Digital Transmission in Free Space through a High-Power Laser

Group 1:

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Meet The Team

Alexander Simmons

Photonic Engineer

Curtiss Kane

Electrical Engineer

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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:	≥ 95% Accuracy	Ensures reliable signal interpretation
Data Transfer Rate:	500 Kbps - 1 Mbps	Allows flexibility in signal speed for different applications
Expected Power Consumption:	≤ 5W	Optimized for low-power, battery-powered operation
Optimal Transmission Distance (OPT):	50-100 feet	Ensures optimal signal integrity and low attenuation
Power Efficiency:	≥ 85% efficiency, ≤ 5% voltage ripple	Ensures portability and long operational life
Interference Immunity:	≥ 40 dB reduction in EMI	Optical transmission eliminates electromagnetic interference
Minimum Focused Laser Power at OPT:	≥5% of original laser power	Ensures sufficient power at a longer distance for detection

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

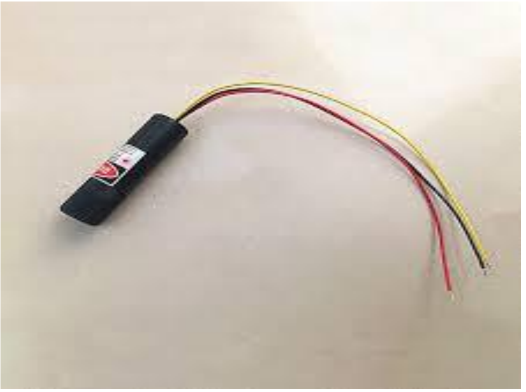
Photodiode

- **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



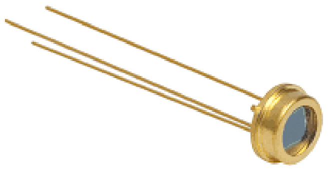
Property	TTL-Modulated Laser Diode	Pulsed Laser Diode Illuminator	Femtosecond Fiber Laser	Ytterbium-Doped Fiber Laser	Ti:Sapphire Laser
Pulse Duration	CW / Modulated	100–200 ns	<150 fs	50 ps – 1 ns	5–100 fs
Repetition Rate	Up to 100 kHz	Up to 10 kHz	1–80 MHz	1–100 MHz	70–90 MHz
Output Power (mW)	≤ 50	≤ 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:

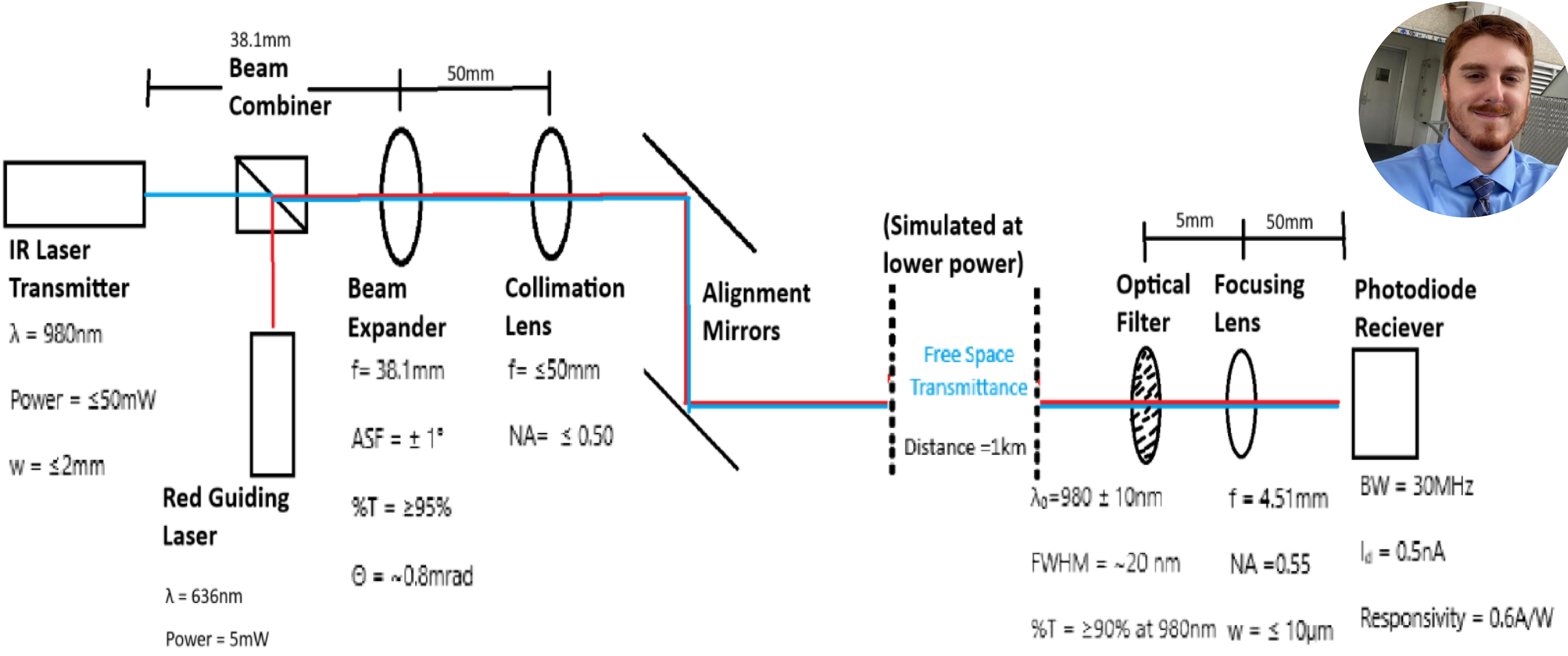
$$Spot\ size \approx \frac{1.22\lambda f}{D} = 1.22\frac{(980 * 10^{-9}) \times (4.51 * 10^{-3})}{3 \times 10^{-3}} \approx 1.8\mu m$$

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 $\lambda < 980$ nm)	≥ 4	2–3 f	2–3
Spectral Width (FWHM)	~20 nm	Not applicable	Not applicable
Cost	~$100	$40 – $70	$40 – $70

Beam Combiner Comparison

Parameter	Polarizing Beam Combiner (PBC)	Wavelength Division Combiner (WDC)	Non-Polarizing Beam Splitter (NPBS)
Efficiency (%)	90–98%	95–99%	45–50% (typically 50/50 split)
Insertion Loss (dB)	0.1–0.5 dB	0.1–0.3 dB	~3.0 dB (50% power loss)
Wavelength Range (nm)	400–1600 nm (dependent on coating)	10–30 nm separation between λs (e.g., 1064/1310 nm)	~±10 nm around design λ
Angular Tolerance (mrad)	1–2 mrad	2–5 mrad	<1 mrad
Beam Type Compatibility	CW or pulsed, polarization matched	CW or pulsed, different λ	CW or pulsed, collimated beams



