ASML: Fast Polarization Switch

A switch for the visible spectrum.

ASML

Single Axis Cross-Flexure Galvo Motor, from ThorLabs

Calcite Crystal

Team Members

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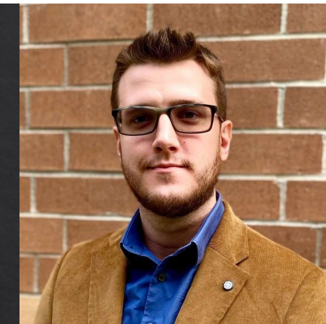
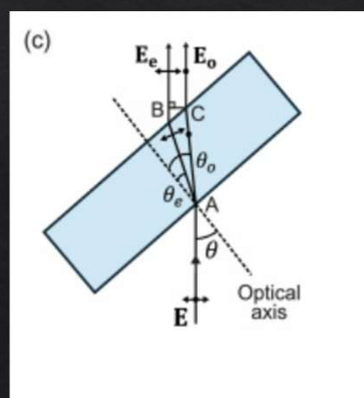


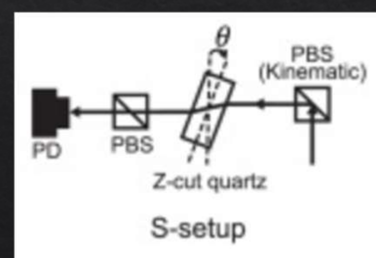
Background and Motivations

Our project is primarily based on the paper "Double-pass rotating z-cut quartz plate as a rapidly variable waveplate."

ASML is hoping to find out whether or not this project will be feasible in helping with semi-conductor metrology.

This paper proves feasibility of our project and provides a clear path on how to approach not only the experimental setup but the mathematical simulations





Byungjin Lee, Kiryang Kwon, and Jae-yoon Choi, "Double-pass rotating z-cut quartz plate as a rapidly variable waveplate," Opt. Express 33, 28739-28751 (2025)

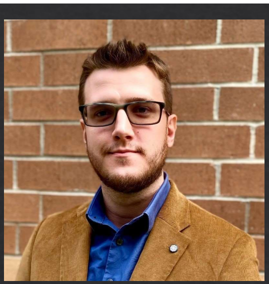
Slide 3

DR1 Add what this type of project can accomplish like explain it can be useful in metrology
David Rich, 2026-04-17T19:05:44.820

Goals and Objectives

- Rapid Selection of polarization states using small angles and fast movement
  - Switch between orthogonal polarization states
  - Move between those states within 5 milliseconds
- A system that works using the visible spectrum
  - System operates and is able to modulate power across 400 nm – 700 nm
- The difference in power between the two states needs to be substantial
  - The polarization extinction ratio of our system needs to be at least 100:1

Engineering Specs



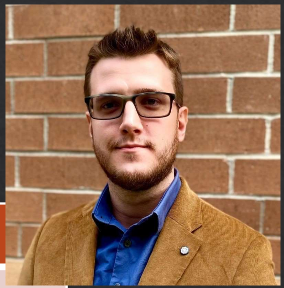
Electrical

Component	Parameter	Specification
Motor	Angle Step Size	$\leq 0.005°$
DAQ Card	Update Rate	5,000 samples per second
ESP32-S3	Max Output Voltage	3.3 V
3.3 V Regulator	Max Output Current	1 A
Op-Amp	Gain Bandwidth	$\geq$ 50 MHz
DAC	Update Rate	$\geq$ 25,000 samples per second

Optical

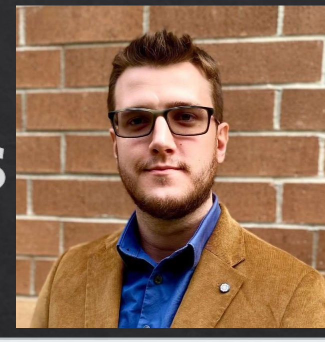
Component	Parameter	Specification
Laser	Wavelength	~630 nm
LED	Wavelength / Power	450 nm / >20 mW
Polarizer	Extinction Ratio	>100:1
Photodiode	Sampling Rate	~5000 samples per second
Crystal	Extinction Ratio	>1000:1

Engineering Requirements



System	Requirement
Power Consumption	≤ 750 W
User Input to Output Time	≤ 3 seconds
Extinction Ratio	100:1
Motor Precision	± 0.005°
Modulation Time	≤ 5 millisecond
Optical Output Power	20 mW
Wavelength Range	400 nm to 700 nm
Polarization Range	0° to 180°
Total Cost of Switch	< $7,000

Crystal Math – Jones Vector Calculus



A good place to start, normalized Jones Vectors

Polarization	Jones vector
Linear polarized in the x direction Typically called "horizontal"	$\begin{pmatrix}1\\0\end{pmatrix}$
Linear polarized in the y direction Typically called "vertical"	$\begin{pmatrix}0\\1\end{pmatrix}$
Linear polarized at 45° from the x axis Typically called "diagonal" L+45	$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$
Linear polarized at −45° from the x axis Typically called "anti-diagonal" L−45	$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\end{pmatrix}$
Right-hand circular polarized Typically called "RCP" or "RHCP"	$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\-i\end{pmatrix}$
Left-hand circular polarized Typically called "LCP" or "LHCP"	$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\+i\end{pmatrix}$

Phase retarders	Corresponding Jones matrix
Quarter-wave plate with fast axis vertical[2][note 1]	$e^{\frac{i\pi}{4}}\begin{pmatrix}1 & 0\\0 & -i\end{pmatrix}$
Quarter-wave plate with fast axis horizontal[2]	$e^{-\frac{i\pi}{4}}\begin{pmatrix}1 & 0\\0 & i\end{pmatrix}$
Quarter-wave plate with fast axis at angle θ w.r.t the horizontal axis	$e^{-\frac{i\pi}{4}}\begin{pmatrix}\cos^2\theta + i\sin^2\theta & (1-i)\sin\theta\cos\theta\\(1-i)\sin\theta\cos\theta & \sin^2\theta + i\cos^2\theta\end{pmatrix}$
Half-wave plate rotated by θ [1]	$\begin{pmatrix}\cos 2\theta & \sin 2\theta\\\sin 2\theta & -\cos 2\theta\end{pmatrix}$
Half-wave plate with fast axis at angle θ w.r.t the horizontal axis[11]	$e^{-\frac{i\pi}{2}}\begin{pmatrix}\cos^2\theta - \sin^2\theta & 2\cos\theta\sin\theta\\2\cos\theta\sin\theta & \sin^2\theta - \cos^2\theta\end{pmatrix}$
General Waveplate (Linear Phase Retarder)[9]	$e^{-\frac{i\eta}{2}}\begin{pmatrix}\cos^2\theta + e^{i\eta}\sin^2\theta & (1-e^{i\eta})\cos\theta\sin\theta\\(1-e^{i\eta})\cos\theta\sin\theta & \sin^2\theta + e^{i\eta}\cos^2\theta\end{pmatrix}$
Arbitrary birefringent material (Elliptical phase retarder)[9][12]	$e^{-\frac{i\eta}{2}}\begin{pmatrix}\cos^2\theta + e^{i\eta}\sin^2\theta & (1-e^{i\eta})\,e^{-i\phi}\cos\theta\sin\theta\\(1-e^{i\eta})\,e^{i\phi}\cos\theta\sin\theta & \sin^2\theta + e^{i\eta}\cos^2\theta\end{pmatrix}$

Crystal Math – Sellmeier Equations

Sellmeier equations give us the wavelength (λ)dependent refractive indexes (no and ne) for our birefringent crystals, which then in turn is used to calculate the change in phase as we rotate our crystal.

Calcite Crystal

Sellmeier Equations: (λ in μm) :

$n_o^2=2.69705 + 0.0192064/(\lambda^2-0.01820)-0.0151624\lambda^2$

$n_e^2=2.18438 + 0.0087309/(\lambda^2-0.01018)-0.0024411\lambda^2$

Alpha - BBO

Sellmeier Equations (λ in μm) :

$no^2=2.67579+0.02099/(\lambda^2-0.00470)-0.00528\lambda^2$

$ne^2=2.31197+0.01184/(\lambda^2-0.01607)-0.00400\lambda^2$

Quartz Crystal

Sellmeier Equations: (λ in μm) :

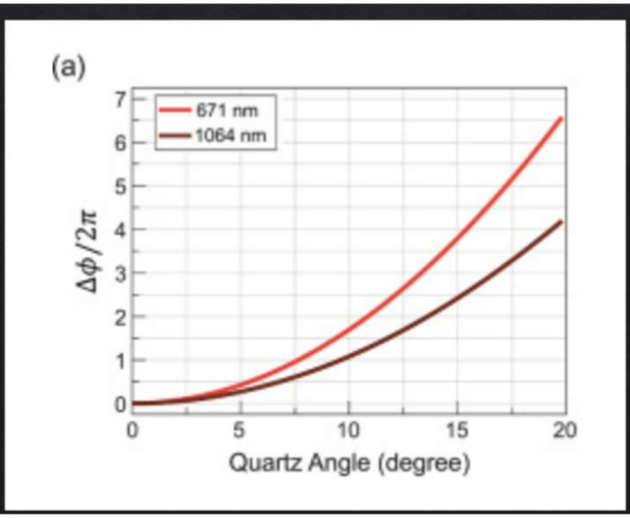
$n_o^2=2.3573-0.01170\lambda^2+0.01054/\lambda^2+1.3414\times10^{-4}/\lambda^4-4.4537\times10^{-7}/\lambda^6+5.9236\times10^{-8}/\lambda^8$

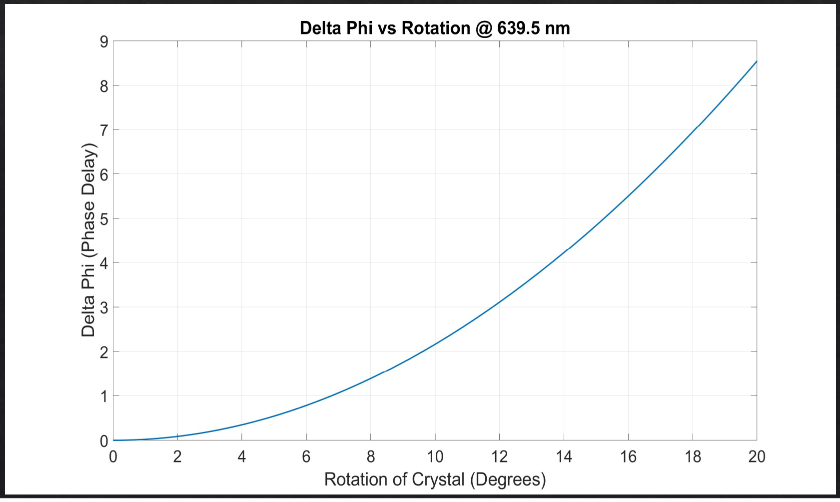
$n_e^2=2.3849-0.01259\lambda^2+0.01079/\lambda^2+1.6518\times10^{-4}/\lambda^4-1.9474\times10^{-6}/\lambda^6+9.3648\times10^{-8}/\lambda^8$

Crystal Math – Change in Phase Delay

Change in phase delay is calculated using the wavelength dependent refractive indices the angle of incidence(θ) and the thickness of the crystal (d)

$$\Delta\phi(\theta) = 2\pi\,\frac{\Gamma(\theta)}{\lambda} = \frac{2\pi}{\lambda} n_o d\left(\sqrt{1-\frac{\sin^2\theta}{n_e^2}} - \sqrt{1-\frac{\sin^2\theta}{n_o^2}}\right)$$





Byungjin Lee, Kiryang Kwon, and Jae-yoon Choi, "Double-pass rotating z-cut quartz plate as a rapidly variable waveplate," Opt. Express 33, 28739-28751 (2025)

Crystal Math – Creation of the Crystal Jones Matrix

In this equation our β is the pitch of the crystal and θ is the angle of incidence we can then combine this with our jones vector calculus to calculate the normalized power output.

$$\boldsymbol{Q}(\beta,\theta) = \begin{pmatrix} Q_{xx} & Q_{xy} \\ Q_{yx} & Q_{yy} \end{pmatrix} = \begin{pmatrix} \cos^2\beta + e^{i\Delta\Phi}\sin^2\beta & (1-e^{i\Delta\Phi}) sin\beta cos\beta \\ (1-e^{i\Delta\Phi}) sin\beta cos\beta & \sin^2\beta + e^{i\Delta\Phi}\cos^2\beta \end{pmatrix} \quad (2)$$

Then with the output Jones Vector we can calculate the stokes parameters and the output polarization

$$\boldsymbol{E}^{(\boldsymbol{S})} = \begin{pmatrix} E_x^{(S)} \\ E_y^{(S)} \end{pmatrix} = \boldsymbol{Q}\left(\frac{\pi}{4},\theta\right) \cdot \boldsymbol{E_i} = \frac{1}{2}\begin{pmatrix} 1-e^{i\Delta\Phi} \\ 1+e^{i\Delta\Phi} \end{pmatrix} \quad (3)$$

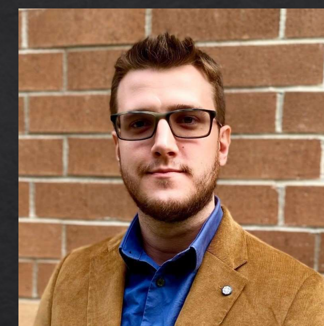
$$\boldsymbol{E}^{(\boldsymbol{D})} = \begin{pmatrix} E_x^{(D)} \\ E_y^{(D)} \end{pmatrix} = \boldsymbol{Q}\left(-\frac{\pi}{4},\theta\right) \cdot \boldsymbol{M} \cdot \boldsymbol{E}^{(\boldsymbol{S})} = \frac{1}{2}\begin{pmatrix} 1-e^{i2\Delta\Phi} \\ -(1+e^{i2\Delta\Phi}) \end{pmatrix} \quad (4)$$

Here we have the calculations of our single and double-pass setups.

Byungjin Lee, Kiryang Kwon, and Jae-yoon Choi, "Double-pass rotating z-cut quartz plate as a rapidly variable waveplate," Opt. Express 33, 28739-28751 (2025)

Crystal Math – Stokes Parameters

To calculate our theoretical polarization, we need to convert from jones vectors to stokes parameters, we can then plot the polarization state on the Poincare sphere by using the stokes parameters.

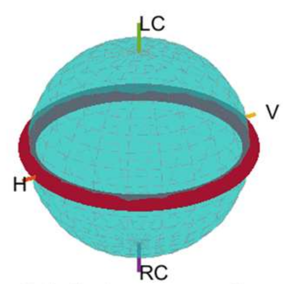


$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

$$x = \frac{S_1}{S_0}, y = \frac{S_2}{S_0}, z = \frac{S_3}{S_0}.$$

$$\begin{aligned} I &= |E_x|^2 + |E_y|^2, \\ Q &= |E_x|^2 - |E_y|^2, \\ U &= 2\mathrm{Re}(E_x E_y^*), \\ V &= -2\mathrm{Im}(E_x E_y^*), \end{aligned}$$

Figure 7.1.3-1



Polarization response of our system when passing through multiple cycles with a static QWP

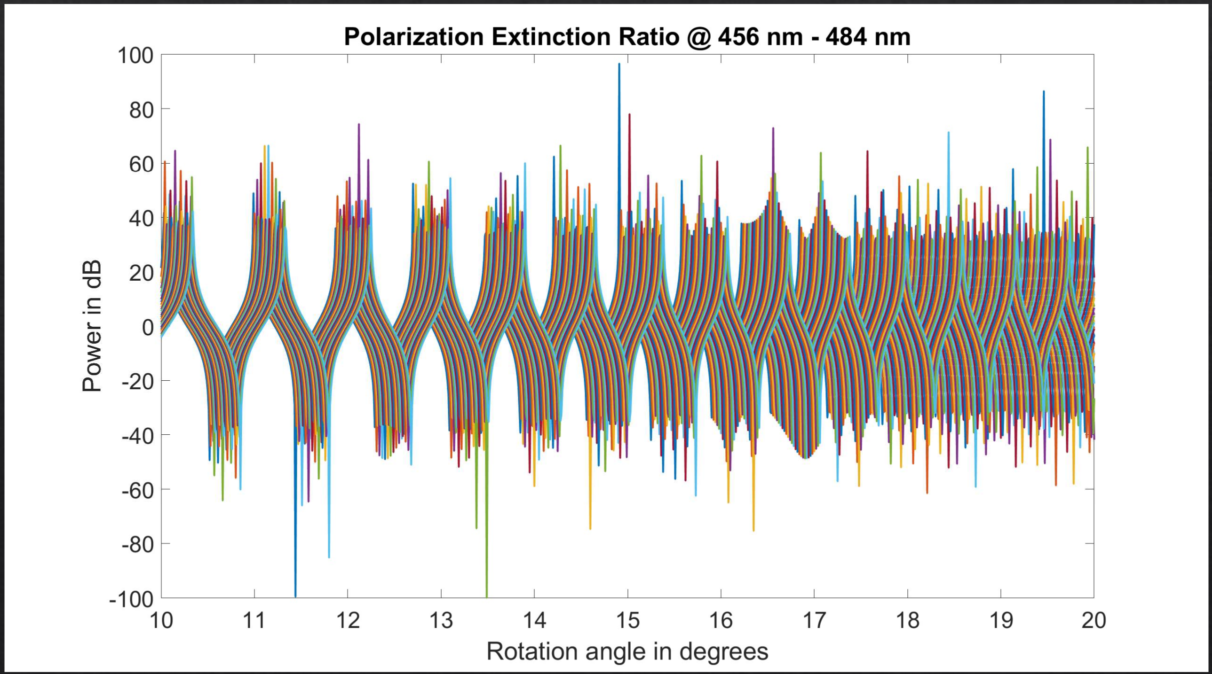
Crystal Math – PER calculations

The Polarization extinction Ratio of our crystal set up was calculated by comparing the theoretical and normalized power values in the vertical and horizontal electric fields.

$$PER = 10log_{10}\frac{|E_x|^2}{|E_y|^2}$$

This formula returns PER in dB.

