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PEEKBot Lunar Water Detector

Team Members: Sid Joshi, Willam Johnson, Peter Noble, Leo Xia
Supervisor: Professor Winnie N. Ye

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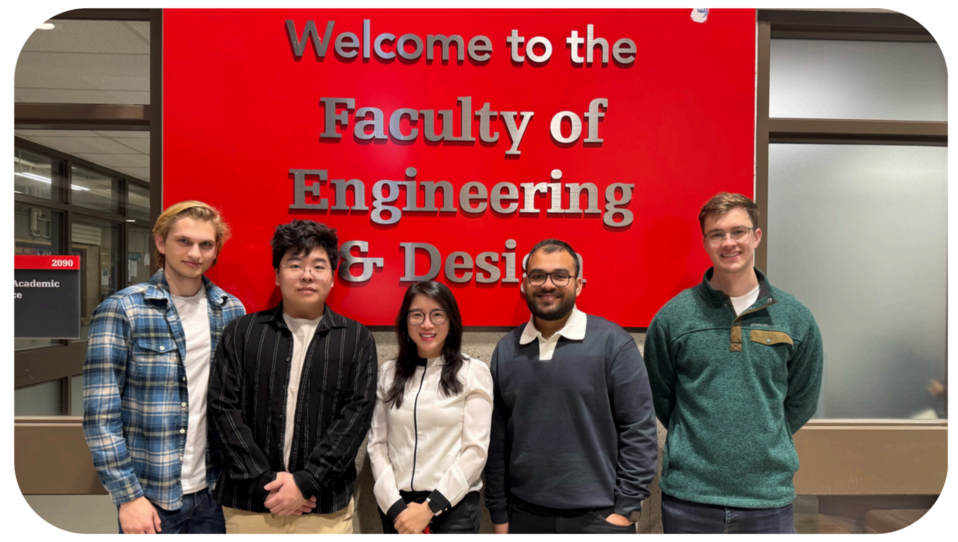


Introduction & Motivation

PEEKBot Lunar Water Detector (PLWD) is collaborating with Canadian Space Agency (CSA), and other Canadian Universities, develops the PEEKBot Rover for lunar water detection, crucial for future space missions.

Our team developed a lunar water detector based on reflective spectrometry, enabling it to identify water's absorption peaks at 1200nm and 1550nm.

