

GLASGOW CALEDONIAN UNIVERSITY

MEng Group Research Project

MMH723842-24-AB-GLAS

**Design and Implementation of a Photodiode
Array-Based Analogue 2D Sun Sensor**

word count: xxx

by Zac McCaffery, Alexandru Belea,
Sebastian Alexander, William Kong, Nassor Salim,

Date: April 14, 2025

Contents

Abstract	8
1. Acknowledgements	9
2. Introduction	10
2.1. Problem Statement	10
2.2. Aim of the Project	10
2.3. Objectives of the Project	10
3. LiteratureReview	12
3.1. CubeSat Design	12
3.2. PSD Enabled Sun Sensor	13
3.3. Mechanical Design and Analysis	13
3.4. Photodiode Simulation and Signal Analysis	13
3.5. IoT Communication Enhancement with LEO Satellites	13
4. Methodology	14
4.1. Prototype Development	14
4.1.1. Lifecycle	14
4.1.2. Signal Conditioning Circuitry	18
4.1.3. Enclosure Design 3D print	19
4.2. Data Acquisition System	19
4.2.1. Functional Requirements	19
4.2.2. Design Approach	20
4.2.3. Technical Specifications	21
4.2.4. Testing Strategy	31
4.2.5. Evaluation of design	32
4.3. Renewable Energy Demonstrator Testbench	32
4.4. Software Model	33
4.4.1. Introduction	33
4.4.2. Theory and Concept	34
4.5. Material Analysis and Selection	34
4.5.1. Material Selection and Requirements	34
4.5.2. PCB Material Selection	35

4.5.3. CubeSat Chassis Material	35
4.5.4. Quality Assurance and Reliability Standards in Space PCB Manufacturing	35
4.6. Thermal Analysis of the PCB	35
4.6.1. Hypothesis	35
4.6.2. Thermal Analysis Parameters	36
4.6.3. Thermal results	36
4.6.4. Finite Analysis Evaluation 1 - Under 200 °C in space	36
4.6.5. Results Evaluation	38
4.7. CubeSat Chassis Design	38
4.7.1. CubeSat Chassis Design 1	39
4.7.2. CubeSat Chassis Design 2	39
5. Results	43
5.1. Sensor Characterization	43
5.1.1. Functional Requirements	43
5.1.2. Design Approach	43
5.1.3. System Architecture	43
5.2. Amplification Performance	44
5.3. Photodiode Angular Response	44
5.4. Enclosure Effectiveness	44
5.5. Data Acquisition System Evaluation	44
5.6. System Performance Analysis	44
5.6.1. Operational Constraints Identified	44
5.6.2. Environmental Factors Impact	44
5.6.3. System Stability and Repeatability	44
5.6.4. Recommendations for Improvement	44
5.7. Comparative Analysis	44
5.7.1. Breadboard vs. Stripboard Results	44
5.7.2. Iteration Improvements Analysis	44
5.7.3. Performance Against Design Requirements	44
5.7.4. Design Evolution Assessment	44
5.8. System Limitations And Considerations	45
5.8.1. Angle accuracy	45
6. Conclusions	46
7. Future Work	47
Bibliography	48

A. Appendix - DAQ Code	49
A.1. Arduino DAQ full code	49
A.1.1. Arduino C++ Code	49
A.1.2. PC-side Python Serial Receive Script	51
B. Appendix - Software Model Code	58
B.1. Section 1 Title	58
B.1.1. subsectiontitle	58
B.2. Section 2 Title	58
B.2.1. subsectiontitle	58
C. Appendix - Photos of Lab Work	59
C.1. Prototype Images	59
C.1.1. BreadBoard Prototype	59
C.1.2. Building the Prototype	59
C.1.3. Prototype Testing	59
C.1.4. RED testbench	59
C.1.5. Solar Lab Prototype Testing	59

List of Figures

4.1.	Signal Noise Analysis, oscilloscope AC coupled	20
4.2.	Flowchart Arduino DAQ C++ program	24
4.3.	FSM Arduino C++ LOOP	25
4.4.	Python Script Flowchart	28
4.5.	Mapping of the s-plane onto the z -plane using the bilinear transformation [1, p.130]	30
4.6.	Frequency Response of 4-pole Butterworth Low-Pass Filter (Cutoff: 2.0 Hz, Order: 4, Fs: 500 Hz)	31
4.7.	PCB model with Parameters applied	36
4.8.	Results under 200 °C radiation	37
4.9.	Results under –200 °C radiation	38
4.10.	Front view of the first CubeSat chassis design	39
4.11.	Angular view of the first CubeSat chassis design	39
4.12.	Front view of 1U Cubesat Skeleton Chassis	40
4.13.	Angular view of 1U Cubesat Skeleton Chassis	40
4.14.	Second chassis design without PCBs	41
4.15.	Chassis with the aperture	42