When the ratio is equal to 0 dB we know that there is equal power between the two fields.



Crystal comparisons

Quartz crystal

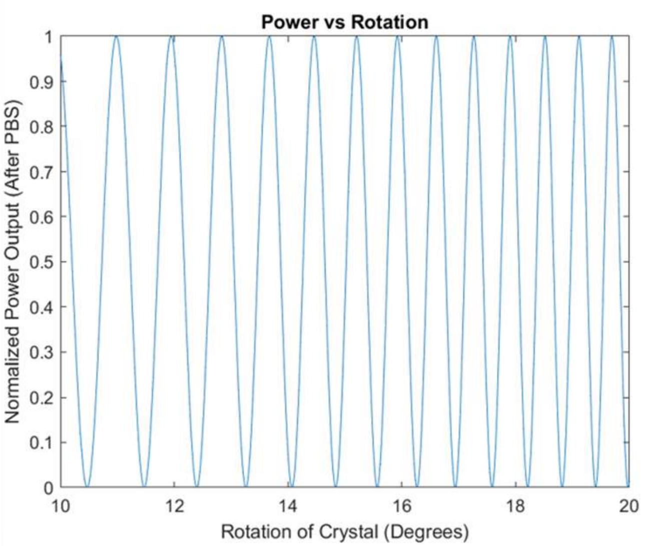


Figure 3.1.2-1

Plot of normalized power while rotating a quartz crystal with a 1 cm thickness, between 10 – 20 degrees with a step size of 0.01°

Calcite Crystal

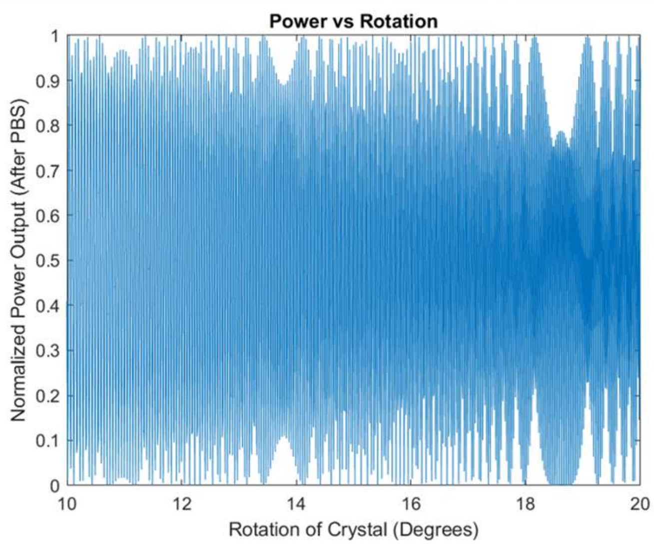


Figure 3.1.2-3

Plot of normalized power while rotating a calcite crystal with a 1 cm thickness, between 10 – 20 degrees with a step size of 0.01°

α - BBO Crystal

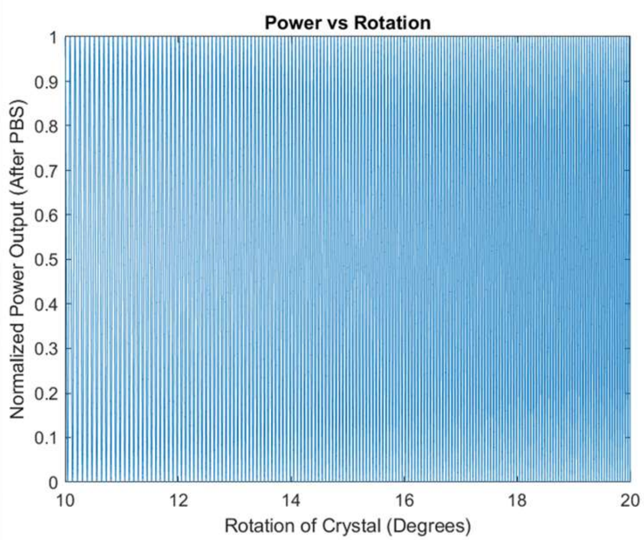
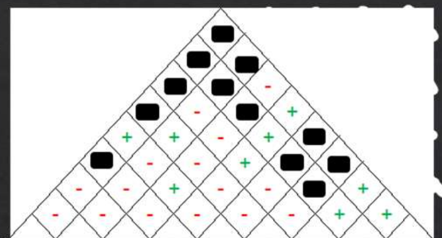


Figure 3.1.2-5

Plot of normalized power while rotating a α - BBO crystal with a 1 cm thickness, between 10 – 20 degrees with a step size of 0.01°

House of Quality

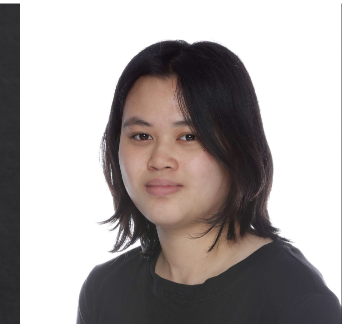


Direction of Desirability	Customer Requirements \ Engineering Requirements	Output Power	Switching Time	Cost	Number of Polarization	Power Consumption	User Input to Output Measurements Time	Rotation Accuracy	Wavelength Range	Extinction Ratio
	Direction of Desirability	▼	▼	▼	▲	▼	▼	▲	▲	▲
▲	Responsiveness	o	↑↑	↓	o	↓	↑↑	↓	o	o
▲	Portability	o	o	↑↑	↓	↑	o	↓	↓	o
▲	Affordability	↓	↓	↑↑	↓	↑	o	↓	↓	o
▲	Ease of Use	o	↑	↑	↓	o	↑	↓	o	o
▲	Longevity	o	o	↑	o	↑	o	o	o	o
▲	Reliability	o	↑↑	↑	↑	↑	↑	↑↑	↑	↑
▲	Power Efficiency	↑	↓	↑↑	↓	↑↑	↓	↓	↓	o
▲	Versatility	↑	o	↓	↑↑	↓	o	↑↑	↑	↑
▲	Upgradability	o	o	↓↓	↑	↓	↓	↑	↑	↑
	Targets for Engineering Requirements	≤ 50 mW	≤ 5 ms	< $10,000	≥ 2	≤ 750 W	≤ 5 s	± 0.001°	500 nm to 700 nm	≥ 1000:1 per wavelength

Correlation	
Positive	+
Negative	-
None	■

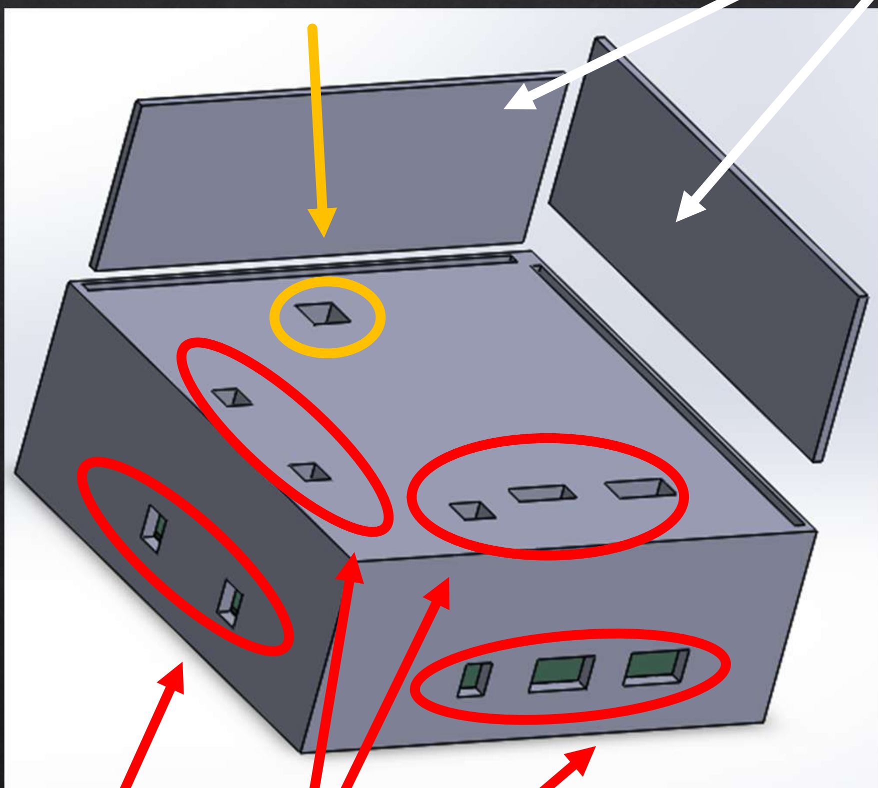
Relationship	
Strongly Positive	↑↑
Weakly Positive	↑
No Relation	o
Weakly Negative	↓
Strongly Negative	↓↓

