Digital Transmission in Free Space through a High-Power Laser

Group 1:

Alexander Simmons, Curtiss Kane,
Ivan Huang, Monica Castro-Suarez

Mentor:

Dr. Lei Wei
Dr. Aravinda Kar

Committee:

Dr. Saleem Sahawneh

Dr. Mark Maddox

Dr. Stephen Eikenberry

Meet The Team

Alexander Simmons

Photonic Engineer

Curtiss Kane

Electrical Engineer

Ivan Huang

Photonic Engineer

Monica Castro-Suarez

Computer Engineer

Background & Motivation

- Long-distance communication was forever changed with the electric telegraph in the 19th century, and the laser and fiber optic cable in the 20th century
- As digital signals are composed of 1s and 0s, a laser can be modulated such that these signals can be represented as a series of pulses
- Free-space laser communications already exist, but mostly with satellites
- The project will demonstrate the possibility of terrestrial free-space laser communications, where rapid transmission of sensitive data is critical

Goals and Objectives

Goals	Objectives
Digital-to-Optical Modulation	• Develop a system with pulse-coded modulation • Purchase a laser with TTL capabilities
Maximum Signal Reception	• Construct an efficient optical system • Select a photodiode that can accept 980nm
Real-Time Decoding	• Develop a microcontroller-based system • Integrate AI/machine-learning capabilities
Optimization of Signal Transmission	• Simulate efficient optical layouts • Search for different types of lenses and mirrors
Off-Grid/ Emergency Capabilities	• Introduce bidirectional capabilities • Develop smaller form-factor systems
Megabit Transmission	• Find a lower wavelength laser • Integrate electro-optical components

Basic

Advanced

Stretch

Engineering Requirements

Requirement	Specification/ Target Value	Purpose
Decoding Accuracy:	$\geq$ 95% Accuracy	Ensures reliable signal interpretation
Data Transfer Rate:	500 Kbps - 1 Mbps	Allows flexibility in signal speed for different applications
Expected Power Consumption:	$\leq$ 5W	Optimized for low-power, battery-powered operation
Optimal Transmission Distance:	20-50 feet	Ensures optimal signal integrity and low attenuation
Power Efficiency:	$\geq$ 85% efficiency, $\leq$ 5% voltage ripple	Ensures portability and long operational life
Interference Immunity:	$\geq$ 40 dB reduction in EMI	Optical transmission eliminates electromagnetic interference
Bit Error Rate (BER):	$\leq 10^{-5}$	Ensures that signal quality is preserved

Optical Component Selection

Laser Source

- **980 nm TTL-modulated diode**
- Chosen for: compatibility with filters, eye safety, and sufficient modulation bandwidth (~100 kHz)

Beam Expander (Transmitter)

- **Positive meniscus lens**
- Reduces divergence to <1 mrad for long-distance stability

Focusing Lens (Receiver)

- **Aspheric lens (NA = 0.55)**
- Minimizes aberration and tightly focuses expanded beam onto photodiode

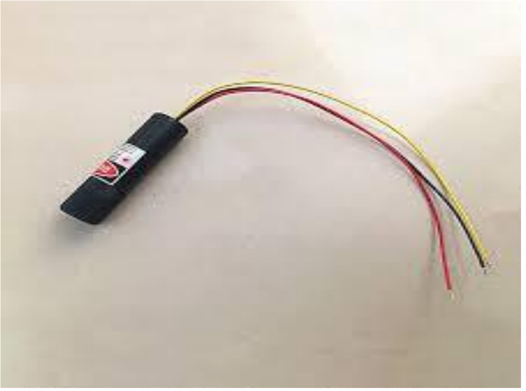
Photodiode

- **Silicon PIN photodiode (0.6 A/W @ 980 nm)**
- Offers low noise, high sensitivity, and 30 MHz bandwidth

Optical Filter

- **Bandpass filter @ 980 ± 10 nm, OD ≥ 4**
- Blocks ambient light, improves signal-to-noise ratio

Laser Component Comparison @980nm



Property	TTL-Modulated Laser Diode	Pulsed Laser Diode Illuminator	Femtosecond Fiber Laser	Ytterbium-Doped Fiber Laser	Ti:Sapphire Laser
Pulse Duration	CW / Modulated	100–200 ns	<150 fs	50 ps – 1 ns	5–100 fs
Repetition Rate	Up to 100 kHz	Up to 10 kHz	1–80 MHz	1–100 MHz	70–90 MHz
Output Power (mW)	≤ 50	≤ 20 W	≤ 20 W	≤ 10 kW	0.4–2.5 W
Beam Quality (M^2)	< 1.5	< 1.5	< 1.2	< 1.3	< 1.1
Best Use Case	Basic optical comms, FSO	Industrial sensing, IR beacon	Biophotonics, microscopy	LIDAR, material processing	Research, ultrafast spectroscopy

Design Calculations:

Power density at 1km: (TTL)

$$Power\ Density = \frac{P}{\pi(r^2)} = \frac{0.05}{\pi(1)^2} = 15.9\mu W/cm\text{^}2$$

Photodiode Component Comparison

Parameter	PN Diode	PIN Photodiode	Avalanche Photodiode (APD)
Responsivity @ 980 nm	0.4 A/W	0.6 A/W	0.7 A/W
Bandwidth (3 dB)	<10 MHz	30 MHz	200 MHz
Internal Gain	1	1	10 – 1000
Dark Current	0.005 – 0.1 nA	0.1 – 0.5 nA	1 – 10 nA
Reverse Bias Requirement	0 – 5 V	5 – 15 V	≥30 V
Cost	~$10	~$35	$150+
Suitability for FSO	Signal detection range <10 m	Up to 1–2 km with lens	Up to 5 km with amplification

Design Calculations:

Photocurrent @50 μW incident power:

$$Isignal = P_{optical} \times R = 0.001W \times 0.6 = 0.6mA$$

SNR estimate (assuming amplifier noise current ~5 nA):

$$SNR = \frac{I_{signal}}{I_{noise}} = \frac{(30 \times 10^{-6})}{(5 \times 10^{-9})} = 6000 = 37.6dB$$

Beam Expander Component Comparison

Parameter	Plano-Convex Lens	Positive Meniscus Lens	Achromatic Doublet
Beam Expansion Quality (Beam Divergence)	~1.2 mrad	~0.8 mrad	~0.6 mrad
Chromatic Aberration (Lateral)	~0.2 mm over 10 mm	~0.08 mm	~0.01 mm
Spherical Aberration	Wavefront error ~λ/4	Wavefront error ~λ/10	Wavefront error ~λ/12
Focal Length Range	50 – 100 mm	38.1 – 76.2 mm	30 – 80 mm
Transmission Efficiency	~92%	~95–96%	~97%
Cost per Unit	$40 – $60	$55 – $80	$120 – $250
Ease of Alignment (Angular Sensitivity)	±2°	±1°	±0.5°

Design Calculations:

Beam Divergence Reduction

- **Wavelength (λ)** = 980 nm
- **Initial beam waist (w_0)** = 0.5 mm (typical diode laser aperture)
- **Initial divergence (θ_0)** without expansion:

$$\theta_0 = \frac{\lambda}{\pi w_0} = \frac{(980 \times 10^{-9} m)}{\pi \times (0.5 \times 10^{-3} m)} \approx 0.624 mrad$$

Implementation (divergence)

- **Collimation lens focal length (f_1)** = 10 mm
- **Expander lens focal length (f_2)** = 50 mm
- **Expansion factor (M)** = $\frac{f_2}{f_1} = \frac{50mm}{10mm} = 5$

$$\theta_{reduced} = \frac{\theta_0}{M} = \frac{5mrad}{5} = 1.0mrad$$

Beam Diameter Post expansion at 1km:

$$Beam\ diameter = 2\theta L = 2 \times (0.001) \times (1000) = 2.0m$$

Beam Diameter without Beam Expander:

$$Beam\ diameter = 2 \times (0.005) \times (1000) = 10m$$

Focusing Lens Component Comparison

Parameter	Aspheric Lens (C230TME-B)	Plano-Convex Lens (LA1131-B)	Achromatic Doublet
Focusing Precision (Spot Size)	≤ 10 µm	~30–50 µm	~8 µm
Aberration Correction (Wavefront Error)	≤ λ/12	~λ/4	≤ λ/10
Focal Length Range	4.51 mm	25 mm	30 – 80 mm
Numerical Aperture	0.55	0.15	0.25 – 0.35
Compatibility @ 980 nm	600–1050 nm AR Coating	600–1050 nm AR Coating	Custom coating (optional)
Cost per Unit	~$65	~$35	$120–$200