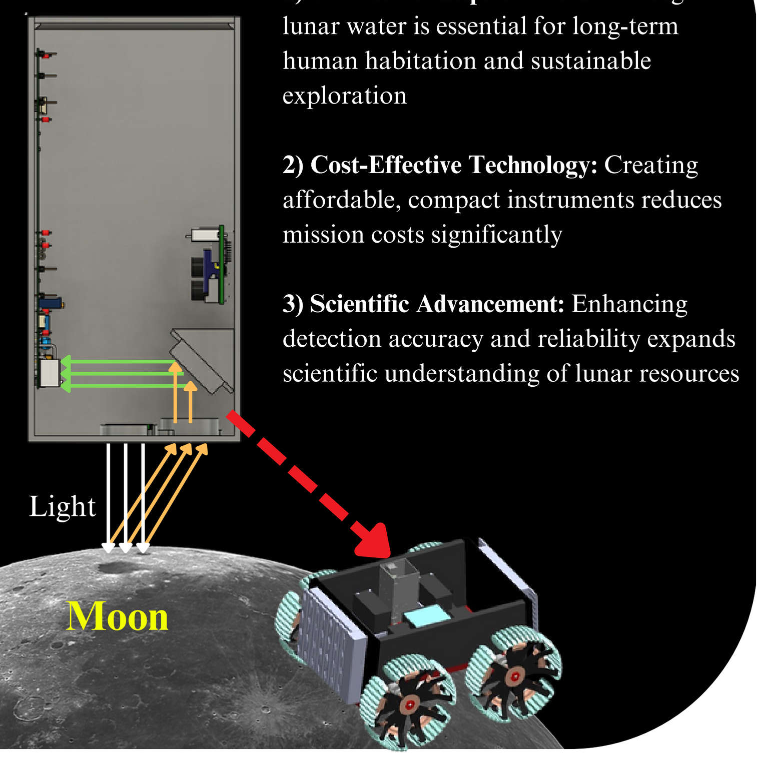


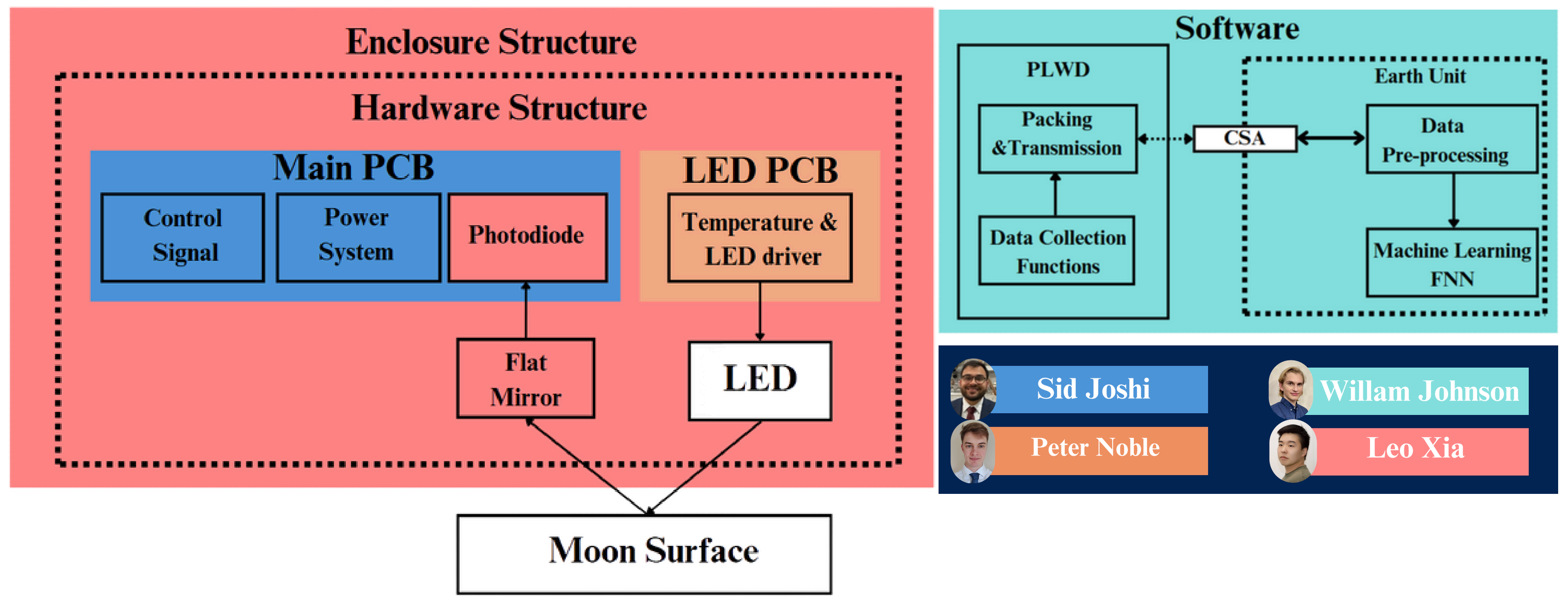
Figure 1: PEEKBot Lunar Water Detector Functionality Overview

1) Sustainable Exploration: Detecting lunar water is essential for long-term human habitation and sustainable exploration

2) Cost-Effective Technology: Creating affordable, compact instruments reduces mission costs significantly

3) Scientific Advancement: Enhancing detection accuracy and reliability expands scientific understanding of lunar resources

Team Structure & Project Description



Project Objectives

- Detect water concentration levels in 10% intervals.
- Analyze IR reflectance at **1200nm and 1550nm.**
- **Maintain compact, modular design (20 x 10 x 10 cm).**
- Operate reliably in lunar conditions **(-133 °C to 123 °C) [1].**
- Limit power usage **(<25W).**
- **Ensure accurate data transmission and prediction.**
- **Complete desired objectives by April, 2025**

Project Contributions & Achievements

- **Dual-wavelength** LED integration.
- **Modular PCB** with **reduced noise**. **(From 5V to 0.05V)**
- Precision LED **temperature monitoring (0 to 60°C).**
- **Robust enclosure** for lunar conditions.
- **Autonomous** data **processing** machine learning software.
- **Validated** detection **sensitivity** and **accuracy (R^2=0.83).**

Optics

- The **LED wavelengths** were initially selected based on the greatest reflectance contrast for water.
- **1550nm** was chosen as the reference peak, while **3400nm** was selected due to its **significant reflectance drop** at meaningful concentrations.
- Due to supply constraints, the 3400nm LED was replaced with a **1200nm** LED, which also exhibits a **characteristic peak.**

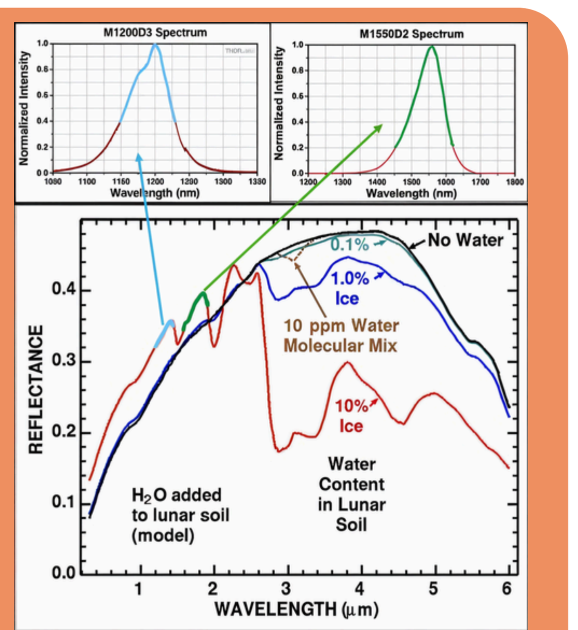


Figure 2: Reflectance characteristics of water [2,7,8]

