SynthSign – An American Sign Language Controlled Synthesizer with a Laser Projection Display

Senior Design Project – Group 8

Our Team

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Project Features

- All-in-One Music Solution: Designed for music hobbyists, offering a new way to create and enjoy music beyond traditional equipment constraints.
- Gesture Recognition Technology: Utilizes computer vision to detect user gestures and translate them into various musical tones.
- Lens System Incorporation: Applies the use of a lens system in collaboration with the computer vision into improving upon the capturing and accuracy of the user detection.
- Laser Projection Interface: Features a graphical user interface (GUI) displayed via a laser projector, enhancing user experience and interaction.
- Advanced Control System: Employs a vertically oriented polygonal mirror controlled by an ESP32 microcontroller for precise GUI projection and smooth mirror movement.

Project Goals

- Core Goals:
  - Ability to synthesize any of the 12 notes within a chromatic scale
  - Provide a 3 octave range from C3 to B5
  - Develop a machine learning model to process American Sign Language (ASL) gestures
  - Develop a Laser Projection Unit (LPU) to provide our graphic user interface (GUI)
- Advanced Goals:
  - Extend octave range from C2 to B6
  - Design a PCB for use within our LPU
  - Introduce a secondary ‘chord’ mode to synthesize triad chords based on a major key signature
- Stretch Goals:
  - Expand PCB design to encompass our microcontroller
  - Add the 12 minor key signatures to our chord mode
  - Implement a sustain functionality to emulate a sustain pedal on a piano
  - Allowing user mapped gestures

Project Objectives

- Core Objectives:
  - Determine 9 gestures for machine learning model to recognize
    - One gesture for each note in a C major scale, one for accidental flag, one for octave change
  - Implement a sound generation library within the application software
- Advanced Objectives:
  - Implement an additional 8 gestures
    - One for each of the 7 triad chords, and one to change key signature
  - Expand sound library for extended note range
- Stretch Objectives:
  - Implement additional required gestures for minor keys and sustain functionality
  - Create an API that allows users to create new gestures and build a new model

Engineering Requirements

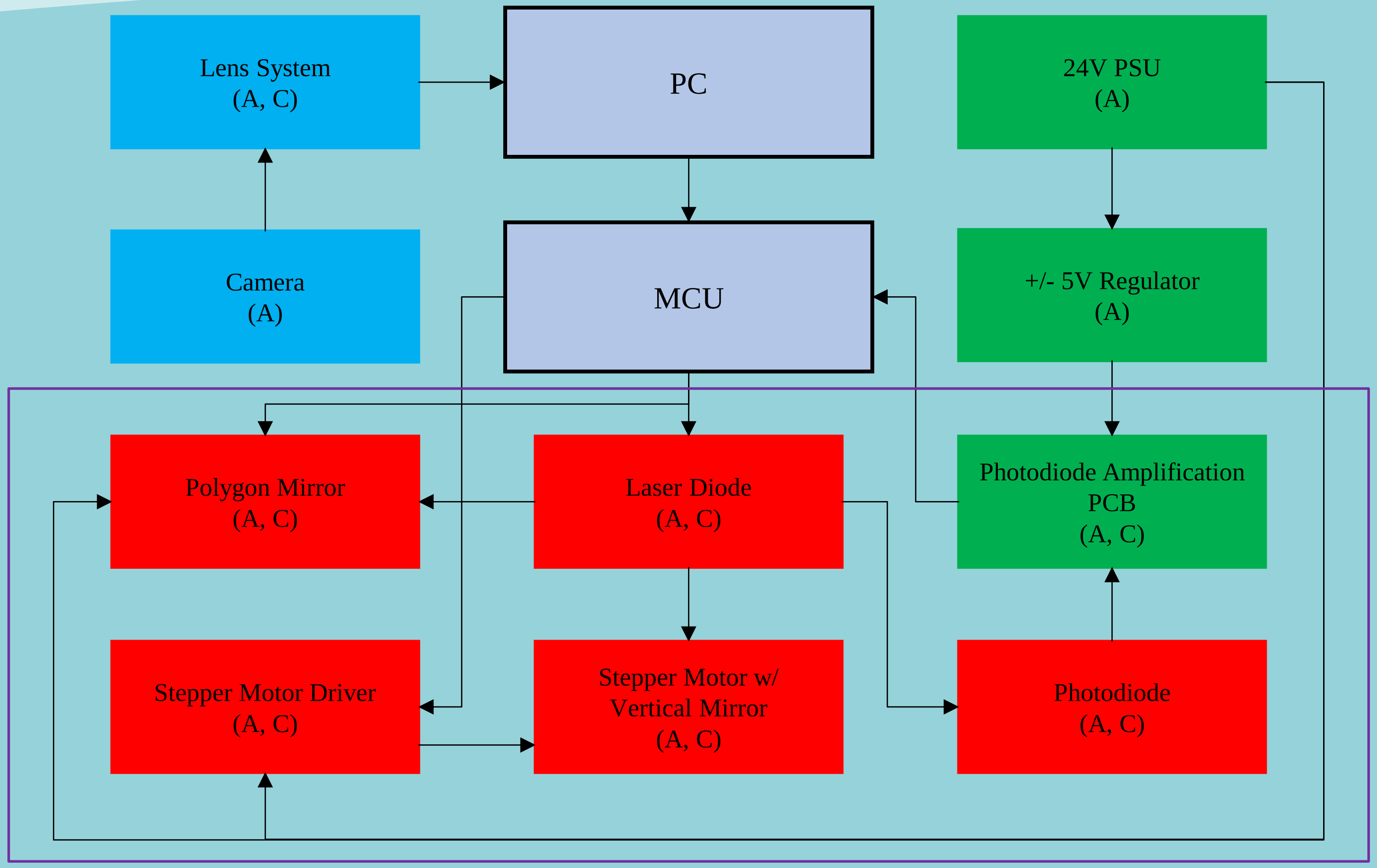
Requirement	Specification	Description
Gesture Detection Accuracy	Shall exceed 80% of captured gestures.	The correct response should be produced from a given gesture for at least 80% of all gestures.
Dimensions	Smaller than 12” x 12” x 6” with a weight not exceeding 20 pounds.	The system should be small enough for easy transportation.
Response Time	Less than 2 seconds	Device must detect and respond to a gesture within two seconds.
Recognition Distance	Less than or equal to 5 feet	User input should be detected within 5 feet directly in front of the camera.
Camera FOV	Horizontal: 60 – 90 degrees Vertical: 45 – 60 degrees	Under these conditions, the user may not have to be directly in front of the camera for gestures to be detected.

Engineering Requirements

Requirement	Specification	Description
Power	120VAC 60Hz power, via a type B wall plug.	Power must be easy to obtain to promote portability.
Laser Projector Projection Region	12” x 9” at 12” from any flat surface	Device data must be easily relayed to the user.
Camera Resolution	720x1280	The images must be of high enough quality for the image processing algorithm to function properly.
Cost	All materials should not exceed $400	Cost should be limited to remain affordable.

Hardware Overview

Hardware Block Diagram



*Purple box indicates the overall Laser Projection Unit (LPU)

Legend

Member Block Assignment

- Tristan Barber
- Jacob Goc
- Christopher Jean
- Christian Parades

Status Codes

To Be Acquired (TBA) – block will be purchased or donated
Acquired (A) – block has been donated or purchased
Research (R) – block design approach is being investigated
Design (D) – block is currently being designed
Prototype (P) – block design is currently being prototyped
Completed (C) – block design is a finished prototype

Machine Learning Technology Comparison

What we need:

- System with enough processing power to run our machine learning models with enough performance to meet our three key engineering specifications
- Ability to communicate with our ESP32 Development Kit

Raspberry Pi 4 + Coral USB Accelerator

- Originally selected among a few SBC options
- Paired with a Coral USB Accelerator for use with TensorFlow Lite ML Models
- 4GB Ram
- Coral USB Accelerator does not improve performance of MediaPipe HandDetector model we are using
- Could communicate with ESP32 using UART

Laptop (Windows Machine)

- Allows for use of TensorFlow instead of TensorFlow Lite
- More powerful system allows for better performance without GPU acceleration
- More compatible with MediaPipe HandDetector Model
- Could communicate with ESP32 using UART

Machine Learning Technology Performance Comparison

- Originally selected Raspberry Pi 4 + Coral USB Accelerator
  - After some performance concerns, benchmark tests were run to compare performance between Pi 4 and a laptop. As shown below, we could not meet our design specifications using the Pi 4.

