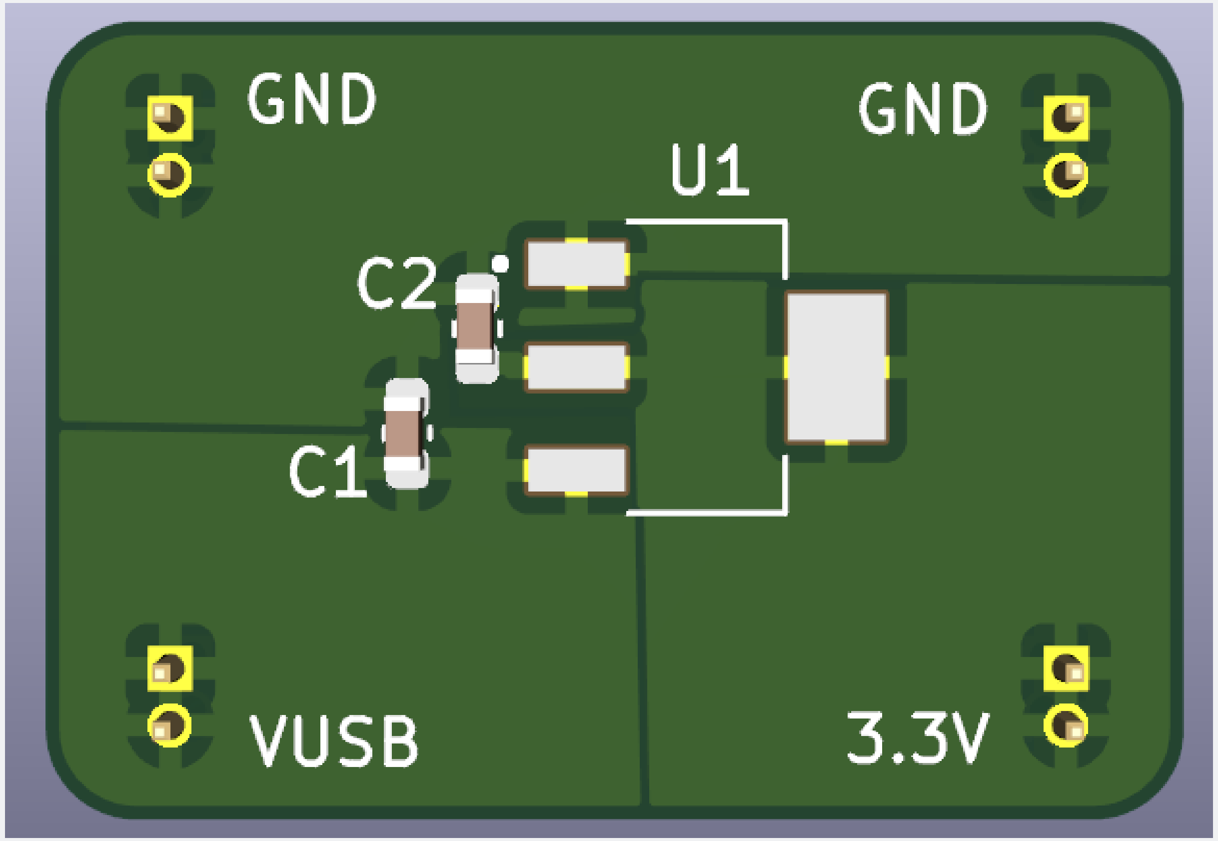
PCB Design

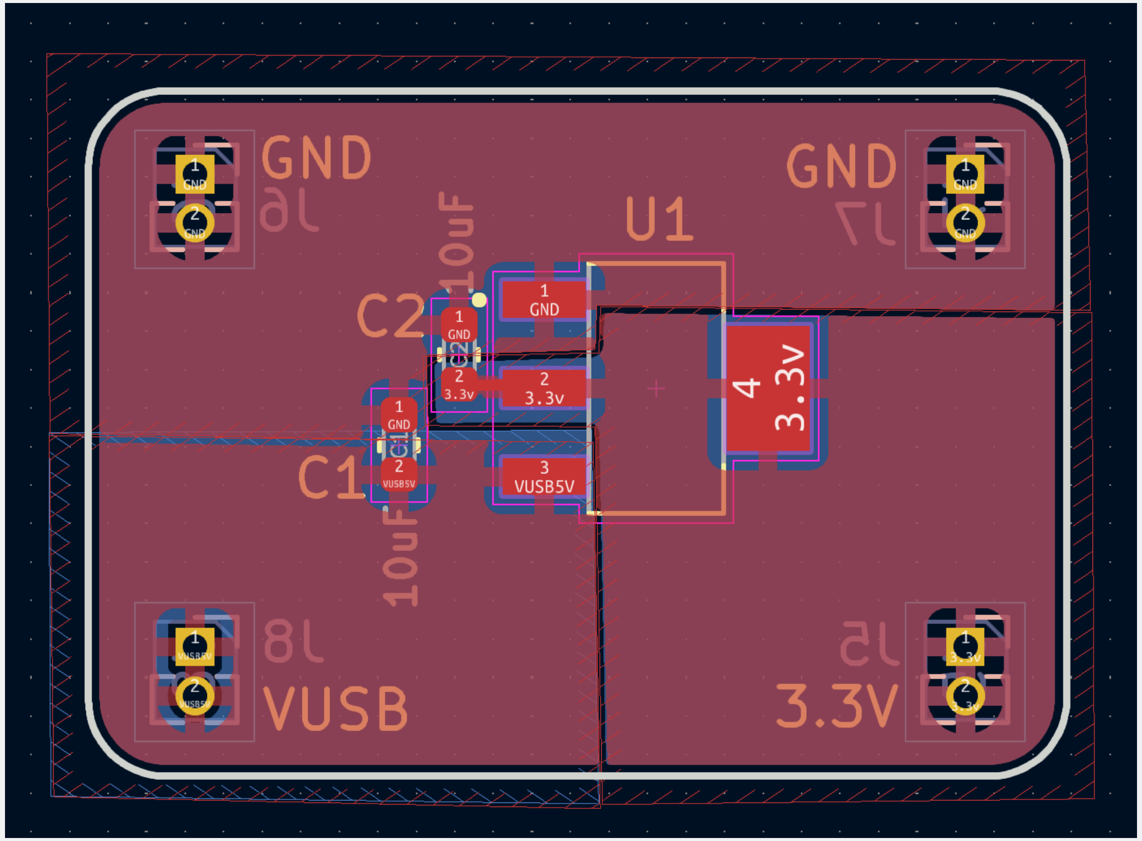
Voltage Regulator Daughter Board Schematic