Design Calculations:

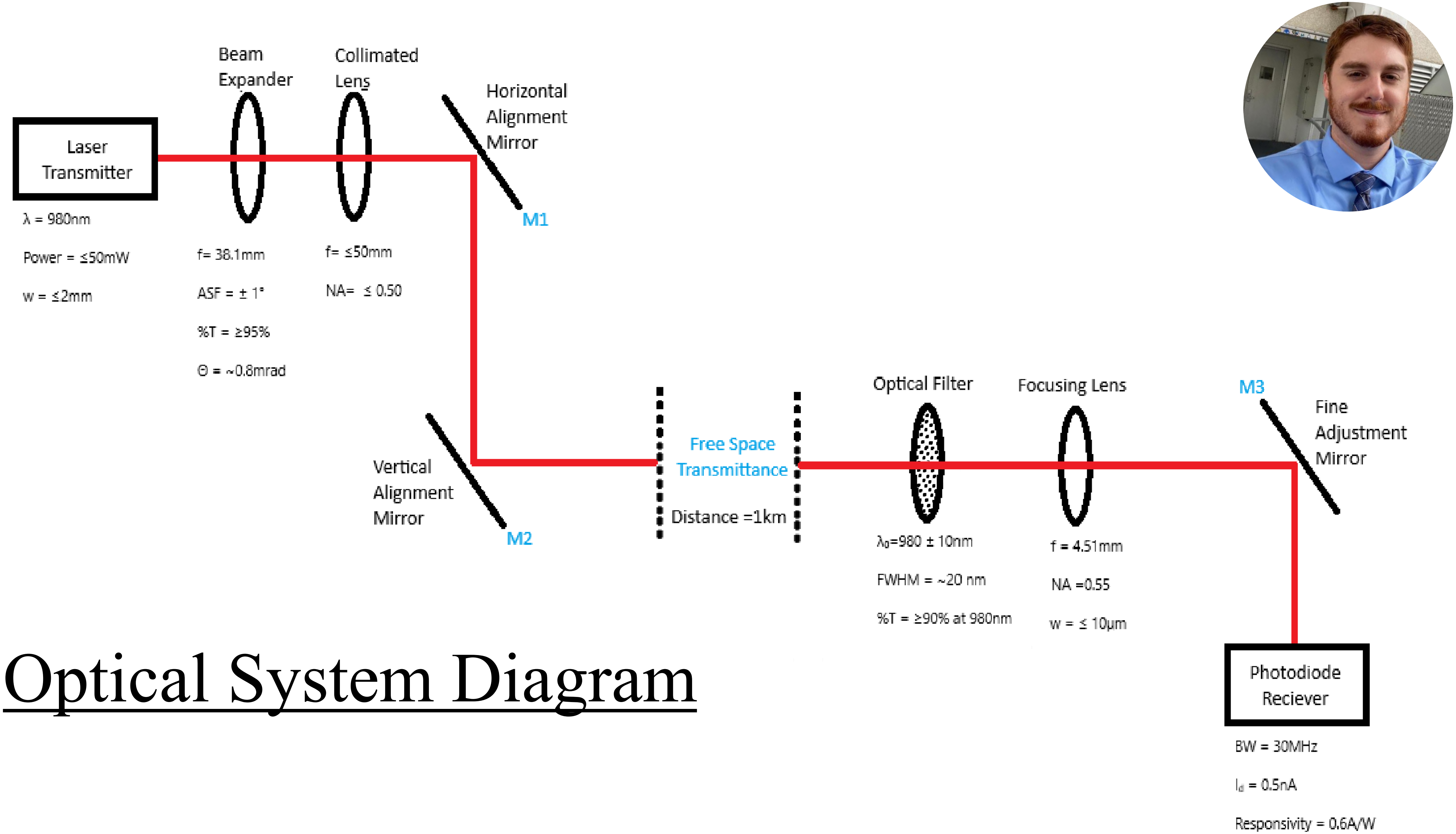
Focusing Lens spot size:

$$Spot\ size \approx \frac{1.22\lambda f}{D} = 1.22\frac{(980 * 10^{-9}) \times (4.51 * 10^{-3})}{3 \times 10^{-3}} \approx 1.8\mu m$$

Optical Filter Component Comparison

Parameter	Bandpass Filter	Shortpass Filter	Longpass Filter
Central Wavelength	980 ± 10 nm	Cutoff at 980 nm	Passes above 980 nm
Transmission Efficiency	≥99% at 980 nm	85–90%	85–90%
Blocking Range (OD for λ < 980 nm)	≥ 4	2–3 f	2–3
Spectral Width (FWHM)	~20 nm	Not applicable	Not applicable
Cost	~$100	$40 – $70	$40 – $70

Optical System Diagram



Impact of Atmospheric Affects on Free Space Optics

Beam Propagation Challenge

In free-space optical (FSO) systems, beam performance is limited by diffraction, divergence, and atmospheric effects. A key tradeoff exists: smaller beam diameters increase divergence, reducing range efficiency.

Gaussian Beam Divergence:

- $\theta = \frac{\lambda}{\pi w_0}$ (λ = 980 nm)
    - Smaller w_0 (beam waist) → greater θ (divergence)
    - Beam spreads over distance, reducing intensity at receiver

Consequences at Long Range (1–2 km):

- Lower received power due to spot mismatch
- Higher alignment sensitivity
- Reduced SNR under turbulence
- Limits raw diode beam range without optical correction

Example of Beam Divergence due to Atmospheric Affect

Figure adapted from:
Barrios, R., & Dios, F. (2012, March). Wireless Optical Communications Through the Turbulent Atmosphere: A Review. In *InTech*. https://doi.org/10.5772/34740

Design Solution:
Beam Expansion and Refocusing

A. Beam Expansion Reduces Divergence

- $\theta_{expanded} = \frac{\lambda}{\pi(M)w_0} = \frac{\theta}{M}$
  - **M**: beam expansion factor (e.g., 3× or 5×)
  - **Result:** beam remains narrower over long distances

This preserves beam intensity, reduces the spread, and ensures more optical power remains within the receiver's capture area.

B. Focusing Lens at the Detector

A focusing lens, such as an aspheric or plano-convex lens, is placed before the photodiode to:

- Re-converge the expanded beam onto the small active area of the photodiode
- Maximize photon-to-current conversion by concentrating light
- Compensate for minor misalignments or atmospheric jitter

Speckle Effects & Beam Expansion Strategy

Speckle Pattern Impact:

Coherent light forms **speckle patterns**—random intensity variations from interference

- At **1–2 mm beam size**, speckle is dense and easier to average or read with receiver
- At **2–4 inch beam size**, speckle grains are larger and difficult to average across the photodiode

Design Solution:

•**Beam expansion** reduces divergence and **spreads speckle pattern**, improving uniformity

•A **focusing lens** at the receiver reconcentrates the beam onto the photodiode

•Result: **Improved SNR**, **reduced alignment sensitivity**, and **more reliable detection**