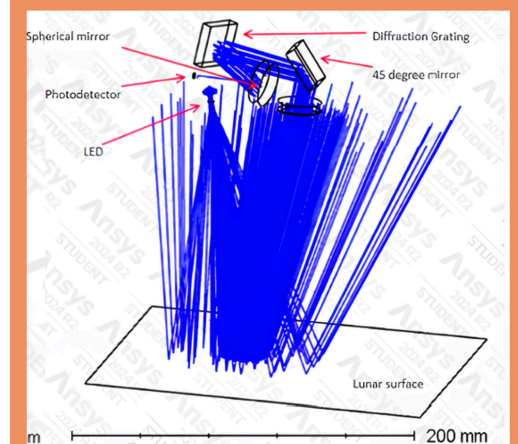


Figure 3: Early iteration optical path simulation using Ansys Zemax

- Initial **simulations** were carried out using **Ansys Zemax,** using the full optical path of the **earliest iteration.** This step ensured that the **principal rays** were reaching the photodetector and the optical pathway was **aligned** correctly.

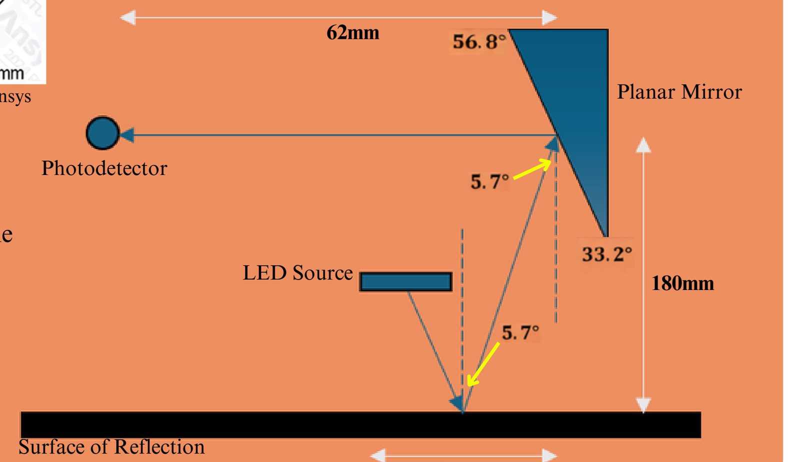


Figure 4: Latest Optical Pathway

- The optical path was simplified and absorption data was collected using the new optical pathway.
- The path length was reduced from 62cm to 39.4cm, boosting optical power.

Thermal Management

- Two **MAX6682 temperature ICs** were integrated into the driver and temperature board—one for each LED.
- **Temperature sensing** is essential, as the LED's emitted wavelength is highly temperature-dependent.
- Resistors and thermistors were selected to enable a **ground-testing** temperature range of **0 to 60°C.**
- Three **Driver IC's** were required, one for each LED and one for future TEC integration.