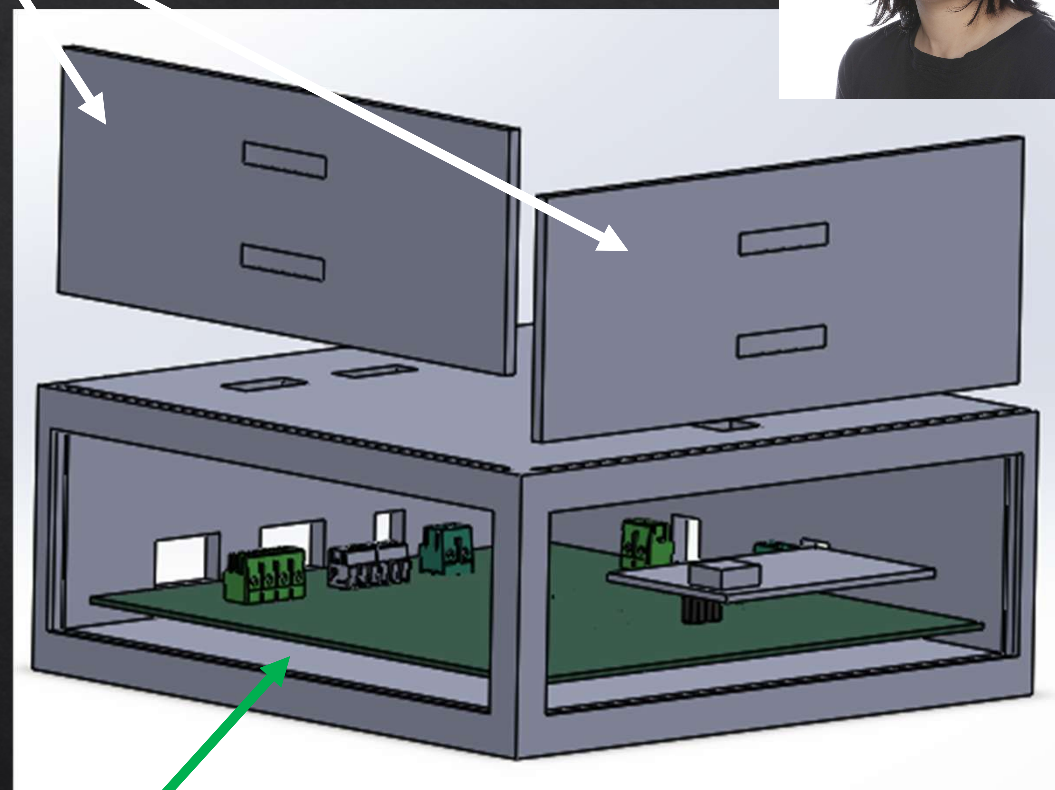
Direction of Desirability	
High	▲
Low	▼

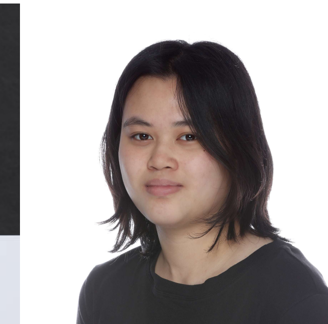


CAD Model – PCB Housing

- Lids
- BNC Connector Access



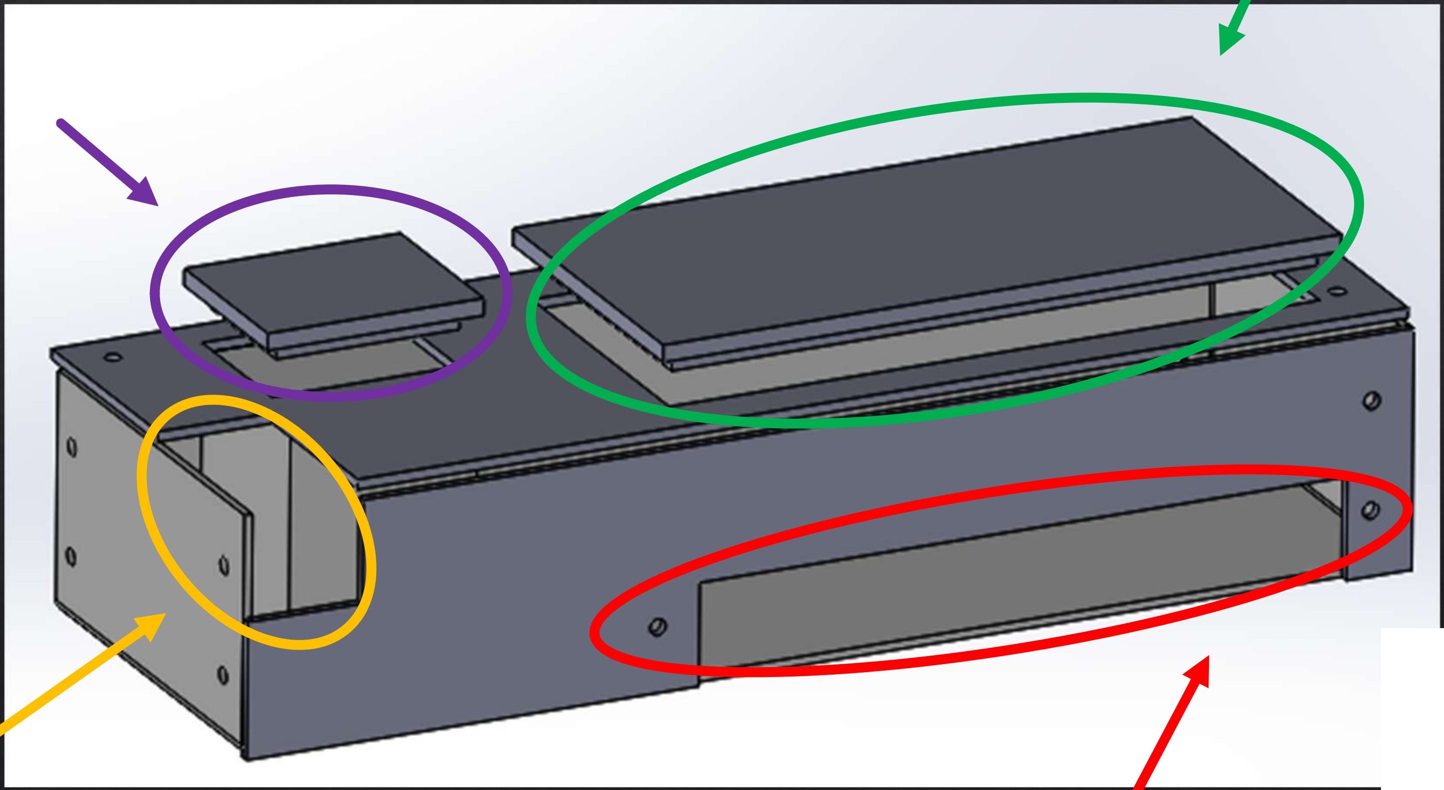




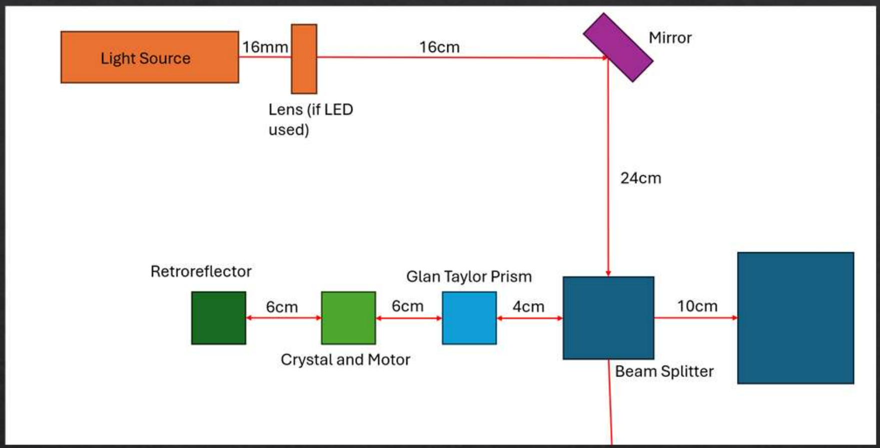
- Screw Terminal Access
- PCB

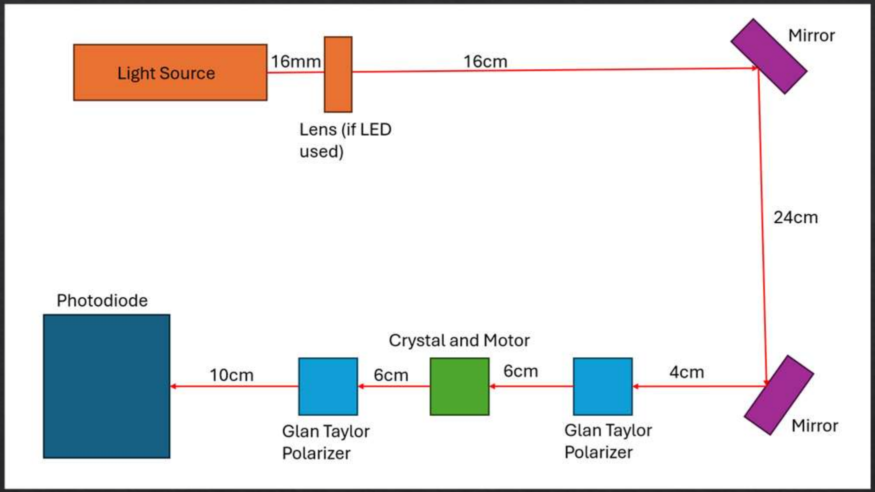
CAD Model – DC Power Supply

- DC Power Regulator Lid
- AC to DC Transformer Lid



- Switch Slot
- Wire Insert Slot

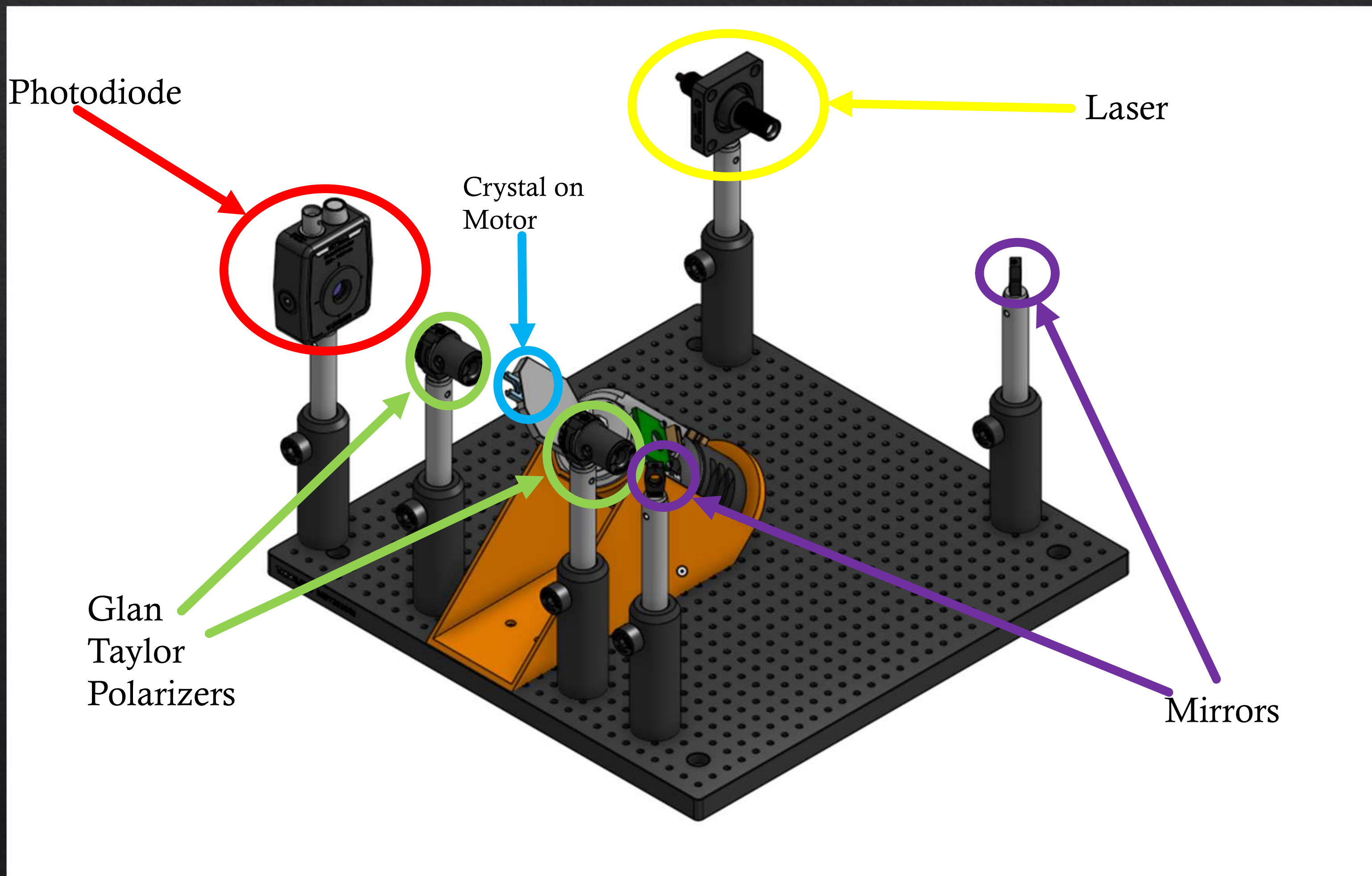




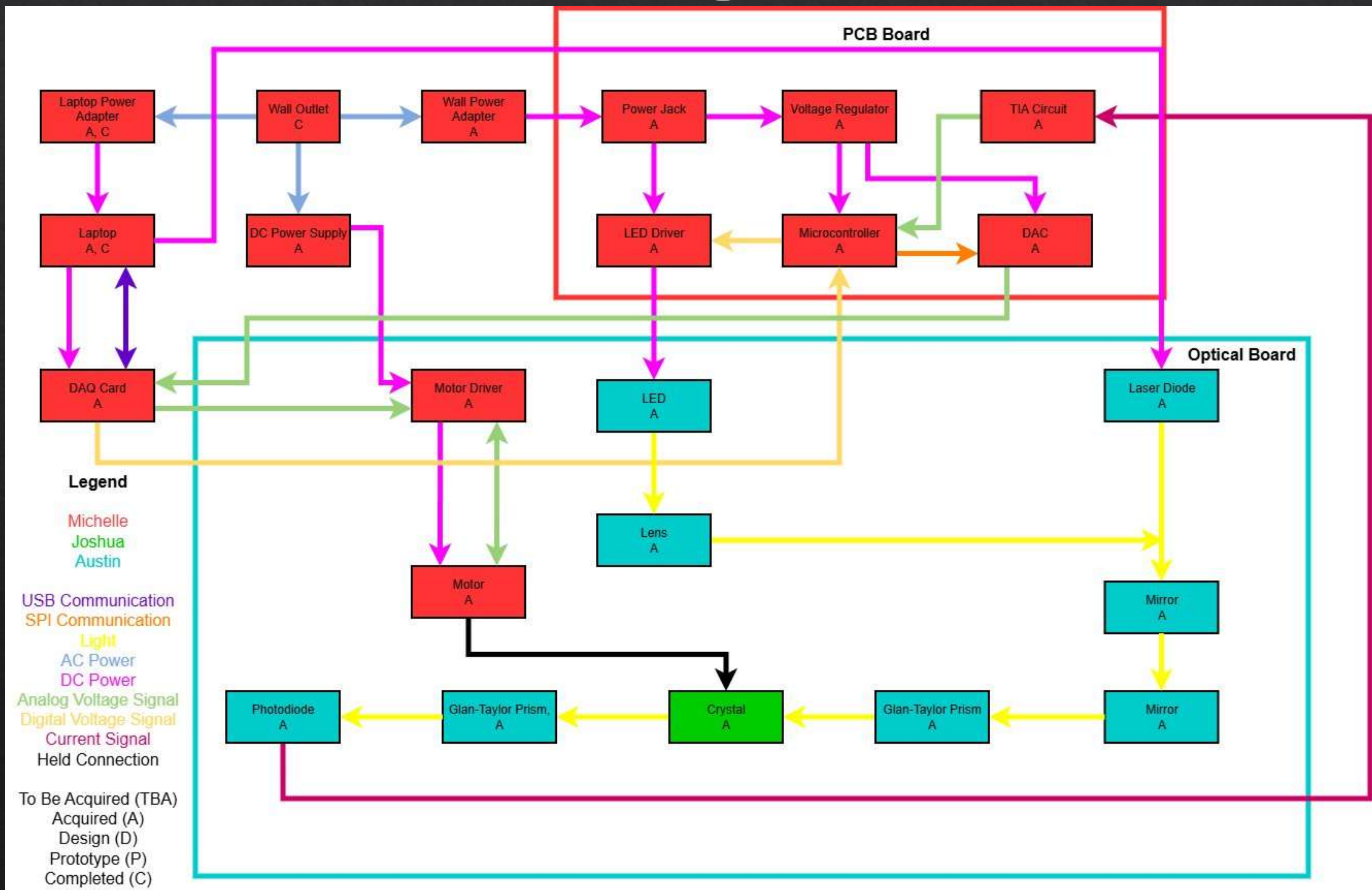
Double Pass Vs Single Pass

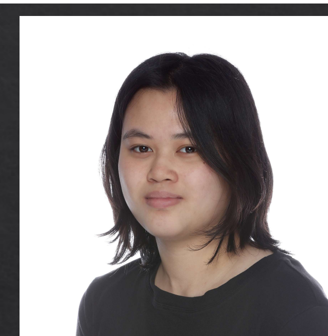
- Double pass requires more precise alignment and less motor rotation
- Single pass uses no beamsplitters, so power is easier to measure
- Therefore, single pass was chosen

CAD Model – Optical Setup



Hardware Block Diagram





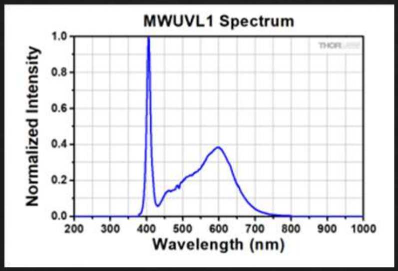
Light Source Considerations

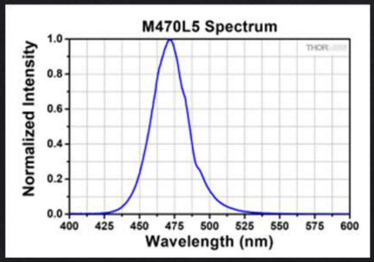
- Want to test across entire visible spectrum
- Want to test a bandwidth of 30nm
- Able to produce around 50mW of optical power

- Leads to us using an LED for the bandwidth and a laser to test different wavelengths in the visible spectrum

LED Comparison and Selection

	MWUVL1 Thorlabs	M470L5 ThorLabs
Wavelength	406 nm	470 nm
Bandwidth @FWHM	300 nm	28 nm
Optical Power	235 mW	1161.7 mW
Cost	$191.10	$261.20





M470L5 Thorlabs LED

- Chosen for its large Bandwidth compared to other choices
- Large optical power allows us to use several beamsplitters without losing too much power and not hitting our specification
- Very expensive LED but is placed on its own heat sink and allows us to test the blue side of the visible spectrum

LED and Lens Calculation

- We want a lens that will effectively collimate the LED light
- Chosen lens is ACL25416U
- Lens has a diameter of 25.4mm, focal length of 16mm, and NA of 0.79
- $\theta = \tan^{-1}((D/2)/f) = 38.4°$.
  - Angle of acceptance
- Collection efficiency = $\sin^2(\theta) = 0.386$
  - So we will collect 38.6% of the light
- $P_{out} = 0.386(P_{LED}) = 448.42mW$
- $\theta_{divergence} = d_{LED}/f = 0.0625$ rad = 3.58°
  - This is a half angle calculation

Laser Comparison and Selection

	Thorlabs PL20X	0220-923-00 Edmund Optics
Wavelength	635 nm, 520 nm, 405 nm	635 nm
Bandwidth	1 nm	5 nm
Output Power	0.9 mW	2 mW
Price	$146.4 - $246.67	$303.03

Thorlabs PL20X

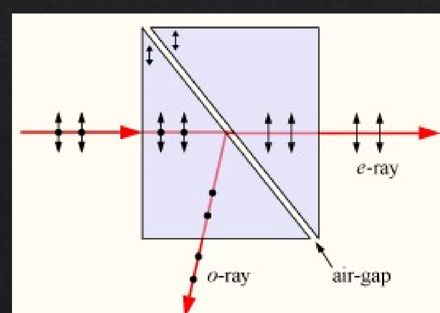
- Several wavelengths across visible spectrum (635nm, 520nm, and 405nm)
- Cheapest reliable laser to test the red end of the visible spectrum
- When combined with the blue LED and red laser we test the entire visible spectrum

Polarizer Consideration

- Largest concern is we need to have an extinction ratio of 100:1
- We need polarizers with a much higher extinction ratio so that we don’t have the polarizers as the limiting factor to our systems overall extinction ratio
- Polarizers need to work across entire visible spectrum

Polarizer Comparison

	Thorlabs GT5	CCM5-PBS201/M Thorlabs (Beamsplitter)
Wavelength Range	350nm – 2.3um	420nm – 680nm
Extinction Ratio	100,000:1	1000:1 transmission 100:1 reflection
Price	$626.65	$331.76



Thorlabs GT5

- Glan-Taylor type polarizer
  - Two crystals with an angled edge between
  - This angle ensures reflection of a specific polarization and allows the other to pass leading to high extinction ratio
- Only extinction ratio that will give us an accurate representation of the extinction ratio of our crystal

Photodiode Considerations

- Photodiode needs to be fast enough to detect a change from max to min power in under a millisecond
- Needs to be sensitive enough to detect low optical power since our laser can only output 0.9mW
- Needs to read a low enough power to determine our extinction ratio

Photodiode Comparison

	Thorlabs S120C and PM103	DET100A2 Thorlabs	Newport 918D-SL-OD2R and 844-PE-USB
Wavelength Range	400nm – 1100nm	320nm – 1100nm	400 nm – 1100nm
Power Range	50 nW – 50 mW	Dependent on outside factors	20 pW – 2 W
Sampling Rate	<1 us	20ns	0.066 ms
Price	$1109.61	$204.65	$1762

DET100A2 and S120C setup

- This Photodiode combined with our own TIA circuit will allow us to control our power range
- Has fastest sampling rate
- High sampling rate will give us the greatest understanding of our fast-switching speed
- With power meter can easily see extinction ratio

Motor Consideration

- Precise position control (to travel 0.1 degree)
- Fast motor speed (for a switching time of 1 ms)

- What type of motor to use?

Motor Type Comparison

Feature	Stepper Motor	Servo Motor	Brushless DC Motor	Galvanometer Motor
Step Angle (Degrees)	0.9 / 0.1125 (with micro stepping)	0.088 (with 12 bits encoder)	N/A	0.000057
Feedback System	Open-Loop	Closed-Loop	Closed-Loop	Closed-Loop
Control System	N/A	Position, Speed, Torque	Speed, Torque	Position
Energy Efficiency	High Power Consumption	Low Power Consumption	Medium Power Consumption	Low Power Consumption
Heat Generation	High	Low	High	Low
Cost	Small: $5 - $50 Medium: $20 - $150 Large: $50 - $1,500+	Small: $5 - $50 Medium: $100 - $2,000 High Torque: $1,000 - $8,000	Small: $15 - $50 Mid-Range: $150 - $1,000 High Torque: $1,000 - $7,000	Small: $50 - $600 High Speed: $300 - $4,500 Industrial: $3,500 - $10,000+

Galvanometer Motor

- Small Step Angle
- Closed-loop feedback system will help with precise angle movement of the motor
- Known for a fast-switching time

Motor Comparison

Features	SCANLAB's dynAXIS	Noavanta 6210K Galvonometer	Cross-Flexure 1D Galvanometer
Cost	Quote	Quote	$3,819.90
Lead Time	4 Months	6 Months	Available Now
Small Step Angle Response	Data Sheet Unavailable	100 µs – 200 µs	150 µs
Repeatability	Data Sheet Unavailable	8 µrad	< 10 µrad

Cross Flexure 1D Galvanometer

- Availability – Available Now, time constraint of project is important to consider
- Cost known, project needs to stay within the given budget

High Level Motor Controller Consideration

- How do we control the motor?
- Chosen galvanometer motor moves based on analog voltage input through the command line that goes to the motor driver

- What controls how much analog voltage goes to the motor driver?

High Level Motor Controller Comparison

Specification	Computer	Microcontroller
External Technology	Galvo Controller Card	Digital to Analog Converter
Software	Company Recommended Software	Arduino Libraries
Energy Efficiency	Low Power Consumption	Low Power Consumption
Cost	Computer: N/A (Personal Laptop) Galvo Controller Card: $300 - $750	Microcontroller: $4 - $35 DAC: $5 - $25

Computer

- Software Capabilities
- ThorLabs recommended Galvo Controller Card setup to control the galvanometer motor
- Ensures compatible with controlling the motor

Galvo Controller Card Consideration

- DAQ was chosen as the galvo controller card
- Recommended by the galvanometer motor's company (ThorLabs) for more complex scanning patterns

- Analog Output Update Rate for control over the switching time and the degree movement of the motor
- Analog Output Voltage must match the input analog voltage of the motor driver

DAQ Card Comparison

Features	USB-6002	PCIE-1812-B	MCC USB-160G
Analog Output Channel	2 Channels	2 Channels	2 Channels
Maximum Sample Rate	50,000 Samples per Second	250,000 Samples per Second	500,000 Samples per Second
Analog Input Resolution	16 bits	16 bits	16 bits
Maximum Update Rate	5,000 Samples per Second	3,000,000 Samples per Second	500,000 Samples per Second
Analog Output Voltage	±10 V	±10 V	±10 V
Cost	$697	$1,333	$919

USB-6002

- Cheapest Model
- Project was quickly reaching the limits of the budget
- 5,000 samples per second = 5 samples per millisecond to control the motor
- Tight control bandwidth but do-able

Microcontroller Consideration

- GPIO pins
- Simplicity of use / to programmed
- Cost of the microcontroller
- Capability of the microcontroller to be used for light control (LED) and ADC reading for our project

Microcontroller Brand Comparison

Features	ESP32	MSP 430	Arduino Uno	STM32
ADC Bit	12-bit	12- or 14- bit	10-bit	12-bit
GPIO Pins	34	4 to 90 (Depends on the Model)	14	37+ (Depends on the Model)
Energy Efficiency	Low Power Consumption	Low Power Consumption	Low Power Consumption	Low Power Consumption
Cost	$3 - $14	$2 - $25	$20 - $55.40	$1 - $25
Suitability for LED Control and ADC Reading	Supports Arduino IDE for simple C programming	Simple programming and more control over the bit values in the registers	Cost a bit more than the other microcontroller	Too complex for the scale of programming in this project

ESP32

- ADC 12-bit (14-bit is too many bits for analog reading to sample 50,000 samples per second)
- Cost is relativity on the cheaper side
- Support simple C programming