List of Tables

4.1. S5971 Photodiode Specifications	15
--	----

List of Equations

1. Default ADC Clock Frequency Calculation	21
2. Optimized ADC Clock Frequency Calculation	21
3. Default ADC Conversion Time	22
4. Optimized ADC Conversion Time	22
5. Total Sampling Time for 4 Channels (Default)	22
6. Total Sampling Time for 4 Channels (Optimized)	22
7. Maximum Theoretical Sampling Frequency (Default)	22
8. Maximum Theoretical Sampling Frequency (Optimized)	22
9. Actual Limited Sampling Frequency	22
10. Total Effective Data Rate	22
11. Frequency Response of 4th-order Butterworth low-pass filter with 2.0 Hz cutoff	31

Abstract

add abstract here

1. Acknowledgements

We would like to express our sincere gratitude to our supervisors, Dr. Roberto Ramirez-Iniguez and Geraint Bevan, for their invaluable guidance and unwavering support throughout this project.

Our appreciation extends to the 3rd Floor EEE Lab Technicians and Dr. Carlos Gamio-Roffe, whose technical expertise and assistance were instrumental in the successful construction of the prototype.

We are particularly grateful to the European Project Semester RED Team members—Nikolay Ivanov Shopov, Stef Hannisse, and Samridhi Gupta—for generously allowing the use of their Renewable Energy Demonstrator as a testbench. Their contribution provided an ideal platform for positioning light sources during the testing phase of this project.

2. Introduction

2.1. Problem Statement

With the ever-increasing commercialization of the space and satellite industry there is a growing need for a cost-effective method of attitude tracking for smaller satellite missions of such as CubeSat as these missions are purpose built for very specific objectives. Whilst the larger commercial satellite missions make use of expensive digital camera systems for tracking purposes, this is not feasible for much smaller CubeSat setups. CubeSats are defined from 1 unit to 12 – where 1U is a 10x10x10 cm satellite. Consequently, there is a demand for a cost-effective and easily implementable attitude tracking system that can provide accurate measurements for CubeSat missions, such as a Position Sensitive Detector (PSD) using photodiodes.

2.2. Aim of the Project

"To investigate and develop a cost-effective and reliable sun sensing solution suitable for Low Earth Orbit (LEO) nanosatellite attitude determination."

2.3. Objectives of the Project

To investigate the design of a sun sensing system for nanosatellites, used in orientation determination, through detection of its relative position to the sun using analogue sensors located on the satellite's body. Our goal is to create a system which balances cost-effectiveness and simplicity. To achieve this, we will create a software model of the analogue sensor(s) to simulate the system's ability to track the sun from various angles in orbit. After which, we aim to build a physical prototype and use a movable light source to simulate the sun's movement, allowing comparison between the real sensor's performance against our simulations. Although the physical prototype will be built using non-space-grade materials, one of the objectives is to look at and analyse materials required for building a space-grade PCB and sensor. For this step, the Mechanical side of the team will perform Printed circuit board (PCB) and aperture device finite analysis using ANSYS to determine resilience to environmental factors such as stress and thermal simulation. The application of signal processing will be explored to provide usable data, filter out

noise, and improve the system's accuracy. This approach aims to develop a cost-effective and reliable, in-house sun sensing solution specifically for nanosatellites operating in Low Earth Orbit. Major Objective points:

- **Conduct literature review:**

- Analyse existing research on sun sensing technologies, with a focus on PSD-based analogue sensors and their applications in nanosatellites.
- Identify current challenges, best practices, and advancements in attitude determination in Low Earth Orbit. Use these insights to guide the design and optimisation of the proposed sun sensing system.

- **Develop software model:**

- Simulate the performance of the PSD-based analogue sun sensor in tracking the sun's position from various angles in Low Earth Orbit.

- **Design and fabrication of physical prototype:**

- Integrate analogue sun sensor components, test and validate its performance under controlled conditions.