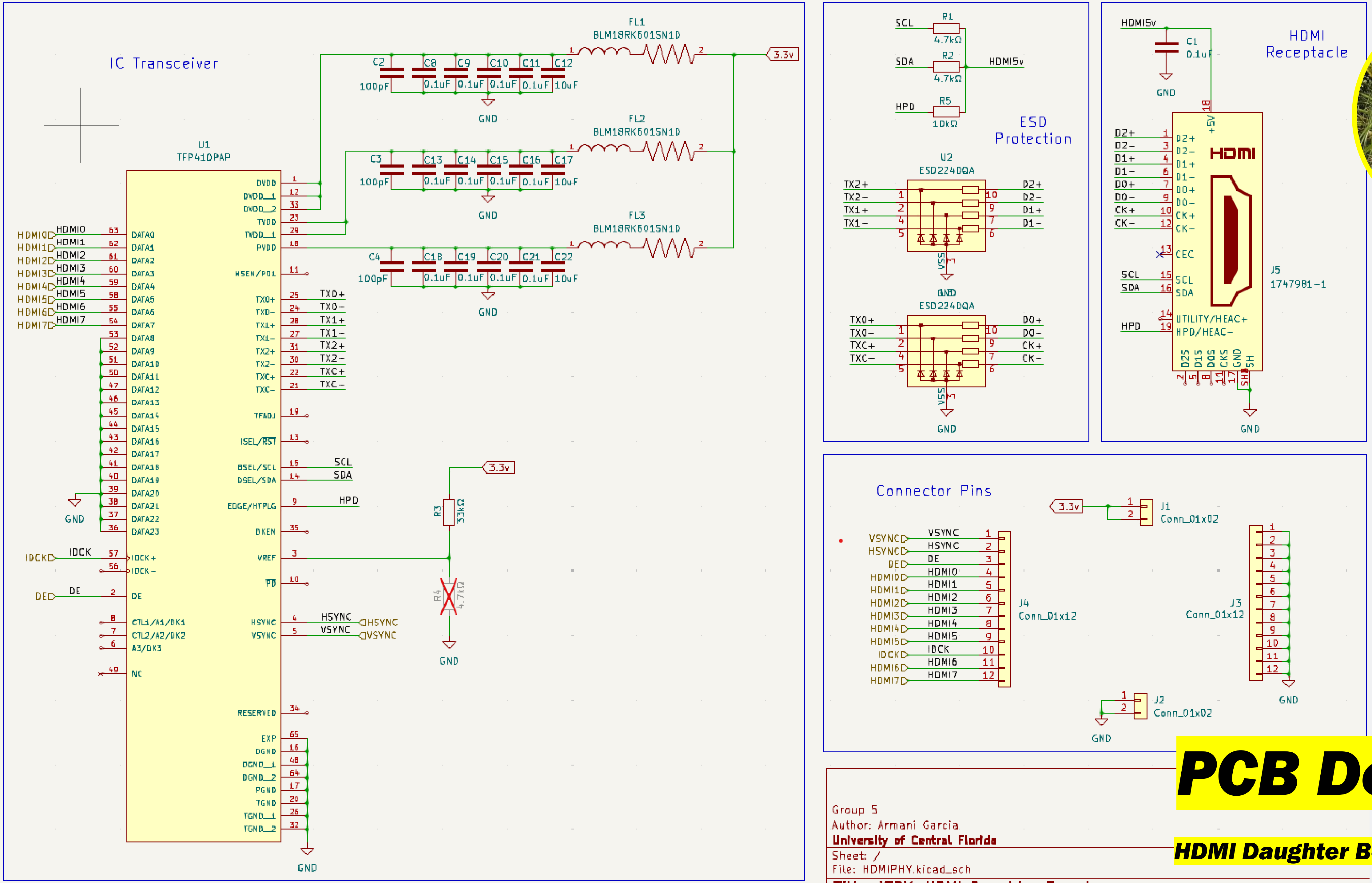


PCB Design

Voltage Regulator Daughter Board





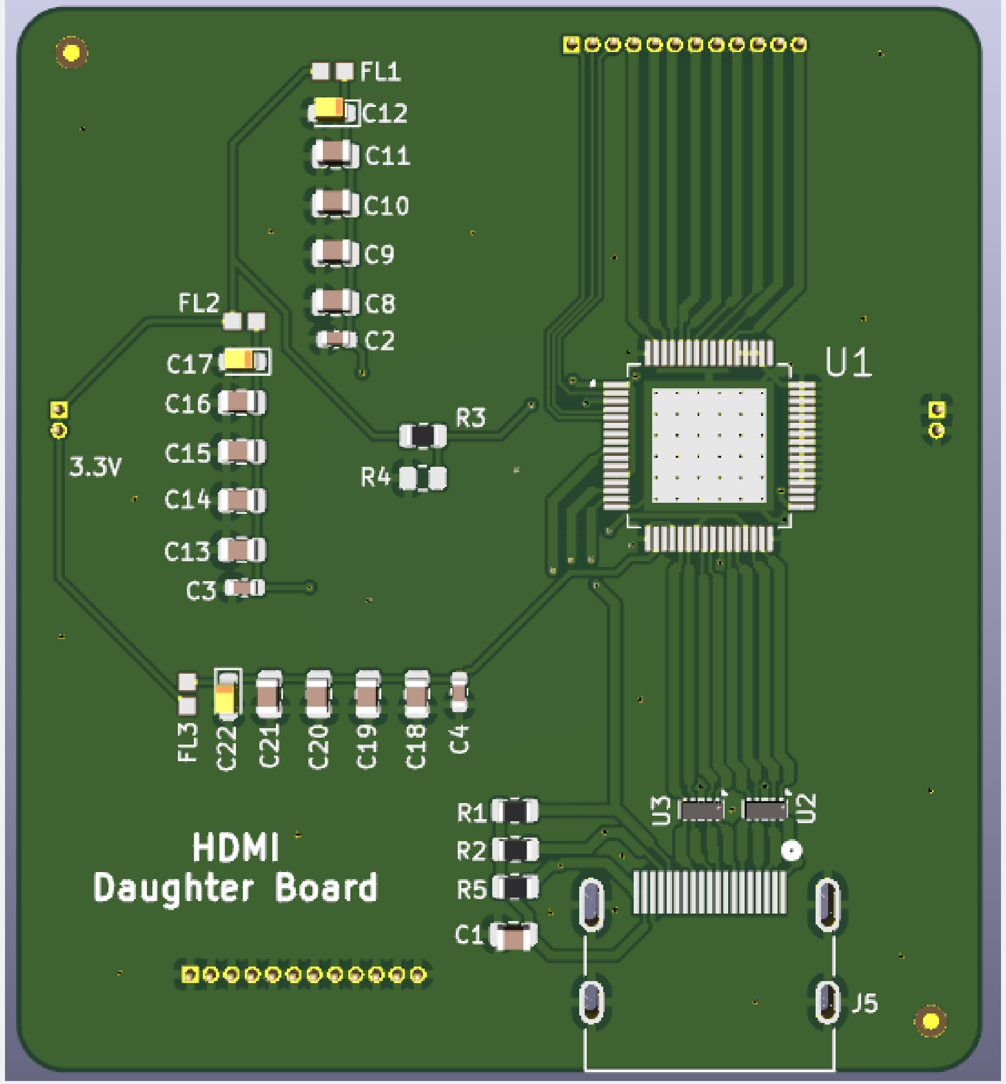


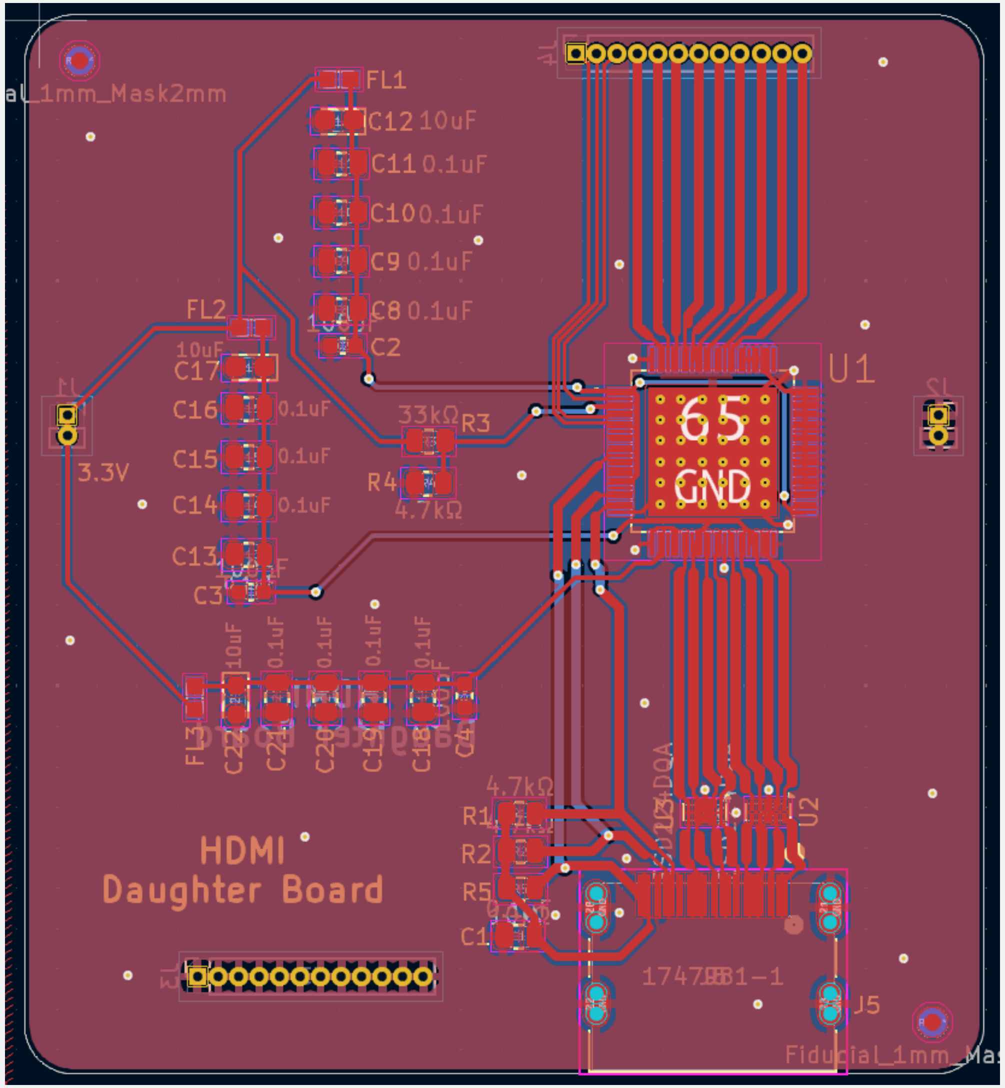
PCB Design

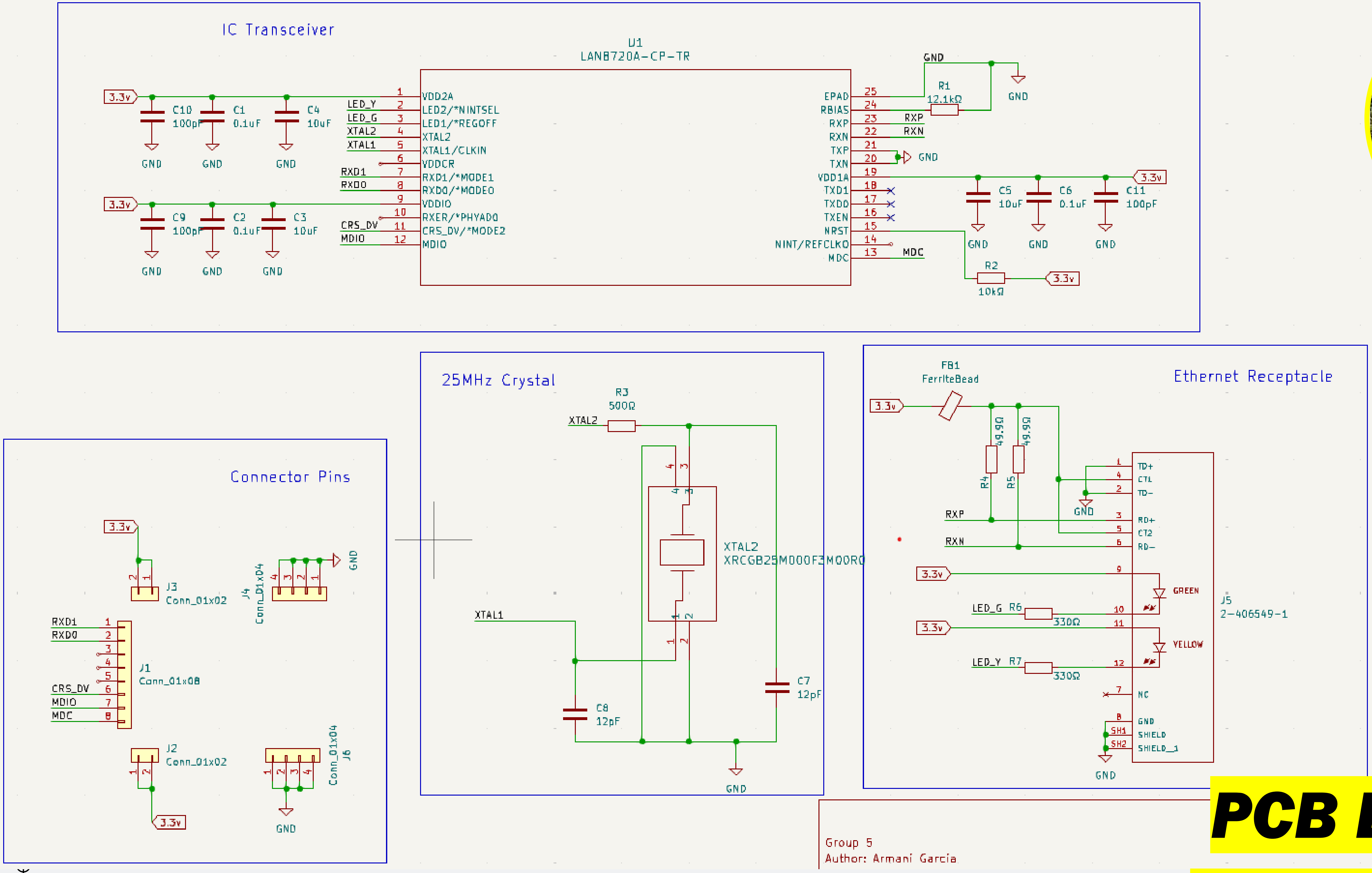
HDMI Daughter Board Schematic

PCB Design

HDMI Daughter Board





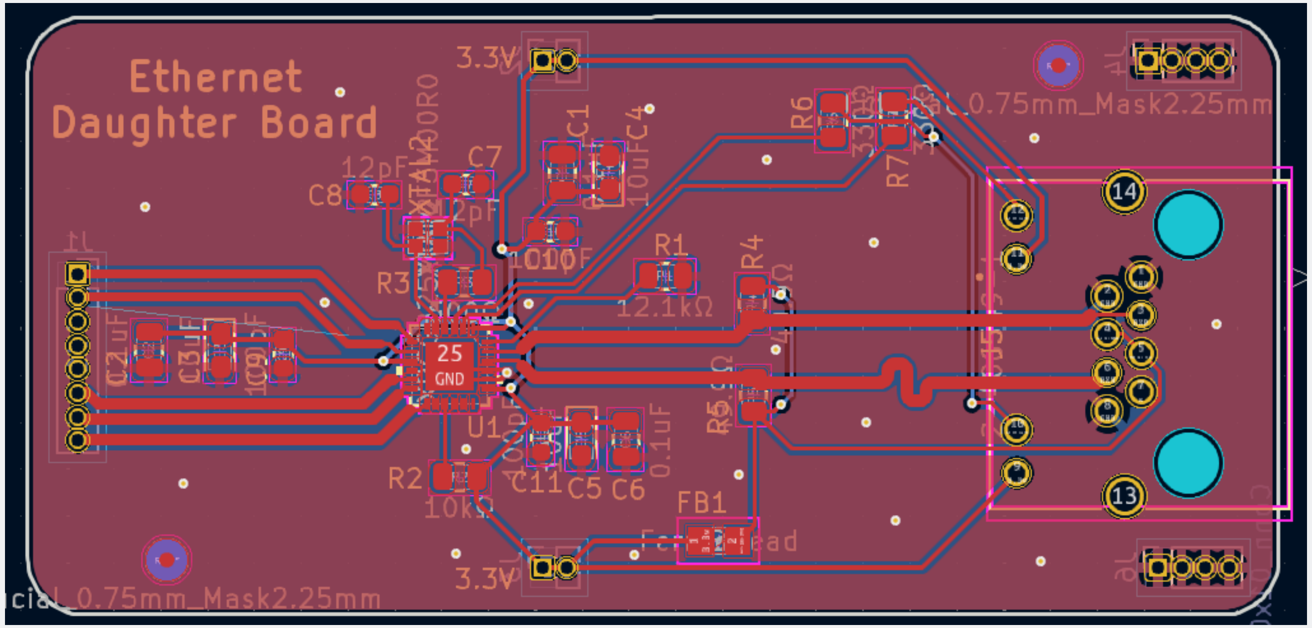


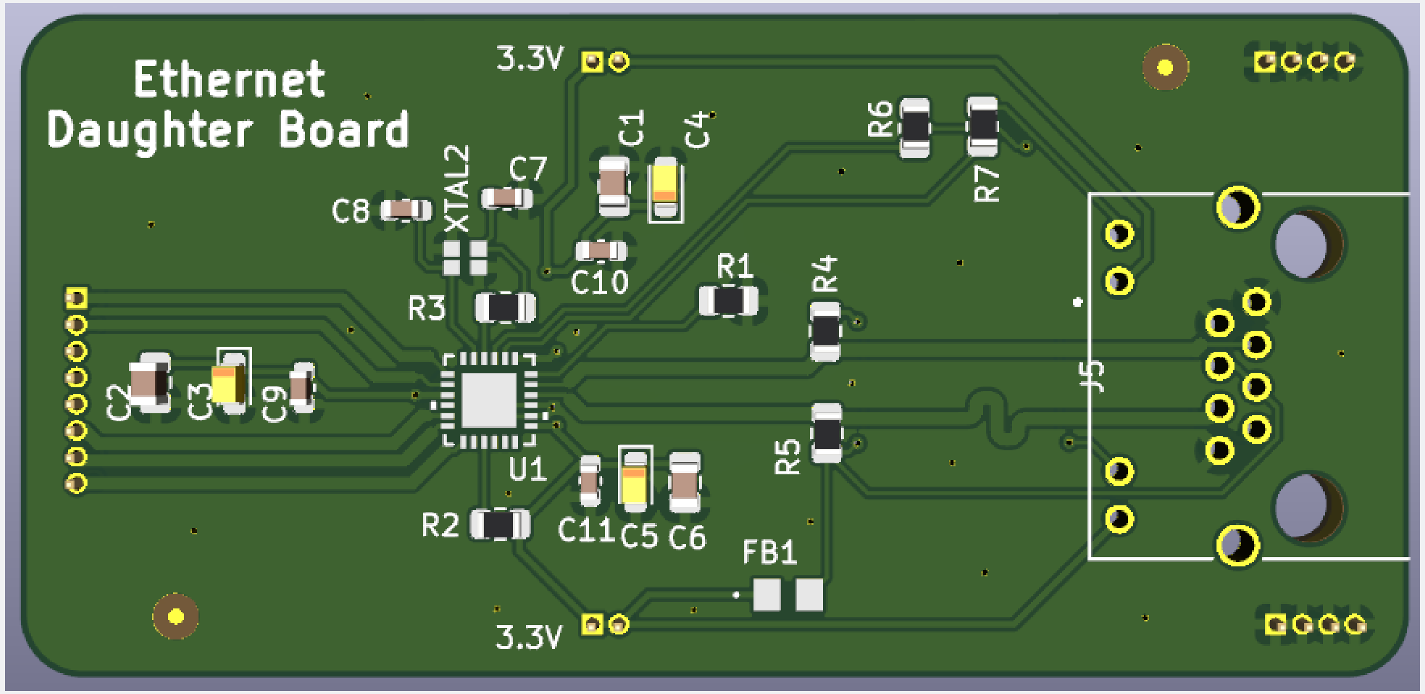
PCB Design

Ethernet Daughter Board Schematic

PCB Design

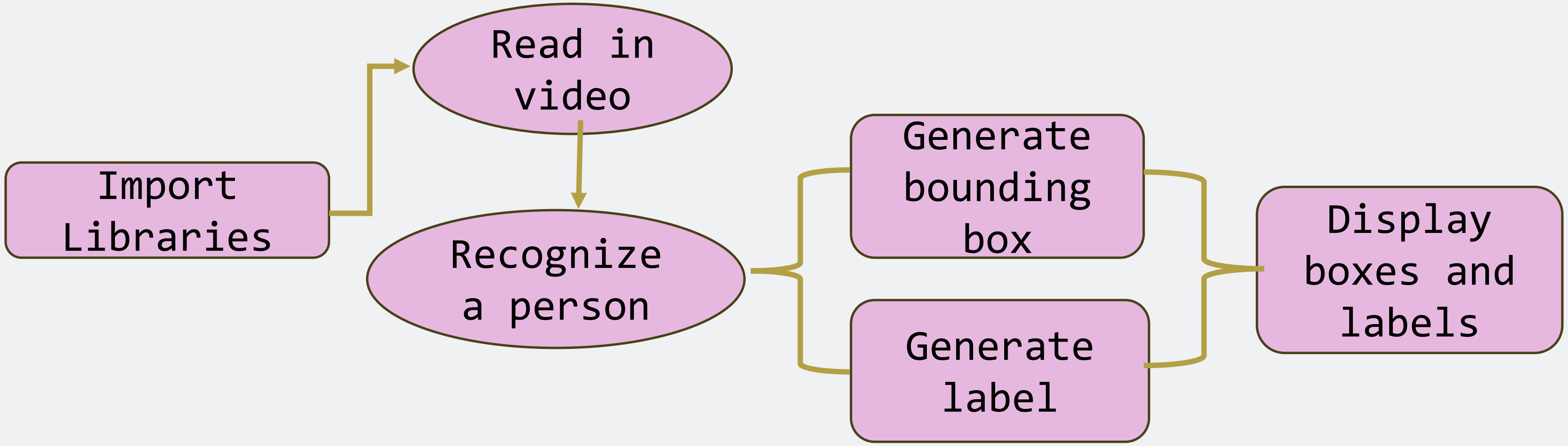
Ethernet Daughter Board





Comparison and Selection of Software

Computer Vision Recognition Program - Overall



- To begin the Computer Vision Recognition Program certain libraries are imported for usage of pretrained models and data
- Looping through frames to recognize people
- To display the result, the program shows the live video feed which includes the bounding boxes and labels

Comparison and Selection of Software

Computer Vision Recognition Program

Challenges

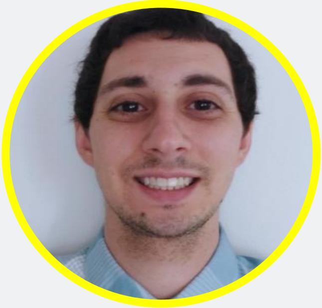