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

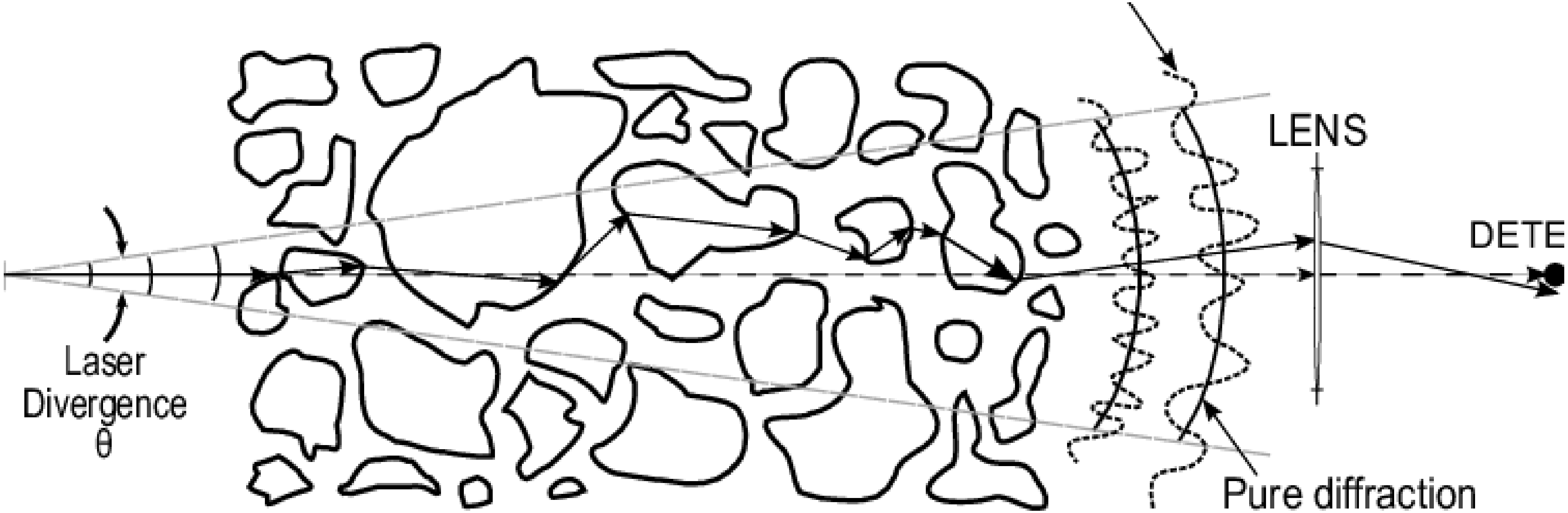


Figure adapted from:
Barrios, R., & Dios, F. (2012, March). Wireless Optical Communications Through the Turbulent Atmosphere: A Review. In *InTech*. https://doi.org/10.5772/34740

Design Solution:
Beam Expansion and Refocusing

A. Beam Expansion Reduces Divergence

- $\theta_{expanded} = \dfrac{\lambda}{\pi(M)w_0} = \dfrac{\theta}{M}$
  - **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

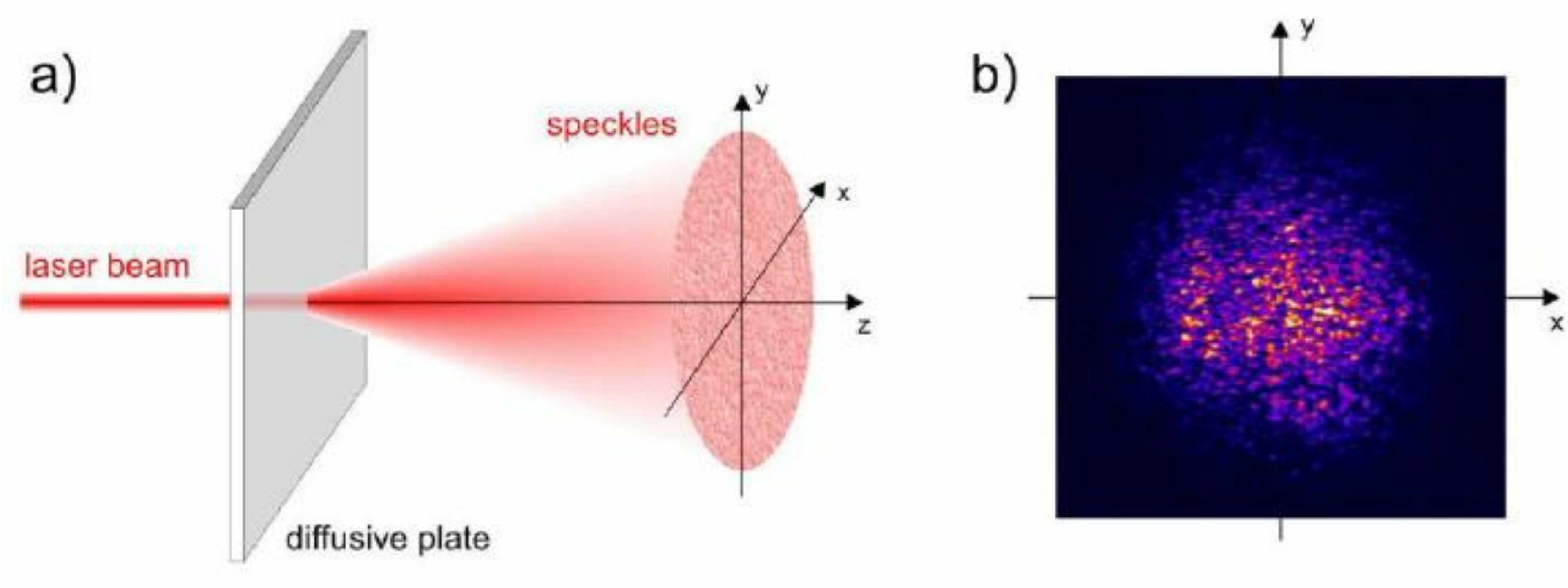


Image adapted from:
Mulansky, M. (2009, June). *Localization Properties of Nonlinear Disordered Lattices*.