ESP32 Development Kit Comparison

Features	S3-DevKitC-1	C3-DevKitM-1	C5-DevKitC-1
Processing Power	Dual-Core, 32-Bit LX7 CPU (240 MHz)	Single-Core, 32-bit RISC-V (160 MHz)	Single-Core, RISC-V (240 MHz)
I/O Pins	34	15	22
RAM	8 MB / 32 MB	4 MB	8 MB
Cost	$15	$9.80	$13.90
Power Efficiency (in comparison)	Medium Power Consumption	Low Power Consumption	High Power Consumption
Suitability for LED Control and ADC Reading	Fast processing power, Dual core (permit parallel task execution), High amount of RAM for flashing, Decent power efficiency	Slower clock speed, Single-core, Low amount of RAM for flashing, Excellent power efficiency	Fast processing power but only single-core, Low power efficiency (in comparison to other models)

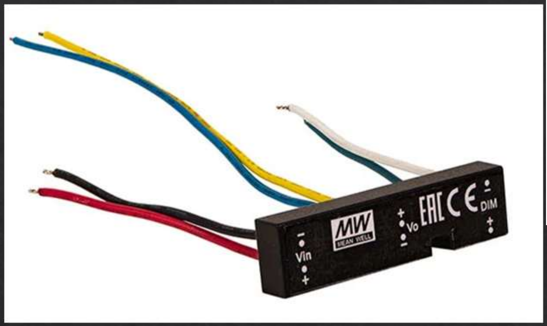
S3-DevKitC-1

- Dual core, permit parallel task execution
- High amount of RAM for flashing
- Lots of GPIO pins

LED Driver Considerations

- Chosen LED needs a LED driver to be powered
- Forward Voltage of 3.8 V
- Maximum Current Input of 1,000 mA (1 A)

LED Driver Comparison



Features	TLM4036DC-1000	LDDS-1000HW	RCD-24-1.00/W
Max Current	1 A	1 A	1 A
Input Voltage	10 V – 30 V	12 V – 56 V	6 V – 36 V
Output Voltage	2 – 26 V	2 – 45 V	3 V – 31 V
Power	26 W	45 W	33 W
Cost	$22.98	$8.87	$24.44

LDDS – 1000 HW

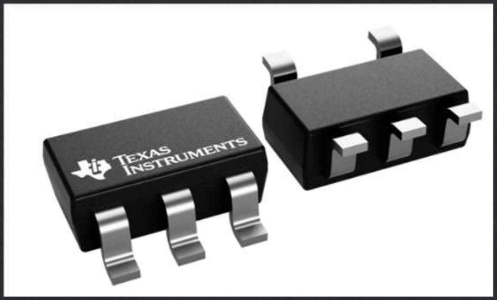
- On/Off Switch, High = On (More power efficient for the overall system) (Can be controlled by the ESP 32 S3)
- Cheapest Model

Op-Amp Considerations

- Create a TIA circuit that is compatible with the chosen Photodiode
- TIA circuit requirements:
- Output Voltage: 0 V to 3 V
- Input Current: 0.1 mA to 9 mA (when LED is used)
- Bandwidth of Chosen Photodiode: 10 MHz

- Op-Amp needs to have a bandwidth of at least 50 MHz to meet the demands of the TIA circuit
- Precise Op-Amp will need to be used to minimalized offset voltage

Op-Amp Comparison



Features	OPA357	OPA354	OPA863A	OPA2863A
Gain Bandwidth	100 MHz	100 MHz	50 MHz	50 MHz
Offset Voltage	8 mV	8 mV	0.095 mV	0.095 mV
Input Bias Current	50 pA	50 pA	730,000 pA	730,000 pA
Supply Voltage Range	2.5 V – 5.5 V	2.5 V – 5.5 V	2.7 V – 12.6 V	2.7 V – 12.6 V
Cost	$2.38	$2.39	$2.39	$3.77

OPA354

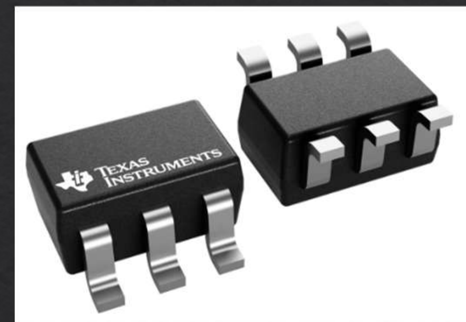
- Gain Bandwidth of 100 MHz, enough room to meet the demands of the TIA circuit
- Datasheet showcase PCB design layout, simpler than the OPA357 PCB design layout

Digital-to-Analog Converter Consideration

- Interface Type between I2C and SPI needs to be chosen for the DAC
- Rate of output needs to be considered

- DAQ can read 50,000 samples per second
- DAQ can receive an input voltage upwards to 5 V

Digital-to-Analog Converter Comparison



Features	DAC6571	DAC6311	DAC53202	DAC53001
Update Rate	125,000 samples per second	83,000 samples per second	25,000 samples per second	25,000 samples per second
Output Voltage	0 V to 5.5 V	0 V to 5.5 V	0 V to 5.5 V	0 V to 5.5 V
Interface Type	I2C	SPI	I2C, SPI	I2C, SPI
Package Type	SOT-23 (DBV)	SOT-SC70 (DCK)	WQFN (RTE)	WQFN (RTE)
Cost	$2.05	$2.01	$3.15	$3.33

DAC6311

- Easy access to pins
- SPI Communications – faster communication speed
- Cheapest model

Power Management

Component	Power Consumption	Operating Voltage	Operating Current
ESP32	Typical: 1,500 mW Max: 2,160 mW	Min: 3 V Max: 3.6 V	Typical: 500 mA Max: 1000 mA
LED	Typical: 3,800 mW Max: 3,820 mW	Typical: 3.8 V Max: 3.82 V	Max: 1000 mA
Laser Diode (520 nm)	Min: 392 mW Max: 520 mW	Min: 4.9 V Max: 5.2 V	Typical: 80 mA Max: 100 mA
Laser Diode (635 nm)	Min: 343 mW Max:468 mW	Min: 4.9 V Max: 5.2 V	Typical: 70 mA Max: 90 mA
Motor Driver	Typical: 60 W Max: 240 W	±15 V to ±24 V	Typical: 4 A Max: 10 A
Motor	Typical: 60 W Max: 240 W	±15 V to ±24 V	Typical: 4 A Max: 10 A
Laptop	45 W	19.5 V	2.31 A
DAQ Card	727.5 mW to 772.5 mW	4.85 V to 5.15 V	Max: 150 mA
Total System	Typical: 171.76 W Max: 532.74 W	Min: ±24 V	Typical: 12.11 A Max: 24.65 A

Power Delivery System Comparison

Features	Battery	Wall Outlet	Solar
Output Behavior	Semi-Constant Voltage	Constant Voltage	Variable Voltage
Energy Source	Stored Chemical Energy	Grid / Stable AC Power	Sunlight
External Equipment	Battery Holder	Power Adapter, Power Jack	Solar Panel, PV Cells
Output Voltage	1.5 V – 12 V	4.5 V – 56 V	10 V – 32 V
Cost	Cheap	Relatively Cheap	Expensive

Wall Outlet

- Some equipment already requires the usage of the wall outlet (laptop, DC power supply for motor)
- System does not need to be portable
- Easy access to wall outlet is always available

Power Adapter Considerations

- Convert AC power of the wall outlet to DC power for the system
- Need to provide at least 12 V to power the LED driver
- Need to provide at least 2 A for the LED driver and ESP32 S3

Power Adapter Comparison

Features	MDS-030AAC07 AB	B00ZWU5L0C	16-00216
Output Voltage	7 V	3 V - 12 V	12 V
Output Current	3 A	2 A	3 A
Power Rating	21 W	24 W	36 W
Plug Size	5.5 mm x 2.1 mm	5.5 mm x 2.1 mm	5.5 mm x 2.1 mm
Cost	$27.64	$13.90	$11.81

16-00216

- Meets the output voltage requirement – 12 V
- Meets output current requirements – 3 A (extra current ceiling for the overall system)
- Cheapest Model

Power Jack Considerations

- Needs to meet the voltage and current ratings of the chosen power adapter
- Handle at least 12 V
- Handle at least 3 A

- Needs to match the plug size and polarity of the chosen power adapter
- 5.5 mm x 2.1 mm
- Center Positive

Power Jack Comparison

Features	B07CTMY9KG	B072BXB2Y8	B08PYT6HZ2
Voltage Rating	12 V	12 V	12 V
Current Rating	3 A	5 A	15 A
Barrel Size	5.5 mm x 2.1 mm	5.5 mm x 2.1 mm	5.5 mm x 2.1 mm
Gender	Female	Female	Female
Polarity	Center Positive	Center Positive	Center Positive
Cost	$5.99	$9.49	$9.99

B072BXB2Y8

- Meets the output voltage requirement – 12 V
- Meets output current requirements – 5 A (extra current ceiling for the overall system)

Voltage Regulator Considerations

- Needs to power the ESP32 S3
- ESP32 S3 needs an input voltage of 3.3 V
- Can draw upwards to 1 A depending on the task being executed

- What type of voltage regulator would be the best for powering the ESP32 S3?

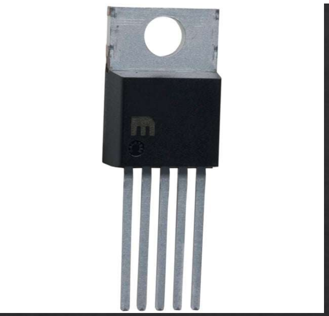
Voltage Regulator Type Comparison

Features	Linear	Switching
Output Voltage	Fixed or Adjustable	Fixed or Adjustable
Heat Generation	High	Low
Efficiency	Low (30% to 60%)	High (70% to 95%)
Complexity	Simple	High
Step Movement	Step-Down	Step-Down, Step-Up

Switching Voltage Regulator

- Low Heat Generation / High Efficiency – can lead to a lack of heat sink needed for the PCB

Voltage Regulator Comparison

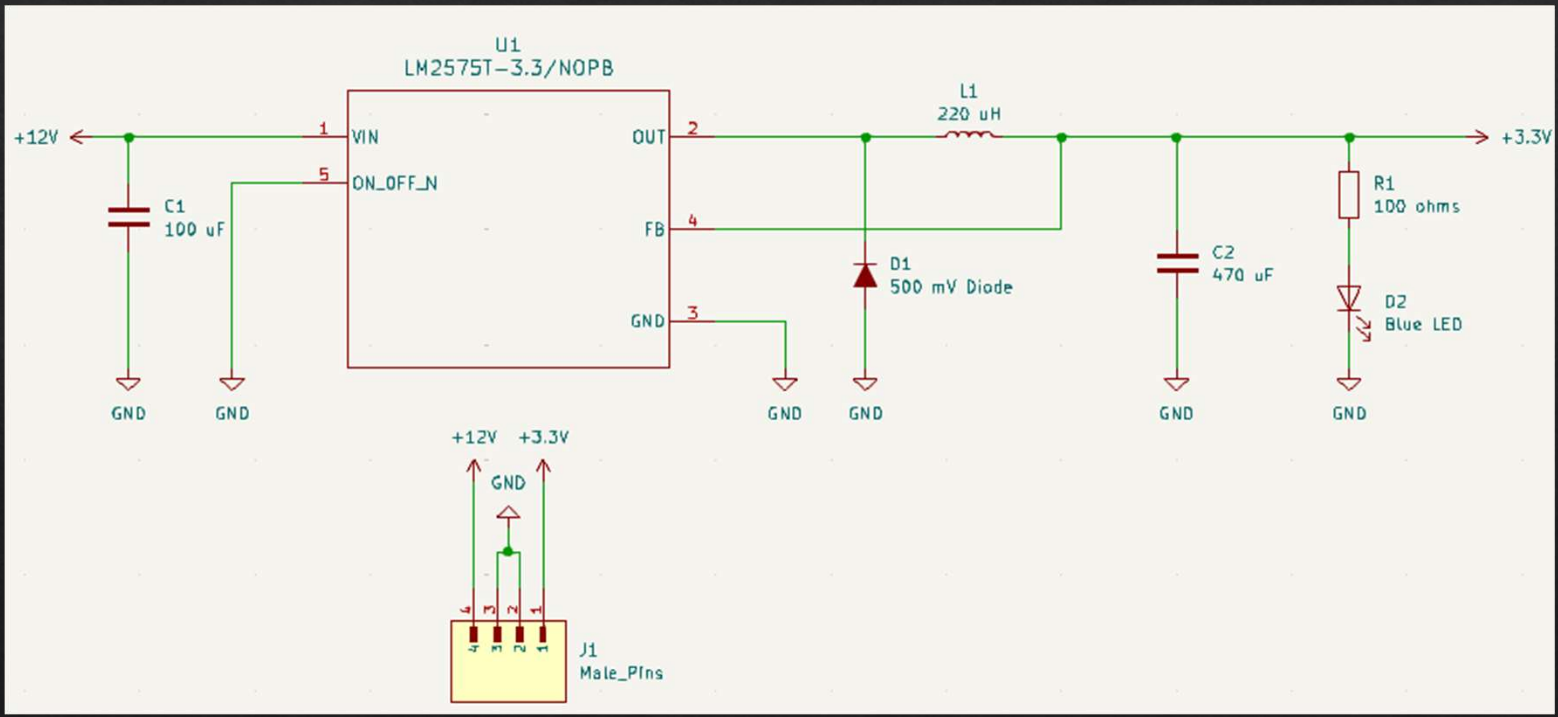


LM2575

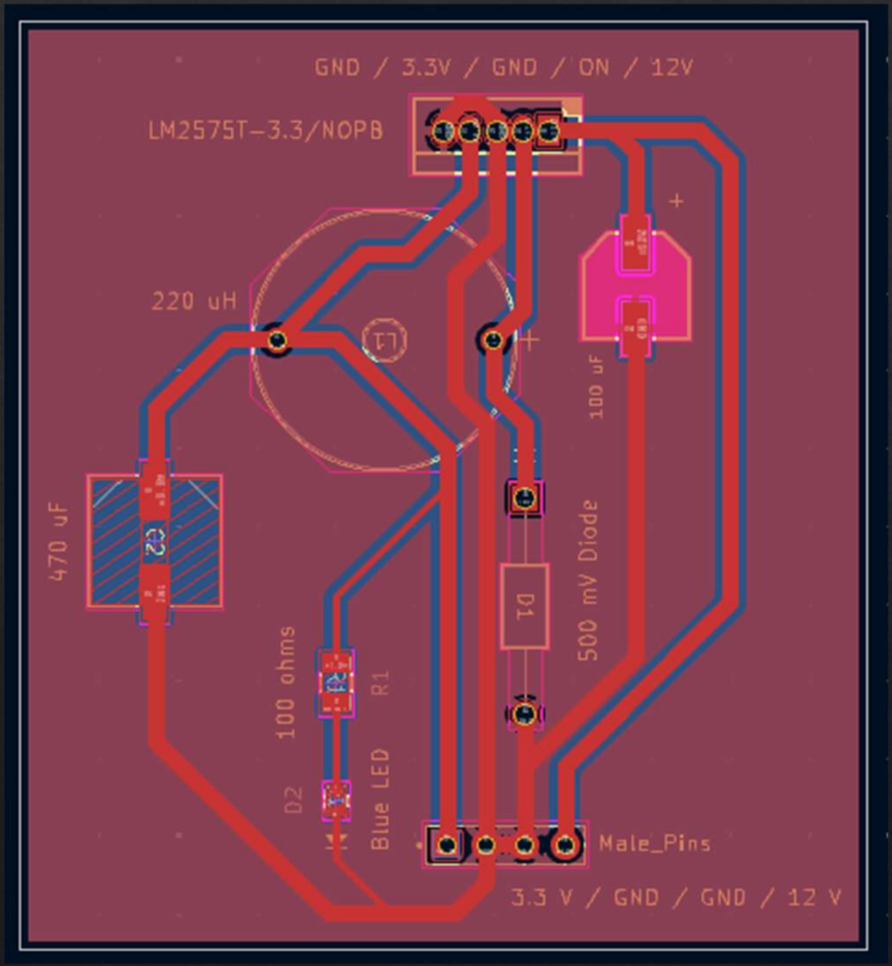
Features	BD9781HFP-TR	LM2575	LM27402
Max Output Current	4 A	1 A	30 A
Efficiency	75% – 80%	75% – 88%	90% – 97%
Input Voltage	7 V – 35 V	4.75 V – 40 V	3 V – 20 V
Output Voltage	1 V – 35 V	1.23 V – 37 V	0.6 V – 18.6 V
Cost	$5.69	$3.63	$3.12

- Caps the output current at 1 A, ensures the ESP32 S3 does not draw more than that
- Wide range of input voltage – permits more variety of options for choosing a power adapter for the system
- Cost is not too expensive