1. Recognizing people in real time
2. Ability to handle recognition quickly and accurately
3. Implement an accurate counter to count the amount of people in each frame

Solution

1. YOLOv11
2. Object Tracking

Model	size (pixels)	mAP^{val} 50-95	Speed CPU ONNX (ms)	Speed T4 TensorRT10 (ms)	params (M)	FLOPs (B)
YOLO11n	640	39.5	56.1 ± 0.8	1.5 ± 0.0	2.6	6.5
YOLO11s	640	47.0	90.0 ± 1.2	2.5 ± 0.0	9.4	21.5
YOLO11m	640	51.5	183.2 ± 2.0	4.7 ± 0.1	20.1	68.0
YOLO11l	640	53.4	238.6 ± 1.4	6.2 ± 0.1	25.3	86.9
YOLO11x	640	54.7	462.8 ± 6.7	11.3 ± 0.2	56.9	194.9

Computer Vision Recognition Program - Computer Vision Algorithm



- When it comes to the computer vision algorithm, we wanted it to be able to handle real time recognition
- The algorithm used had to meet certain parameters such as response time and fluent recognition
- YOLOv11 algorithm was able to meet requirements as specified

Detection (COCO) Segmentation (COCO)

Model	size (pixels)	mAP^{val} 50-95	mAP^{val} 50	params (M)	FLOPs (B)