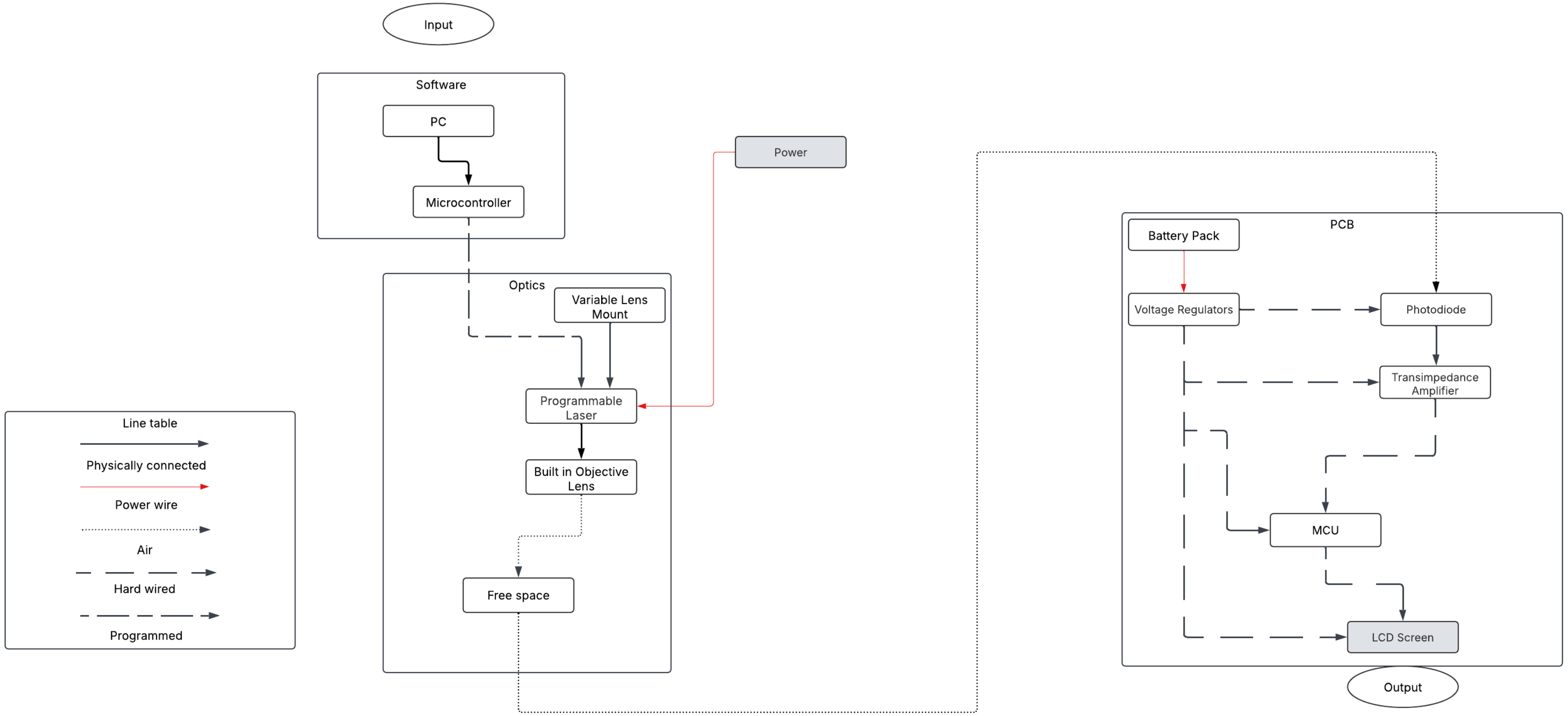
System Testing & Optical Calculations

- 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

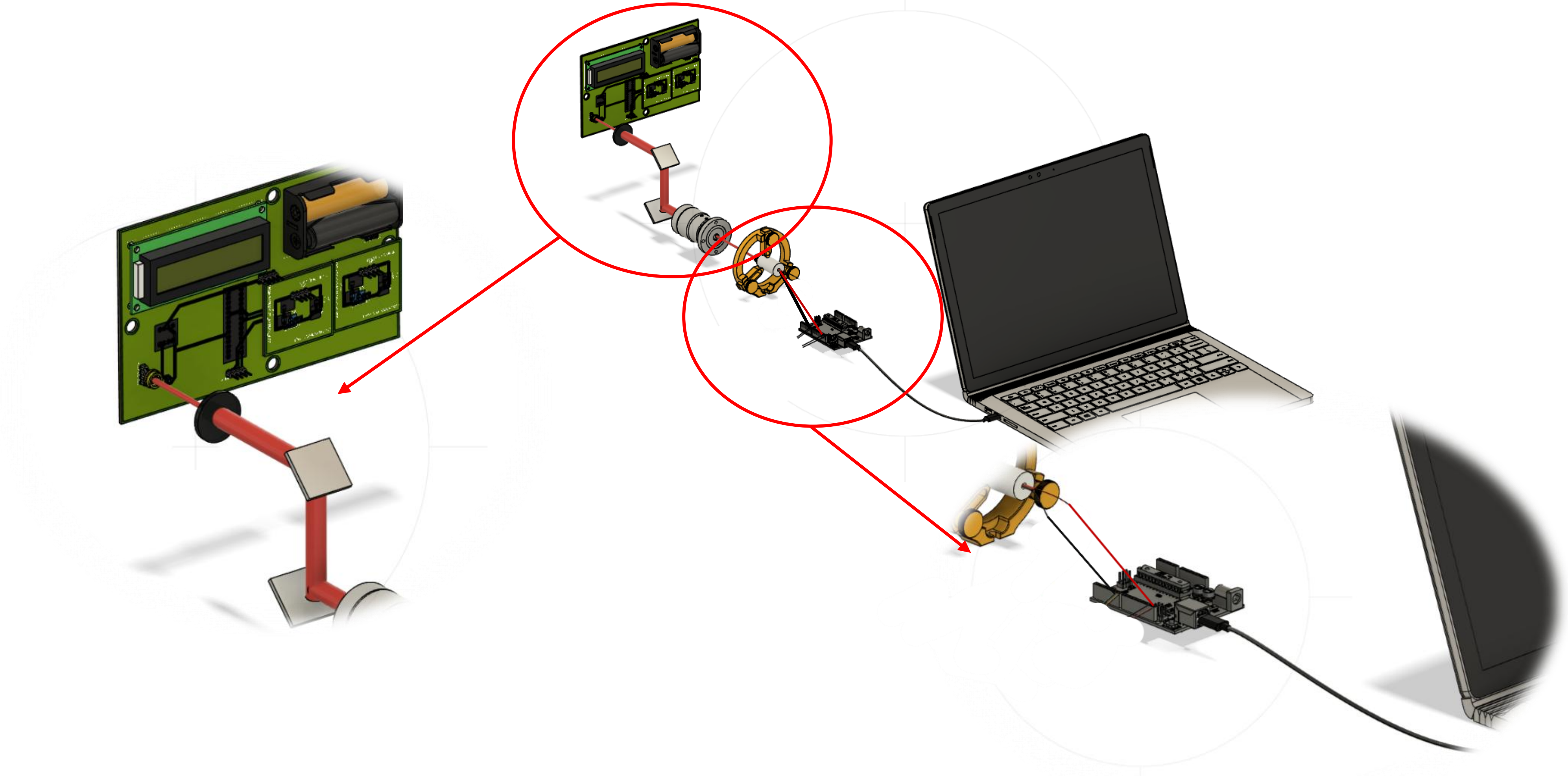
MSP430G2553				
	Code Composer	Arduino IDE	MicroPython	Notes
Language	C Language	C Language	Python	C is significantly faster than Python
Performance	High	Medium	Low	Depending on the libraries used.
Experience Required	Intermidate	Beginner	Beginner	Perfect for beginners and quick prototyping.