Example of Speckle Pattern in Laser Beam

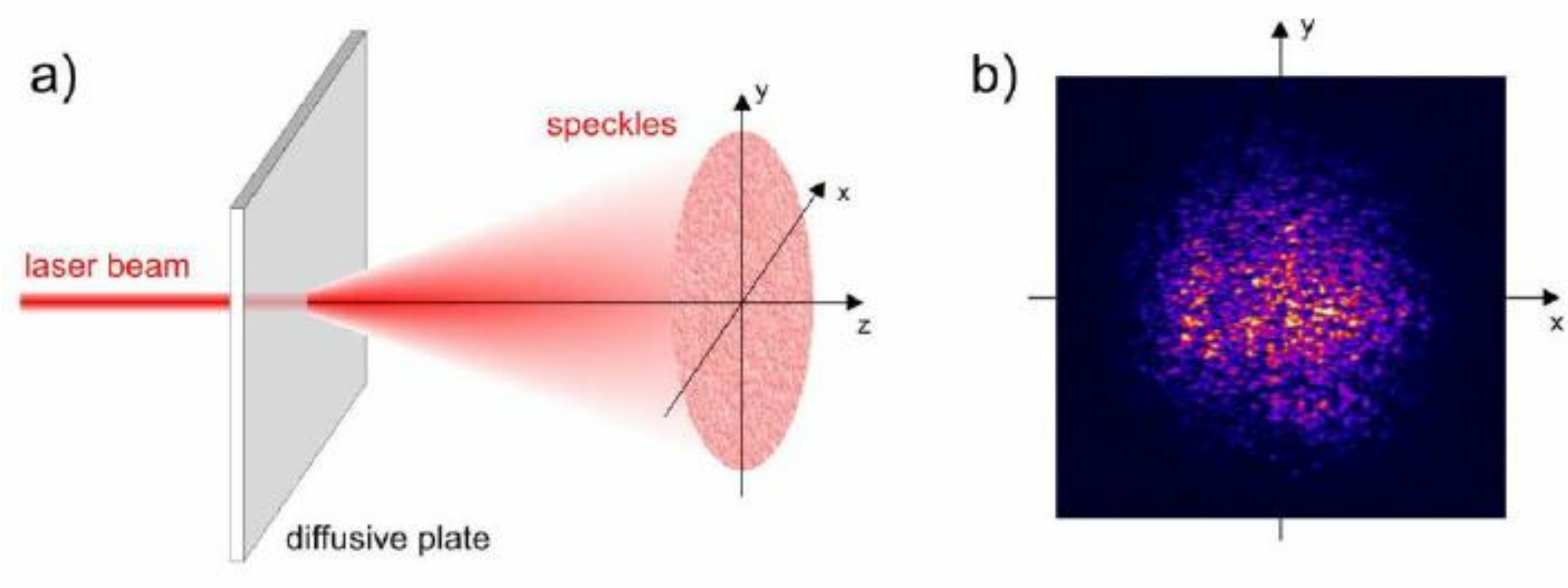


Image adapted from:
Mulansky, M. (2009, June). *Localization Properties of Nonlinear Disordered Lattices*.

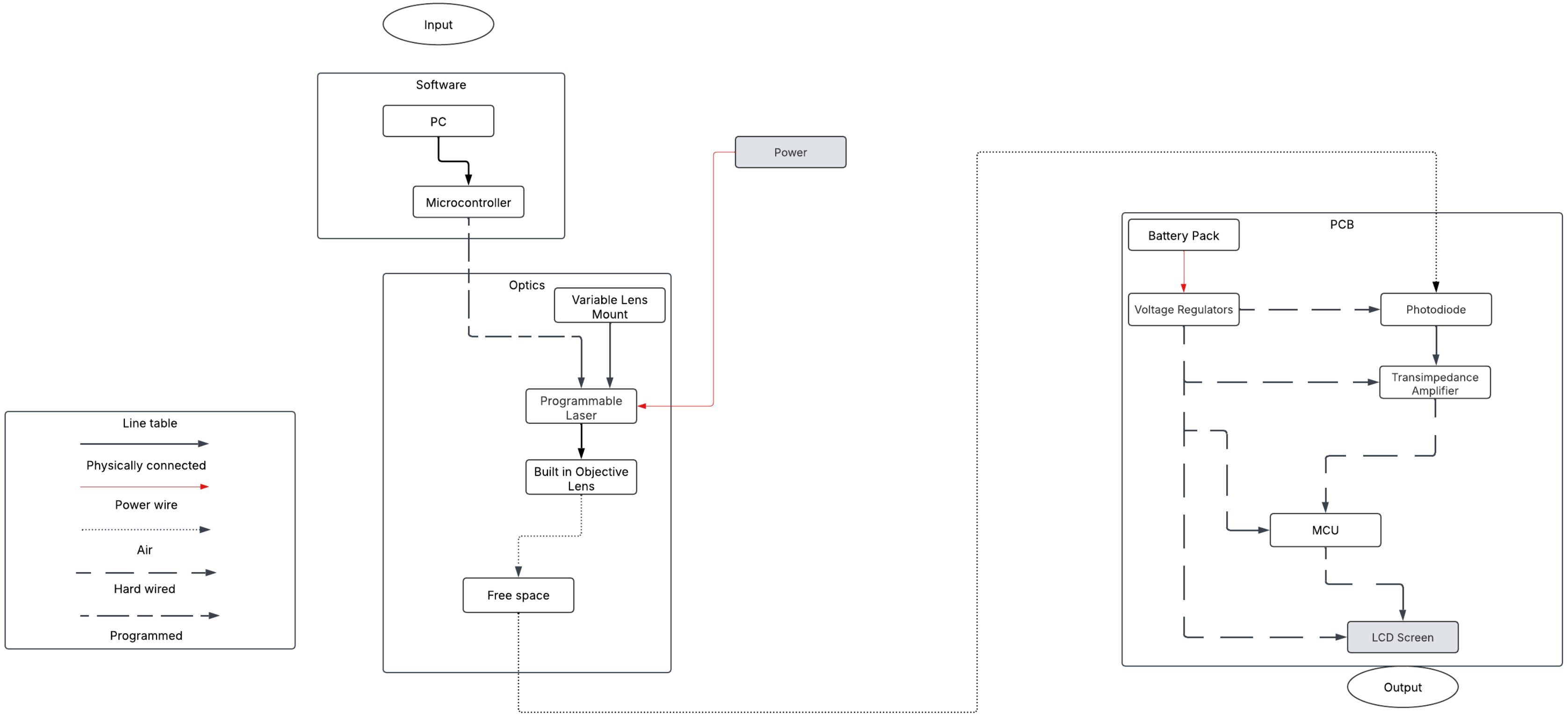
System Testing & Optical Calculations

- Attenuation: $\alpha = 2.5$ dB/km ⇒ Power Loss = 15 mW × 10^(-2.5/10) ≈ 8.4 mW
- Beam Spread: $\theta = 1$ mrad ⇒ 1 km → Beam Diameter = 1 meter
  - Effect: Reduced power density at photodiode, impacts detection fidelity
- Software Tools: Zemax & MATLAB for modeling
- (More testing in further slides)