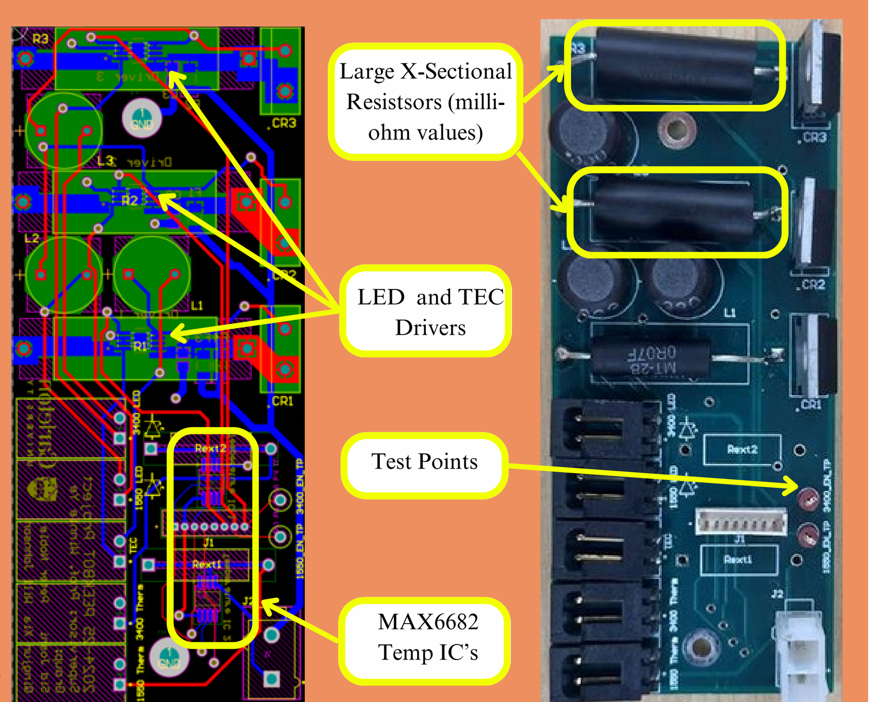
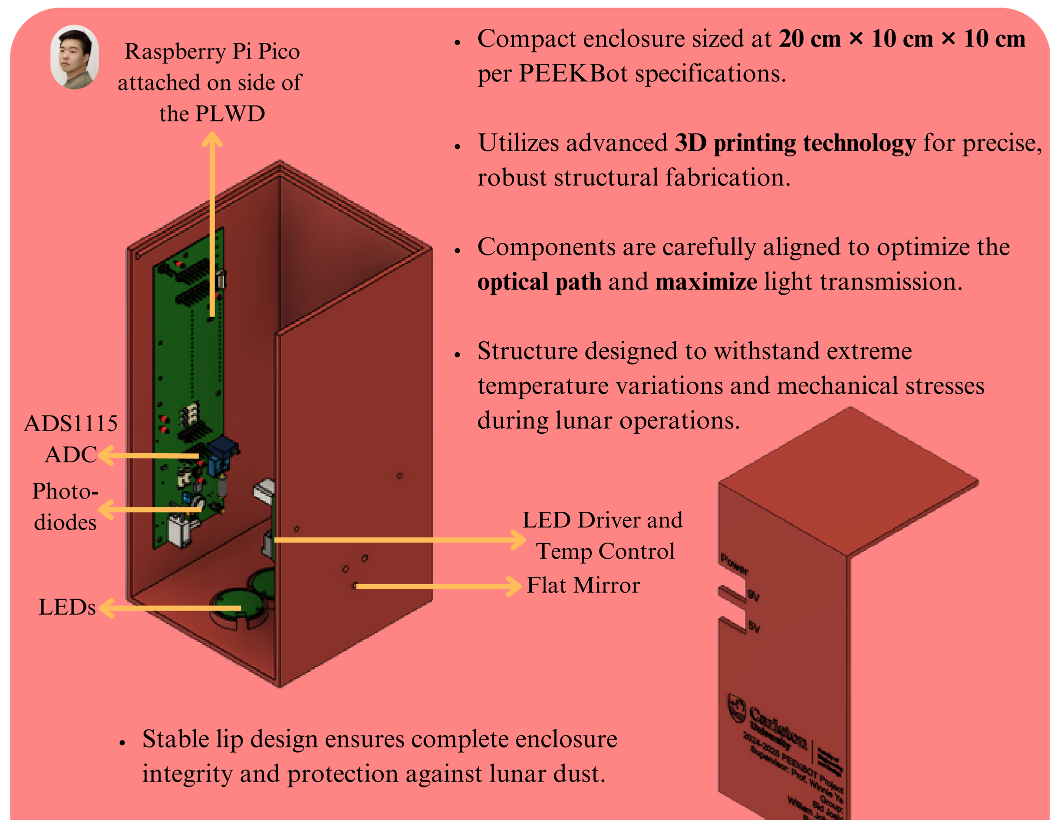


Figure 5: Thermal and Driver PCB

Structural Design



- Compact enclosure sized at **20 cm × 10 cm × 10 cm** per PEEKBot specifications.
- Utilizes advanced **3D printing technology** for precise, robust structural fabrication.
- Components are carefully aligned to optimize the **optical path** and **maximize** light transmission.
- Structure designed to withstand extreme temperature variations and mechanical stresses during lunar operations.
- Stable lip design ensures complete enclosure integrity and protection against lunar dust.