YOLOv9t	640	38.3	53.1	2.0	7.7
YOLOv9s	640	46.8	63.4	7.2	26.7
YOLOv9m	640	51.4	68.1	20.1	76.8
YOLOv9c	640	53.0	70.2	25.5	102.8
YOLOv9e	640	55.6	72.8	58.1	192.5

Model	mAP	Latency (ms)
YOLO-NAS S	47.5	3.21
YOLO-NAS M	51.55	5.85
YOLO-NAS L	52.22	7.87
YOLO-NAS S INT-8	47.03	2.36
YOLO-NAS M INT-8	51.0	3.78
YOLO-NAS L INT-8	52.1	4.78

Computer Vision Recognition Program - Computer Vision Model

- Accuracy and speed are factors in real time recognition
- We focused on three YOLO algorithm models: YOLOv10N,YOLOv11N and YOLO-NAS S
- YOLOv11N model was used due to its accuracy and latency

Model	Model 1	Model 2	Model 3
Algorithm + Model	YOLOv10N	YOLOv11N	YOLO-NAS S
Precision	38.5	39.5	47.5
Latency (ms)	1.84	1.55	3.21

Comparison and Selection of Software

Compression Requirements

- A codec must be selected that will suit our system’s needs.
- Image quality must be maintained to a certain point as to not lose too much detail during compression and transmission.
- It must be efficient as to reduce latency on the receiving side of the system.

Comparison and Selection of Software

Codec Selection

- The codec should be compatible with the Raspberry Pi 4 Model B.
- The codec should be efficient and preferably use a lower amount of computational power due to the lower power of the Raspberry Pi 4 Model B.
- H.264 is a good choice because of how widely used it is and how efficient it is.

Parameter	Codecs				
Brand	H.264	H.265	VP8/9	AV1	FFV1
Type	Lossy/Lossless	Lossy/Lossless	Lossy	Lossy	Lossless
Efficiency	High	Very High	High	Very High	High
Pros	Widely used and compatible with most devices	Better version of H.264	Open source and efficient on web	Open source and very efficient	No data loss during compression, open source, efficient
Cons	Not the best for higher resolutions	More computational power and not as widely used	Not as widely used	Requires more computational power	Not typically used for live transmission