Software Comparison

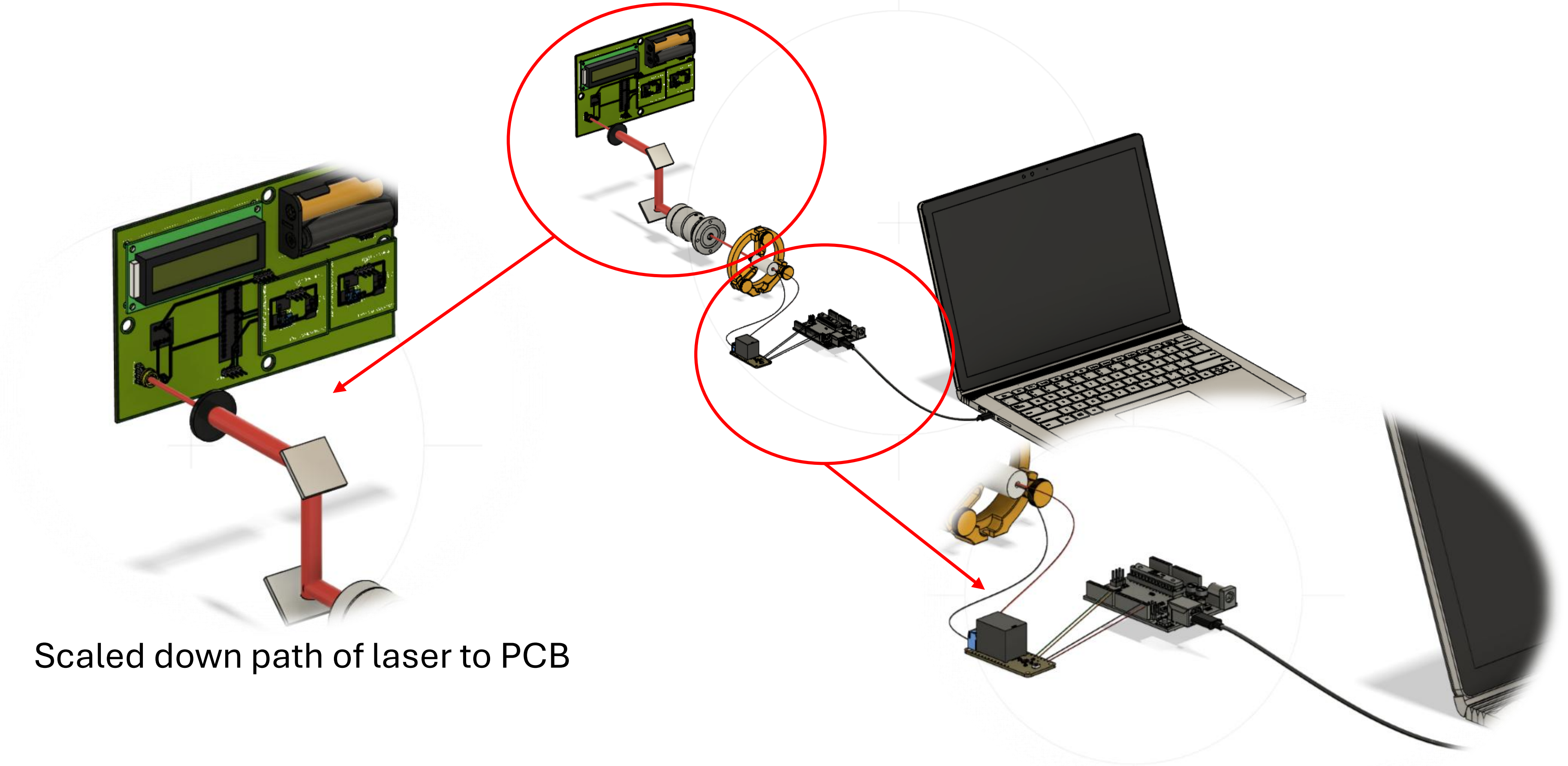
MSP430G2553				
	Code Composer	Arduino IDE	MicroPython	Notes
Language	C Language	C Language	Python	C is significantly faster than Python
Performance	High	Medium	Low	Depending on the libraries used.
Experience Required	Intermidate	Beginner	Beginner	Perfect for beginners and quick prototyping.

Hardware Design



- Key subsystems:
  - Programmable laser → Optical Path through lenses and mirrors→ Photodiode Receiver → Microcontroller → LCD.

3D Model of Hardware Design



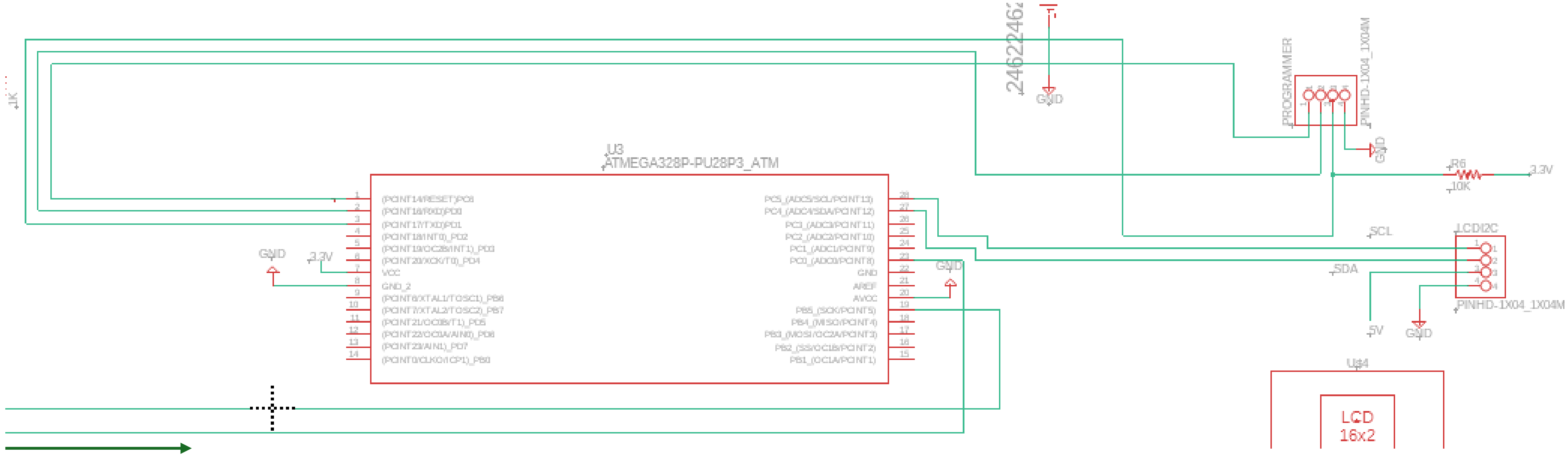
Scaled down path of laser to PCB

Microcontroller toggling the laser

Hardware Comparison & Selection

Feature	MSP430G2553	MSP430FR2355	STM32L031K6	ATmega328P
Architecture	16-bit RISC	16-bit RISC	32-bit ARM Cortex-M0+	8-bit AVR
Flash Memory	16 KB	32 KB	32 KB	**32 KB**
RAM	512 B	4 KB	8 KB	**2 KB**
ADC Resolution	10-bit	12-bit	12-bit	**10-bit**
Clock Speed	16 MHz	24 MHz	32 MHz	**20 MHz**
GPIO Pins	24	43	37	**23**
Operating Voltage	1.8–3.6 V	1.8–3.6 V	1.8–3.6 V	**1.8–5.5 V**
Peripherals	UART, SPI, I2C	UART, SPI, I2C	UART, SPI, I2C	**UART, SPI, I2C, PWM**
Price (approx.)	$2.64	$2.88	$1.24	**$1.50–2.00**
Best For	More memory	High-precision analog	IoT/High-speed tasks	**Widespread support, versatile development**