Figure 6: CAD structural Mode

Control Signals & System Power

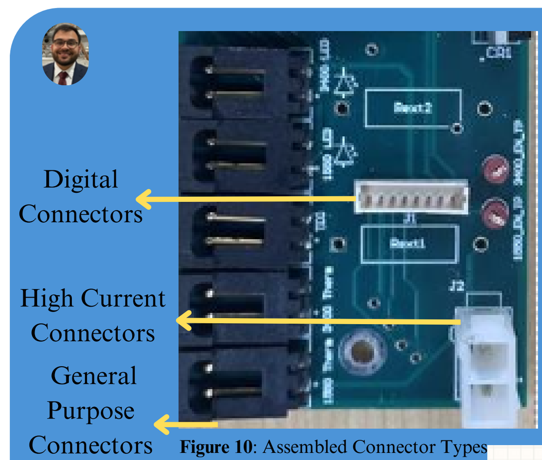


Figure 10: Assembled Connector Types

- Focus on **modularity** with implementation of **connectors** and **jumpers** to allow efficient **debugging** and **testing.**
- Design and integration of **SPI and I2C buses.**
- Addition of **fuses** to protect sensitive circuits in case of unexpected loading.
- Use of **Polygon Pour** routing for power supply layouts .
- **Minimizing Impedance** and **trace length** on sensitive **driver feedback.** Effect of parasitic resistance on driver current estimated using following eqn.

$$I_{out} = \frac{0.1}{R_S} = \frac{0.1}{(R_{feedback} + r_{parasitic})} \quad (2)$$

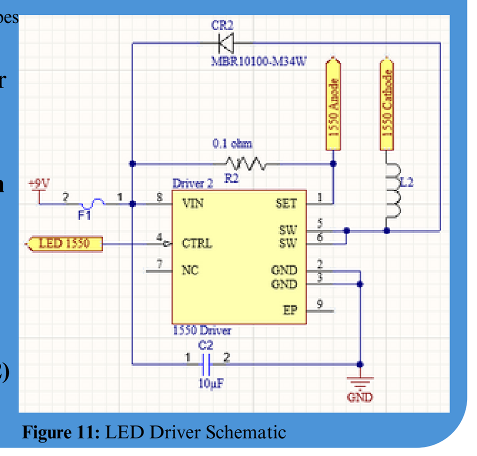


Figure 11: LED Driver Schematic

Microcontroller Data Collection

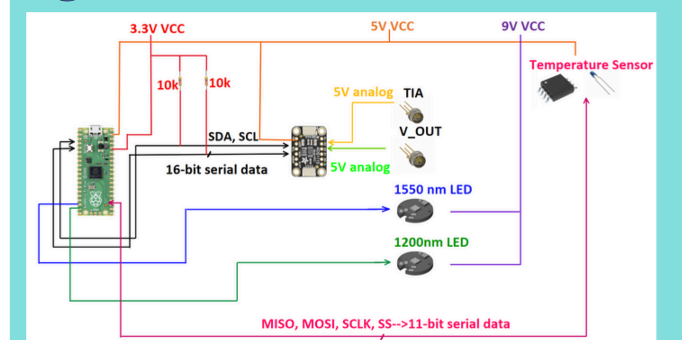


Figure 13: Microcontroller Schematic Summary of Hardware Peripherals

- **Raspberry Pi Pico** houses **Micropython** functions.
- Software was developed for **collecting, packing,** and **transmitting** lunar data, complete with component-level test cases and CSV conversion for explainability.
- LEDs remain in sleep mode by default and only powered on during data collection to conserve energy and prevent overheating.

Top level Data Collection Procedure uses **2720 Bytes** Total, with I2C collection at **400kHz** in fast mode)

Reading #	Voltage (V)	LED Temp (˚C)	Photo Temp (˚C)
170x32 bits	170x32 bits	170x32 bits	170x32 bits

Both LEDs Off	1550nm On	1200nm On	Both LEDs On
V=20x32 bits	V=20x32 bits	V=20x32 bits	V=20x32 bits
Avg. LED temps=20x32 bits	1550 LED temp =20x32 bits	1550 LED temp =20x32 bits	Avg. LED temps=20x32 bits

Figure 14: PLWD Top Level Data Collection

Photodiode Integration

- Two-stage amplifier converts photodiode current signals to voltage signals:
  - First stage: **OPA380** transimpedance amplifier detects currents as low as 1 nA and amplifies the signal by **100x**
  - Second stage: MAX4238 operational amplifier provides **adjustable** amplification up to **20x** (Removed)
- **Capacitor** included to **reduce AC noise** and **enhance signal clarity.**