Hardware Design



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

3D Model of Hardware Design



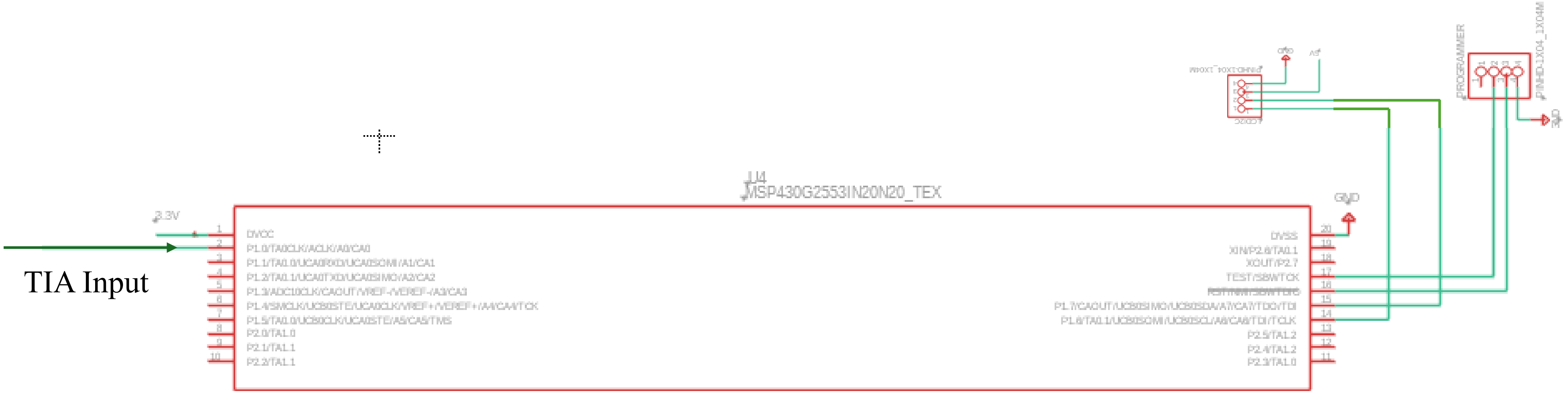
Scaled down path of laser to PCB

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**

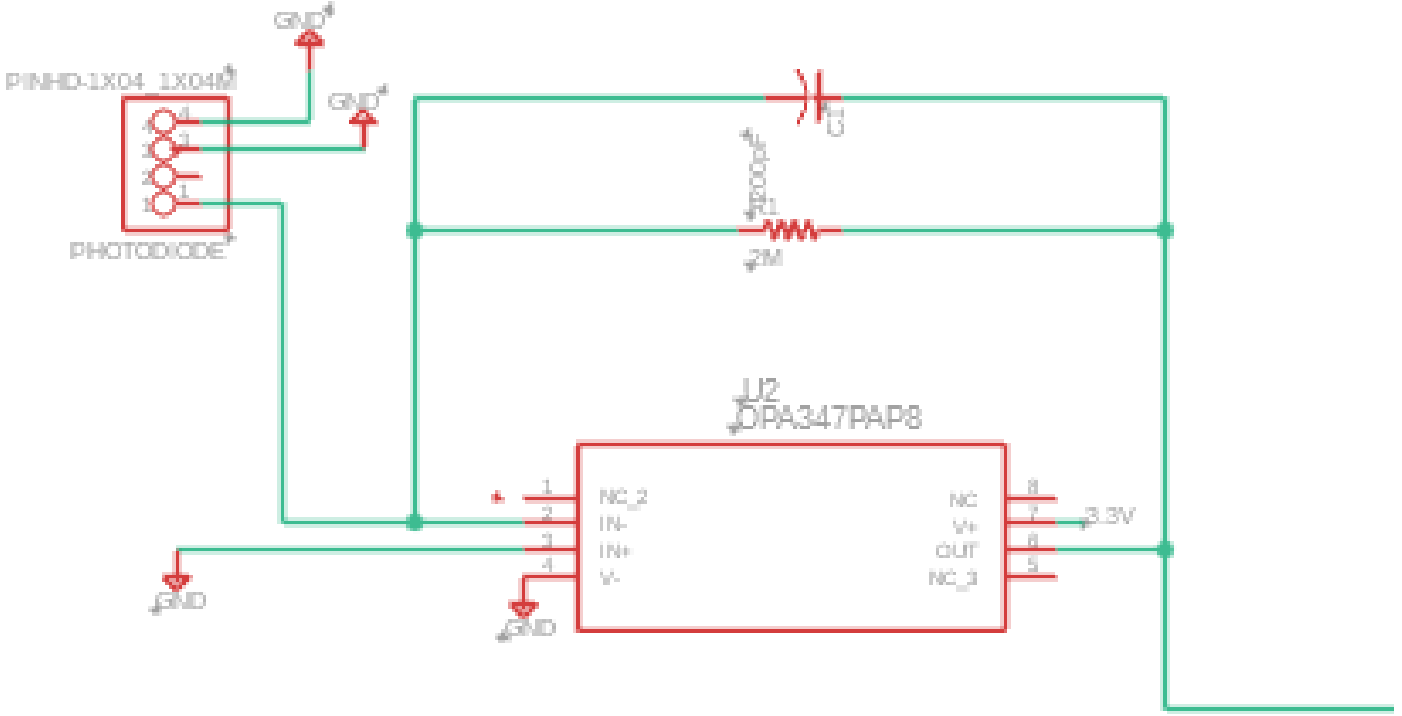
MCU Schematic



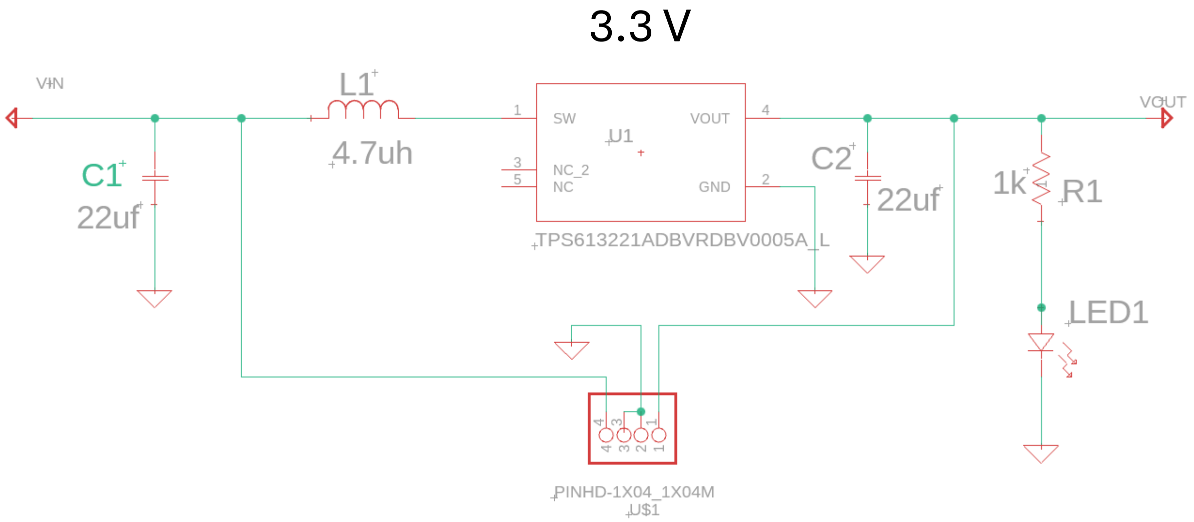
Hardware Comparison & Selection

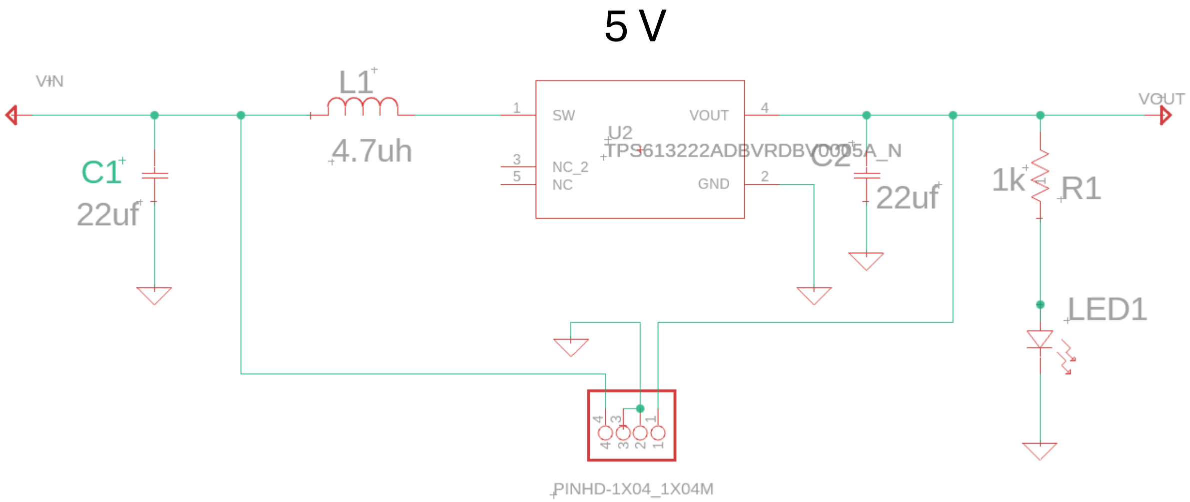
Op-Amp Model	Input Bias	Gain Bandwidth (GBW)	Supply Voltage	Power Consumption	Best For	Price
OPA381AIDGKR (TI)	3pA	18MHz	2.7V – 5.5V	1.5mA	Low-current photodiodes, precision applications	$1.98
LMP7721 (TI)	2fA	17MHz	1.8V – 5.5V	1.3mA	Ultra-sensitive, low-light photodetectors	$4.84
ADA4530-1 (Analog Devices)	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