- **Compare simulated and experimental results:**

- Establish evaluation methodology between simulated and experimental test results to ensure that topology evaluation is applicable.

- **Optimise sensor topology:**

- Research and evaluate various configurations of analogue sun sensing systems to maximise sun detection accuracy and minimise blind spots.

- **Investigate environmental factors:**

- Evaluate the material requirements of the PCB and aperture device.

- **Implement signal processing algorithms:**

- Investigate the filtering of noise to enhance the signal-to-noise ratio and otherwise ensure the acquisition of usable data for accurate sun position determination.
- Implement data handling which optimises scanning rates and efficiently processes the analogue signal data for real-time attitude determination.

- **Document results and overall cost-effectiveness:**

- Develop criteria for final evaluation of sun sensing systems, on which to base the final presentation of project findings.

3. LiteratureReview

3.1. CubeSat Design

Puig-Suari, Turner and Ahlgren published an IEEE paper in 2001 with the help of their students at California Polytechnic State University exploring a need for micro satellites for use by universities in an ever-expanding space programme. They provide as a solution a standard satellite form-factor that will bring down the cost of both manufacture and deployment of satellites by smaller entities: the CubeSat. The paper identifies a key component for the success of this form factor a need for a standard CubeSat deployer mechanism which can deploy several satellites safely and develop such a platform, called Poly Picosatellite Orbital Deployer or P-POD. They point out the need and provide microsatellite size and shape of the CubeSat form factor [2]. Sai balaji et al. performed a study using MATLAB simulation of several attitude control algorithms to look at the ability to control a CubeSat of size 1U. They also simulated sensors such as sun sensors, magnetometer, and gyroscope. They concluded that it is possible to operate the satellite using a magnetorquer type actuator and an array of mathematical models and algorithms: it would take 2000 seconds for a 1U satellite to stabilize at 505km, 98° degree attitude in orbit with the methods utilized by them [3]. Incentivised by the rapidly increasing use of LEO, Lopez-Calle and Franco perform a quantitative comparative study on the catastrophic failure of CubeSats and Nanosats from radiation exposure due to the harsh environment of space versus failure due to collisions in the increasingly busy Low Earth Orbit (LEO). The authors concluded that while sustained damage and damage protection from radiation exposure used to be and currently still is the most crucial factor in protecting LEO microsatellites, increasingly the risk of debris collisions is becoming more important and will become the most important in the following 50 to 70 years. The authors conclude that microsatellite designers need to move their focus more towards defence from debris impacts as these, even if not resulting in catastrophic failure of the satellite, they will impact the attitude of the satellite [4].

- 3.2. PSD Enabled Sun Sensor**
- 3.3. Mechanical Design and Analysis**
- 3.4. Photodiode Simulation and Signal Analysis**
- 3.5. IoT Communication Enhancement with LEO Satellites**

4. Methodology

4.1. Prototype Development

4.1.1. Lifecycle

This section provides an overview of the Prototype Development Lifecycle.

Conceptualization and Requirements Definition

- The prototype must have four photodiodes in an xy pattern with respective circuitry required to output 0-5 Volts that will be read by an Arduino based Data Acquisition System (DAQ). The circuit must be able to react to light intensity changes, however the change will be at low frequency (below 1Hz) as a satellite attitude is considered to change only gradually.
- While the prototype may not have a high accuracy, it is hoped that it will be enough to measure light position changes roughly, even if at a low accuracy of 10° or 20° but this will remain to be seen.
- The prototype within the scope of this paper will show the ability to detect the position of light at normal room conditions, therefore it does not need to withstand temperature changes or radiation that a final product would require if deployed in space.
- Interface requirements: the prototype electrical output needs to be compatible with the Arduino Analog to Digital Converter (ADC) input. Therefore, the signal shall not go below 0 Volts or exceed 5 volts.
- Size and weight are not of high importance, but the device must fit in the testing equipment, which is the Renewable Energy Demonstrator arch. Preferably a height not higher than 5cm.