Comparison and Selection of Software

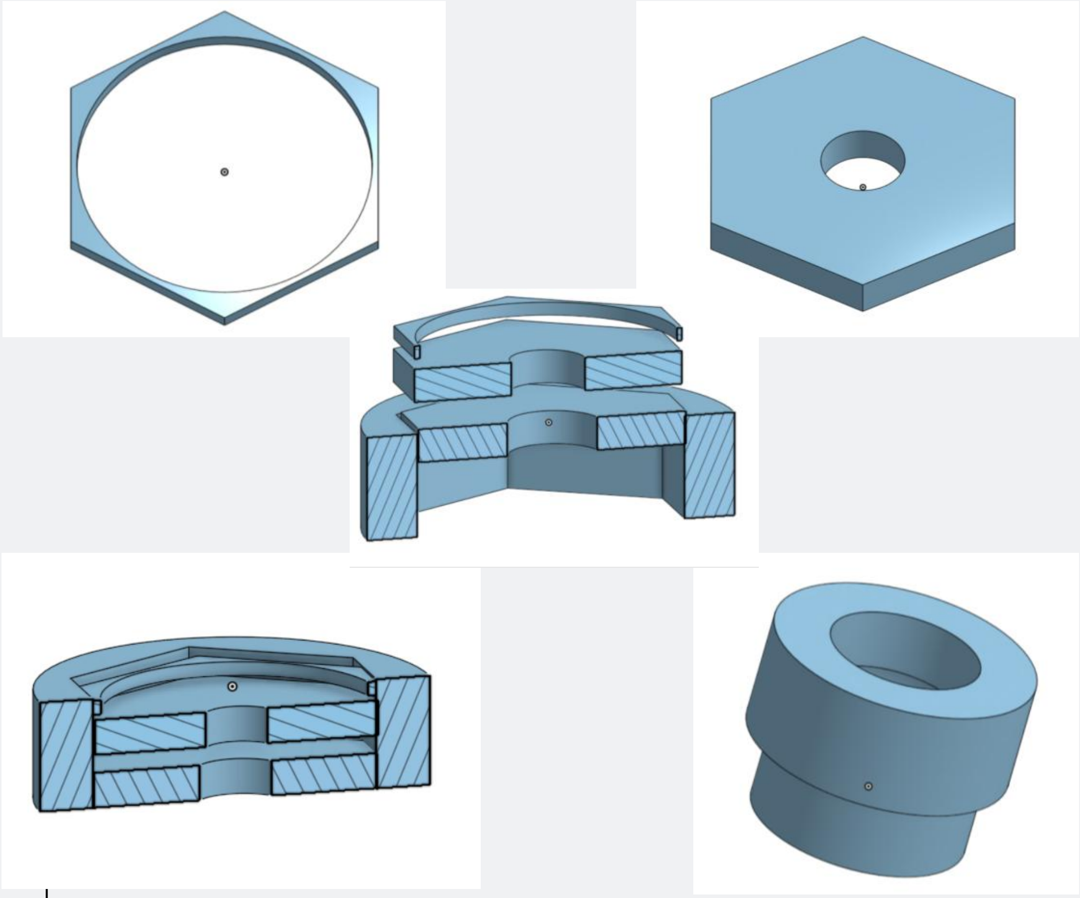
Library Comparison

- A library must be selected to utilize H.264 for compression of the video stream.
- The coding language used in this project is python so the library will be chosen from select python libraries.
- FFmpeg was selected as most other python libraries utilize Ffmpeg already.

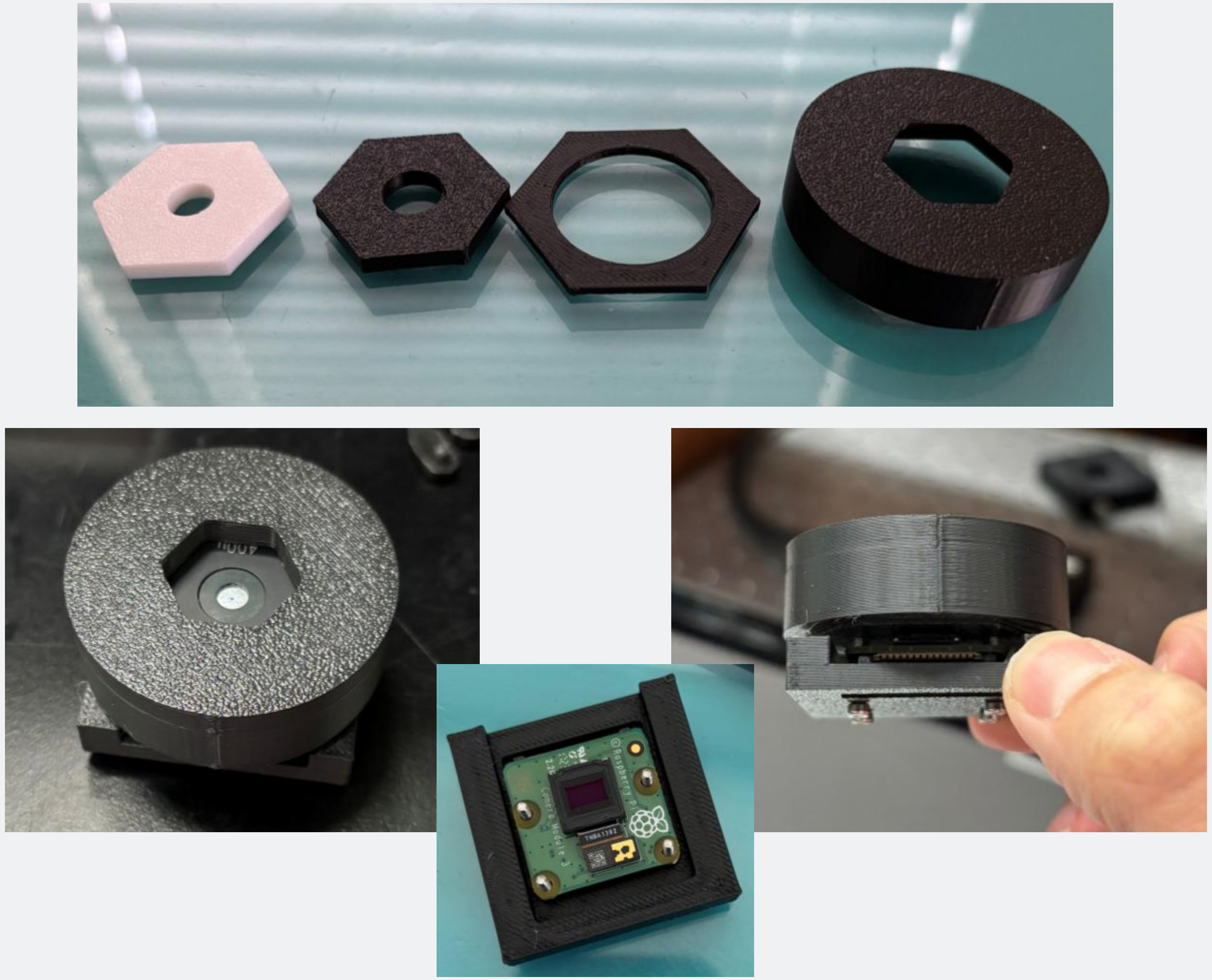
Parameter	Libraries		
Library	PyAV	MoviePy	FFmpeg-Python
Performance	High	High	High
Supports Multiple Codecs?	Yes	No (mainly a video editing tool)	Yes
Well documented?	Yes	Yes	Yes
Optimized For Live Feed?	Yes	No (Mainly a video editing tool)	Yes