Raspberry Pi 4:	1	2	3	4	5	6	7	8	9	10	% Correct
A:	A	A	A	A	A	A	A	A	A	A	100%
B:	B	B	F	B	D	B	F	B	B	B	70%
C:	C	C	O	C	E	C	C	O	C	O	60%
D:	D	D	D	D	D	F	D	D	F	D	80%
E:	E	E	E	A	C	E	E	E	C	E	70%
F:	F	F	F	F	F	B	F	F	F	F	90%
G:	G	G	G	G	G	G	G	G	G	G	100%
Octave (ASL O):	O	O	C	O	O	C	O	O	O	E	70%
Accidental (ASL K)	K	D	D	G	D	K	G	D	K	D	30%

Laptop:	1	2	3	4	5	6	7	8	9	10	% Correct
A:	A	A	A	A	A	A	A	A	A	A	100%
B:	B	B	B	B	B	B	B	B	B	B	100%
C:	C	C	C	C	C	C	C	C	E	C	90%
D:	D	D	D	D	D	D	D	D	D	D	100%
E:	E	E	E	E	A	E	E	E	E	E	90%
F:	F	F	F	F	F	F	F	F	F	F	100%
G:	G	G	G	G	G	G	G	G	G	G	100%
Octave (ASL O):	O	O	O	O	O	O	O	O	O	O	100%
Accidental (ASL K)	K	D	K	K	K	K	K	D	K	K	80%

	Steady State Inferencing FPS	Transitionary State Inferencing FPS
Pi 4 + TPU	5-6 FPS	2-3 FPS
Laptop	15 FPS	13 FPS

  - Gesture detection accuracy specification is 80%. Pi 4 averaged 74% and laptop averaged 96%
  - Additionally, laptop provided an average 173% increase in inferencing FPS, with a 420% increase during transitionary periods
    - Inferencing speeds are important for meeting the gesture detection speed specification of 2 seconds.

Machine Learning Technology Choice - Laptop

- Although it was not our first choice, our team ultimately decided that the inclusion of a laptop was necessary for meeting our design specifications
- Added bonus is that the application software can now be marketed as a ‘software package’
  - This way, potential users could download an executable and run the synthesizer portion of the software from Windows machine

- For those interested, an extensive four-page write-up justifying our decision to switch to a laptop can be found on our website.

Microcontroller

Microcontroller	MSP430FR6989IPZ	ATmega328P	ESP32-S3
Cost	$10.77	$2.89	$1.85
Low-Power Mode	Yes	Yes	Yes
GPIO Pins	83	23	45
Clock Speed	16 MHz	20 MHz	240 MHz
Operating Voltage	1.8V ~ 3.6V	2.7V ~ 5.5V	3V ~ 3.6V
ROM Size	128KB	32KB	384KB
RAM Size	2K x 8	2KB	512KB
SPI	4	3	4
UART	2	2	3
I2C	2	2	2
USB	No	No	1

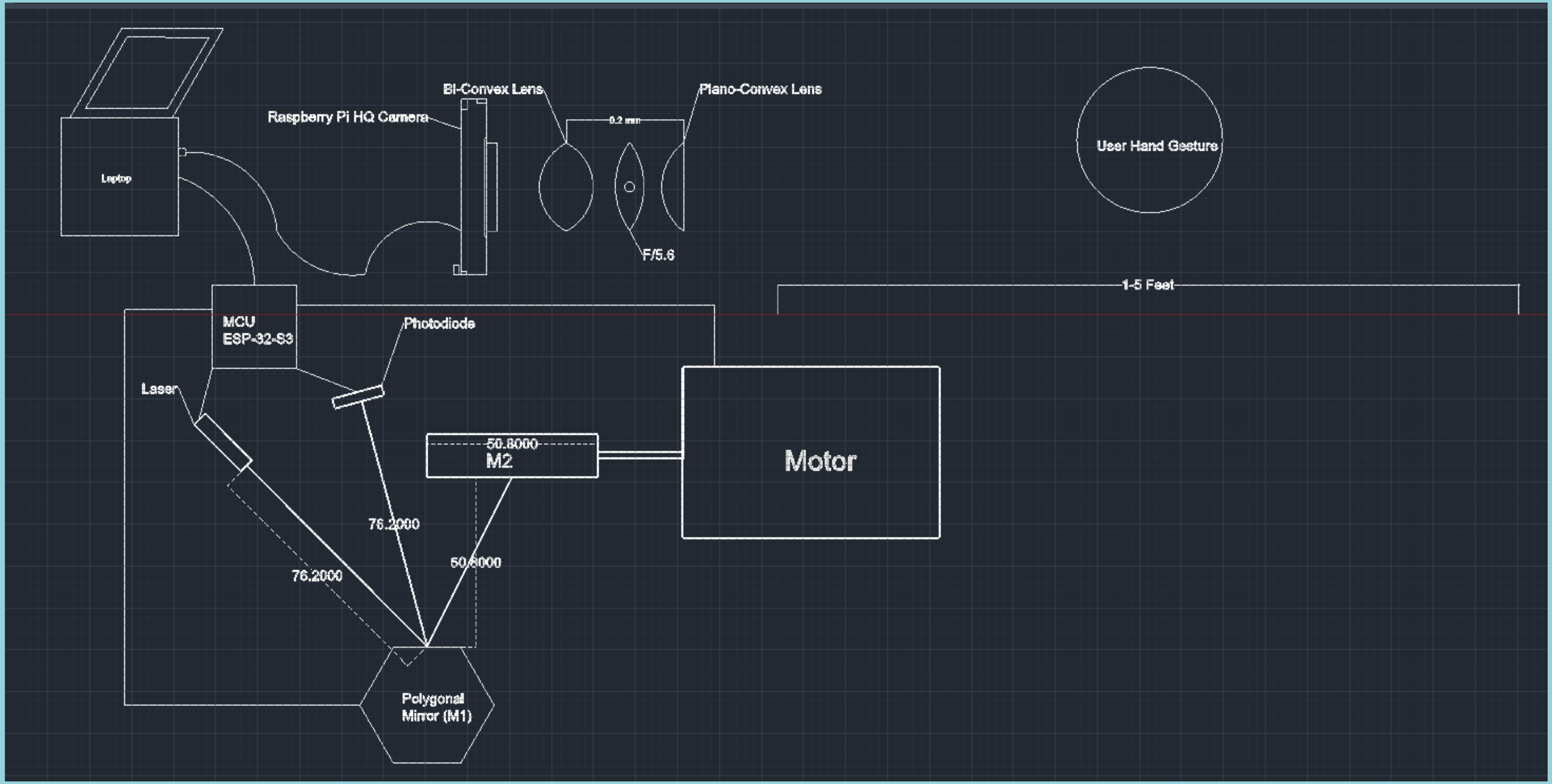
Key Features of ESP32-S3:

- 32-bit Dual-Core Processor: Max clock speed of 240 MHz, ideal for real-time gesture analysis.
- Built-in Wi-Fi and Bluetooth: Provides enhanced connectivity options.
- Dual Mode Bluetooth: Enables efficient low-energy communications.
- Optimized for IoT Applications: Well-suited for services and software integrating data analysis and decision-making.