Theoretical Design

- Photodiodes were researched and several options were found, most of which were quite expensive, such as 2D PSD type sensors like the Hamamatsu S5990 but were

both prohibitively expensive and surface mount, which would have been harder to prototype but would allow for much higher resolutions, while also complicating the project. A decision was made to base the project on 1D photodiodes, and four Hamamatsu S5971 were purchased, which offered a good compromise in price and specifications: for under £10 a piece, the s5971 has the following specifications:

Table 4.1.: S5971 Photodiode Specifications

Parameter	Value
Spectral response range (λ)	320 to 1060 nm
Peak sensitivity wavelength (λ_p)	920 nm
Photosensitivity S (A/W) at λ_p	0.64
Photosensitivity S (A/W) at 780 nm	0.55
Photosensitivity S (A/W) at 830 nm	0.6
Short circuit current I_{sc}	1.0 μ A
Dark current I_d (Typical)	0.07 nA ^{*3}
Dark current I_d (Maximum)	1 nA ^{*3}
Cutoff frequency f_c	0.1 GHz ^{*3}
Terminal capacitance C_t (f=1 MHz)	3 pF ^{*3}
Noise equivalent power NEP ($V_R=10$ V, $\lambda=\lambda_p$)	7.4×10^{-15} W/Hz ^{1/2}

$$V_R = 10 \text{ V}$$

-

- Model sun sensor geometry and aperture design
- Determine optimal photodiode placement for coverage and accuracy
- Develop mathematical models for sun vector determination
- Simulate sensor performance under various lighting conditions

Preliminary Design

- The design of the Prototype must have four photodiodes in an xy pattern with respective apertures placed such that they cover opposite halves of the photodiodes. This is to facilitate light location detection by the aperture shadowing the photodiode when the light is on one side but not the other.

Component Selection and Procurement

- Select appropriate photodiodes (spectral response, sensitivity)
- Choose microcontroller/processor

- Source analog-to-digital converters
- Identify appropriate materials for aperture and housing
- Procure test equipment for validation

Breadboard Testing

- Assemble basic circuit on breadboard
- Test photodiode response characteristics
- Verify analog front-end performance
- Validate signal processing approach
- Identify design weaknesses and optimization opportunities

First Prototype Development

- Design printed circuit board (PCB)
- Manufacture PCB
- Design and fabricate aperture mask
- Develop housing/enclosure
- Assemble prototype components
- Write initial firmware implementation

Initial Testing and Characterization

- Conduct functional testing
- Measure photodiode response curves
- Characterize sun angle determination accuracy
- Test temperature sensitivity
- Evaluate power consumption
- Assess signal-to-noise ratio

Design Refinement

- Analyze test results
- Modify aperture design if needed
- Optimize photodiode configuration
- Update signal processing algorithms
- Refine PCB layout
- Improve firmware algorithms

Second Prototype Development

- Implement design improvements
- Manufacture revised PCB
- Fabricate improved aperture
- Enhance housing design
- Update firmware with optimized algorithms
- Assemble refined prototype

Comprehensive Testing

- Laboratory performance testing (angular accuracy, resolution)
- Environmental testing (thermal cycling, vibration)
- Radiation testing (if applicable for space applications)
- Interface compatibility testing
- Long-term stability assessment

Validation and Calibration

- Develop calibration procedures
- Create calibration fixtures
- Perform sensor calibration
- Document calibration coefficients
- Validate sensor performance against requirements

Documentation and Production Readiness

- Create detailed technical specifications
- Document calibration procedures
- Prepare assembly instructions
- Write user manual/interface control document
- Develop acceptance test procedures

Pre-production Prototype

- Build small batch of pre-production units
- Conduct acceptance testing
- Verify production processes
- Validate consistency between units
- Finalize design for production

Technology Transfer to Production

- Document manufacturing processes
- Train production personnel
- Establish quality control procedures
- Define production testing requirements
- Prepare for volume manufacturing

4.1.2. Signal Conditioning Circuitry

A photodiode produces a certain amount of current when light hits the depletion region. Therefore, a larger depletion region is desirable, to produce more current. [2021KeiserFi-breOptics]

Functional Requirements

Design Approach

Technical Specifications

Implementation Plan

Testing Strategy

Deployment Process

Evaluation

4.1.3. Enclosure Design 3D print

This section provides an overview on the design and fabrication of the enclosure for the prototype. The enclosure is a critical component that houses the electronic components and provides protection against environmental factors. The design process involves several steps, including conceptualization, modeling, and fabrication.