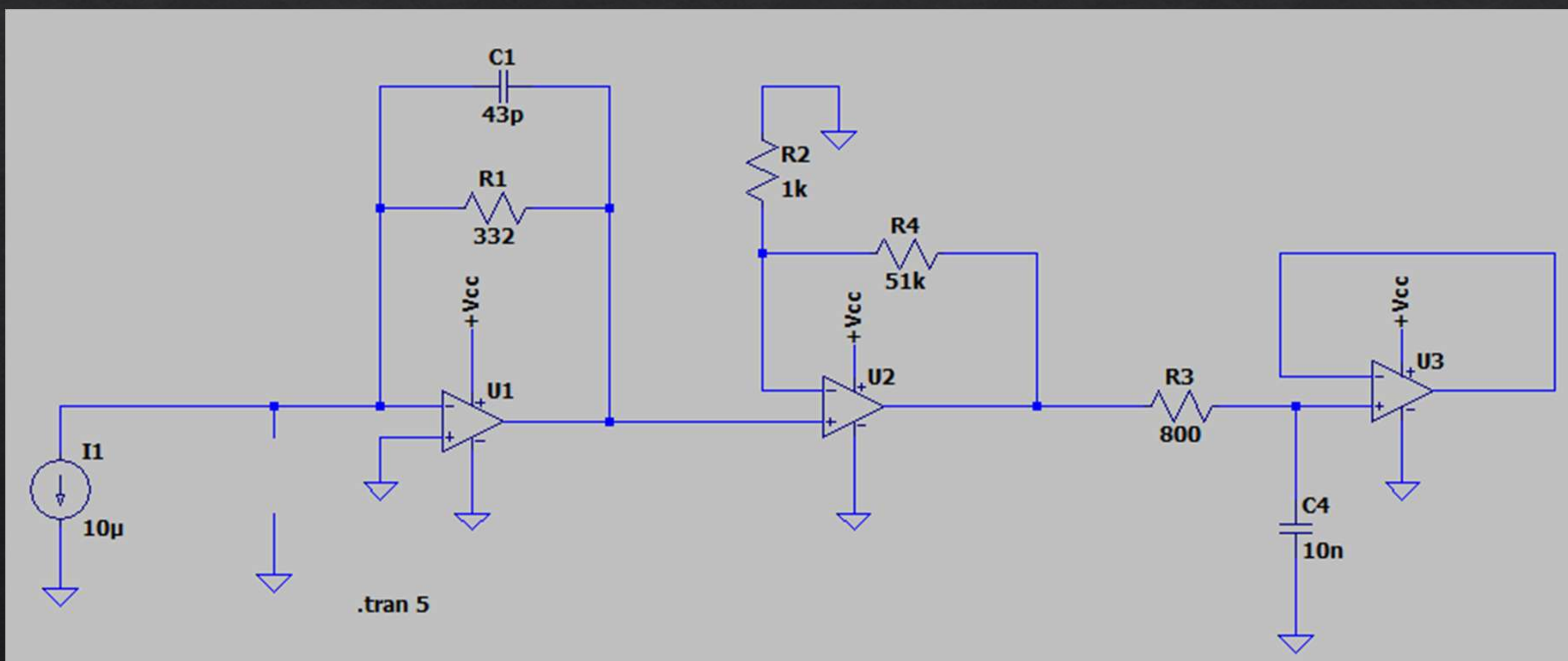
PCB Schematic – 3.3 V Regulator

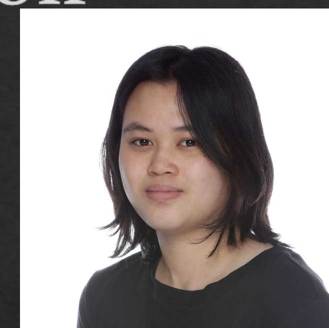


PCB Layout – 3.3 V Regulator

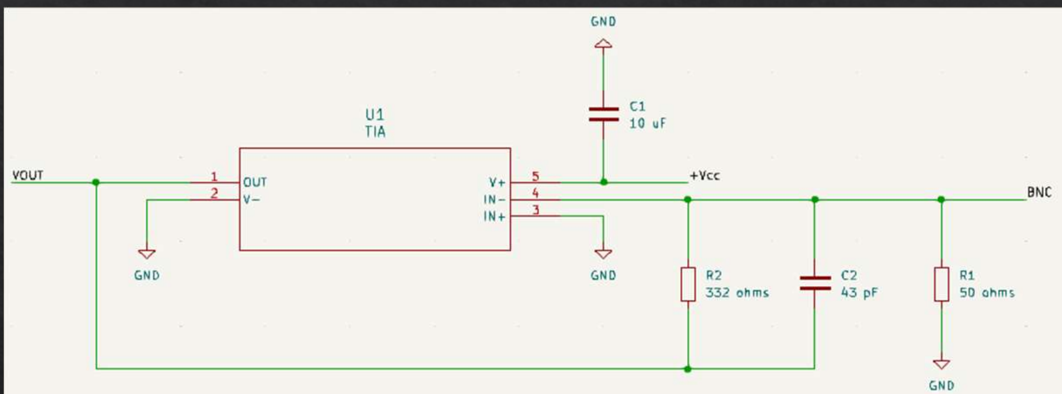


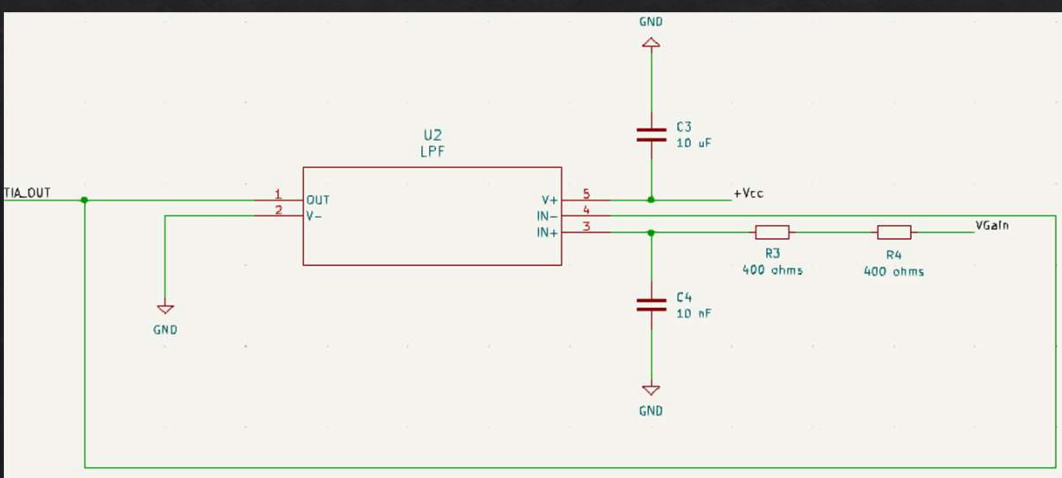
Hardware Design – LTSpice Simulation

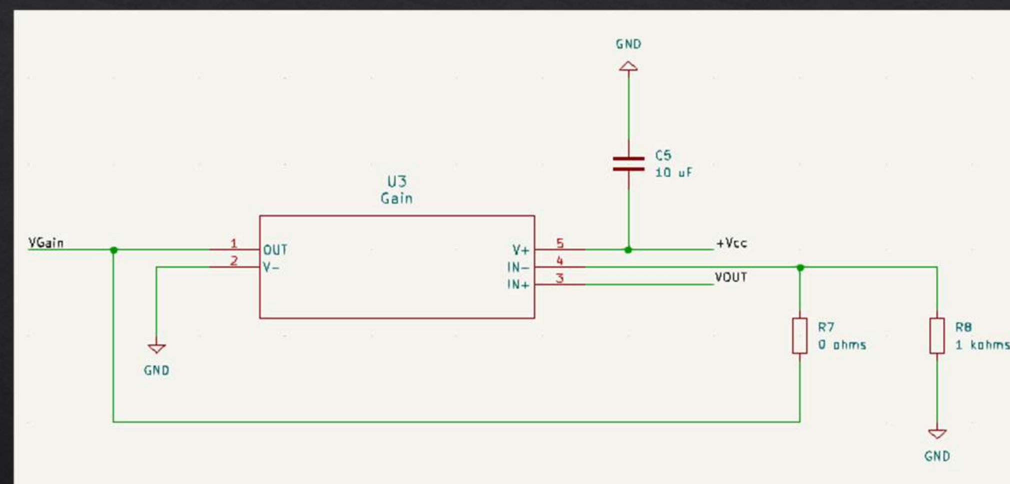




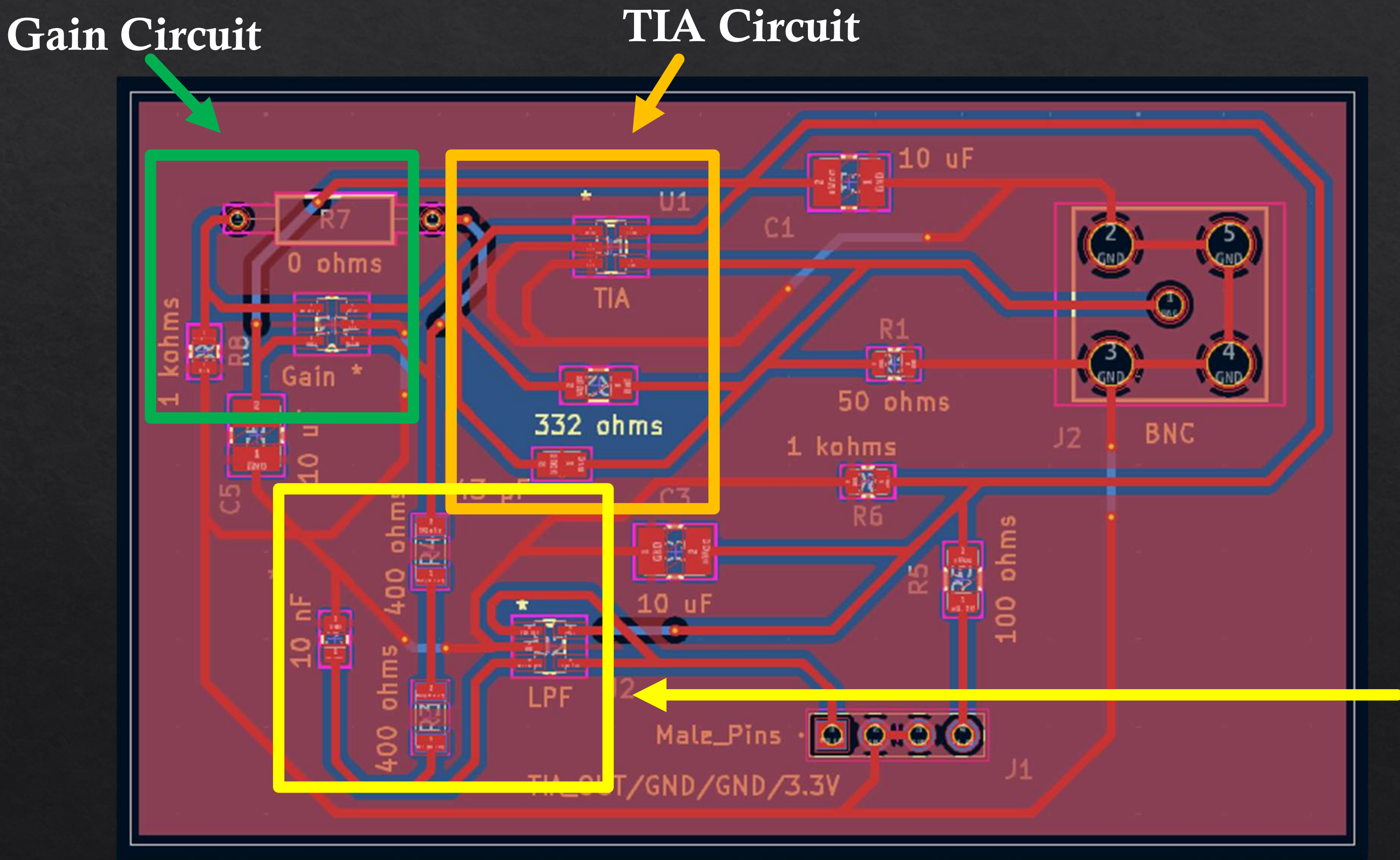
PCB Schematic – TIA Board



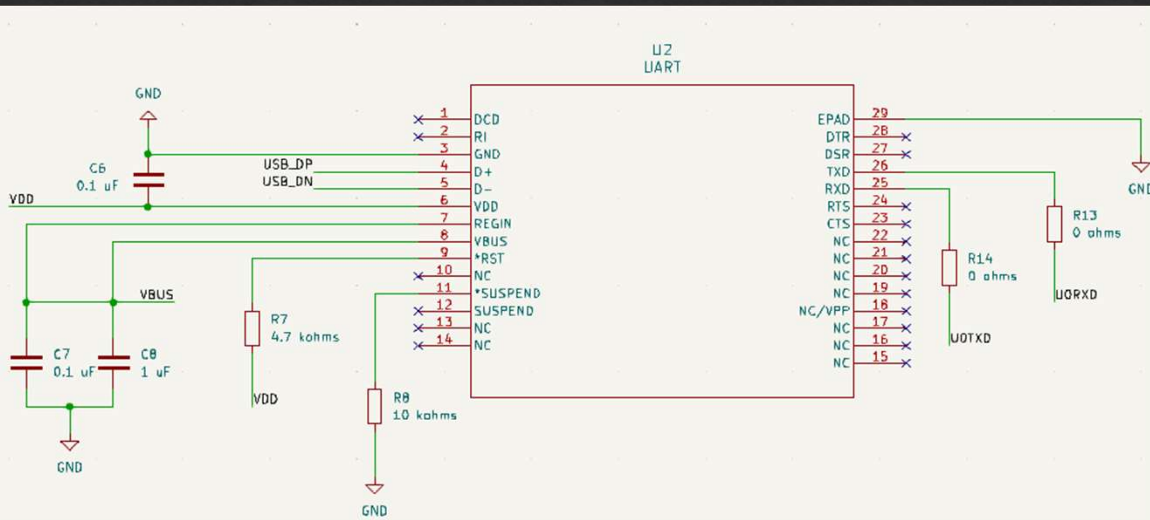


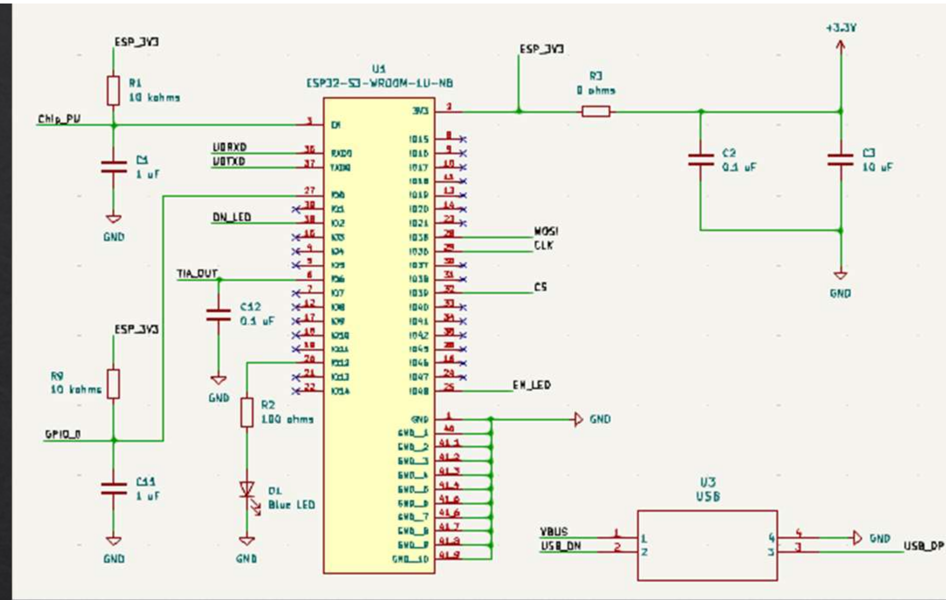


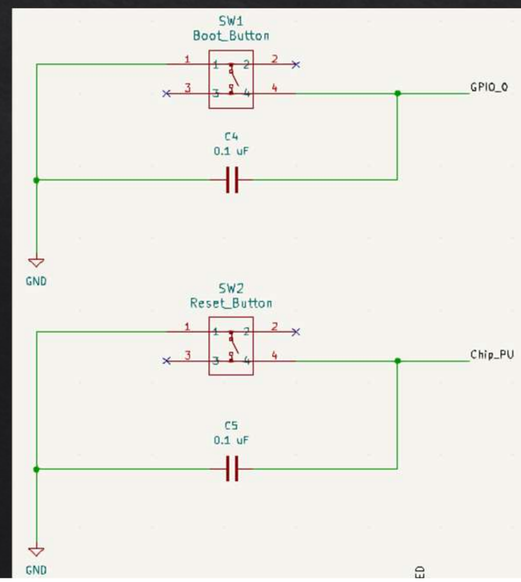
PCB Layout – TIA Board

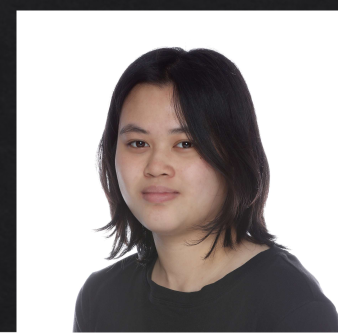


PCB Schematic – Main Board

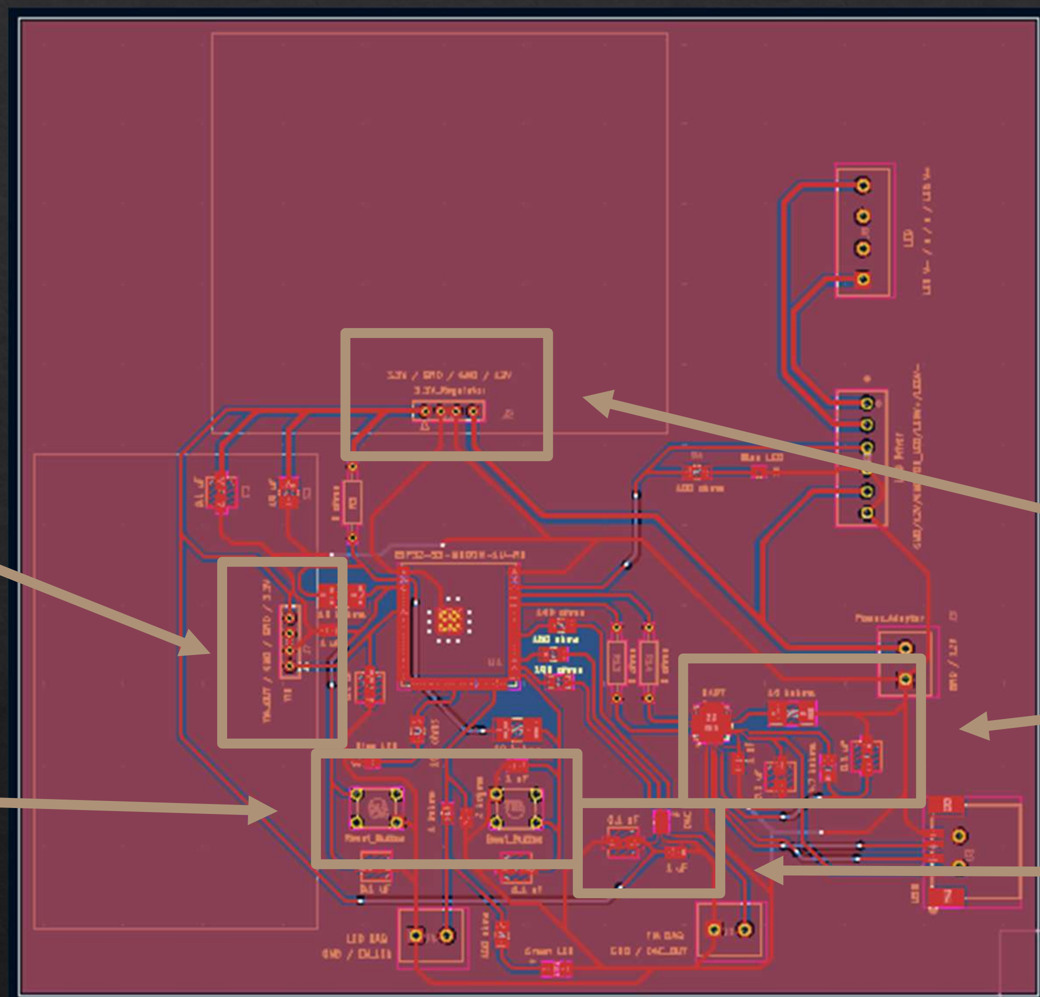








PCB Layout – Main Board



TIA Board

Buttons

3.3 V Regulator Board

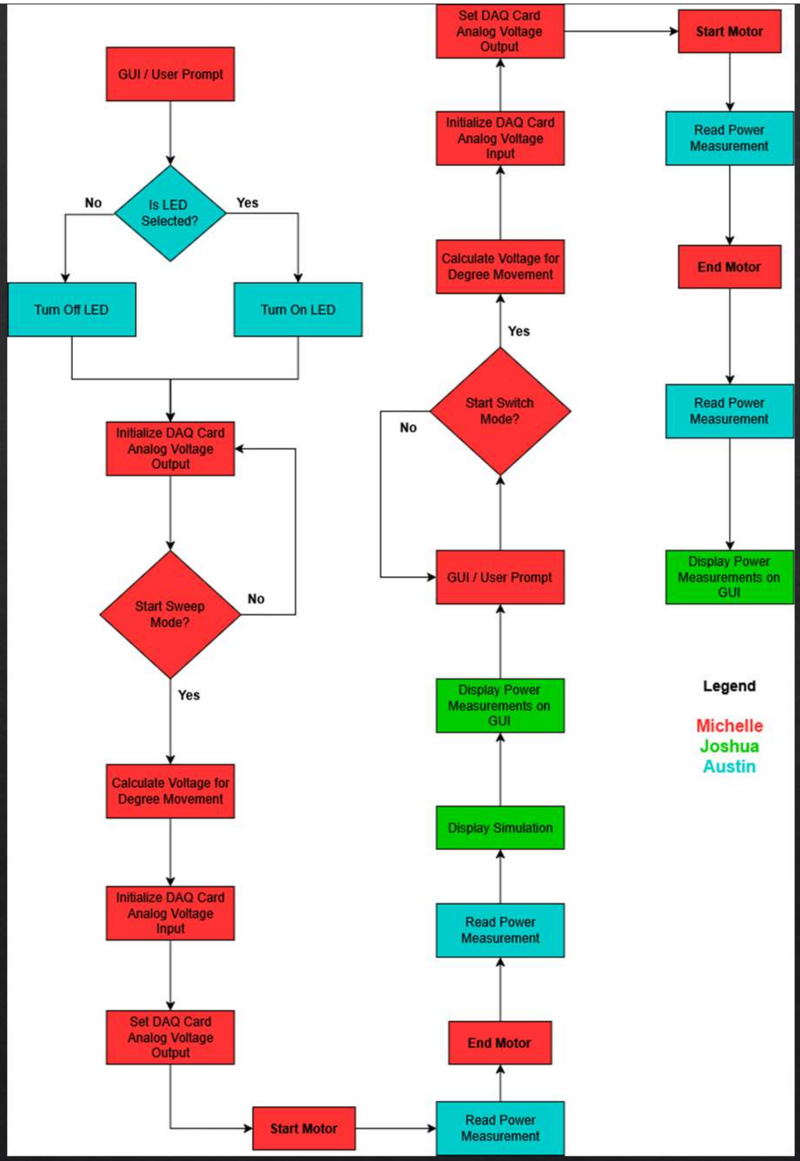
USB to UART

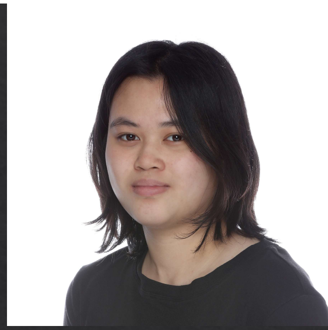
DAC

Software Block Diagram

- Diagram shows how the software will interact with final prototype

- GUI
- Light Source Control – LED
- Motor Control
- Power Reading Control





Communication Protocol – SPI

- Serial Peripheral Interface
- Master and Slave device communicate
- Synchronous communication protocol
- Offer faster frequencies than I2C (important for switching time data collection)
- Can be 3 or 4 wire (3 wire for our system):
  - Clock
  - Chip Select
  - MOSI (Master Out, Slave In)
  - MISO (Master In, Slave Out) (not used in our system)

Communication Protocol – UART

- Universal Asynchronous Receiver-Transmitter
- Data transfer bit by bit across 1 or 2 lines (2 lines for our system):
  - Transmitter (Tx)
  - Receiver (Rx)
- Baud Rate (Data Transfer Rate) needs to be the same on both devices (115200 for our system)
- Only One Master and One Slave (max of two devices talking to each other) (Laptop to ESP32-S3 module)