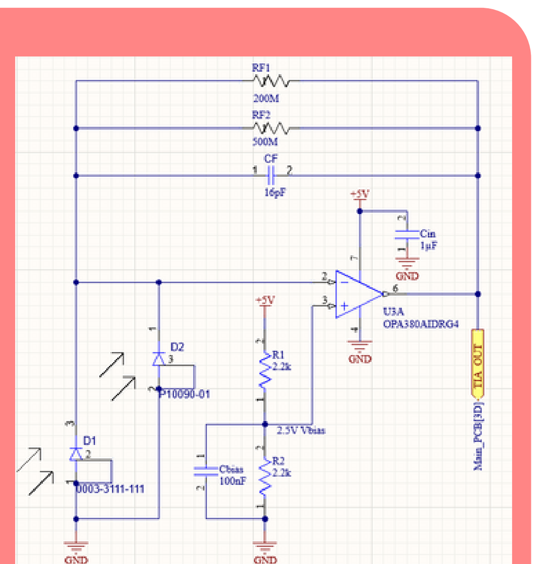


Figure 7: Photo Diode Schematic

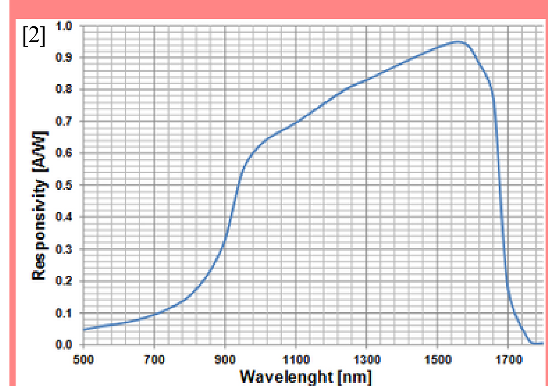


Figure 8: Responsivity of Photodetector [3]

- **Broadband photodiode** with detection range from 900 nm to 1700 nm.
- **Two parallel-connected** photodiodes **double** the overall current output.

$$P_{incident}(W) = PhotodiodeResponsivity(W/A) * \frac{OutputVoltage@TIA(V)}{10^{\frac{TIAGain(dB)}{20}}(V/A)} \quad (1)$$

Flat Mirror Optical mount

- Mount designed with an optimal reflection angle of **33.2 degrees** for **maximum efficiency.**
- **Modular design** facilitates easy installation and replacement, ensuring maintenance simplicity and system flexibility.

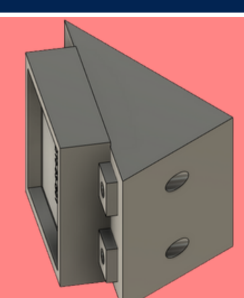


Figure 9: CAD Model for Flat Mirror

Main PCB

- Introduction of dedicated **internal ground layers** to remove **ground loops** and improve **EMI shielding.**
- Strategic **spatial re-arrangement** of components to **reduce interference** and isolation of sensitive circuits.
- Division of signal routing between top layer and bottom layer:
  - Top Layer: Photodiode signals only on top layer, allowing significant reduction in **EMI noise.**
  - Bottom Layer: Fast switching digital signals and high voltage supplies.
- Photodiode cathode trace length to **ensure integrity** of already extremely small current generated.