Critical Role in the Project:

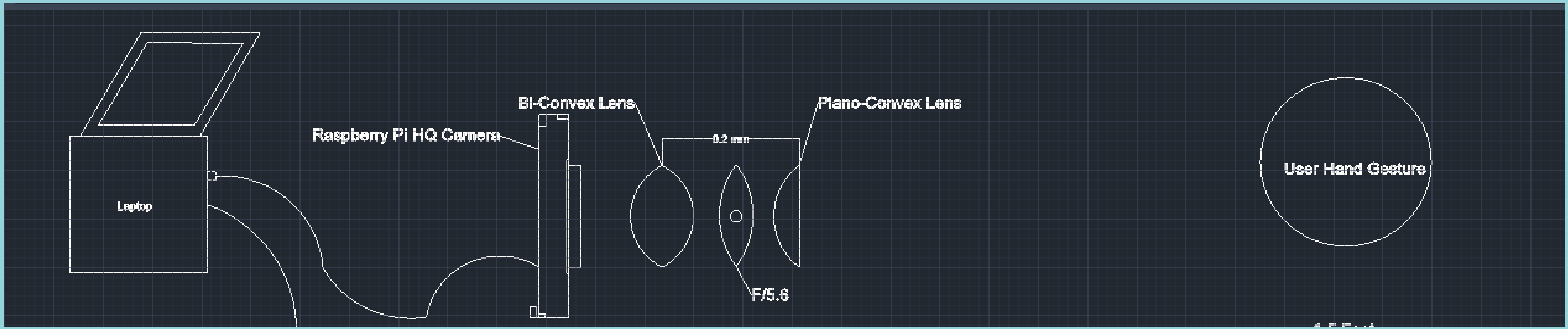
- Managing the Laser Projection Unit: Adjusting laser intensity, focus, and projection patterns for precise visual output.
- Serving as a Bridge: Connecting the computer and laser projection unit, ensuring coordinated operation.
- I/O Pin Allocation: Facilitating communication with peripherals like the laser projection unit, computer, and Bluetooth module.

Overall Optical Schematic Diagram



Lens System Schematic

- Lens System



Lens System Design

Compounded Lens Equation

$$\frac{1}{f} = \frac{1}{f1} + \frac{1}{f2} - \frac{d}{f1f2}$$

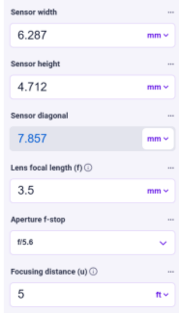
- Our lens system will be fixated in a housing within an m12 lens adapter, that will be placed within a m12 mount fixed on our selected camera.
- Comprising of the two lenses we have selected via our research and simulation within Zemax of a bi-convex lens and a plano-convex lens.
- An aperture will be placed within these two lenses.
- To understand this firstly, we used the compounded lens equation to gather our two lenses at a fixed distance to reach our total effective focal length.
- Since the bi-convex lens (f1) contains a focal length of 4.5mm and the plano-convex lens (f2) contains a focal length of 15mm, with the correct spacing between, we were able to calculation the focal length of the system.
- This turned out to be 3.56mm, as our total effective focal length.

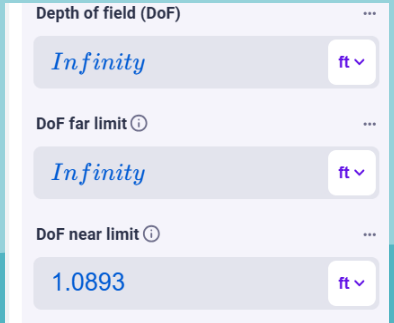
TECHSPEC® 3mm Dia. x 4.5mm FL Uncoated, Double-Convex Lens	Lens #1 (f1)
TECHSPEC® 12.7mm Dia. x 15.0mm FL, Uncoated, Plano-Convex Lens	Lens #2 (f2)

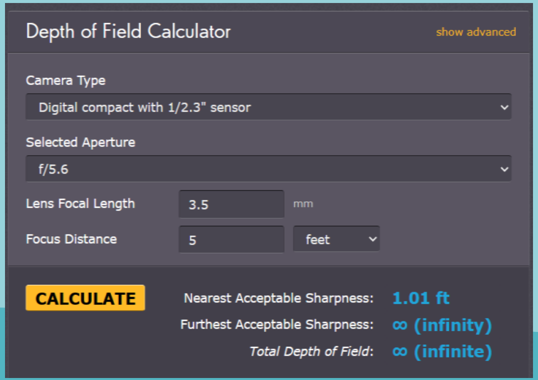
Aperture Implementation in System

Aperture Size:f/#	
Small Aperture = High f/#	Deeper DOF
Large Aperture = Low f/#	Shallow DOF

- Due to the fact that our sensor size is a crucial component towards our distance requirement, we implemented an aperture towards our lens system.
- Since we need to meet a specification of 5 feet, this required a mid-length aperture that would allow for a deeper depth of field.
- However, we had to properly balance the aperture size due to the light loss causing a significant degrade towards our overall image quality.

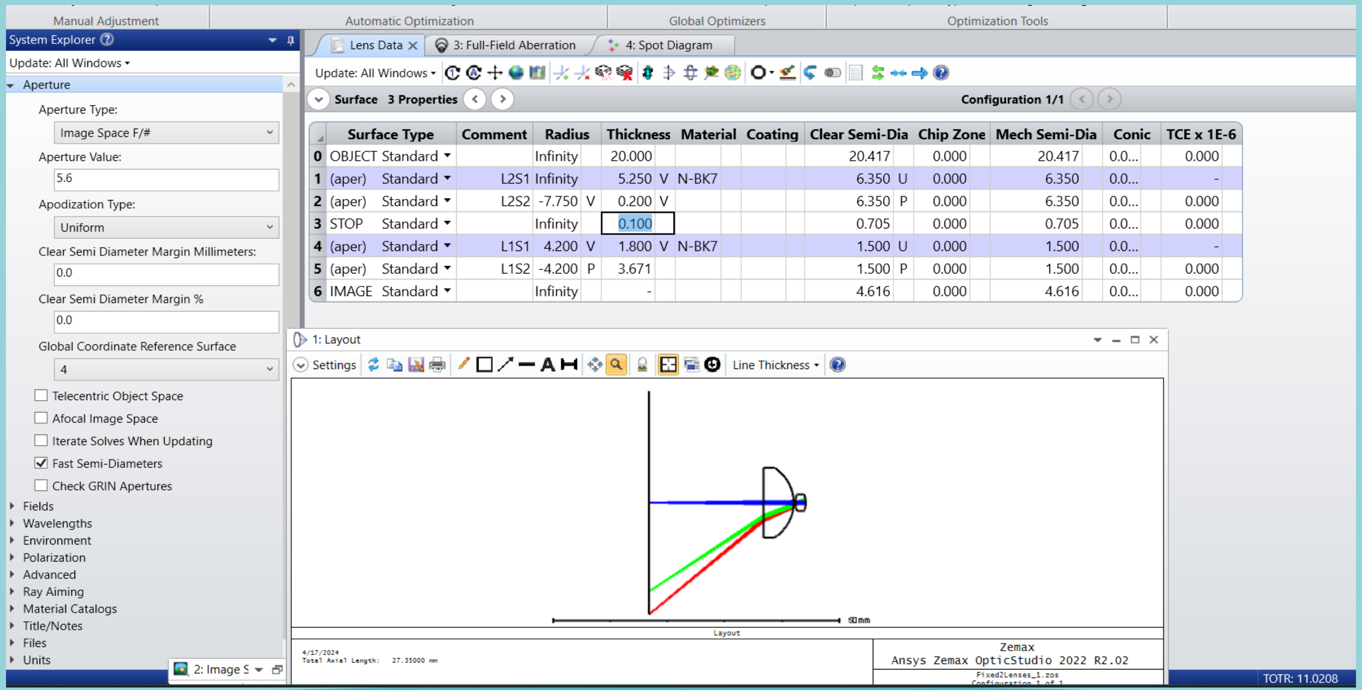






Lens System Zemax

- In Zemax, we were able to run a simulated idea of what our lens system would look like.
- From the lens data, we were able to properly place the distances in which we place the lenses, as mentioned before in the previous slides.
- From the layout, we can visually see the proper placement within the setup, as well as the aperture size of f/5.6.