ESP32 Programming Languages

Features	C	Python	MircoPython	CircuitPython
Description	Low-level programming and supports high level programming	Object-oriented programming	Python 3 programming for embedded and MCU	Simplified version of MicroPython
Embedded Programming	Direct access to machine level hardware Dynamic memory allocation	Not supported Have to use MircoPython or CircuitPython	Can be used to code MUC that has small storage and RAM	No need to compile code Turns the MCU into a plug and play device Lacks access to low level hardware on MCU
Syntax	Complex	Simple	Simple	Simple
Library Support	Lots of libraries available	Lots of libraries available	Less libraries available for usage	Less libraries available for usage
Development Environments	Arduino IDE Espressif IDE	N/A	PyCharm Professional Visual Studio Code	Visual Studio Code

C

- IDE Support
- Lots of resources online
- Lots of library support
- Familiarity with the language

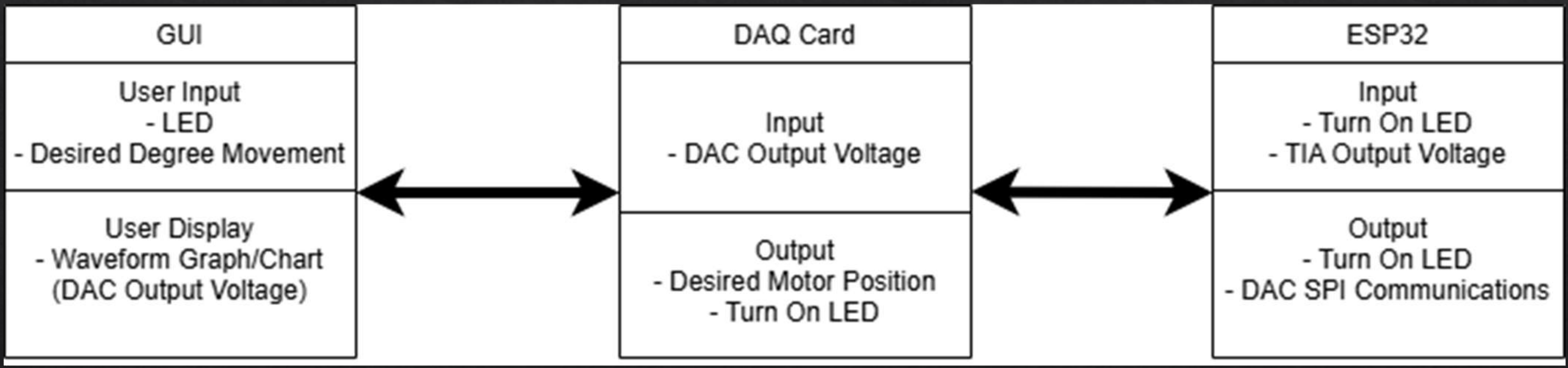
ESP32 Development Environment

Arduino IDE	Espressif IDE (ESP-IDF)
Extensive Library and Community Support	Extensive Documentation on its subsystems, configuration file, and API
Beginner Friendly – easy user interface and little configuration required	Steep learning Curve – more complex to use
Fast compiling time – helpful for developing and prototyping the code	Easy Scalability and continuously software updates, ensures compatibility with future ESP32 MCU

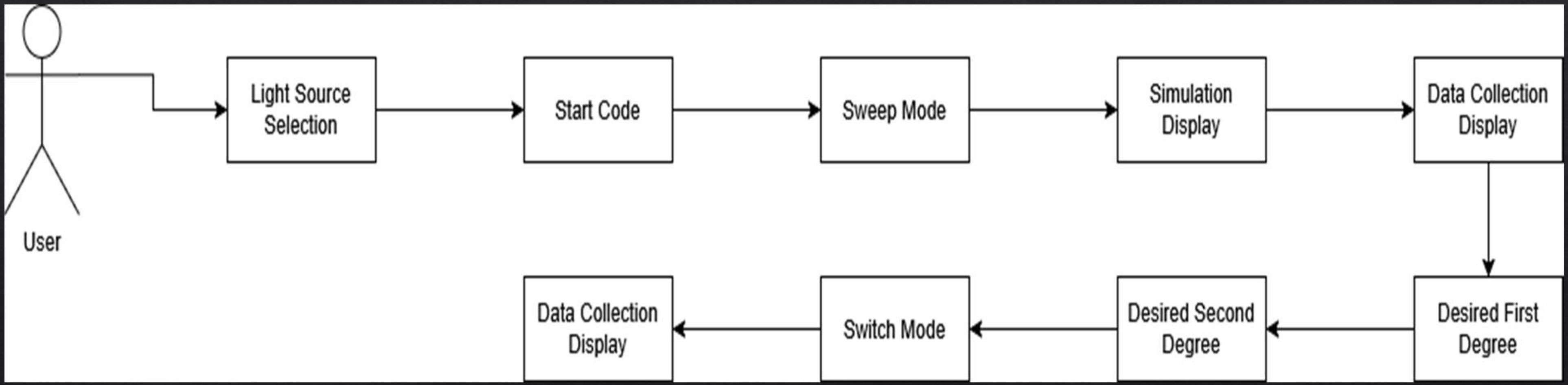
Arduino IDE

- Extensive community support – ease the learning curve for coding the necessary programs
- Beginner Friendly
- Fast Compiling Time – helps with the time constraint of prototyping the code