Dark Photo Diode Measurement	23/24 Design	24/25 Design
Noise ΔV (V)	5V	0.05V

Table 1: Photodiode performance at high current load and absent light source

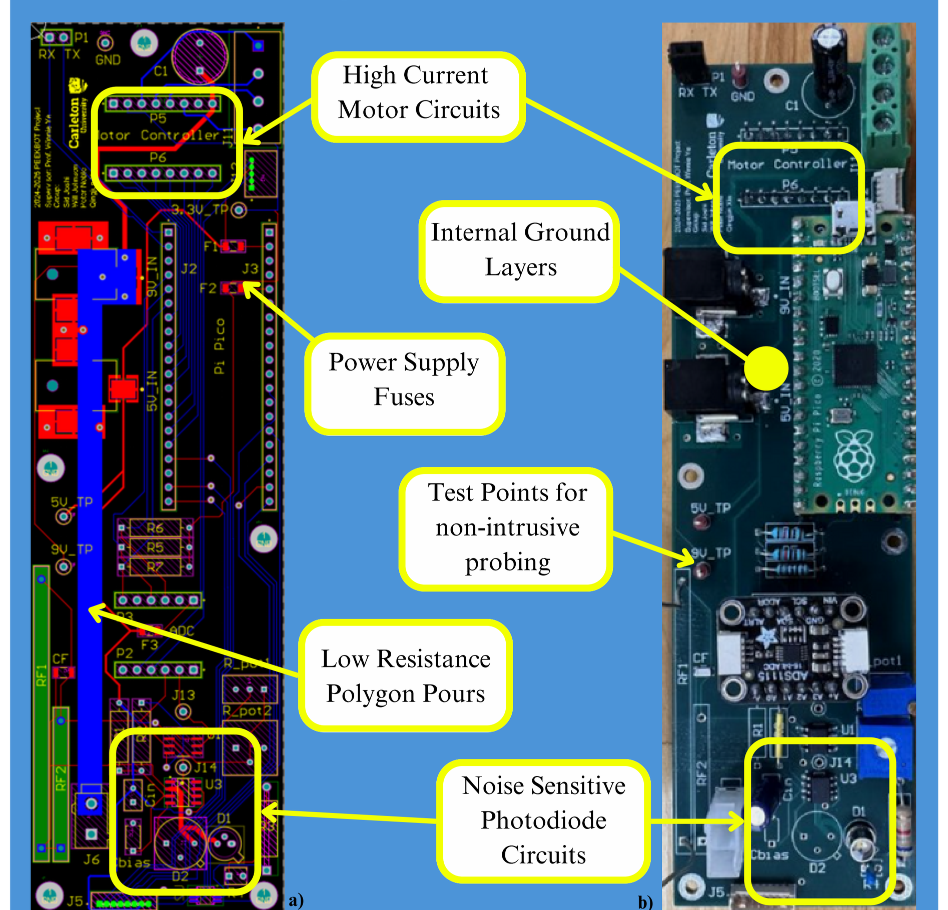


Figure 12: Main PCB Top View a) Designed Layout b) Fabricated and Assembled PCB

Machine Learning FNN and Results

- Data is extracted, and preprocessed in Python to prepare it for the feedforward neural network (FNN).
- Data is converted into feature–label pairs, where **i** indexes the number of samples, $x^{(i)}$ represents the input feature vector, and $y^{(i)}$ is the corresponding concentration label [4].

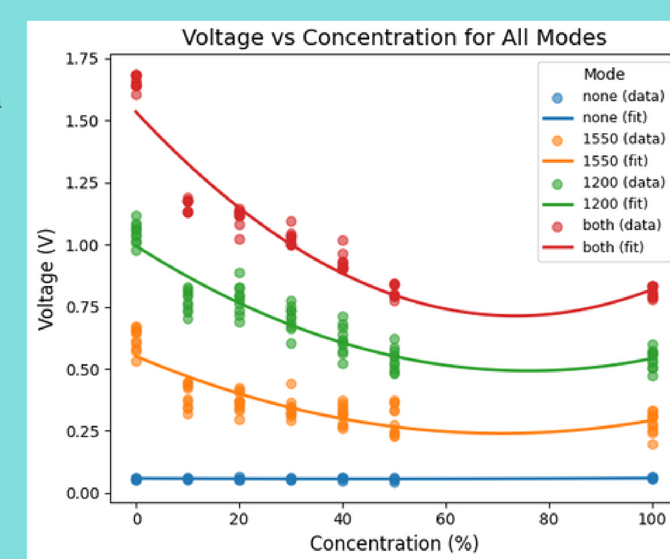


Figure 15: PLWD Photodiode Voltage vs Concentration of Water

$$y^{(i)} = \text{concentration}^{(i)} \quad (3)$$

$$y^{(i)} \in \{0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100\} \quad (4)$$

$$\mathbf{x}^{(i)} = \begin{bmatrix} x_1^{(i)} \\ x_2^{(i)} \\ x_3^{(i)} \\ x_4^{(i)} \\ x_5^{(i)} \\ x_6^{(i)} \\ x_7^{(i)} \\ x_8^{(i)} \\ x_9^{(i)} \end{bmatrix} = \begin{bmatrix} \text{voltage}_{1550} \\ \text{voltage}_{1200} \\ \text{voltage}_{both} \\ \text{LED\_temp}_{1550} \\ \text{LED\_temp}_{1200} \\ \text{LED\_temp}_{both} \\ \text{photo\_temp}_{1550} \\ \text{photo\_temp}_{1200} \\ \text{photo\_temp}_{both} \end{bmatrix} \quad (5)$$

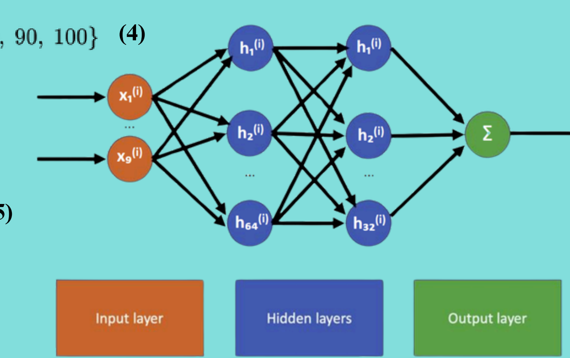


Figure 16: PLWD Feedforward Neural Network Architecture [5]

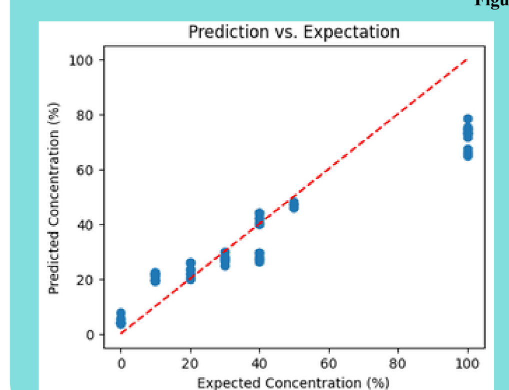


Figure 17: FNN Performance for Predicting Water

- The FNN uses one **input layer**, one 64 neuron **hidden layer**, one 32 neuron **hidden layer** and an **output layer**.
- The model utilizes **batch normalization** and **ReLU** activation.
- The model generalizes well to unseen data, accurately predicting concentration levels without labels **(R^2=0.83).**