Prototyping and Testing

CAD model



Prototype

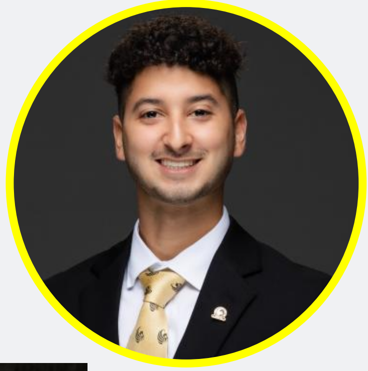


Prototyping and Testing

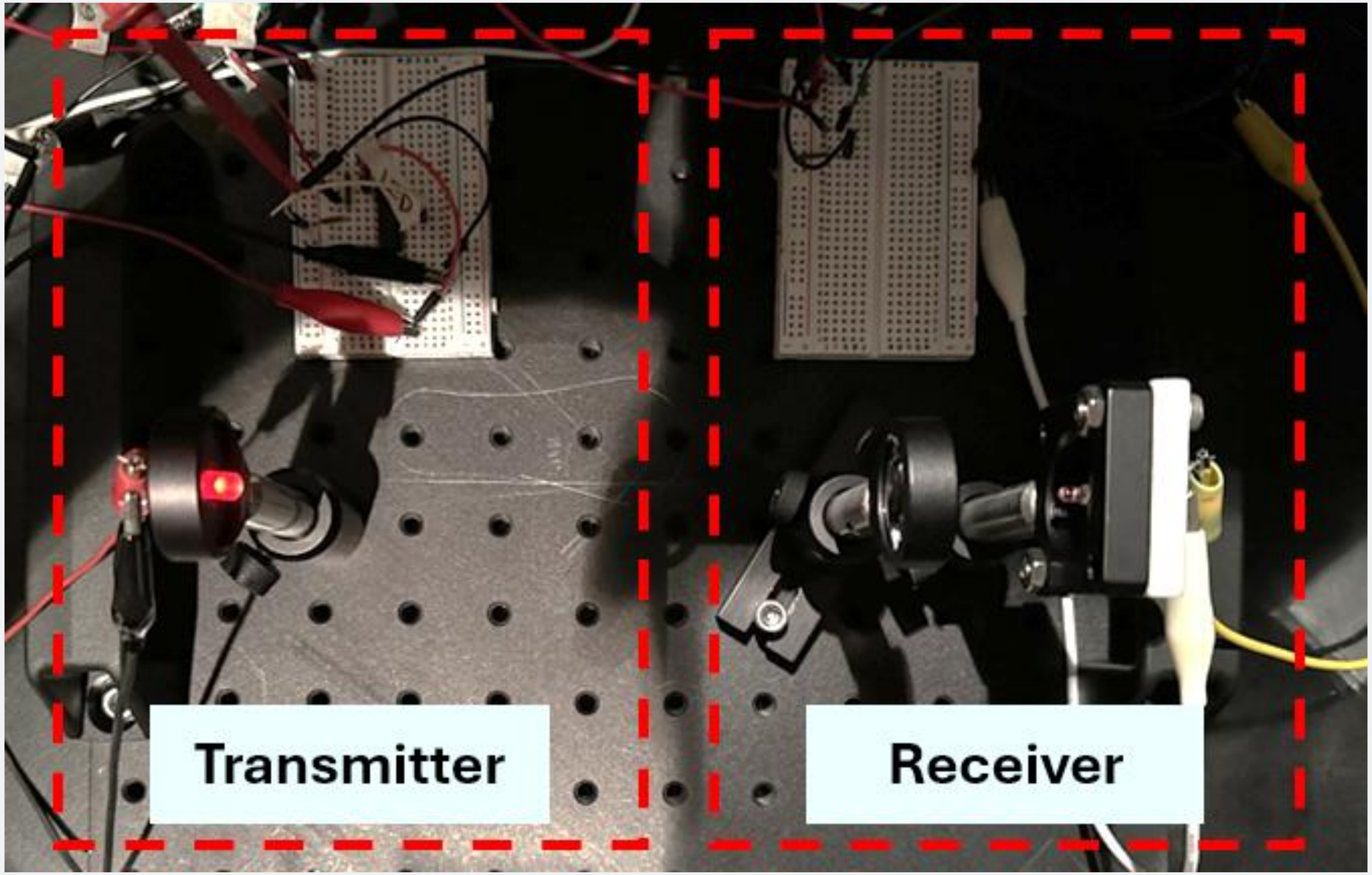
- First Trial 1/21/25

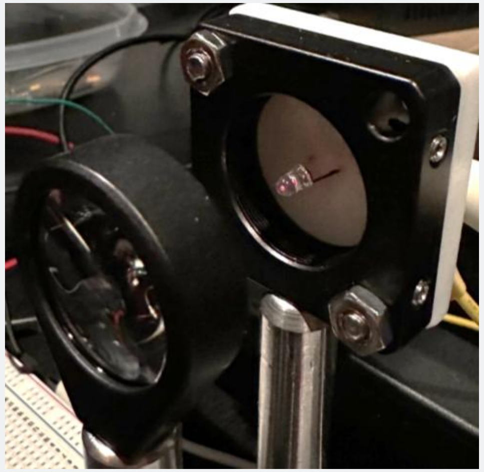
- Second Trial 1/28/25

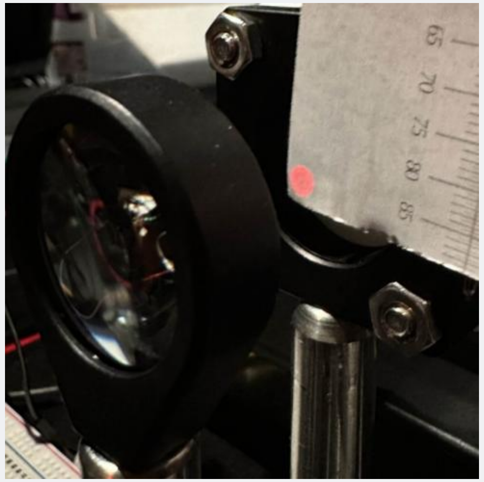
Prototyping and Testing



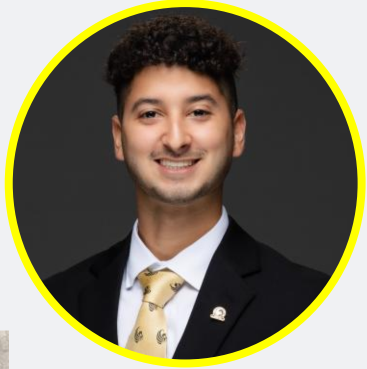
Early Free-space Audio Communications Prototype