MCU Schematic

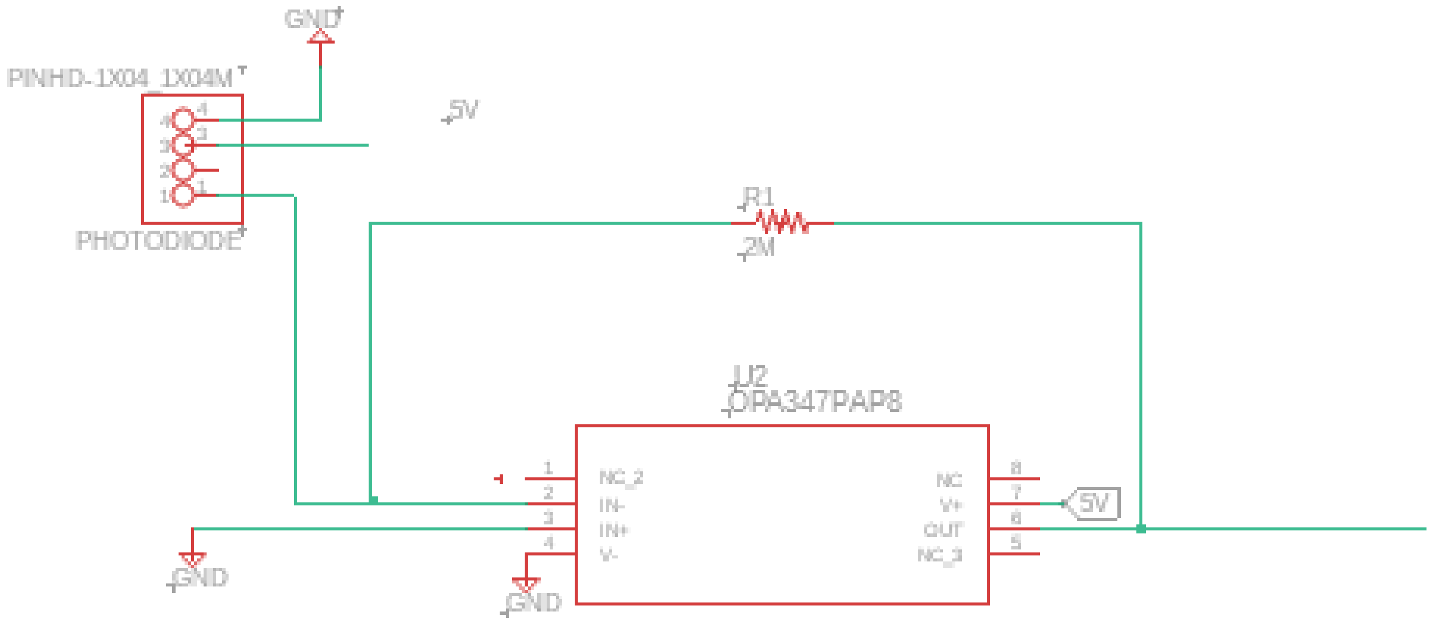


TIA Input

Hardware Comparison & Selection

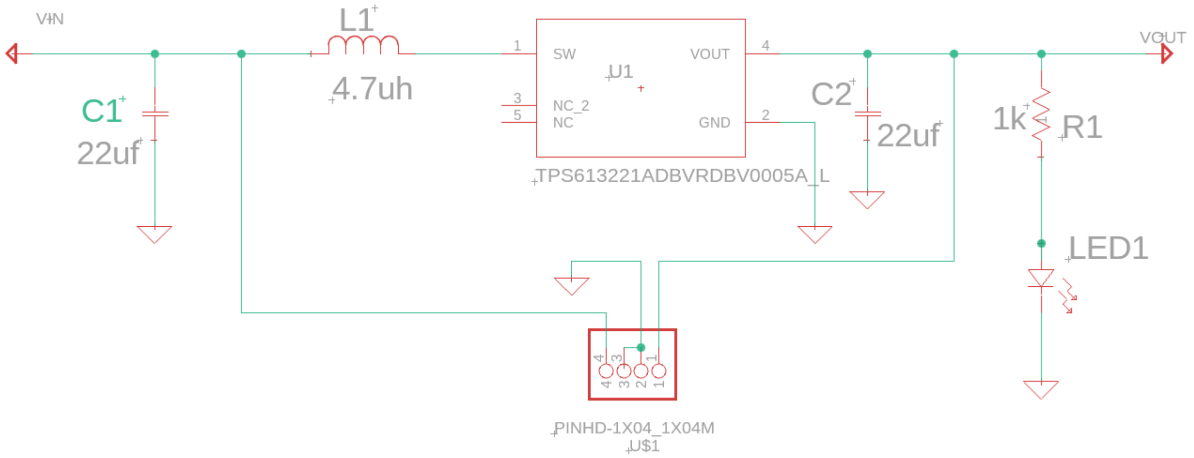
Op-Amp Model	Input Bias	Gain Bandwidth (GBW)	Supply Voltage	Power Consumption	Best For	Price
OPA381AIDGKR **(TI)**	3pA	18MHz	2.7V – 5.5V	1.5mA	Low-current photodiodes, precision applications	$1.98
LMP7721 **(TI)**	2fA	17MHz	1.8V – 5.5V	1.3mA	Ultra-sensitive, low-light photodetectors	$4.84
ADA4530-1 **(Analog Devices)**	20fA	2MHz	2.2V – 5.5V	1.5mA	High-impedance, ultra-low noise circuits	$31.09
MCP602 **(Microchip TECH)**	1pA	10MHz	2.5V – 5.5V	0.23mA	Cost-effective, general photodiode circuits	$0.82