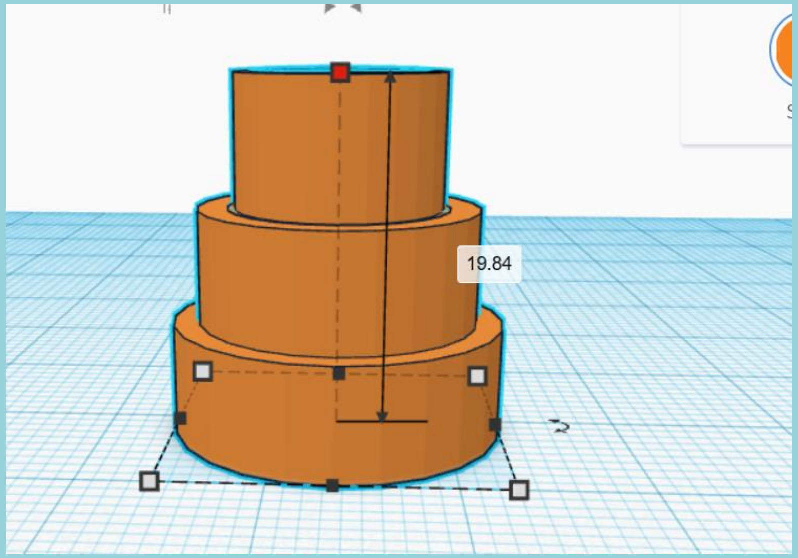


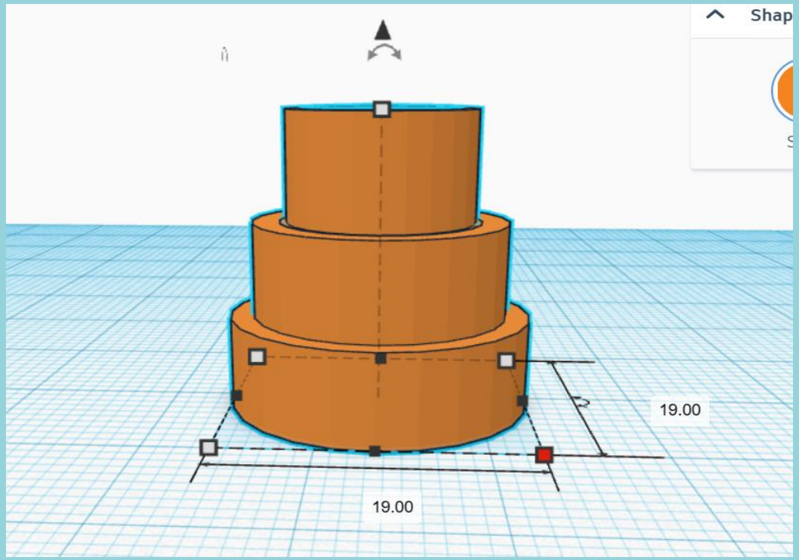
Lens System Zemax Data

- To help with understanding the way our lens system interacts, we were able to gather information in our standard spot diagram and the image simulation.
- As we can see, the images appears to have a vignetting effect and slight distortion towards the edges, with the central point of the image being clear.

Lens Housing

- Within the lens holder, we will be implementing a few spacers to help properly space the distances between the lenses and aperture.
- Due to the m12 lens adapter being utilized to help thread the lens system into place, we had to carefully create balanced sizes amongst, understanding that the adapter had a fixed size.





Camera Selection

- We decided upon the raspberry pi high-quality camera, primarily due to a method in which we found that could allow for adaptation towards usb connectivity.
- However, this will involve using an adapter to properly integrate directly to a laptop
- The choice was ultimately made due to the necessary need for a larger sensor than what USB cameras offer.
- As well it will allow for the proper construction of a lens system to meet our goals and specs regarding field of view and sharpness throughout the image.

Camera:	**Raspberry Pi HQ Camera**	**Arducam 1080p Usb Camera**	**Logitech C922 Webcam**
Camera Type:	CSI	USB 2.0	USB 2.0
Resolution:	4056 x 3040	1945 x 1109	1920 x 1080
Sensor:	12.3Mpixels	2Mpixels	3Mpixels
FOV:	Needs Lens	160	78
Focal Length:	Needs Lens	6	Autofocus
Optical Size:	1/2.3"	1/2.8"	N/A
Price:	$50.00	$50.00	$56.00

Raspberry Pi HQ Camera

- Since it was apparent that we needed a larger sensor then a typical USB camera, we implemented an adapter to allow for the use of a larger sensor, which will allow for more light to converge towards our sensor.
- The Arducam CSI to USB adapter allows for the use of our camera with our lens system.
- This is crucial in allowing for the camera to allow for more light to reach its sensor when passing through the lens system in its entirety.

Raspberry Pi HQ Camera
Sensor: IMX477
Sensor Size: 6.287mm x 4.712mm (7.9mm Diagonally)
Sensor Width: 6.287mm
Sensor Height: 4.712mm
Pixel Size: 1.55µm x 1.55µm = 1.55µm
Optical Size 1/2.3"

Focal Length Required:

$$F = \frac{Horizontal\ Sensor\ Dimension}{2 * \tan(\frac{AFOV}{2})}$$

Camera Effective Focal Length Requirement

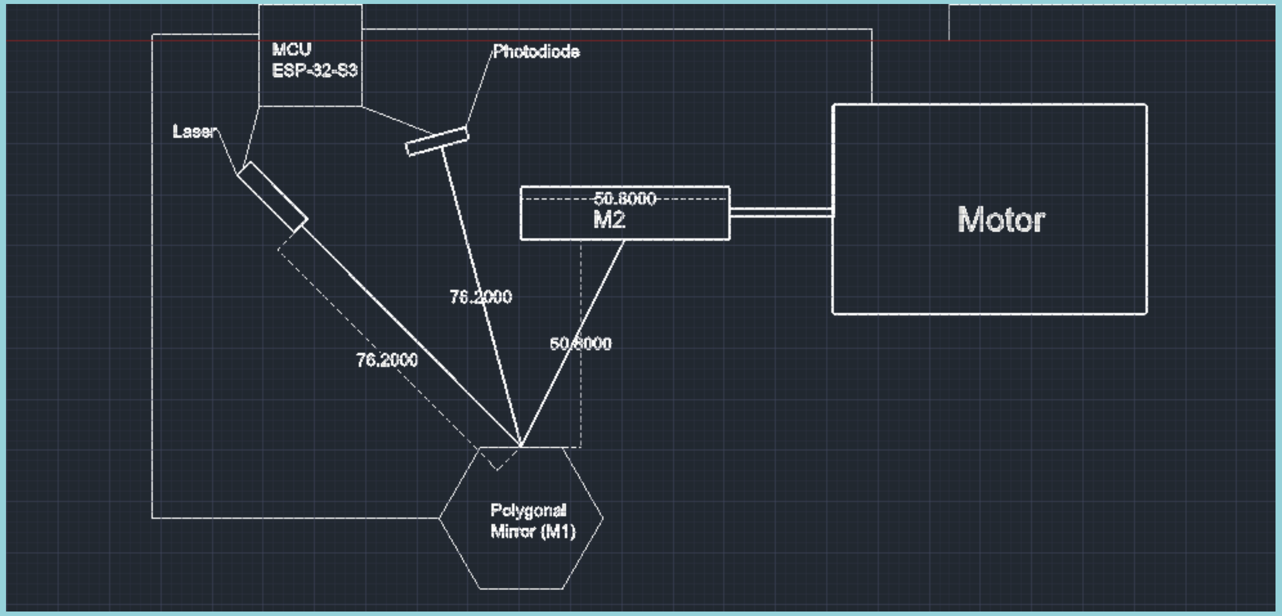
- With our selected camera of the raspberry pi hq camera, we had to calculate the necessary focal length required to achieve the angular field of view in either direction.
- Seeing this, to meet the specification regarding the field of view, we had to use the focal length requirement equation above in conjunction with the sensor size to see the total focal length required.
- As we can see from the calculations below, we need at least a focal length of 3.746mm to achieve the angular field of view in either direction, which we meet currently from our calculated focal length and zemax simulation of 3.5mm.

Focal Length Requirement on Angular HFOV	
Angular HFOV (in Degrees)	Focal Length (mm)
60	5.445
65	4.934
70	4.489
75	4.097
80	3.746
85	3.431
90	3.144
95	2.88
100	2.638
105	2.412
110	2.201

Focal Length Requirement on Angular VFOV	
Angular VFOV (in Degrees)	Focal Length (mm)
30	8.793
35	7.472
40	6.473
45	5.688
50	5.052
55	4.526
60	4.081
65	3.698
70	3.365
75	3.07
80	2.808

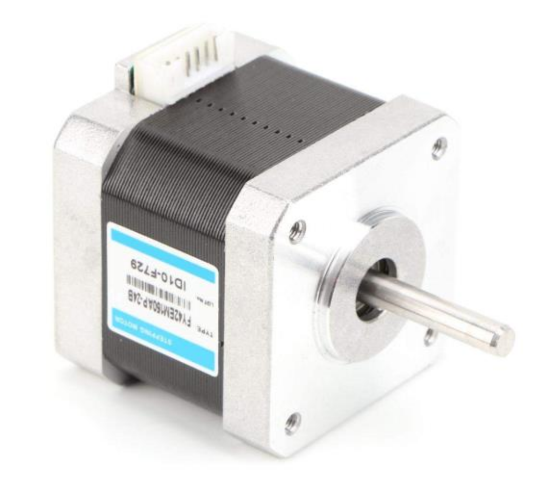
LPU Schematic

The schematic for our LPU is shown on the right. All units are in millimeters.
Not shown is the angle the laser diode makes with the polygonal mirror, which is around 49.4 degrees.