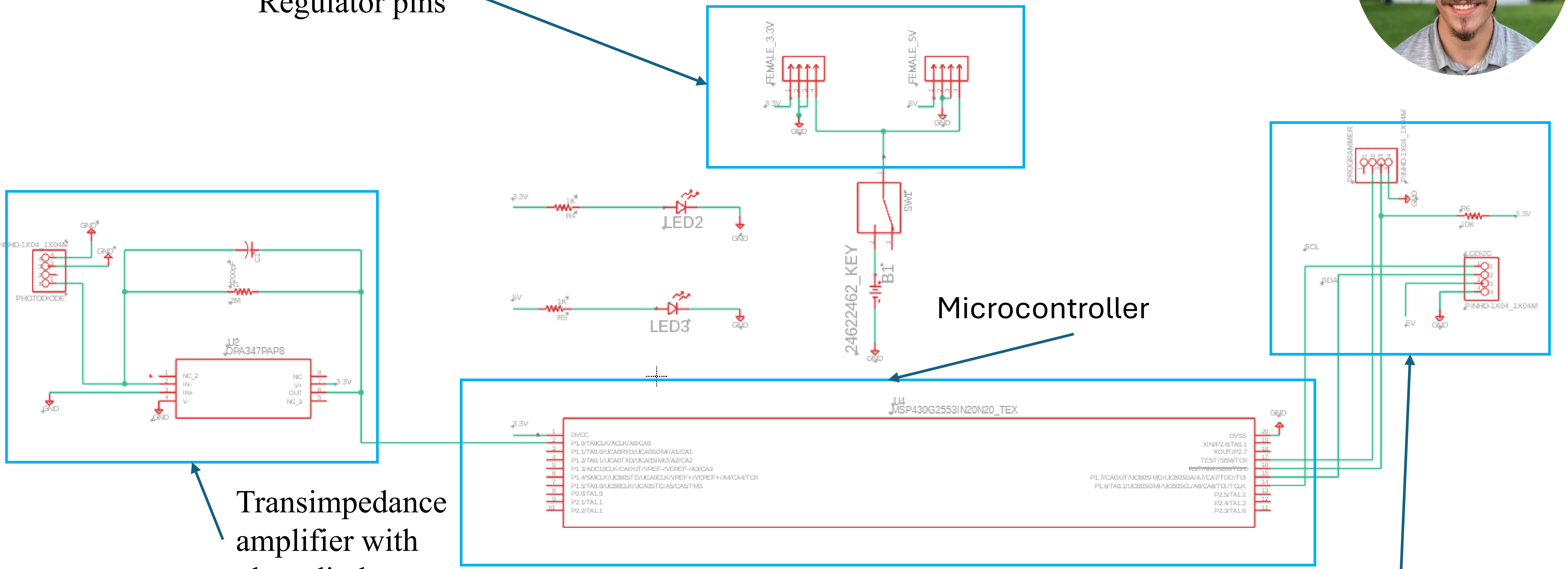


Regulator Schematics





3.3V and 5V Regulator pins



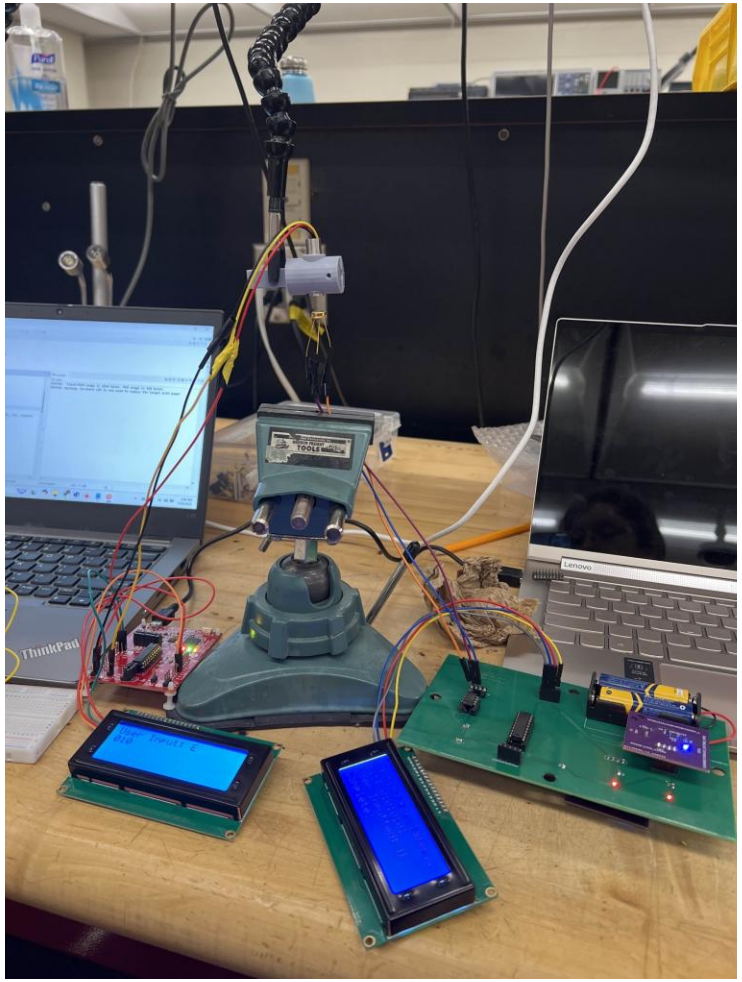
Microcontroller

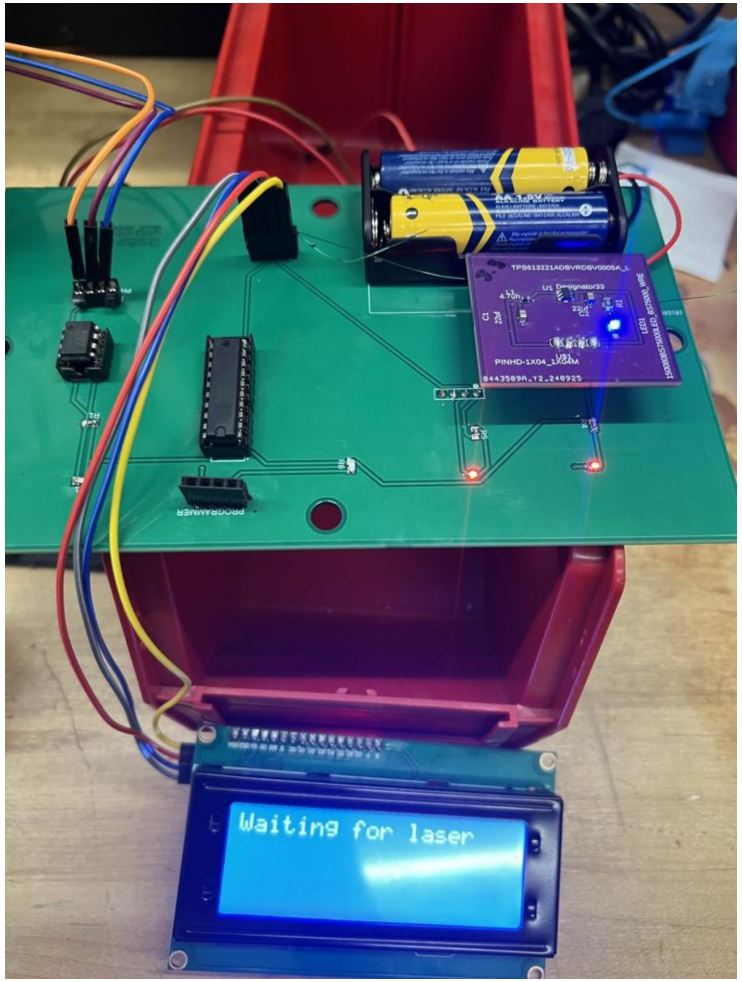
Transimpedance amplifier with photodiode