Prototyping and Testing



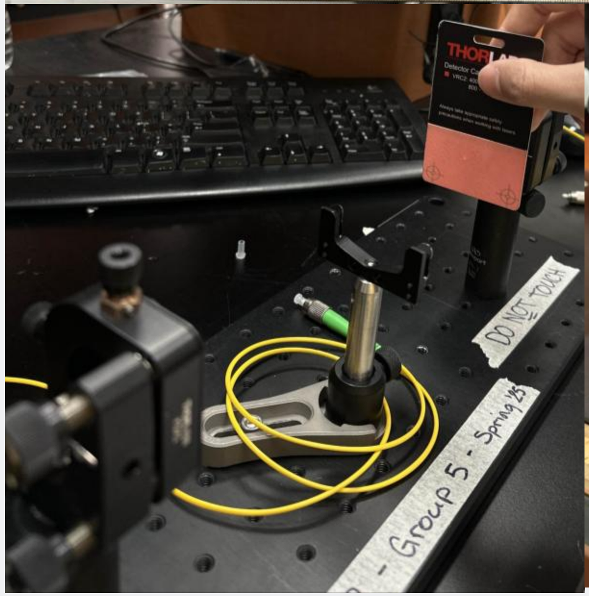
Fiber Prototype

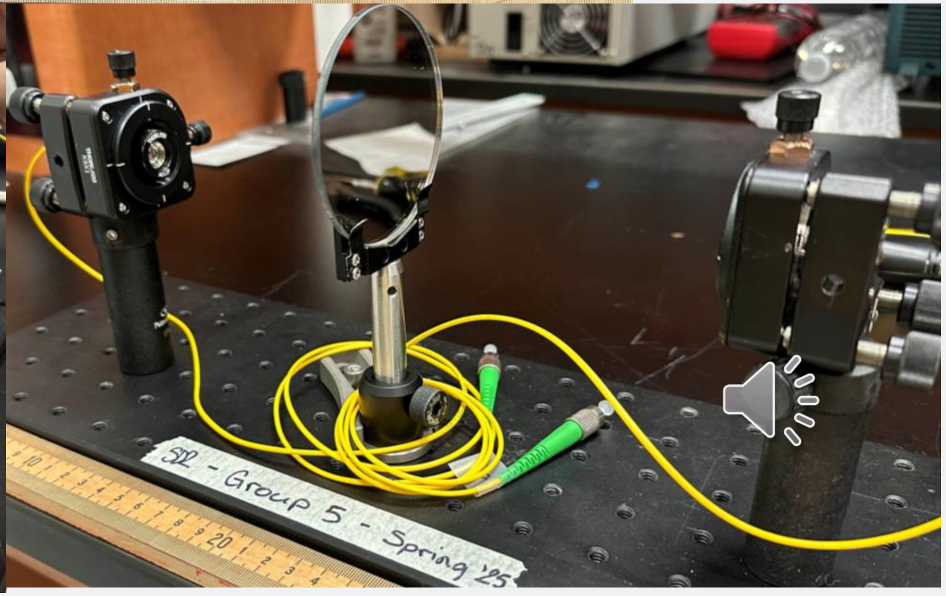
Internet speed test

888.1
Mbps download

805.7
Mbps upload

Free-space Prototype

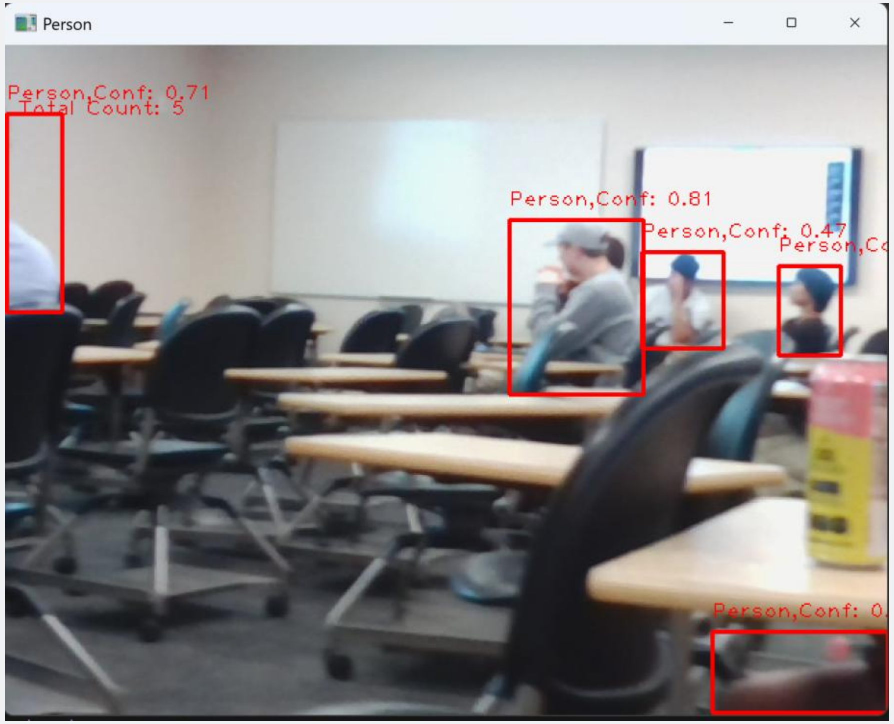




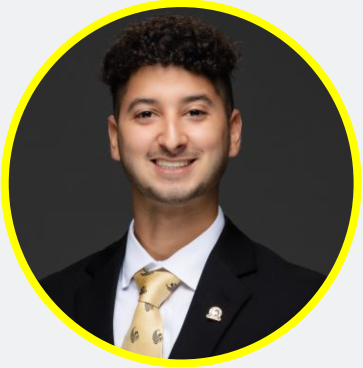
Prototyping and Testing

First Prototype

Current Prototype



Bill of Materials – Optics



Sub-System	Component	Part Name	Budget	Quantity	Per Unit Cost	Real Cost
Imaging	Camera Module	Raspberry Pi Camera Module 3	$80.00	2	$31.77	$63.54
	Imaging Optics	Pinhole	$300.00	1	$78.00	$0
		Aspheric Lens		1	$139.92	$0
		Spherical Lens		1	$35.00	$0
Communication	Tx/Rx Components	Brocade E1MG-EZX-100	$100.00	2	$48.00	$96.00
	Media Converter	Open-SFP to RJ45	$50.00	2	$18.99	$1.00
	Collimating Optics	F280FC-1550	$300.00	2	$181.00	$0.00
	Optical Fiber	SMF-28e	$25.00	2	$6.65	$13.3

Bill of Materials – Electronics

Sub-System	Component	Part Name	Budget	Quantity	Price per Item	Real Cost
PCBs	Base Carrier	iSPY	$60	5	$17	$17
	Daughter Boards	HDMI		5	$52.15	$52.15
		Ethernet		5	$40.25	$40.25
		Voltage Regulator		5	$10.20	$10.20
Power	Ext. Power Supply	Meanwell LRS-50-5	$30	2	$17.01	$34.02
PCB Components	Misc	~	~	90	$115	$115

Progress and Future Milestones

Current Status of Hardware and Software

Acquired: part has been acquired, and it is now on testing phase.

Under review: hardware/software is being reviewed to optimize results.

On the way: part has been purchased, and it is on the way.

- CMOS sensor*
- Lenses (for Image Acquisition System)
- Lens Mount/Case
- Evaluation Board
- PCB
- Lenses (collimation)
- Transceivers
- Code*

*Currently under integration phase

Future Milestones

Task	Status	Deadline
Prototype Development	In progress	Week 6
Testing*	In progress	-
Troubleshooting*	In progress	-
Optimizing*	In progress	-
CDR	In progress	February 5, 2025
Senior Design Showcase Project Summary Form Submission	In progress	February 21, 2025
Midterm Demo Group Meeting	Standby	March 10-13, 2025
Conference Paper	Standby	Week 13
CREOL Showcase	Standby	April 17, 2025
ECE Showcase	Standby	April 18, 2025

***These tasks are in progress, and our goal is to have our project fully functional by the midterm week.**

Thank you!