Design Iteration

2023/24 Design

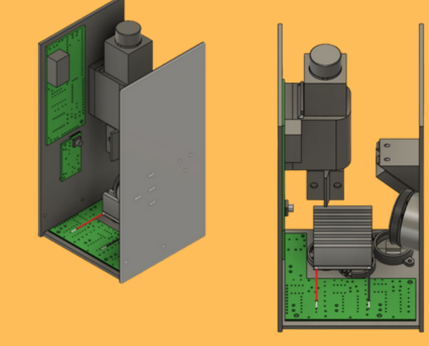


Figure 18: PEEKBot Design 2023/2024

Our team dismantled last year's protype and reused as many parts as possible. Our design was then conceptualized beginning at the initial research stage.

First CAD Model

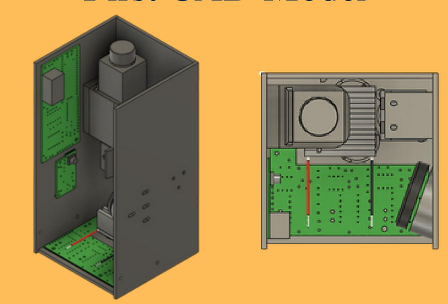


Figure 19: CAD and Optical model First Iteration

New CAD model improved structural strength to allow for precise alignment and accurate data collection.

Boosting optical power

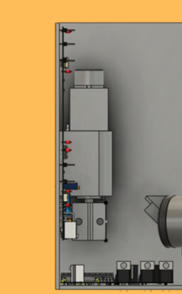


Figure 20: CAD and Optical model Second Iteration

Optical power losses were huge along the long optical path. The path was intially reduced from 62cm to 45cm, boosting power recieved.

Radical change of plan

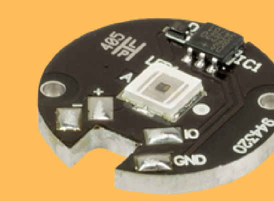


Figure 21: Thorlabs LED PCB [6]

The 3400nm LED did not get shipped so our team had to adapt and switch back to the original 1200nm LED as the second optical source.

Final Design

Figure 22: CAD and Optical model Final Iteration

To produce strong, reliable data we had to reduce design complexity and scale down the path for data collection.

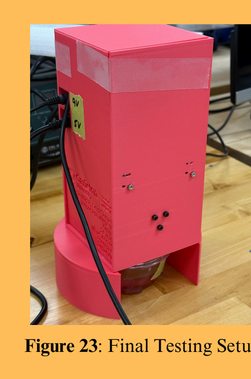


Figure 23: Final Testing Setup

Conclusions

The PEEKBot Lunar Water Detector (PLWD) successfully demonstrates a compact, low-power spectrometric system capable of identifying water concentrations on the lunar surface by targeting absorption peaks at 1200 nm and 1550 nm in 10% intervals. Through dual-wavelength LED integration, modular low-noise electronics, and autonomous data processing, the system achieves reliable performance across the Moon's extreme thermal environment.

The project effectively meets its core design objectives: it analyzes IR reflectance at key wavelengths, fits within a compact 20 × 10 × 10 cm modular form factor, operates between −133 °C and 123 °C, consumes under 25 W of power, and maintains accurate data transmission.

Each of these performance targets was verified through focused validation and system-level testing. Notably, the machine learning algorithm used for data processing achieved a detection accuracy of R^2 = 0.83, confirming the system's sensitivity and reliability under constrained conditions.

This project serves as a strong proof of concept—functional, technically sound, and field-adaptable—despite being developed over just eight months by a team of four undergraduate students. While further refinement is needed for mission-grade deployment, the current system validates the core sensing approach and lays a solid foundation for future advancement.

Future works & Improvements

- **Modify 2nd stage filter to perform second order filter response to filter noise for better noise at even lower signal strengths.**
- **Use of a collimating lens at the source output to increase optical power received at the photodetector.**
- **Implementation of fiber optic lines to replace free-space optical transmission and replace diffraction gratings with fiber bragg grating.**
- **Sourcing a 3400nm LED to measure the large absorption response at that wavelength, aiding in the identification of water's characteristic absorption at lower concentrations.**

References

- [1] L. Science, "What temperature is the moon?" https://www.livescience.com/space/the-moon/what-temperature-is-the-moon, 2025, accessed: January 8, 2025.
- [2] R. N. Clark, "Detection of adsorbed water and hydroxyl on the moon," Science, vol. 326, no. 5952, pp. 562-564,2009
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