Vertical Motor Selection

- Selected the NEMA 17, as although it is the most expensive, it allows the embedded SW to track the position of the motor. This is critical for coding the LPU



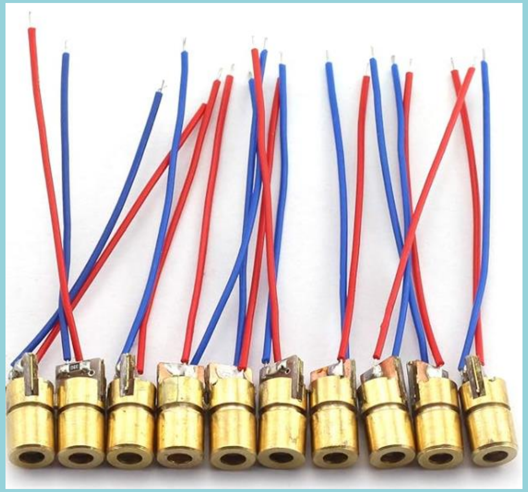
	PPN7PA12C1	ROB-11696	711	NEMA 17
Rated Voltage	5VDC	12VDC	6VDC	24VDC
Voltage Range	1-7VDC	1-3VDC	4.5-9VDC	-
Load Current	270mA @5VDC	110mA @1VDC	-	1.5A per phase
Dimensions	D = 15.6mm	-	D = 20mm	4.2cm x 4.2cm x 4cm
Total Length	31.8mm	-	28mm	6.4cm
Shaft Length	9.5mm	-	<8mm	2.2cm
Mass	10g	26g	17.7g	-
Load Speed	11600rpm	6600rpm	9100rpm	600rpm
Price	$3.34	$2.10	$1.95	$16.71

Horizontal Polygon Mirror and Motor

- Not many product options out there, given that this is a specific piece of equipment.
- Selected a Brother MFC-8220. This is a motor and mirror combo out of a Brother printer.
  - 24V DC input
  - Rotational speed set by a clock signal sent from the MCU

Laser Diode Selection

- Selected Tegg model because the price was significantly better than all other options
- With the price being so cheap, reliability is questionable. However, it is easy to swap out laser diodes if need be.



	HL6312G Laser Diode	L635P5 Laser Diode	Instapark DRM104-D003	Tegg Mini Laser Diode
Optical Power	5mW	6mW	1.8-2.8mW	5mW
Operating Voltage	2V	2V	3V	3.3V
Operating Current	40mA	30mA	20-40mA	20-40mA
Wavelength	625-640nm, 635nm typical	635-643nm	640-660nm, 650 typical	650nm
Beam Divergence	8° parallel, 31° perpendicular	8° parallel, 32° perpendicular	N/A	N/A
Spot Size	N/A	N/A	10mm at 15m	N/A
Price	$24.45	$27.13	$4.79	$6.99 for 10

Photo Diode Selection

- Hamamatsu S5973 met all our estimated requirements at the lowest cost.
- A small photosensitive area is perfectly fine, and even preferable. The pulse emitted by the photodiode should be as short as possible for LPU motor synchronization timing.

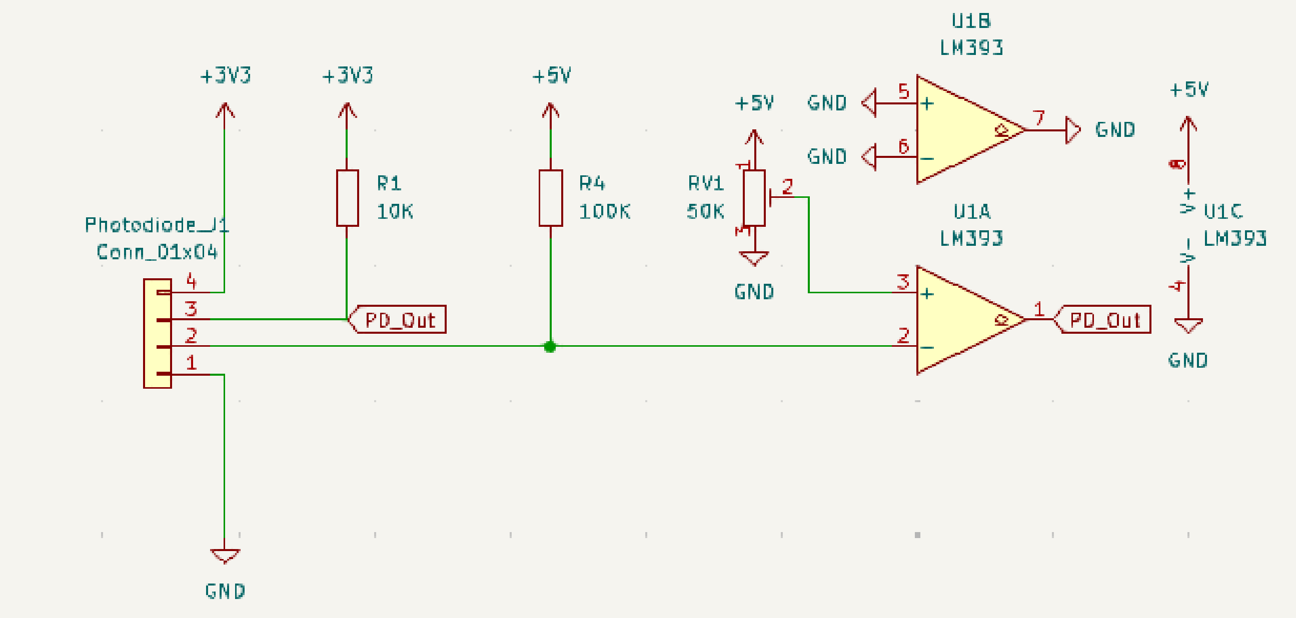
	Hamamatsu S2387-33R	Hamamatsu S5973	OSI Optoelectronics UV-015
Photosensitivity	0.37A/W @ 633nm	0.44A/W @ 660nm	0.4A/W @ 633nm
Short-circuit Current	5.8μA	90nA	100μA
Dark Current	5pA	1pA	-
Photosensitive Area	2.4mm by 2.4mm	0.4mm diameter	3.05mm by 3.81mm
Operating Temperature	-20°C to 60°C	-40°C to 100°C	-20°C to 60°C
Price	$49.95	$24.95	$49.95