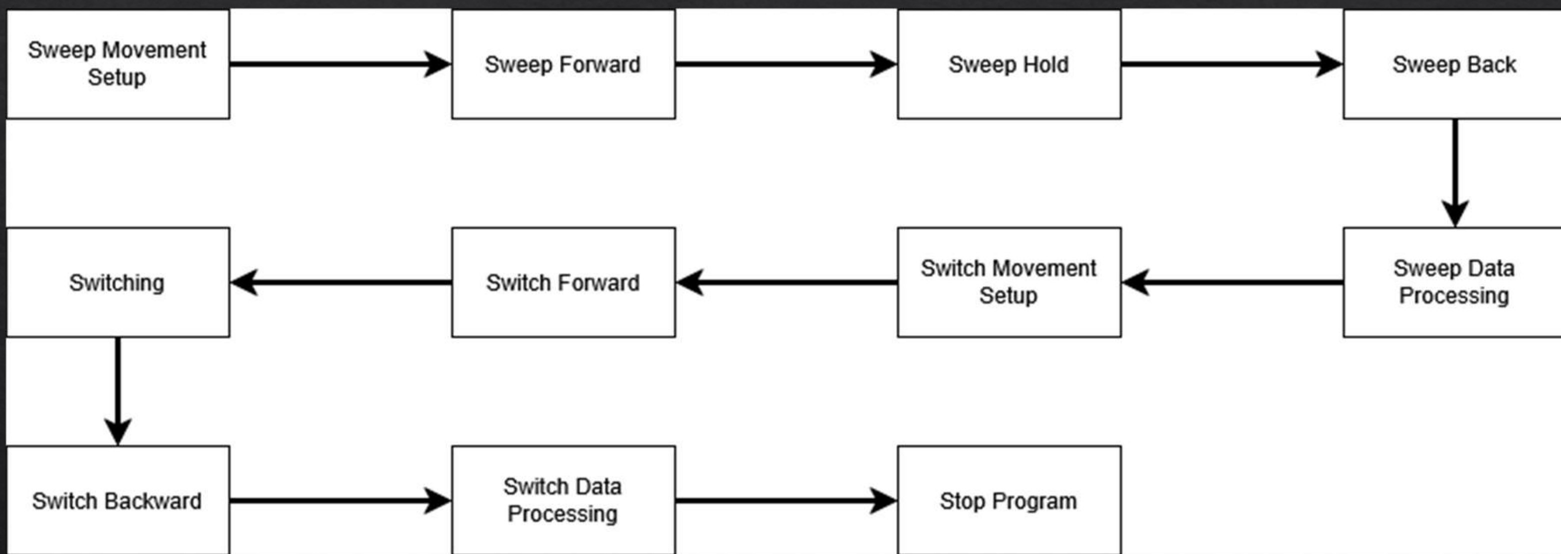
Software Design – Overview

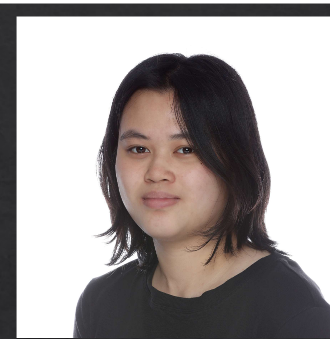


Software Design – LabVIEW: GUI

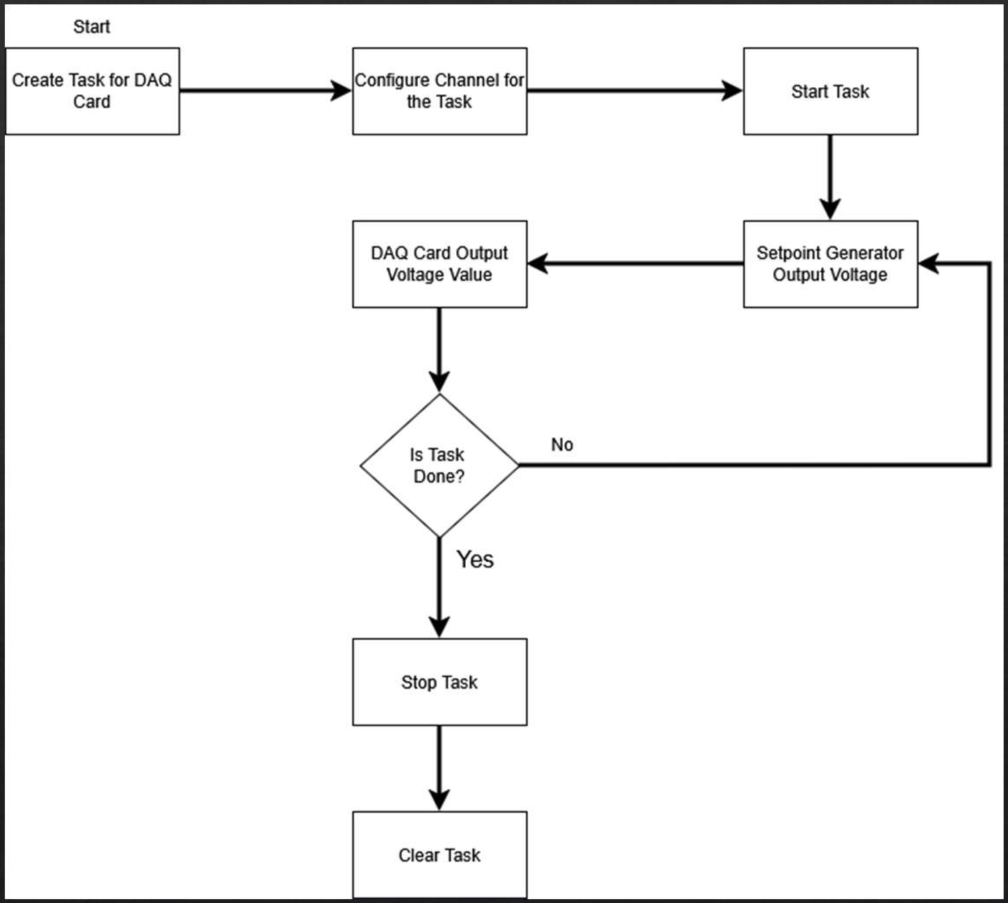


Software Design – LabVIEW: Case Structure

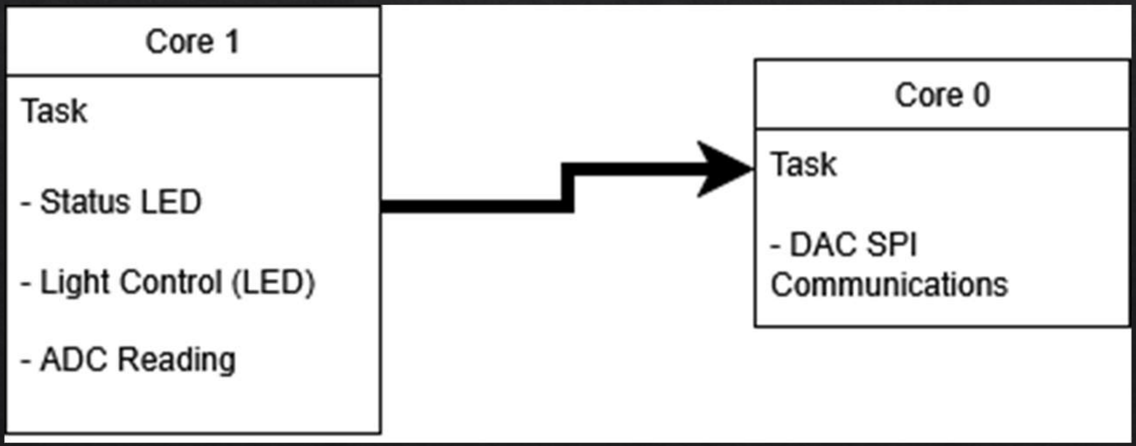


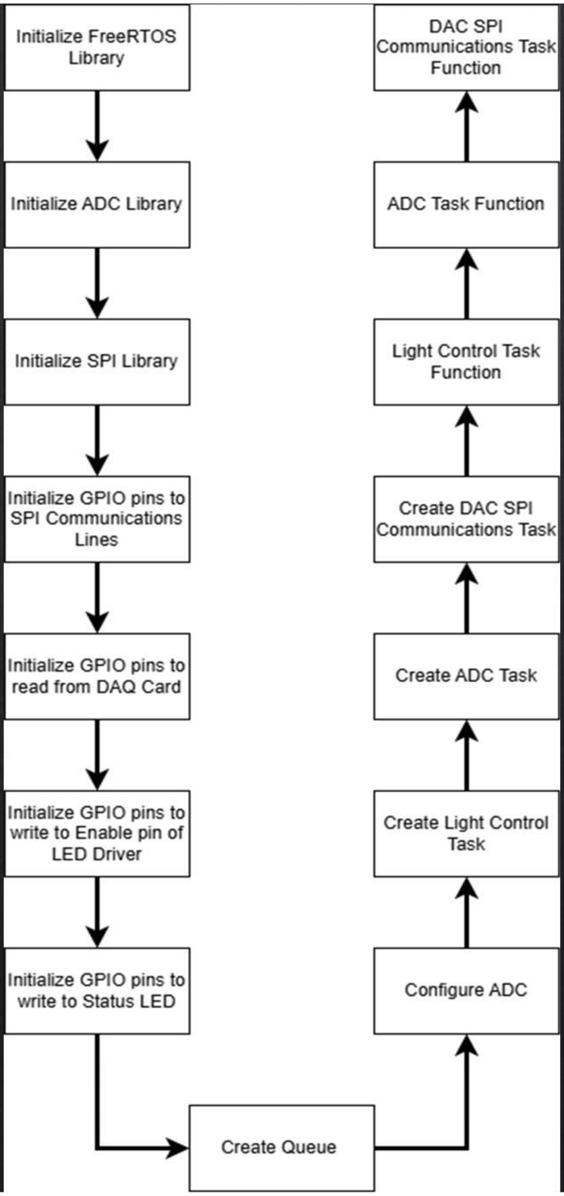


Software Design – LabVIEW: Motor Movement

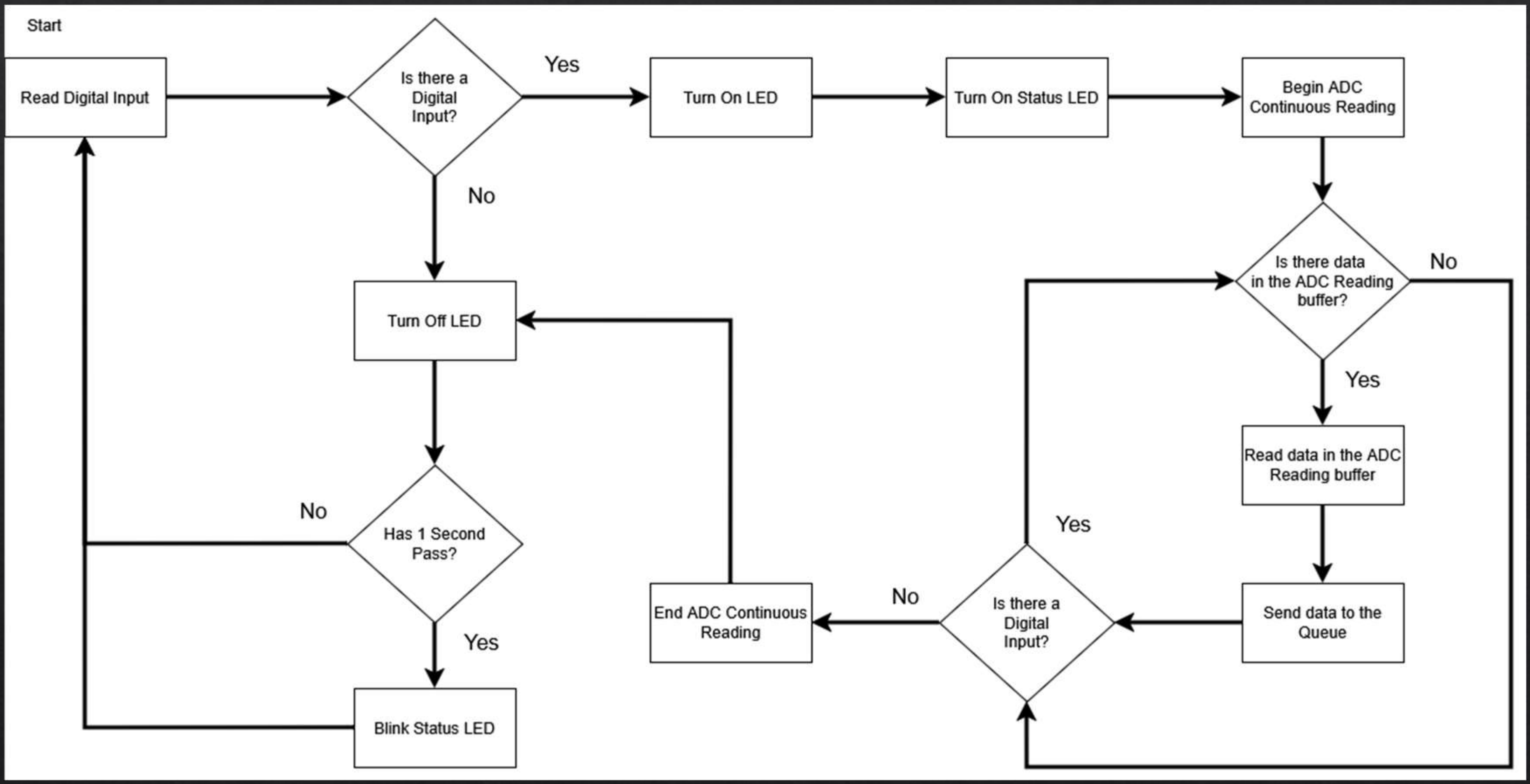


Software Design – ESP32: Overall

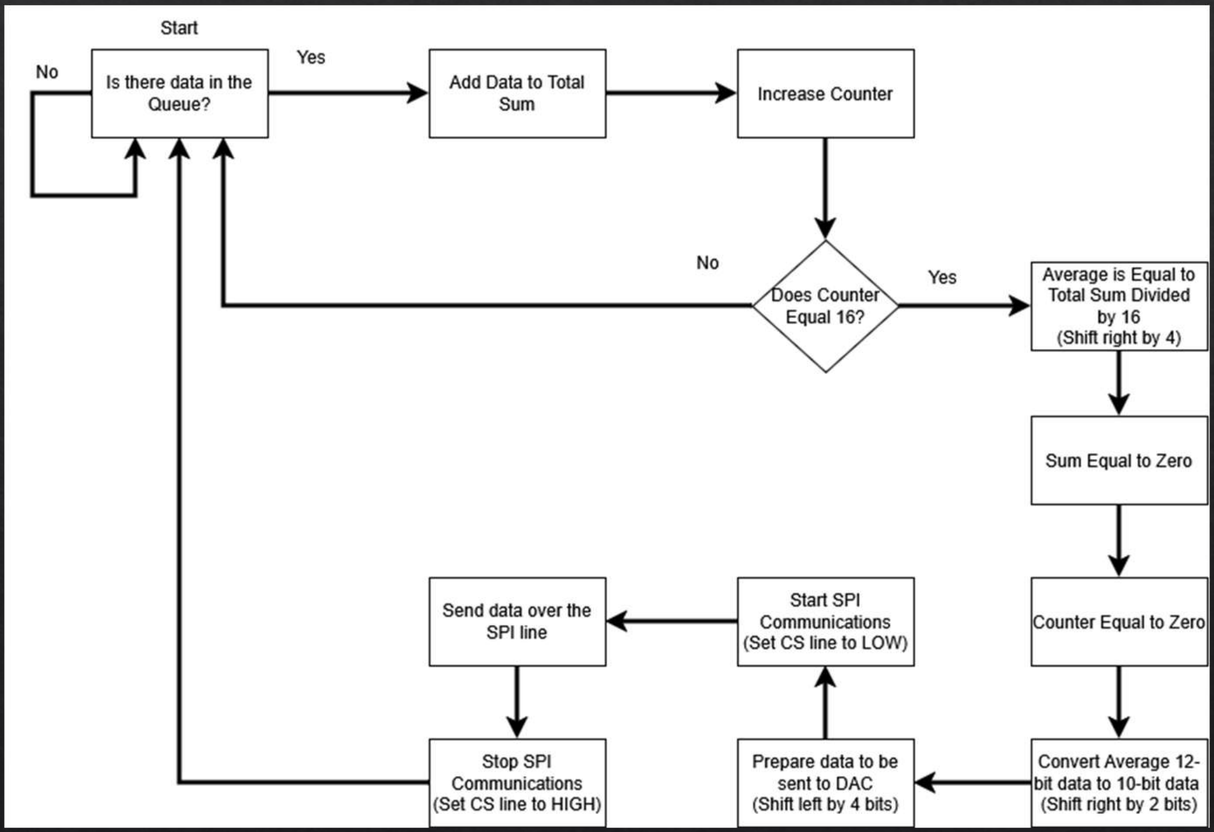




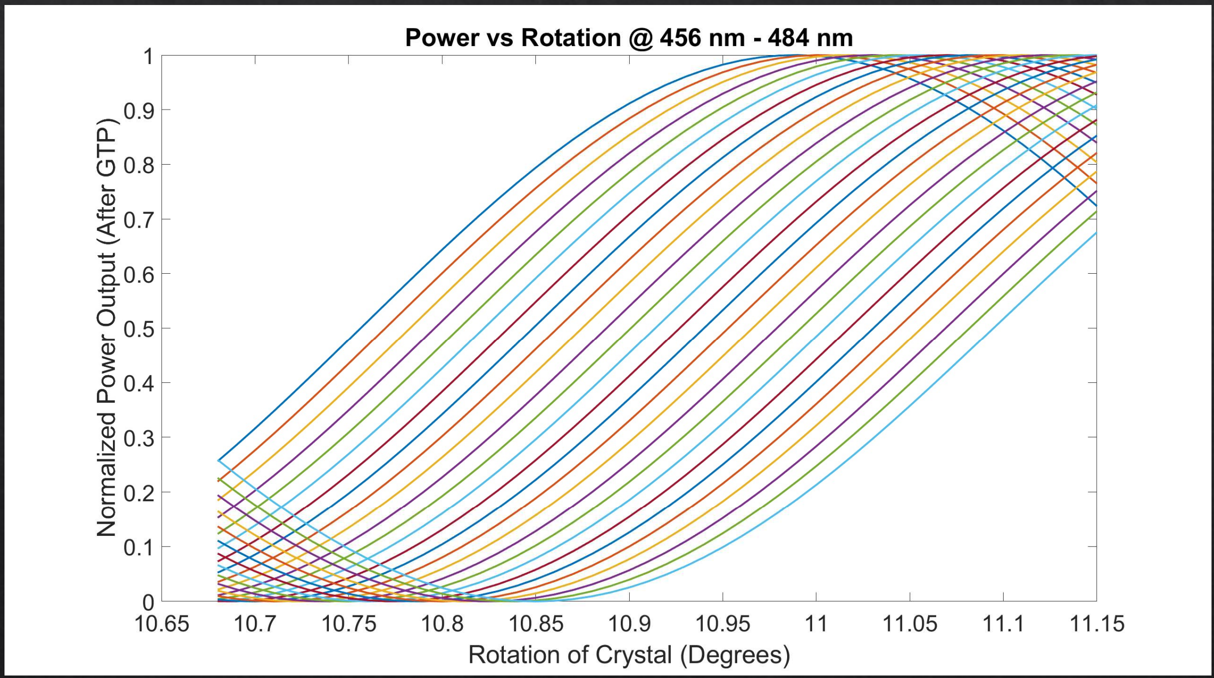
Software Design – ESP32: Core 1



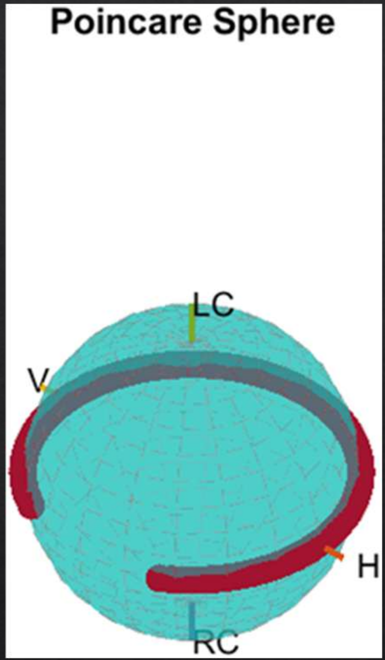
Software Design – ESP32: Core 0



Software Design - MATLAB

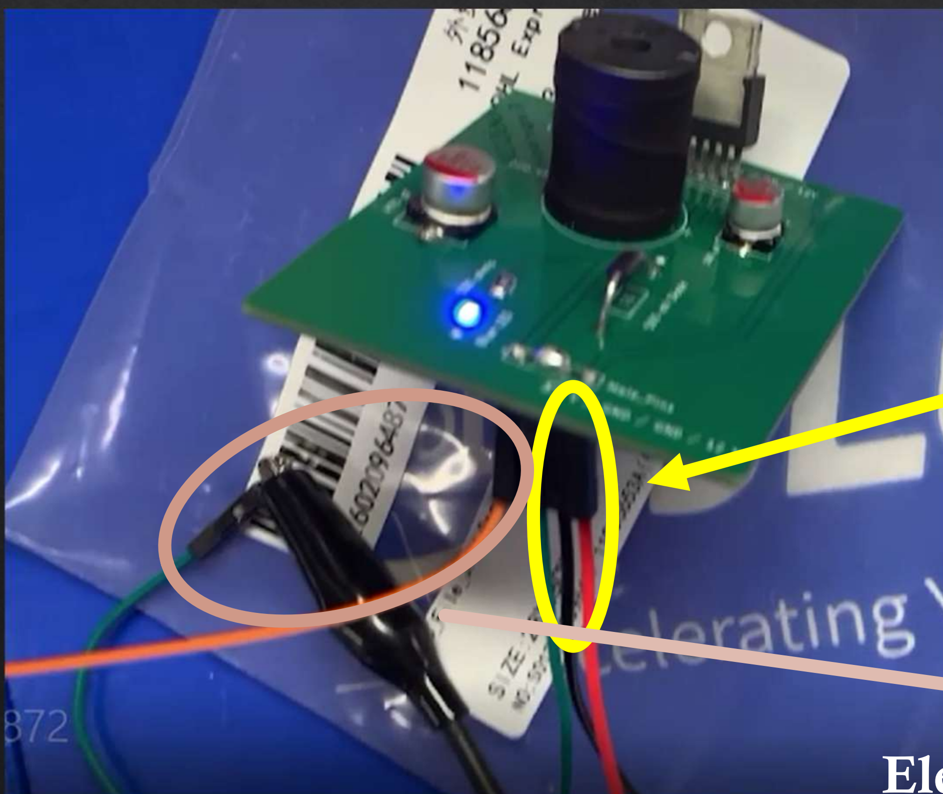


Normalized Power Response with an emission spectrum fitting corresponding to the FWHM of our LED.