Pins for programming the microcontroller and outputting data to LCD

Overall Schematic

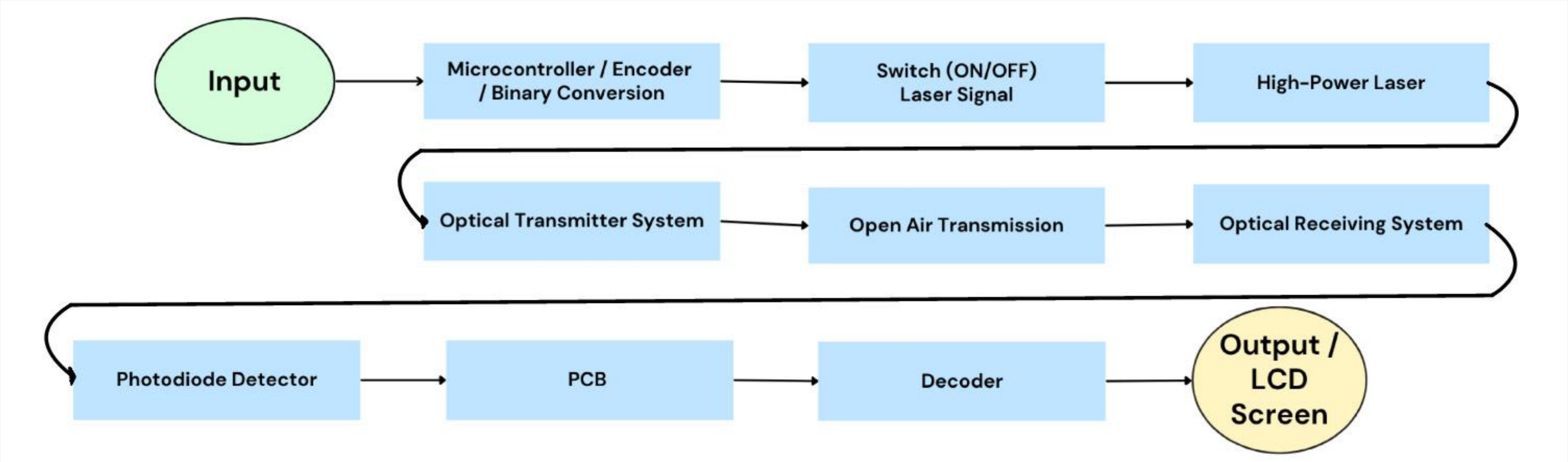
Prototyping & Testing





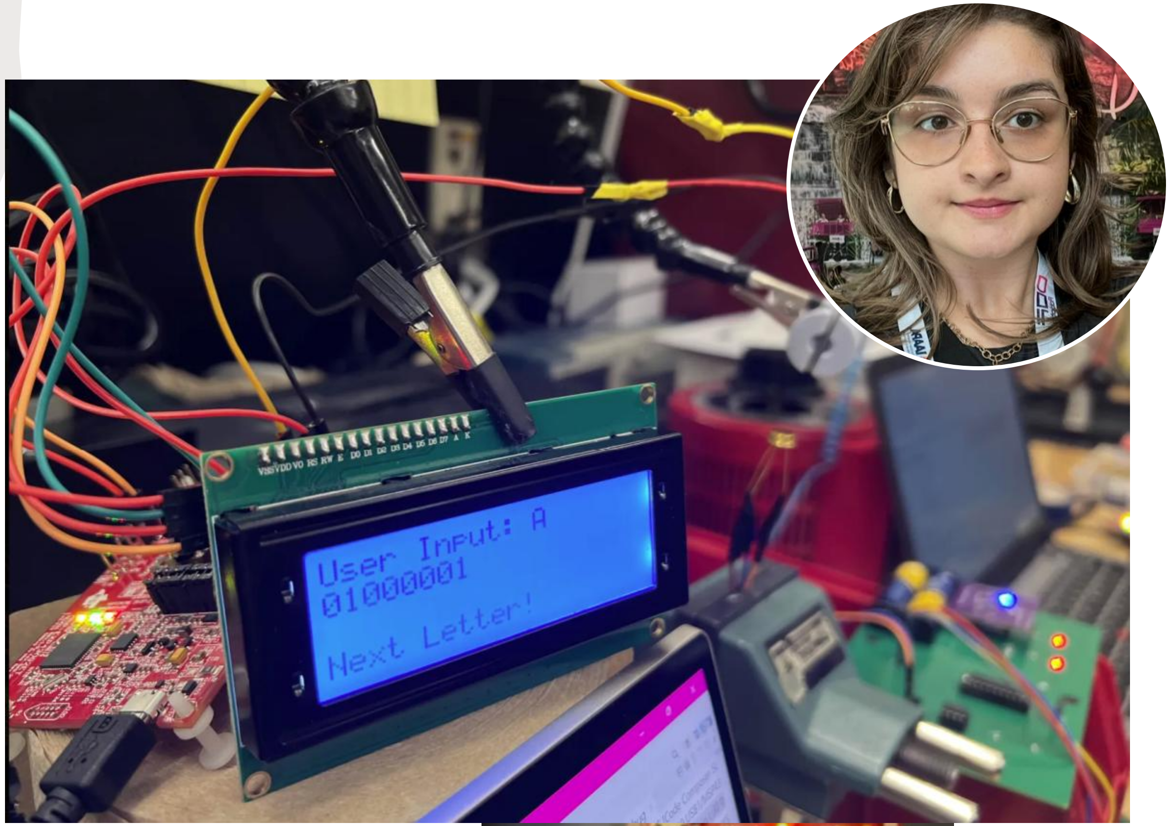
- **Problems Encountered/Solutions developed**:
  - In initial testing with the ATMEGA microcontroller, we ran into many Issues in having this MCU align its timings with the MSP430 based transmitter, leading to incorrect results
  - Swapping to the MSP430 on the receiving end to match the transmitting end helped greatly in troubleshooting

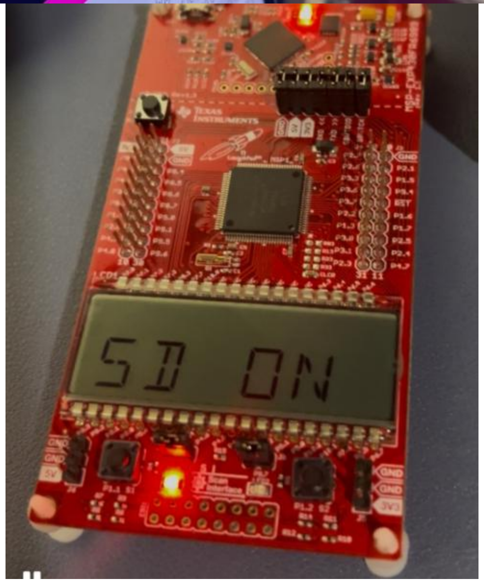
Software Design Flow Chart



Prototype & Testing (Software)

- Tested LCD and LED logic before integrating final hardware.
- Initially used the MSP430FR6989 for its built-in LCD and low power features.
- Switched to the MSP430G2553 for the final demo due to:
  - Better integration.
  - Easier compatibility with external components (e.g., I2C LCD, laser control).