Photodiode Comparator Circuit Requirements

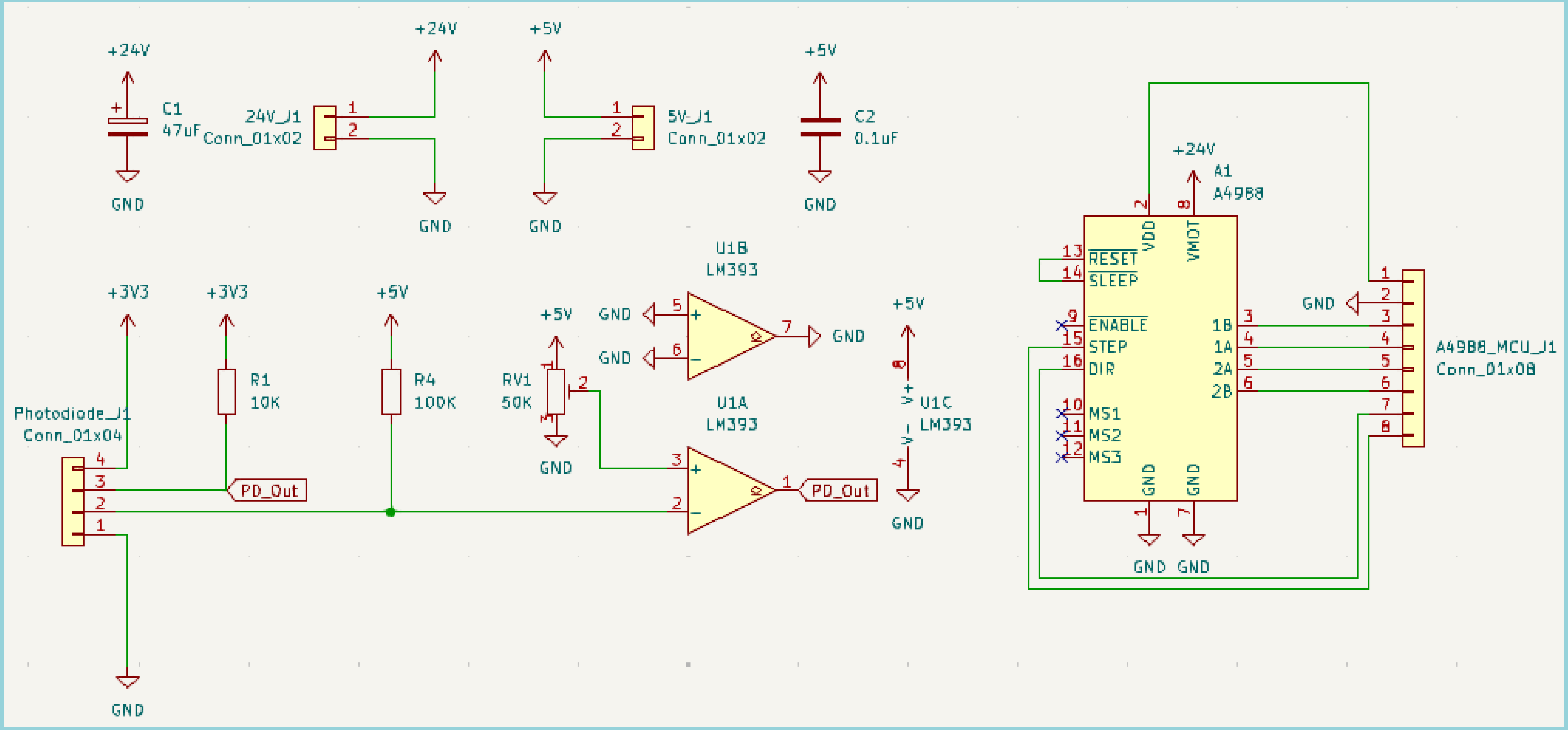
- Voltage comparator circuit that uses a potentiometer connected to a 5V source to allow for an adjustable reference voltage
  - 2 pin connector must be used to provide 5V power and GND
- Photodiode must not be soldered directly onto the board, as it has optical mounting constraints within the LPU
  - Thus, must be connected through jumper wires with male pins on the PCB (2 pins)
  - Additionally need a pin for MCU to provide 3.3V power and a pin for MCU to read circuit output
- A4988 Motor Driver should be solderable right onto the PCB
  - 8 pin connector must be used to allow MCU to interface with A4988
  - 2 pin connector must be used to provide 24V power and GND
- Decoupling caps for the 5V and 24V sources

Photodiode Comparator Circuit Schematic

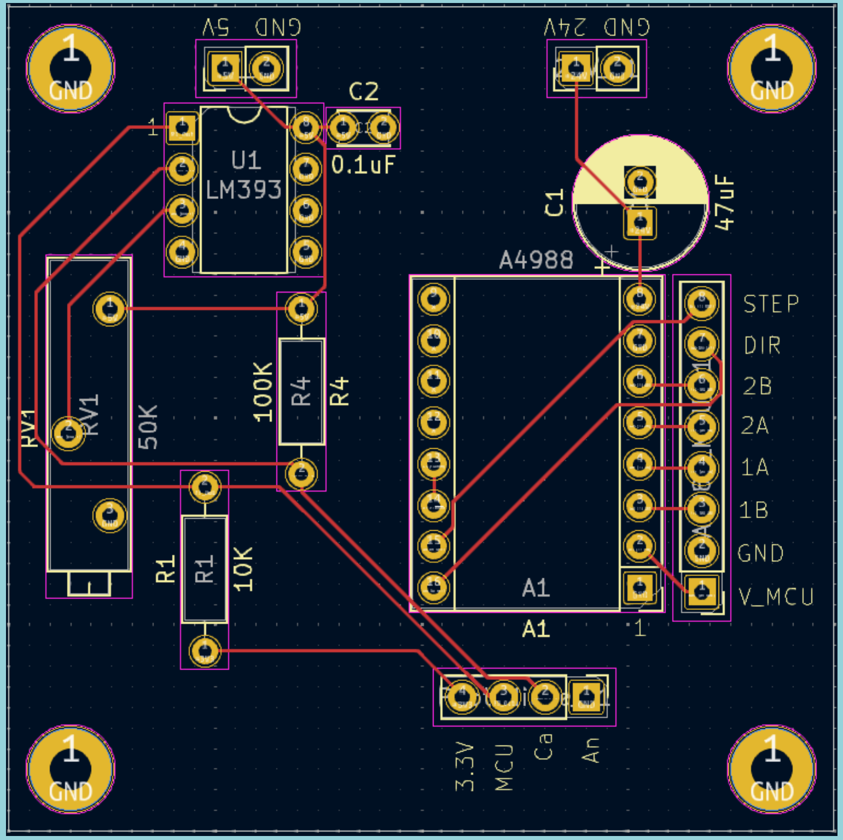
- Photodiode connects in a reversed biased configuration between pins 1 and 2
  - This results in a voltage divider with the 100K resistor
- 10K pull-up resistor is used on pin 3, which connects to MCU
- Pin 4 allows MCU to provide 3.3V source
- Unused comparator pins are grounded



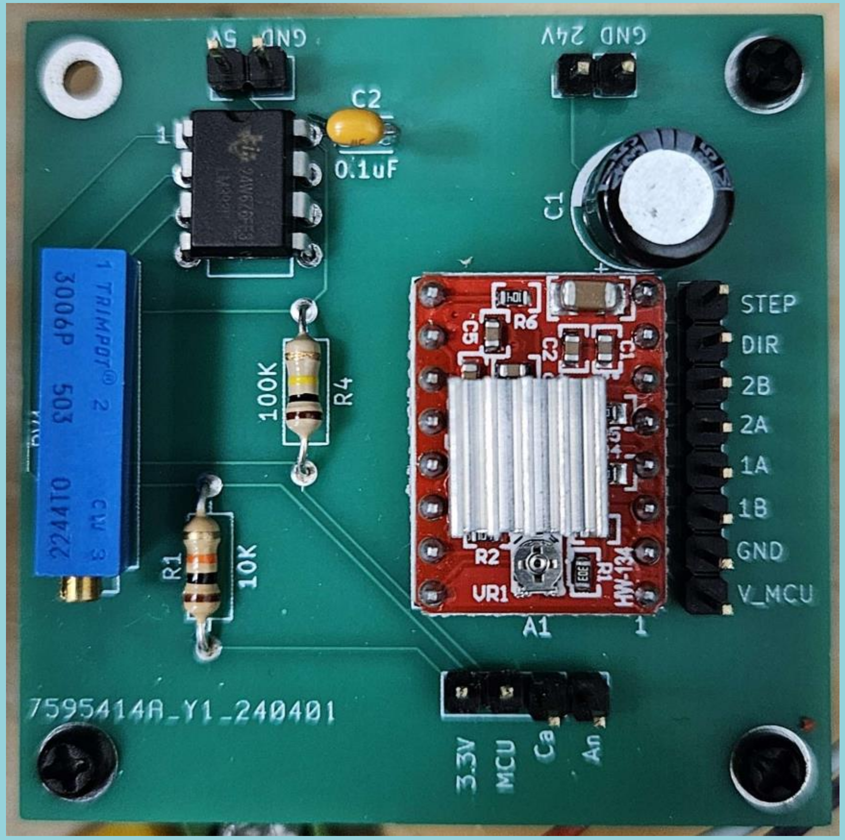
Overall Circuit Schematic



PCB Layout



GND 5V
GND 24V
C2
0.1uF
U1
LM393
C1
47uF
A4988
RV1
50K
100K
R4
R1
10K
A1
STEP
DIR
2B
2A
1A
1B
GND
V_MCU
3.3V
MCU
Ca
An
GND