TIA Schematic

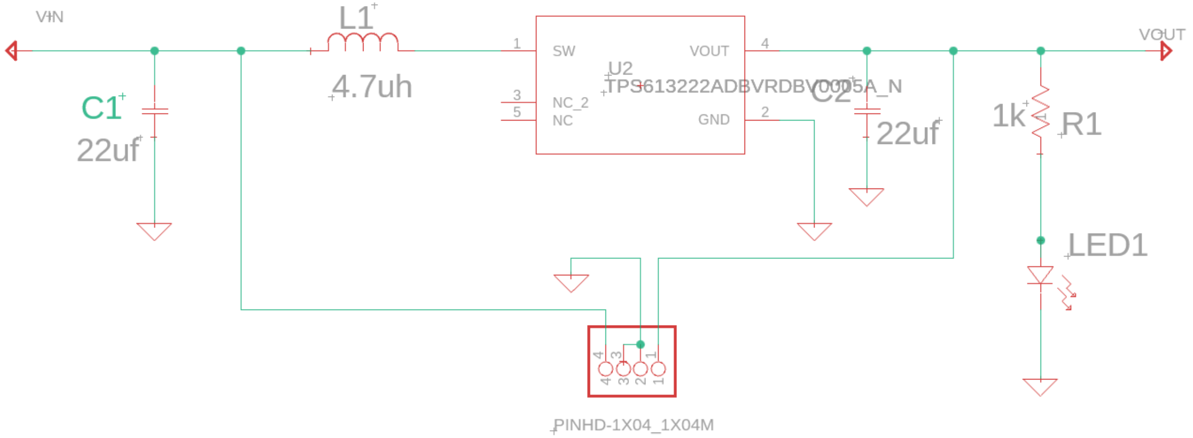


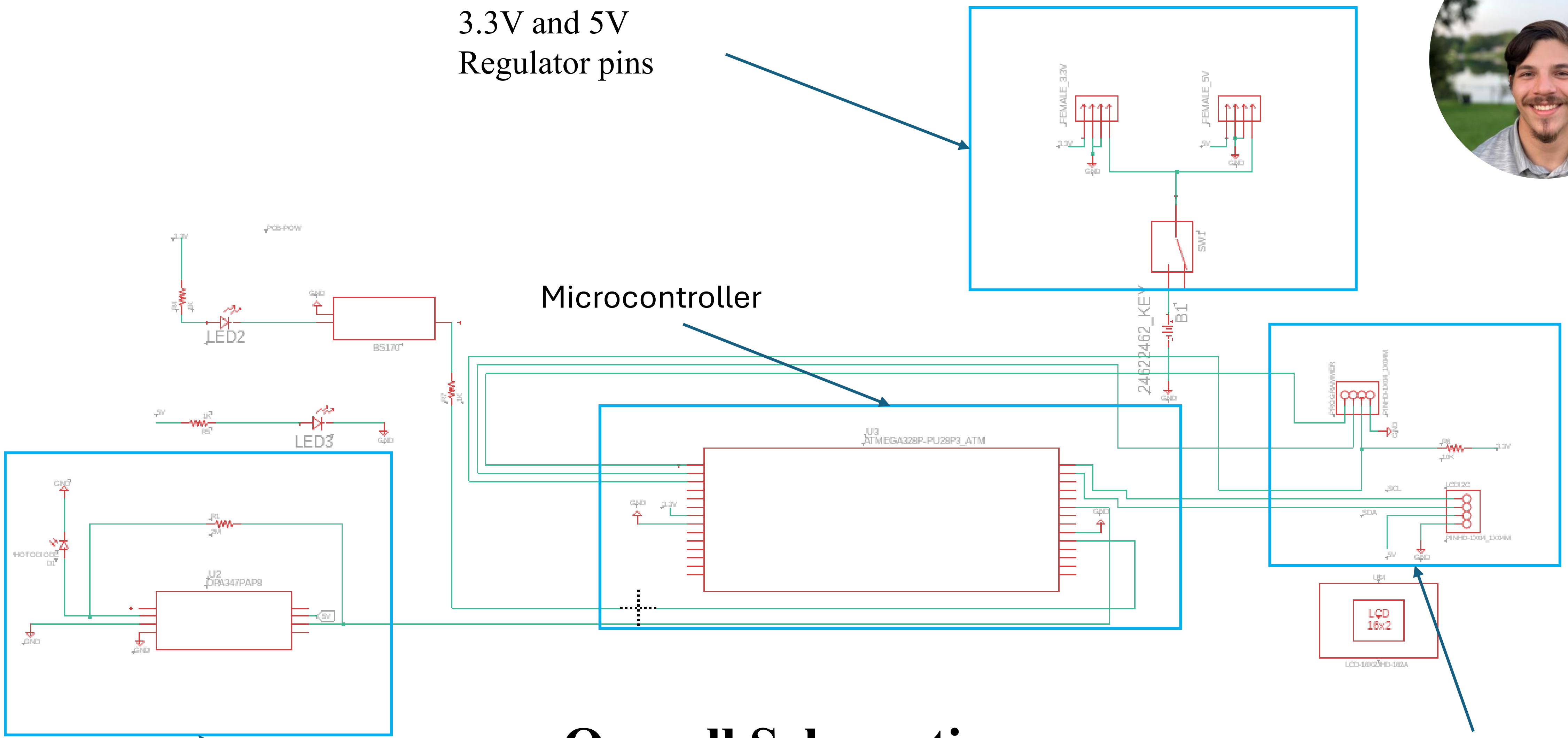
Regulator Schematics

3.3 V



5 V





3.3V and 5V Regulator pins

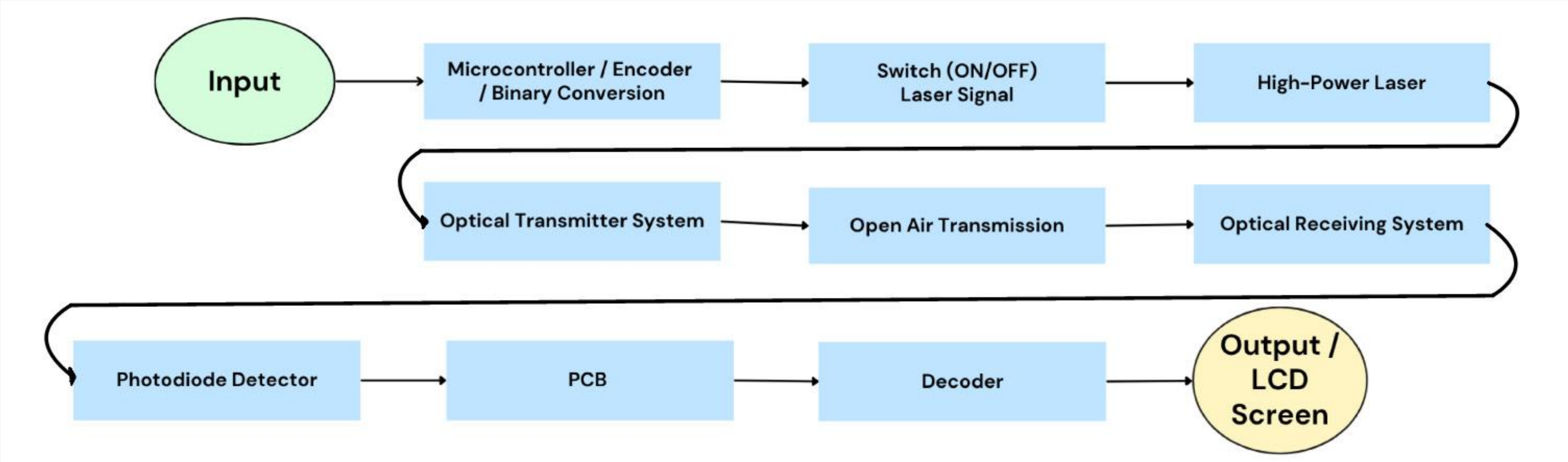
Microcontroller

Transimpedance amplifier with photodiode

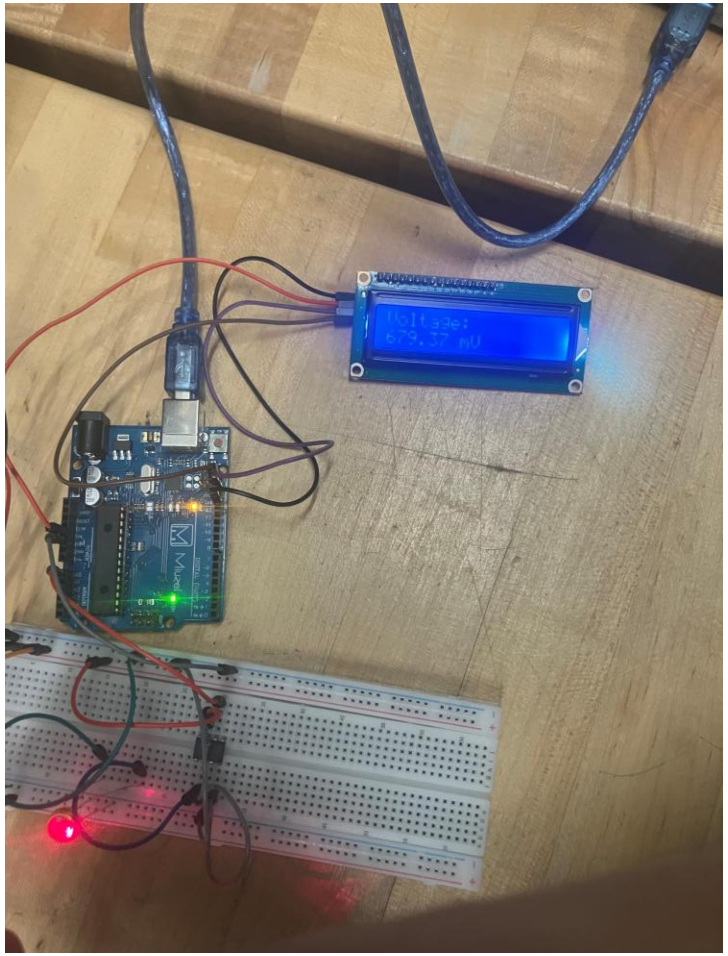
Overall Schematic

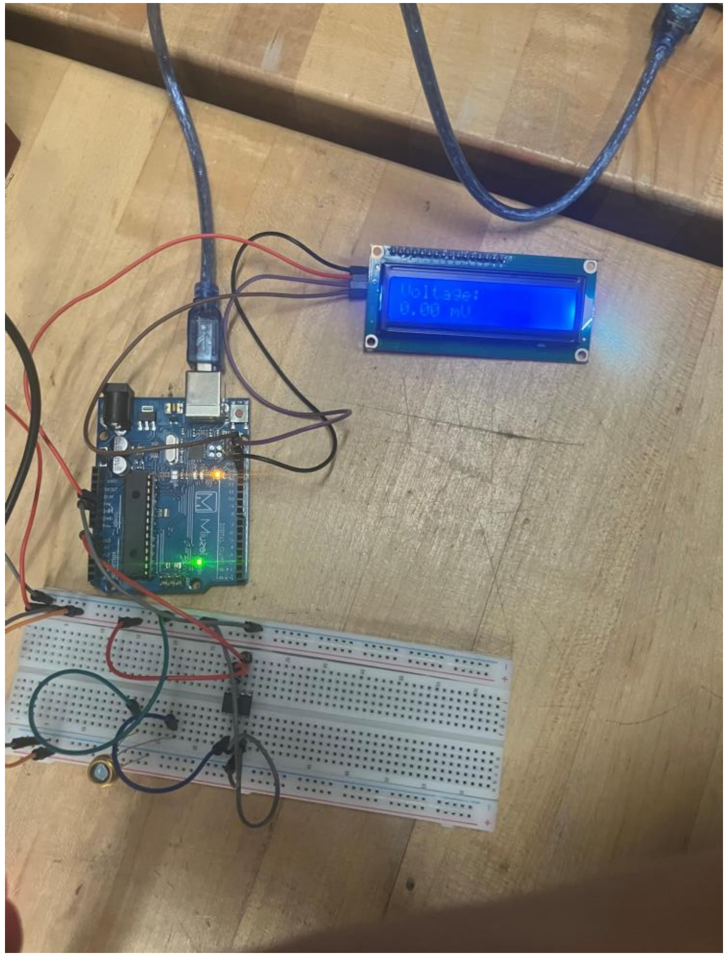
Pins for programming the microcontroller and outputting data to LCD