The polarization states achieved by our setup with the broadband source

System Testing – Voltage Regulator Setup



DC Power Supply Connection

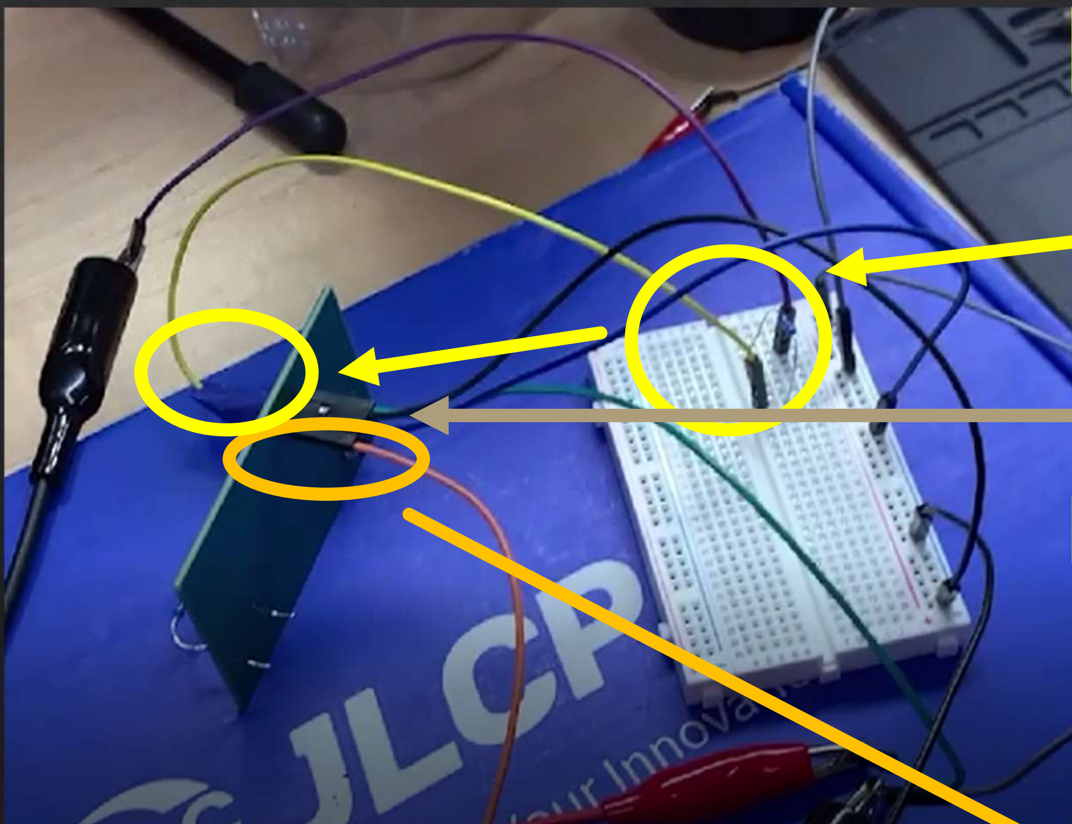
Electronic Load Connection

System Testing – Voltage Regulator Data

Current Load Draw	Input Power	Output Power	Power Efficiency
100 mA	0.53 W	0.33 W	62.26415%
200 mA	0.92 W	0.64 W	69.56522%
300 mA	1.32 W	0.96 W	72.72727%
400 mA	1.73 W	1.26 W	72.83237%
500 mA	2.14 W	1.56 W	72.8972%
600 mA	2.56 W	1.85 W	72.26563%
700 mA	2.98 W	2.14 W	71.81208%
800 mA	3.41 W	2.42 W	70.96774%
900 mA	3.84 W	2.69 W	70.05208%

Average Power Efficiency: 70.59819%

System Testing – TIA Circuit Setup



Voltage Supply for Current Input

Voltage Supply for Op-Amp

Output Voltage of TIA Circuit PCB

System Testing – TIA Circuit Data

Input Current	Simulation	Experiment	Error Percentage
10 uA	172.58 mV	2.67581 V	1450.475%
20 uA	345.21 mV	2.72787 V	690.206%
30 uA	517.84 mV	2.78422 V	437.6603%
40 uA	690.47 mV	2.84454 V	311.9716%
50 uA	863.10 mV	2.89913 V	235.8973%
60 uA	1.0357 V	2.95894 V	185.6947%
70 uA	1.2083 V	3.01498 V	149.5225%
80 uA	1.3809 V	3.06964 V	122.2927%
90 uA	1.5536 V	3.13900 V	102.0469%
100 uA	1.7262 V	3.18472 V	84.49311%

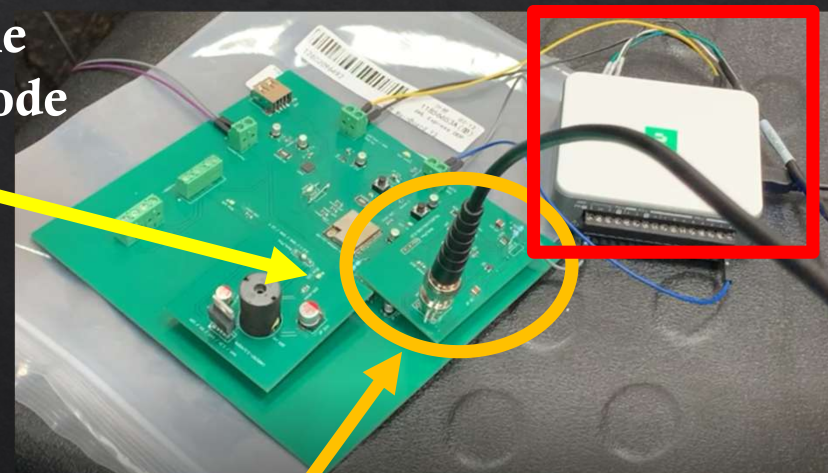
Average Error Percentage: 377.026%

System Testing – Switching Time Setup

Photodiode

Input Current from the Photodiode

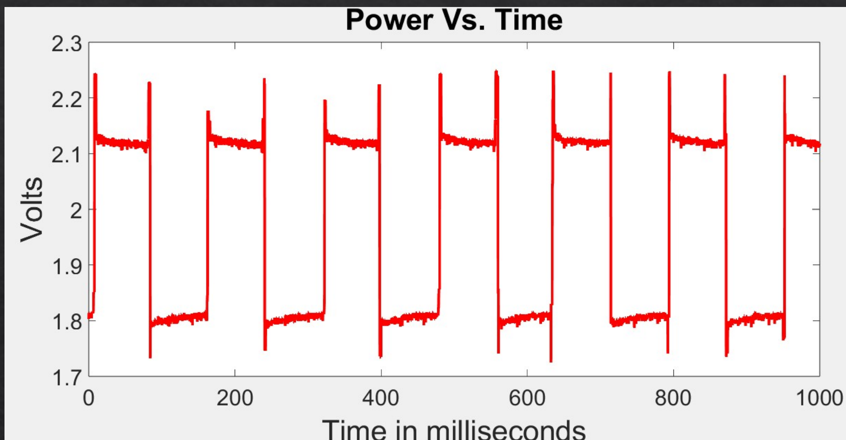
DAQ Card

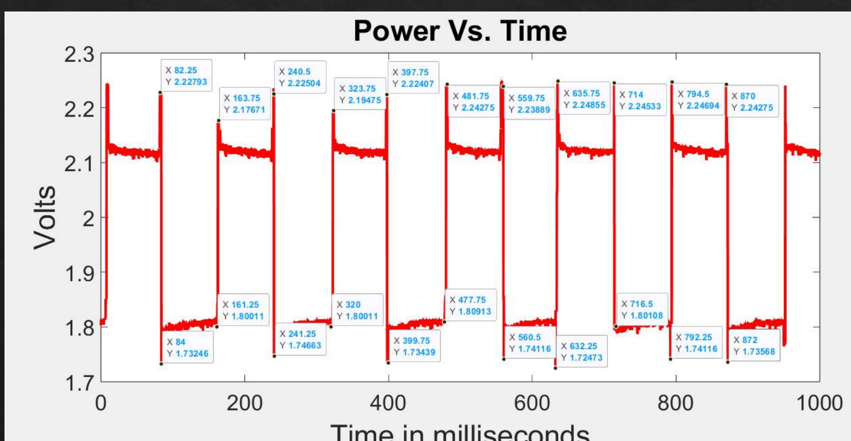


Laser through Crystal

TIA Circuit PCB

System Testing – Switching Time Data

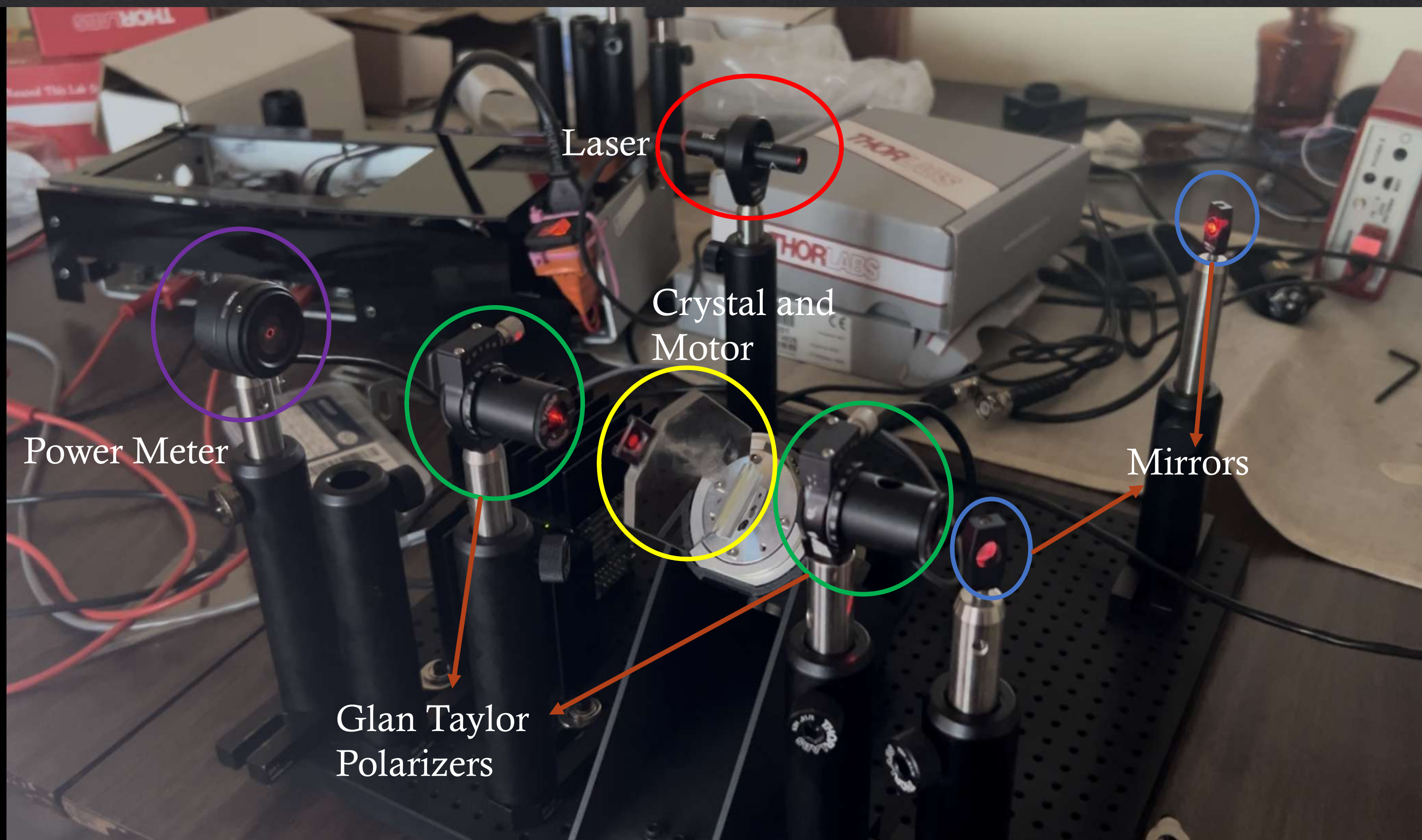




Test Number	Average Switching Time
1	2.10 ms
2	2.39 ms
3	5.57 ms
4	3.23 ms
5	3.00 ms
6	2.30 ms
7	3.05 ms
8	3.20 ms
9	2.34 ms
10	2.18 ms

Average Switching Time: 2.94 ms

System Testing – PER Setup



System Testing – PER Data

Red Laser

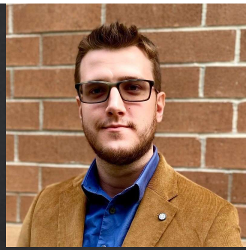
Test	Max Power uW	Min Power uW	PER	Deviation
1	481	2.47	194.7368421	-16.61686969
2	485	2.24	216.5178571	31.46038588
3	484	2.29	211.3537118	0.340495931
4	483	2.61	185.0574713	-26.34603751
5	479	2.27	211.0132159	-3.209006363
6	482	2.28	211.4035088	25.24966262
7	482	2.25	214.2222222	-3.877325289
8	484	2.6	186.1538462	-30.4380821
9	482	2.21	218.0995475	11.5845324
10	483	2.23	216.5919283	10.44760683
	Average PER:	**206.5150151**	**Standard Deviation:**	**0.098650295**

Green Laser

Test	Max Power uW	Min Power uW	PER	Deviation
1	328	2	164	-7.35678392
2	334	2.09	159.8086124	-1.841872997
3	341	1.99	171.3567839	6.182654566
4	333	2.06	161.6504854	-2.705950207
5	332	2.01	165.1741294	3.710714719
6	332	2.02	164.3564356	2.893021009
7	331	2.05	161.4634146	-2.083383395
8	331	2.05	161.4634146	-2.893021009
9	332	2.03	163.546798	-0.170852944
10	332	2.02	164.3564356	0.666185997
	Average PER:	**163.717651**	**Standard Deviation**	**0.64774377**

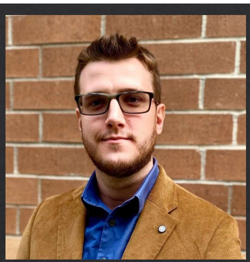
Major Challenges and Solutions

- Motor Acquisition: The delay in choosing the motor caused some height mismatch with the original opto-mechanics chosen
  - Chose a motor that had no lead time and could be used "off the shelf"
  - Acquired new opto-mechanics to correct for the height
- Mounting Crystal to the Motor
  - Due to limitations in motor acquisition, the motor we used is designed to be operated with the attached mirror
  - We attached our crystal using a light-weight housing and gluing directly to the mirror
- This project required a high level of precision, but we didn't have many adjustable parts
  - We adjusted the motor mount and the beta of our crystal by putting washers underneath the print giving us a way to adjust the beta by tightening or loosening the screws in the mount
- We overestimated how much power would be reaching our photodiode
  - We had to increase the gain on our TIA circuit to compensate for the low current coming from the diode.



Future Improvements

- Motor designed to Operate with the Crystal used
  - Guarantees proper orientation of the alignment between the fast axis of the crystal and rotating axis of the motor.
  - Improves PER
  - Allows for longer lifetime in operation
- Adjustable Opto-mechanics
  - Having the ability to finely tune the alignment of your mirrors ad light source will further guarantee your ability to match the rotating axis of the motor and crystal to a 45° orientation with respect to the optical axis
  - Would allow for the proper testing of the double pass setup as we were unable to appropriately align that system.
- Testing the system with multiple kinds of crystals
  - Would be great to compare crystals of different thicknesses and to see if there is some correlation to the PER there. Maybe a thicker crystal has a higher PER despite the difference in birefringence



Budget

10.1.1.1 Thorlabs

Part Name	Part Number	Quantity	Unit Price	Total Price
BNC Cable	2249-C-36	1	$ 21.23	$ 21.23
Glan-Taylor	GT5	1	$ 626.65	$ 626.65
Optical Post	MS1R/M	7	$ 7.96	$ 55.72
M3 Screw Kit	HW-KIT5/M	1	$ 123.30	$ 123.30
Post Holder	MSH075	7	$ 39.10	$ 273.70
LED Connector	CON8ML-4	1	$ 39.10	$ 39.10
Retroreflector	PS974M-A	1	$ 205.91	$ 205.91
Lens	ACL25416U	2	$ 22.00	$ 44.00
1/2 Wave Plate	LCC1111U-A	1	$ 388.95	$ 388.95
Beamsplitter	CCM5-BS016/M	3	$ 224.99	$ 674.97
Post Clamp	PCM/M	1	$ 48.63	$ 48.63
Photo Detector	DET100A2	1	$ 204.65	$ 204.65
Mirror	BB03-E02	4	$ 49.85	$ 199.40
Mirror mount	MFM7/M	4	$ 31.15	$ 124.60
520 nm Laser	PL201	1	$ 199.63	$ 199.63
635 nm Laser	PL202	1	$ 146.40	$ 146.40
Galvo Cables	CBLS3F	1	$ 105.72	$ 105.72
Power Supply	GPWR15	1	$ 600.27	$ 600.27
Galvanometer	SS30Y-AG	1	$ 3819.90	$ 3819.90
LED	M470L5	1	$ 261.20	$ 261.20
Breadboard	MBY3030/M	1	$ 369.15	$ 369.15

10.1.1.2 Amazon

Part name	Part number	Quantity	Unit price	Total price
USB 2.0 Socket	B09WQHPXH6	1	$ 5.89	$ 5.89
ESP32-S3	B0BX2MSCRT	1	$ 15.00	$ 15.00
M8 Plug IP67	B0DGXB6PPQ	1	$ 9.98	$ 9.98

10.1.1.3 DigiKey

Part name	Part number	Quantity	Unit price	Total price
Breadboard	1738-1326-ND	1	$ 2.90	$ 2.90
3.3 V REG	LM2575T-3.3/NOPB	1	$ 3.63	$ 3.63
LED Driver	LDDS-1000HW	1	$ 8.87	$ 8.87
IC PWR Switch	296-34970-1-ND	1	$ 0.77	$ 0.77
AC/DC Adapter	16-00216	1	$ 11.81	$ 11.81
DC Power Jack	2057-ADC-002-1-ND	1	$ 0.33	$ 0.33
22AWG Jumper Kit	BKWK-3-ND	1	$ 5.60	$ 5.60
DAQ DEVICE	2270-782606-01-ND	1	$ 784.12	$ 784.12

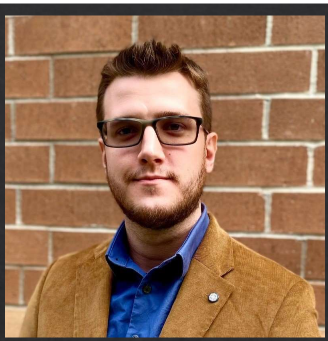
With a primary system budget (Polarizers, Motor, and Crystal) of $7000, and some extra costs for testing components to be able to characterize our system our total cost was 10,130.55

Work Distribution

While this distribution shows a breakdown of responsibilities, a lot of them have overlap and multiple people work together on each other's responsibilities when we hit a road block or we want to find a better way than our first instinct.

Electrical Engineering	**Responsibilities: Software**	**Hardware**
Michelle Nguyen	• Initialize Motor Library • Initialize MCU pins to motor • Set motor speed • Function: Calculate time for motor to spin to reach calculated degree • Set motor spin time • Break out of Switch Statement • Start motor • Stop motor	• Power Supply • Microcontroller • Motor Driver • Motor
Optical Engineering		
David "Austin" Rich	• Initialize MCU pins for laser diodes • If / Else Statement: Turn on/off laser diodes based on User Prompt • Read Power Measurement	• Laser Driver • Laser Diode • Power Detector
Joshua Hendry	• GUI / User Prompt • Function: Calculate needed degree for selected polarization • Switch Statement: Case selection based on User Prompt (polarization selected) • Set motor angle • Display Power Measurement on GUI	• Laptop • Mirror • Retro-Mirror • Crystal

Thanks for Watching



- Thank you to ASML, and Gregory Jenkins for sponsoring the project and supporting us a long the way

- Thank you to Dr's. Weeks, Chan and Kar for their help and guidance during this process

- This was made possible because of viewers like you.