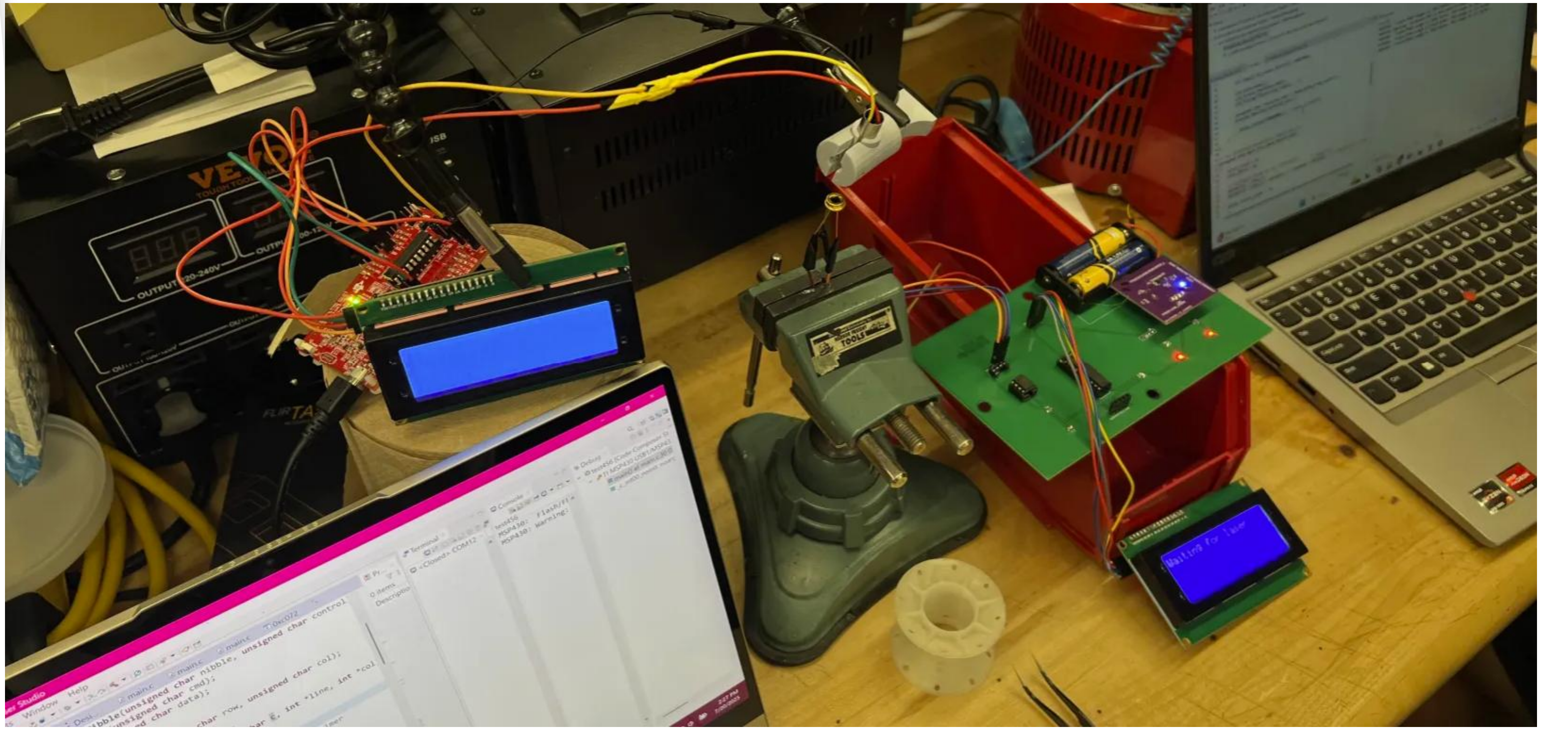




Prototype & Testing (Software)

Problems Encountered/Solutions developed:

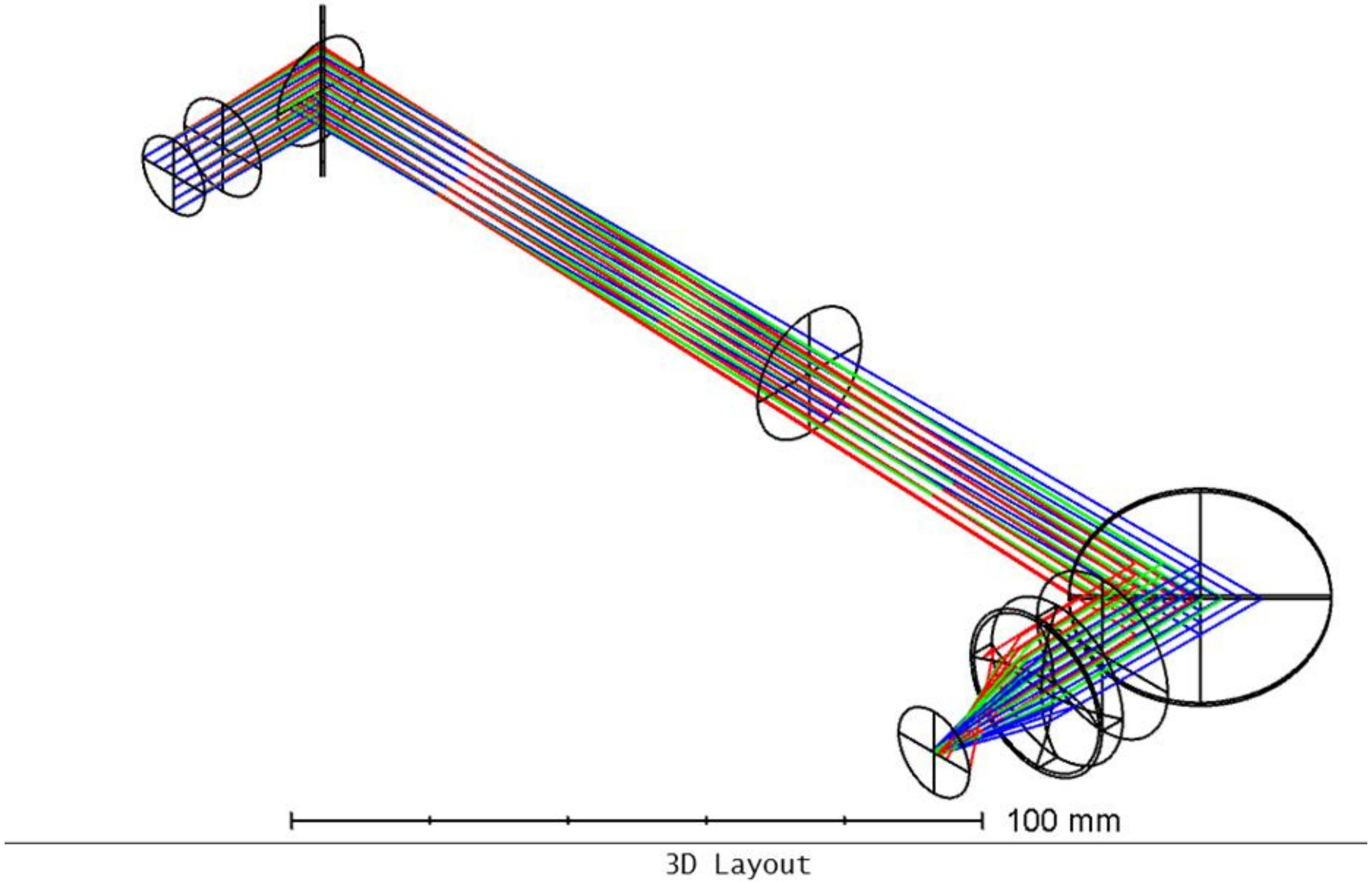
- Syncing issues between transmitter and receiver
- UART communication with PuTTY not working as intended.
- Binary display and laser blinking verification



Prototyping & Testing (Photodiode Measurements)

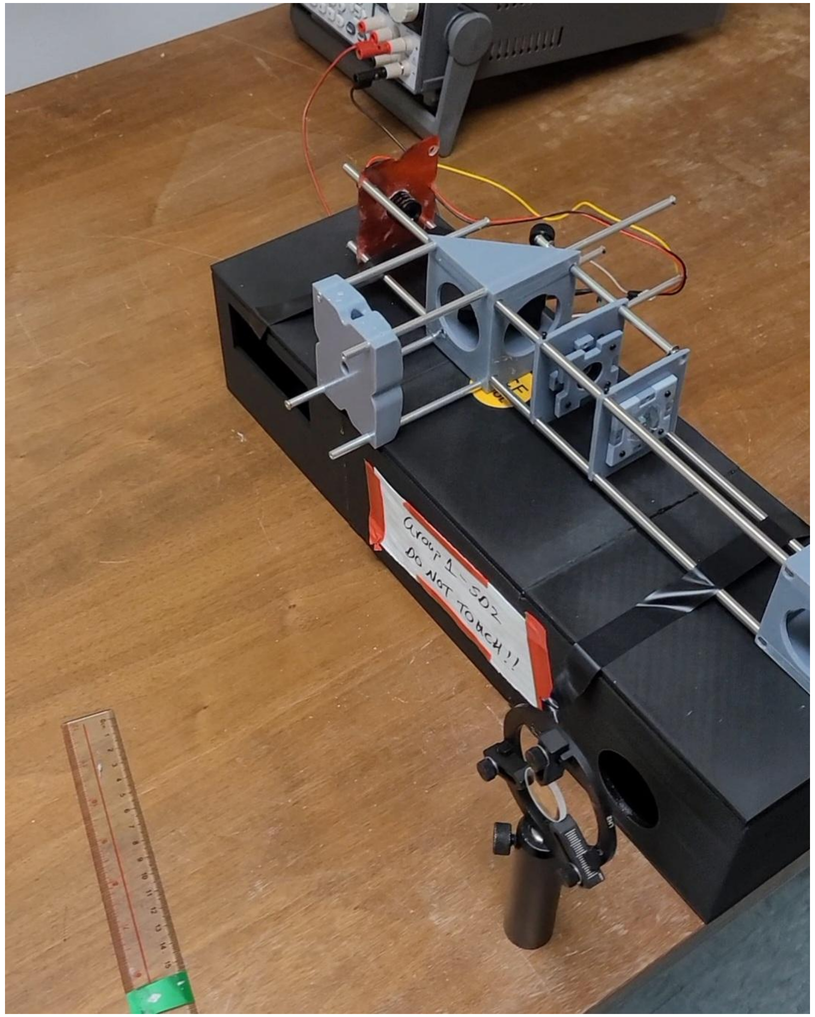
- Photodiode Model: FDS100 Si Photodiode
- Measured responsivity @ 980nm- 0.585 A/W
- Theoretical responsivity- 0.6 A/W @ 980nm