Software Design Flow Chart



Prototyping & Testing

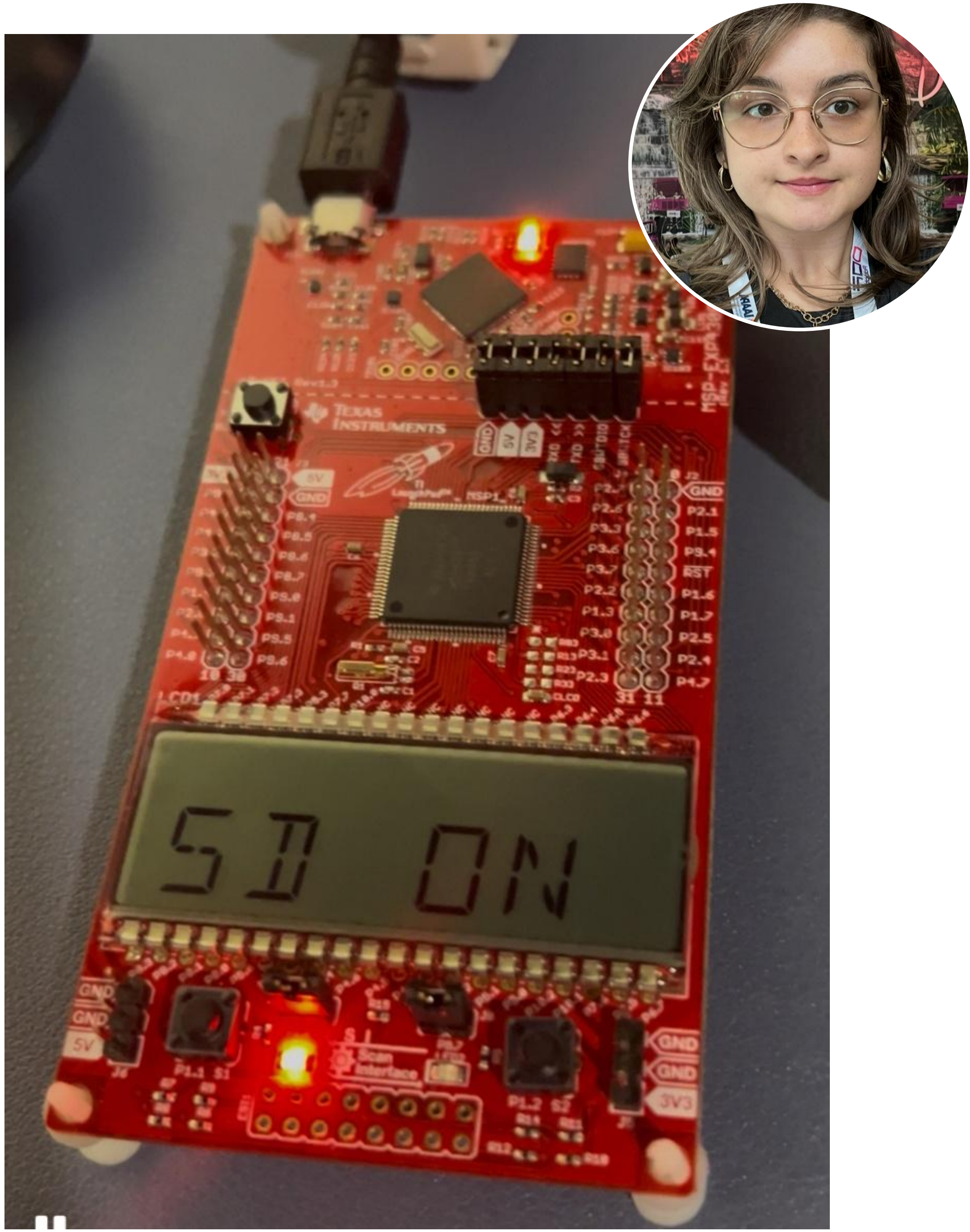




- **Problems Encountered/Solutions developed**:
  - In initial testing with the msp430 microcontroller, we ran into many Issues in having the built in ADC reading the voltage properly, switching to the Atmega328, solved this problem and simplifies the code
  - Miscalculations in the output current of the photodiode resulted in too large of an amplification and incorrect readings

Prototype & Testing (Software)

- Tested LCD and LED logic before final hardware.
- Used MSP430FR6989 for its built-in LCD and low power use.
- Displayed “430” and controlled red LED on P1.0.
- Future version will show words like “HELLO” in binary with LED blinking.
- Serves as early proof-of-concept for Senior Design II.



Prototype & Testing (Software)

Problems Encountered/Solutions developed:

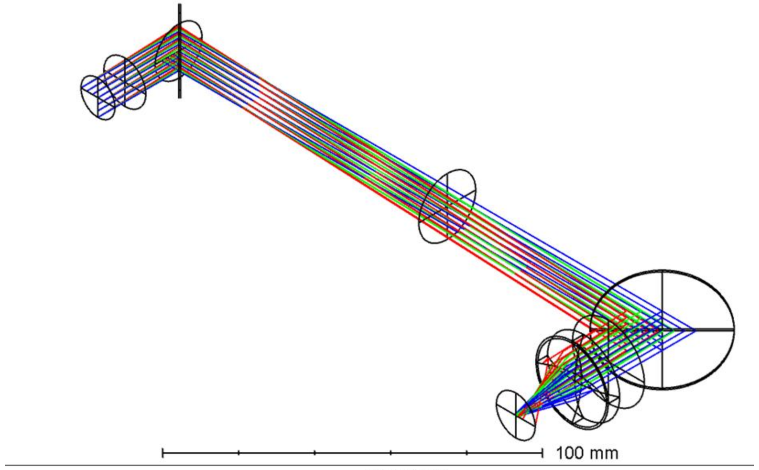
- Faced early challenge choosing the right MSP430 board.
- Considered MSP430FR6989 vs. MSP430G2553.
- Chose MSP430FR6989 for its built-in LCD and easy testing.
- Final system will use MSP430G2553 to match the custom PCB.
- Code will be ported for compatibility with final hardware.

Prototyping & Testing (Photodiode Measurements)

- Theoretical responsivity- 0.6 A/W @ 980nm
- Measured responsivity @ 980nm- TBD
- Photodiode Model: FDS100 Si Photodiode

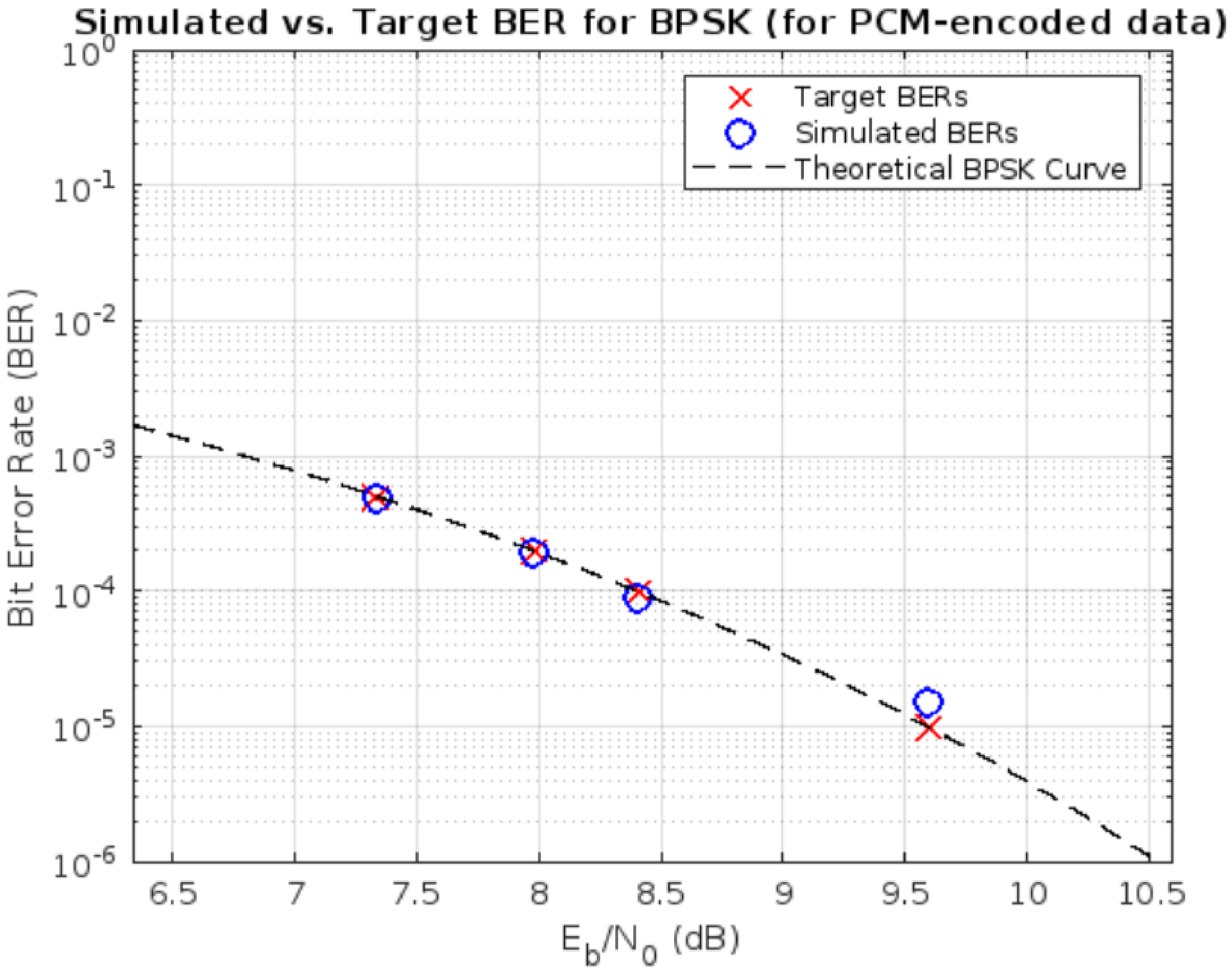
Prototyping & Testing (Zemax Simulation)