Conceptualization

Material Selection

Fabrication Process

Testing and Validation

Iterations and Improvements

Final Enclosure Specifications and Documentation

4.2. Data Acquisition System

4.2.1. Functional Requirements

The output signal from the photodiode array amplifier is required to be converted to digital form for post-processing. This requirement is filled by designing a Digital Acquisition System (DAQ) capable of recording the signal from the four photodiode circuits simultaneously. The choice of design was conceived by analyzing the analog signal and determining some basic requirements of the Analog to Digital Converter (ADC) the DAQ must possess.

Analog Signal Characteristics

- The signal is four channel, one per photodiode, and between 0 and 5 Volts, as the TIA and post amplification was designed specifically for this output.

- Close to DC frequency, i.e., static in nature, due to light intensity remaining static under most tests. One test is performed at 0.2Hz, which is still very low frequency, with the light completing a semicircular arc once in 130 seconds (26 positions of 5 seconds each).
- Later in testing it was found that the signal is impacted by interference of 400mVpp at a frequency fluctuating from 160kHz to 180kHz from the RED testbench power supply, as pictured in Figure 4.1.

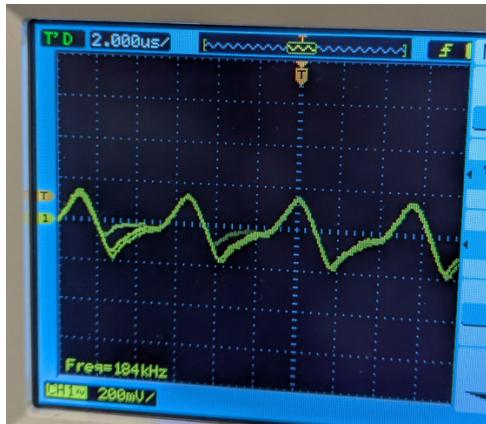


Figure 4.1.: Signal Noise Analysis, oscilloscope AC coupled

CSV Data Structure and Format Specification is as follows:

The output of the DAQ is to be saved in Comma Separated Values (CSV) file format, with columns as follows: Sample(nr.), Time(ms), A0(V), A1(V), A2(V), A3(V). This allows for easy post-processing and plotting.

4.2.2. Design Approach

The characteristics of the signal being low frequency, combined with the requirement to read all four signals simultaneously and in sync, meant two things: the Sampling Rate could be quite low due to Nyquist theorem telling us that the sampling rate must be at least twice the frequency of the signal being sampled, in order to maintain the original signal without aliasing [1, p. 146]. Therefore a low performing ADC is acceptable for a signal changing at under 1Hz. And secondly, the DAQ must support sampling from at least four analog inputs. These requirements meant that a cheap Arduino based DAQ could fit perfectly the needs of the project: it is powered by the Atmega328P which has an included ADC of 15 ksps [5, p.205]. And the Arduino Nano has four analog inputs.

Arduino Programming

The Arduino-based DAQ will require both a C++ program written for the Arduino itself, as well as a program or script on the PC receiving the digitized signal, this is because the Arduino lacks both the memory requirements and capability to store the recorded digitized signal to some internal memory.

The Arduino C++ Program must be able to listen to commands from the user on the PC receiving, start a recording, and immediately transmit to the PC over serial communication.

4.2.3. Technical Specifications

Arduino Code

The Arduino Code which uses the Arduino ADC is formed of the setup() function triggered once at the start/reset of the device and a standard continuous loop triggered after setup completes. Inside the loop, two if statements check for instructions from the PC script. The recording time limit is hardcoded as a global function. Figure 4.2 shows the algorithm as a Flowchart that checks for Serial data in, waits for a command to start recording, and if recording time has reached the preset limit, it stops recording, sends the last values to the Python script on the PC and a "recording_stopped" command. A FSM diagram is also available in Figure 4.3. The pseudocode used while designing the Arduino side of the DAQ system, is available in Listing 4.1. The final code is available in Appendix A.1.1.