GND 5V
GND 24V
C2
0.1uF
C1
100K
R4
R1
10K
A1
STEP
DIR
2B
2A
1A
1B
GND
V_MCU
7595414A_Y1_240401
3.3V
MCU
Ca
An

Power Distribution

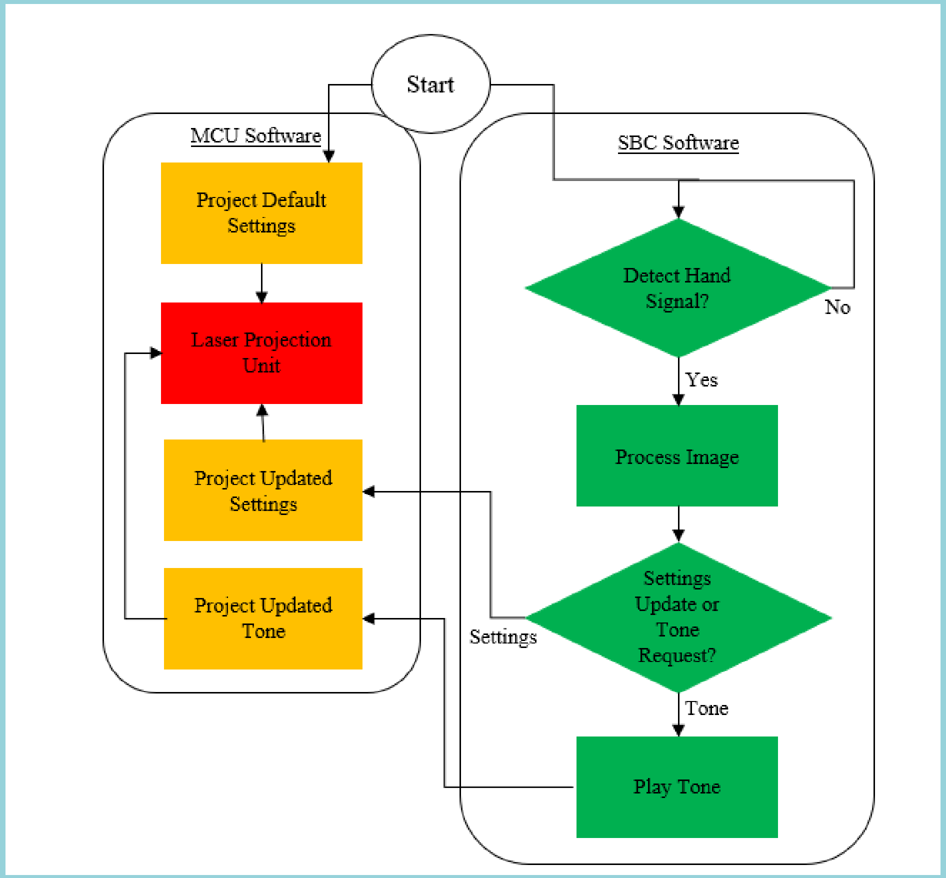
- 24V 10A DC Power Supply Required as primary power source for the system:
  - Vertical motor requires 24V supply
  - Horizontal motor requires 24V supply
  - Horizonal motor has a startup current of 8 Amps

- 24V to 5V DC/DC Converter is used to provide auxiliary power:
  - 5V used for Vcc within the photodiode comparator circuit
    - 3.3V also used within photodiode comparator circuit, comes directly from ESP32 GPIO pins

Software Design

Software Block Diagram

- Software is broken down into two main components
- Application Software controls object detection and playing sounds
- MCU Software controls the laser projection unit (LPU)



Application Software Overview

- Multi-threaded application, with between 5 to 8 concurrent threads at any given time
  - Main thread handles data transfer between other threads
  - Thread for getting video from the webcam
    - Uses OpenCV to capture webcam data
  - Thread for classifying the image
    - Uses MediaPipe for HandTracking Module
    - Uses cvzone for classifier object that runs our machine learning models
  - Thread for playing notes/chords based on image classification results
    - This thread will spawn 1-3 sound wave threads depending on synth or chord mode
    - Sine wave generation function was written, and sine wave data is passed to PyGame library for audio waveform creation and output
  - Thread for outputting video stream with classification results
    - Primarily used for testing and debugging, as the LPU provides the GUI

Machine Learning Technology Comparisons

TensorFlow

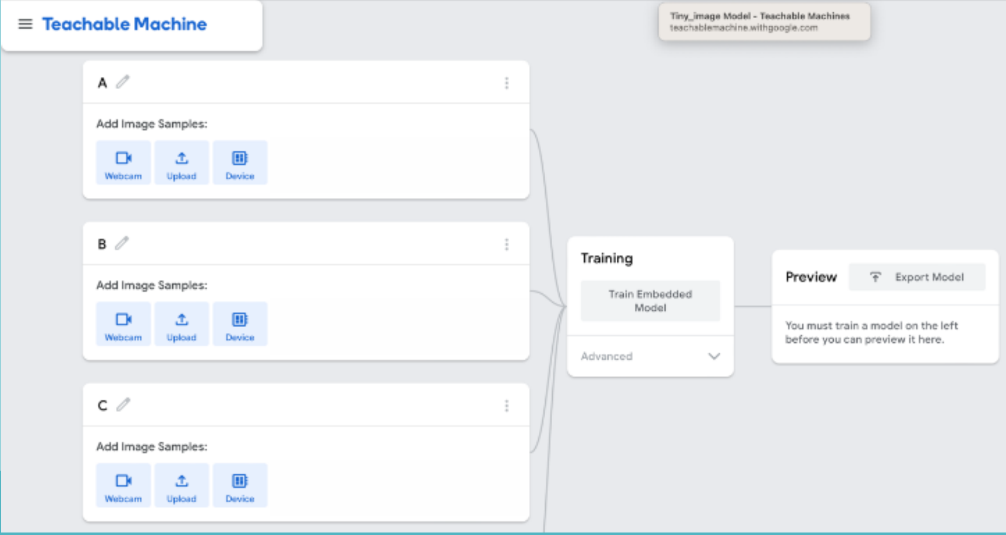
TensorFlow Lite

PyTorch

- Extensively compared TensorFlow, TFLite, and PyTorch
- Originally decided to use TensorFlow Lite because of performance limitations with the Raspberry Pi 4
  - Once the switch to the laptop was made, we also switched our model development efforts to TensorFlow, for better detection accuracy and performance

Machine Learning Model Creation Process

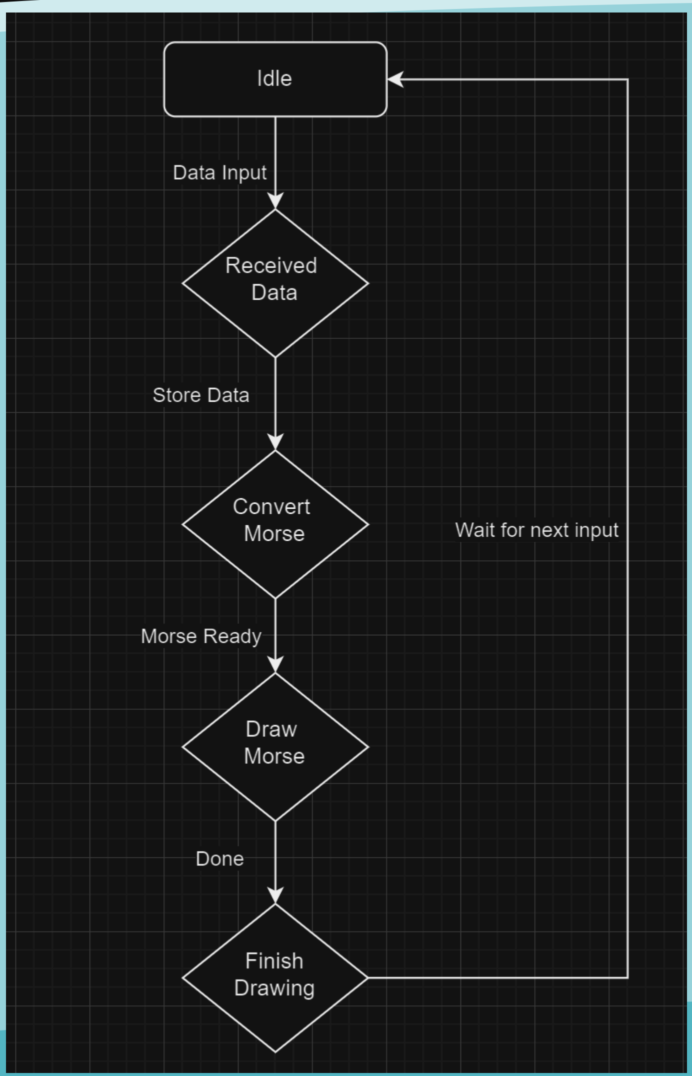
- Python script was written to collect hand gesture data for each required gesture
- Google's Teachable Machine was used to train a machine learning model based on our collected data
  - Teachable machine provides a quick and easy interface for training simple models, though model performance was less consistent than desired