	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	Standard	Waist	Infinity	Infinity			0.000	0.000	0.000	0.0...	0.000
1	Standard	Laser O/P	Infinity	10.000 V			6.327 U	0.000	6.327	0.0...	0.000
2	Standard	AP Stop (Beam Diam)	Infinity	20.000 V			7.327	0.000	7.327	0.0...	0.000
3	Coordinate Break			0.000	-		0.000	-	-		-
4	Standard	Mirror 1	Infinity	0.000	MIR...		7.327	0.000	7.327	0.0...	0.000
5	Coordinate Break			0.000	-		0.000	-	-		-
6	Standard	Coord break fold45	Infinity	100.0... V			7.327	0.000	7.327	0.0...	0.000
7	Standard	Prop after M1	Infinity	80.000 V			7.327	0.000	7.327	0.0...	0.000
8	Coordinate Break			0.000	-		0.000	-	-		-
9	Standard	Mirror 2	Infinity	0.000	MIR...		7.327	0.000	7.327	0.0...	0.000
10	Coordinate Break			20.000	-		0.000	-	-		-
11	Standard	Coord break	Infinity	10.000 V			7.327	0.000	7.327	0.0...	0.000
12	Standard	Focus lens back	25.000	2.445 V	N-BK7		7.327	0.000	7.327	0.0...	-
13	Standard	focus lens front	-25.000	22.037 V			7.253	0.000	7.327	0.0...	0.000
14	Standard	image	Infinity	-			0.166	0.000	0.166	0.0...	0.000



Prototyping & Testing (Bit-Error Rate Simulation)

- MATLAB simulation with code generated by Gemini to compare the BER of NRZ modulation at 1 error, 10 errors, 20 errors, and 50 errors per 100 kilobits (or BERs of BERs of 1e-5, 1e-4, 2e-4, and 5e-4, respectively).



Administrative Content (Work Distribution)

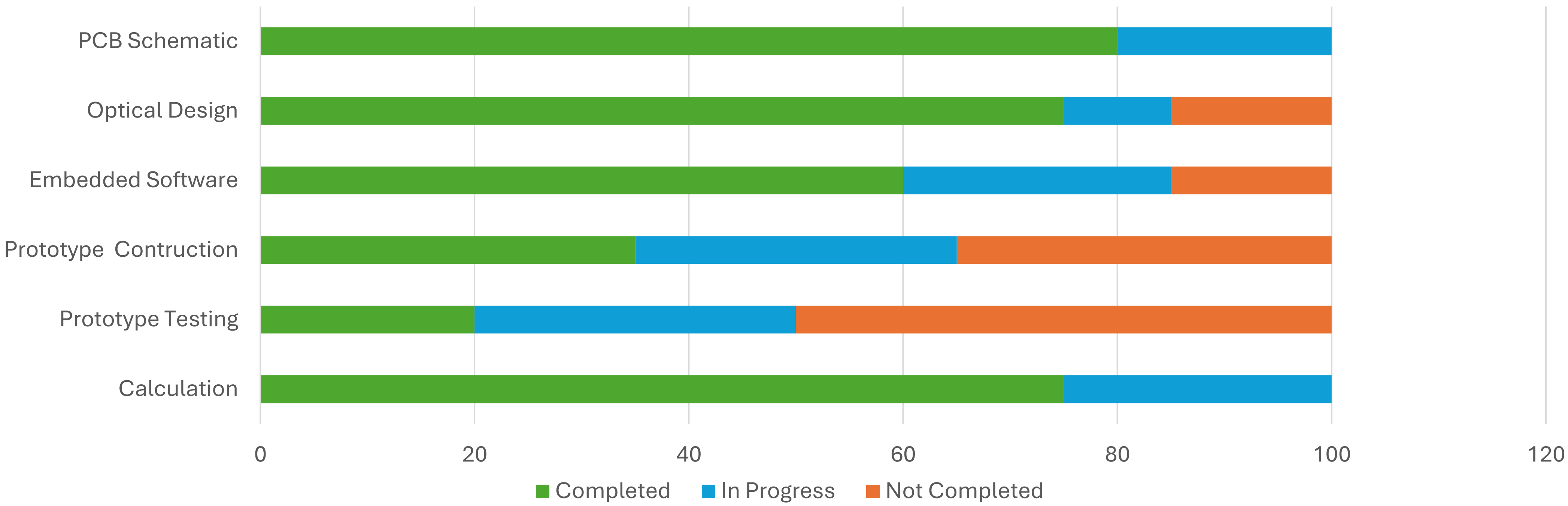
	Curtiss Kane	Monica Castro-Suarez	Alexander Simmons	Ivan Huang
Primary	• PCB Design	• Embedded Coding & Software Design	• Optical Design	• Optoelectronics Testing
Secondary	• 3D Modeling	• Website Design & Management	• Laser Calibration and Alignment	• Optical Simulations

Administrative Content (Budget and Financing)

Component	Cost	Quantity	Add. Costs	Total
Laser diode w/ TTL	$13.46	1	NA	$13.46
Photodiode	$17.55	1	NA	$17.55
Mirrors, set of 3	$24.64	1	NA	$24.64
Lenses, 6pc.	$24.49	1	NA	$24.49
Focusing Lens	$25.93	1	NA	$25.93
Optical Filter	$35	1	NA	$35
LCD Screen	$26.60	2 (single pack)	NA	$26.60
Transimpedance Amplifier	$1.98	1	NA	$1.98
Microcontrollers	$2.89	5	NA	$14.45
PCB	$10.50	5 (single order)	$33.46	$43.96
Power source	$16.98	2 (single pack)	NA	$16.98
			Total	$245.04

Progress and Plan for Completion

Progress Chart for Senior Design II



Plan for Completion

- Table of future tasks for Senior Design 2

Senior Design II – Summer 2025	
Week	**Task**
4	• CDR submission (6/4, 5pm) • CDR assignment & PCB review and order (6/6, 11:59pm)
5-7	• Work on project • PCB acquisition (6/27, 11:59pm) • Midterm demo (6/28, 5pm)
8-9	• 8-page conference paper (7/7, 12pm) • Reserve time slot for final presentation/review meeting (7/11, 11:59pm) • Continue working on project
10	• CREOL and CECS Showcase (7/18, 10am-12pm) Final project review submission (7/20, 5pm)
12	• Final documentation & Junior Design survey (7/29, 12pm)

Questions?