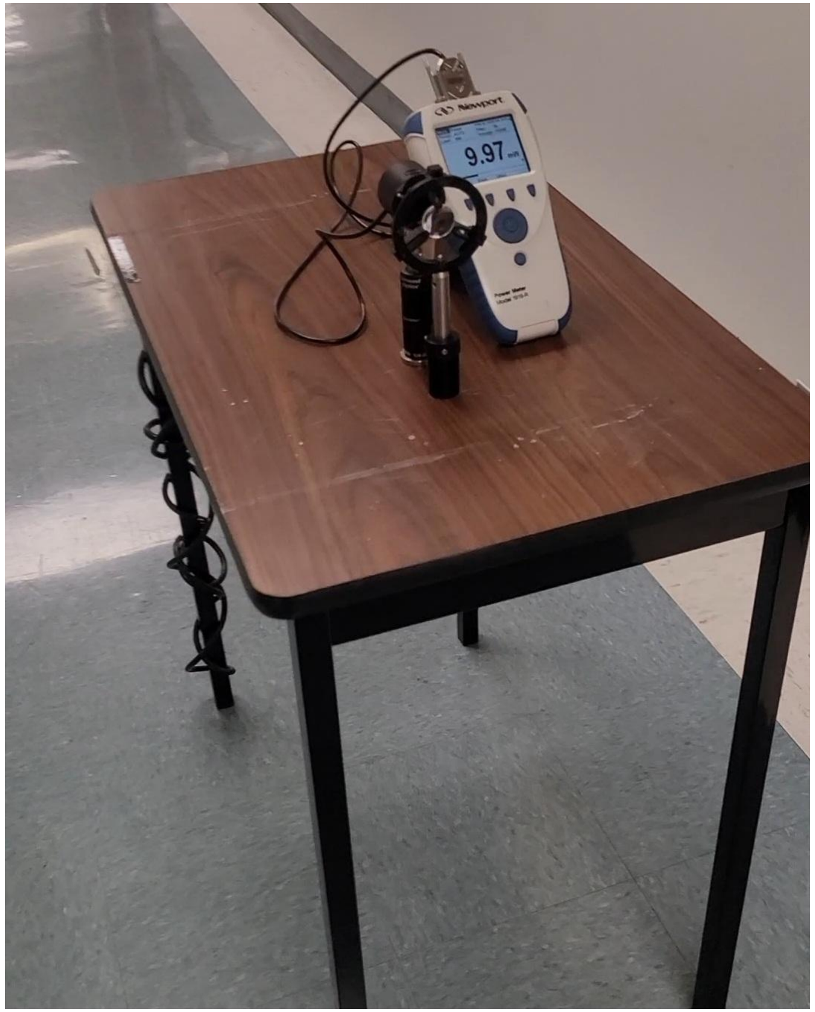
Prototyping & Testing (Zemax Simulation)



Prototyping & Testing (Range Test)

- Testing how far the IR laser can travel without losing a significant amount of power, up to 100 feet.





Administrative Content (Work Distribution)

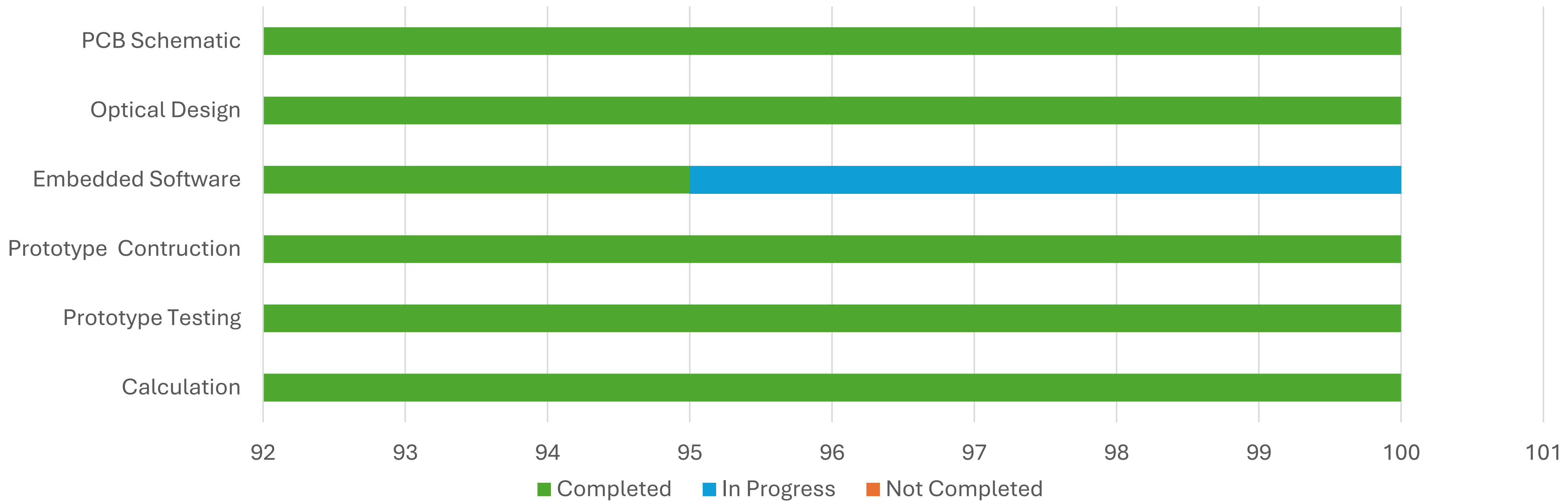
	Curtiss Kane	Monica Castro-Suarez	Alexander Simmons	Ivan Huang
Primary	• PCB Design & Assembly	• Embedded Coding & Software Design	• Optical Design	• Optoelectronics Testing
Secondary	• Embedded Coding	• Website Design & Management	• Laser Calibration and Alignment • 3D Modeling	• Optical Simulations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

Administrative Content (Budget and Financing)

Component	Cost	Quantity	Add. Costs	Total
5mW IR Laser Diode	$61	1	$15	$76
60mW IR Laser Diode	$26.58	1	$41	$86.08
120mW IR Laser Diode	$18.50	1		
5mW Red Laser Diode	$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~~
LCD Screen	$26.60	2 (single pack)	NA	$26.60
Transimpedance Amplifier	$1.98	1	NA	$1.98
Microcontrollers	$2.89	5 (single pack)	NA	$14.45
~~PCB (first batch)~~	~~$10.50~~	~~5~~	~~$33.46~~	~~$43.96~~
PCB (second batch)	$18.70	5 (single pack)	$74.70	$93.40
Power source	$16.98	2 (single pack)	NA	$16.98
Stainless Steel Rods	$17.69	5 (single pack)	1.24	$18.93
			Total	$458.52

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?