ESP32 Software Overview

- Utilizes the C ++ programming language, adhering to the ISO/IEC 9899:2018 standard (C18) for embedded programming, ensuring strict compliance with international standards.
- Pulse Width Modulation (PWM): Critical for controlling the speed of the DC motor driving the polygonal mirror for horizontal GUI projection.
- GPIO Pin Programming: Adjusts PWM signals for precise control over the mirror's rotational speed, directly affecting GUI projection accuracy.
- Photodiode Integration: Synchronizes audio-visual outputs with photodiode input for interactive feedback.
- Real-Time Responsiveness: Optimizes programming for immediate system reaction to input, ensuring an engaging user experience.

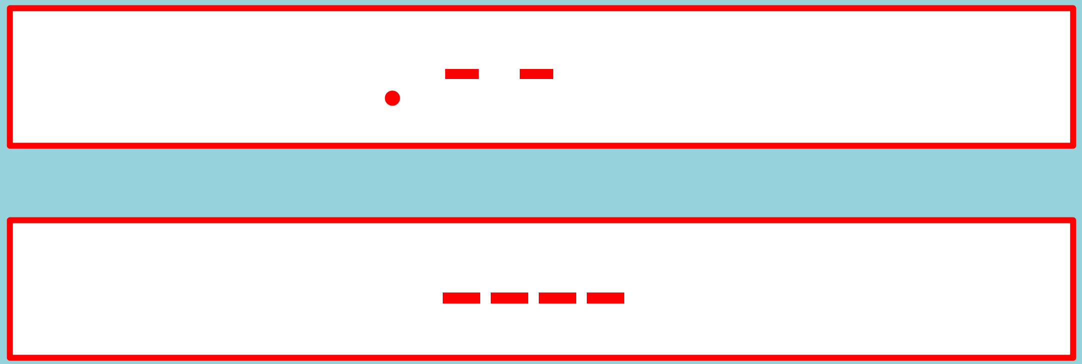
ESP32 Software State Machine



- IDLE
- Received Data
- Convert Morse
- Draw Morse
- Finish Drawing

GUI Design

- Morse Code
  – Each note will be displayed as morse code equivalent



Administration

Design Constraints

- Economic
  - Project is self-funded by the group
- Time
  - Occasions in which certain parts require the completion of others.
- Environmental
  - No potential harm to the environment.
- Social
  - Creation of a look-up table to help with catering to the general audience.
- Ethical
  - Security for users to operate.
- Health and Safety
  - Avoiding of any physical harm with the laser diode.
- Manufacturing
  - Constant prototyping to ensure product meets requirements set.
- Sustainability
  - Operation of product without failure.

Standards

- Python Language
  - Python Enhancement Proposal (PEP) 8
  - General layout for coding
  - Good practices
- IPC PCB
  - Design characteristics
  - Documentation
  - Processes for embedded PCB components
- Laser Safety
  - ANSI Z136
  - Safe use of lasers in any environment
- C Language
  - ISO/IEC 9899:2018
  - Representation, semantics, and representation of I/O data for C programs
  - Syntax and constraints of C language
  - How C programs transform and is transformed by use

Work Distribution

Tristan Barber

Tristan is the project manager, organizes meetings, and worked both in hardware and software development.

- Project Manager
- ML model training
- Synthesizer Application Development
- Electrical Design and Power Distribution (Primary)

Christopher Jean

Christopher is focused on the embedded software effort involving the laser projection unit.

- Embedded Software
- Electrical Design and Power Distribution (Secondary)

Christian Paredes

Christian works with the camera and lens system design for use with the AI and ML software.

- Camera Selection
- Lens Design
- Mechanical Design (Secondary)

Jacob Goc

Jacob oversees the design and development of the laser projection unit. As a result, he also leads the mechanical design efforts.

- Laser Projection Unit Design (Primary)
- Mechanical Design (Primary)

Bill of Materials (Budgeting)

Item:	Qty Purchased:	Cost Per Unit:	Net Cost:	Purchased Fron	Purchase	Brief Description	Link
ESP32-S3-DevKitC-1-N8R2	1	$16.05	$16.05	Amazon	Christopher	Devkit board for testing	
PPN7PA12C1	1	$3.34	$3.34	Digi-Key	Jacob	Motor for LPU mirror	Link
Instapark DRM104-D003	1	$4.79	$4.79	Ebay	Jacob	Laser diode for testing	Link
Brother MFC-8220	1	$9.99	$9.99	Ebay	Jacob	Spinning mirror for project	Link
Hamamatsu S5973	3	$24.95	$74.85	Ebay	Jacob	Photodiode for mirror calibration	Link
Alitove 24V 10A PSU	1	$19.59	$19.59	Amazon	Tristan	Power supply for overall device	Link
Raspberry Pi HQ Camera	1	$50.00	$50.00	Sparkfun	Christian	Camera for capturing	
Plano-Convex Lens	1	$29.99	$29.99	Thorlabs	Christian	Lens #1 for Lens system	
Bi-Convex Lens	1	$50.00	$50.00	Thorlabs	Christian	Lens #2 for Lens system	
24 to 5 DC DC Converter	1	$12.50	$12.50	West3D	Tristan	Converter for PSU to 5V Output	Link
5 to 3.3 DC DC Converter	1	$12.07	$12.07	Adafruit	Tristan	Converter for 5V to 3.3V Output	
PCB Version 2	5 PCBs (1 Purchase)	$10.44	$10.44	JLCPCB	Tristan	PCB for Photodiode Comparator	
Digikey PCB Components	1	$25.61	$25.61	Digi-Key	Tristan	Digikey PCB Components	
IC INVERT SCHMITT 6CH 1INP 14DIP	3	$0.98000	$2.94	Digi-Key	Christopher	Schmitt trigger to try and reduce noise from photodiode	Link
LM393PE3 IC COMPARATOR 2 DIFF 8DIP	3	$0.40000	$1.20	Digi-Key	Christopher	Comparator to reduce noise from photodiode	Link
OPA344PA IC OPAMP GP 1 CIRCUIT 8DIP	3	$1.67000	$5.01	Digi-Key	Christopher	Comparator to reduce noise from photodiode	Link
HiLetgo 5pc A4988	1	$10.19	$10.19	Amazon	Jacob	Motor Driver	Link
Sorand NEMA 17 Stepper Motor	1	$16.71	$16.71	Amazon	Jacob	Motor for mirror 2	Link
Jetec 25pc Mini Size Acrylic Square Mirror	1	$9.39	$9.39	Amazon	Jacob	Mirror 2	Link
2x12 Lumber	1	$20.00	$20.00	Home Depot	Jacob	Wood for final product	
Fasteners	1	$7.00	$7.00	Home Depot	Jacob	Fastening for LPU	
Laser Diodes 10 pack	1	$7.44	$7.44	Amazon	Tristan	Laser Diodes	
Standoff Set	1	$10.64	$10.64	Amazon	Tristan	Standoff Screw set to mount boards onto wood	
Laser Diodes 10 pack	2	$6.99	$13.98	Amazon	Christopher	Laser Didoe	
Arducam CSI to USB Adapter	1	$39.99	$39.99	Amazon	Christian	Adapter to allow for direct connection to laptop	
Waveshare Portable Mini Tripod	1	$17.99	$17.99	Amazon	Christian	Stand for Pi Camera	

Total Cost = $474.71

Future Milestones – Plenty of Room for Growth

- Improved GUI
- PCB redesigned
- Noise reduction
- GUI on computer
- Build material

Thank you all for your support and guidance throughout our time in Senior Design and at UCF!