The Atmega328P does not have a separate ADC clock input, therefore the CPU clock is used by first dividing by a default rate of 128, this divider is changed to 16 by changing bits 2-0 to 100, as per [5, p.219]. This increases the clock speed available to the ADC for a higher sampling rate. This results in a 1MHz clock signal to the ADC (16MHz/16) which seemed needed when dealing with multiplexing four analog inputs to a single ADC. The process is as follows:

Original ADC Clock Speed (with default prescaler of 128):

$$f_{\text{ADC-default}} = \frac{f_{\text{CPU}}}{\text{Prescaler}_{\text{default}}} = \frac{16 \text{ MHz}}{128} = 125 \text{ kHz} \quad (1)$$

Optimized ADC Clock Speed (with modified prescaler of 16):

$$f_{\text{ADC-optimized}} = \frac{f_{\text{CPU}}}{\text{Prescaler}_{\text{optimized}}} = \frac{16 \text{ MHz}}{16} = 1 \text{ MHz} \quad (2)$$

Conversion Time Calculations: ADC requires approximately 13 clock cycles for each conversion [5, p.208] Optimized ADC Clock Speed (with modified prescaler of 16):

$$T_{\text{conversion-default}} = 13 \times \frac{1}{f_{\text{ADC-default}}} = 13 \times \frac{1}{125 \text{ kHz}} \approx 104 \mu\text{s} \quad (3)$$

$$T_{\text{conversion-optimized}} = 13 \times \frac{1}{f_{\text{ADC-optimized}}} = 13 \times \frac{1}{1 \text{ MHz}} \approx 13 \mu\text{s} \quad (4)$$

Time required to sample all 4 analog inputs:

$$T_{\text{4channels-default}} = 4 \times T_{\text{conversion-default}} = 4 \times 104 \mu\text{s} \approx 416 \mu\text{s} \quad (5)$$

$$T_{\text{4channels-optimized}} = 4 \times T_{\text{conversion-optimized}} = 4 \times 13 \mu\text{s} \approx 52 \mu\text{s} \quad (6)$$

Maximum theoretical sampling frequency for all 4 channels:

$$f_{\text{sampling-max-default}} = \frac{1}{T_{\text{4channels-default}}} = \frac{1}{416 \mu\text{s}} \approx 2.4 \text{ kHz} \quad (7)$$

$$f_{\text{sampling-max-optimized}} = \frac{1}{T_{\text{4channels-optimized}}} = \frac{1}{52 \mu\text{s}} \approx 19.2 \text{ kHz} \quad (8)$$

Actual limited sampling frequency (based on minSampleInterval = 2ms):

$$f_{\text{sampling-actual}} = \frac{1}{2 \text{ ms}} = 500 \text{ Hz per channel} \quad (9)$$

Effective data rate across all channels:

$$\text{Data Rate} = 4 \text{ channels} \times 500 \text{ Hz} = 2000 \text{ samples/second} \quad (10)$$

In real testing the actual sampling rate was closer to 330Hz for 5 second recordings or

100Hz for a 2 minute recording - after some investigation the only explanation was the relativly small size of the transmission buffer implemented by the Serial C++ library. The buffer is of only 64 bytes, and when it fills, the function Serial.write() (used by println()) will block the write untill there is space in the buffer[ref:arduino.cc/serial.write]. As our line of text is quite long "498,5000,0.059,0.054,0.073" for example has 26 characters (last line of a 5 second recording). For larger recording length, where the first and second column, Sample and Time, can get quite large, the sampling rate decreased considerably, but was kept constant (around 10ms for a 2 minute recording). Presumably due to optimization in the Arduino Serial Hardware/Software or compiler, it remains constant at 10ms. However this was not investigated further as for our near-DC signal, even 10ms was a fast enough sampling rate for our DC-like signal.

```

1  recordingDuration = 5000 // for how long to record in milliseconds
2
3  minSampleInterval = 2      // control how fast to sample to avoid
4                      // relying on Arduino performance
5  // Initialize serial communication
6  // Initialize analog inputs
7  // Setup ADC
8
9  // Infrom PC listening on Serial Connection: Arduino is ready to
10 // record
11 Serial.print("Arduino_DAQ_Ready")
12 // enter the loop
13 void loop(){
14     //listen for command from PC script:
15     String command = Serial.read()
16     //set system state
17     if (command == "START"){
18         // Send header of csv
19         Serial.println("Sample,Time(ms),A0(V),A1(V),A2(V),A3(V)")
20         // keep track of system state
21         state = recording
22         // keep time
23         startTime = currentTime()
24         // send confirmation
25         Serial.println("recording in progress")
26     }
27     // check if recording
28     if (state == recording){
29         // check if within recording period
30         currentTime = currentTime()
31         elapsedTime = currentTime - startTime
32         if(currentTime <= recordingDuration){
33             // Also check not recording too fast
34             if(currentTime - lastSampleTime >= minSampleInterval){
```

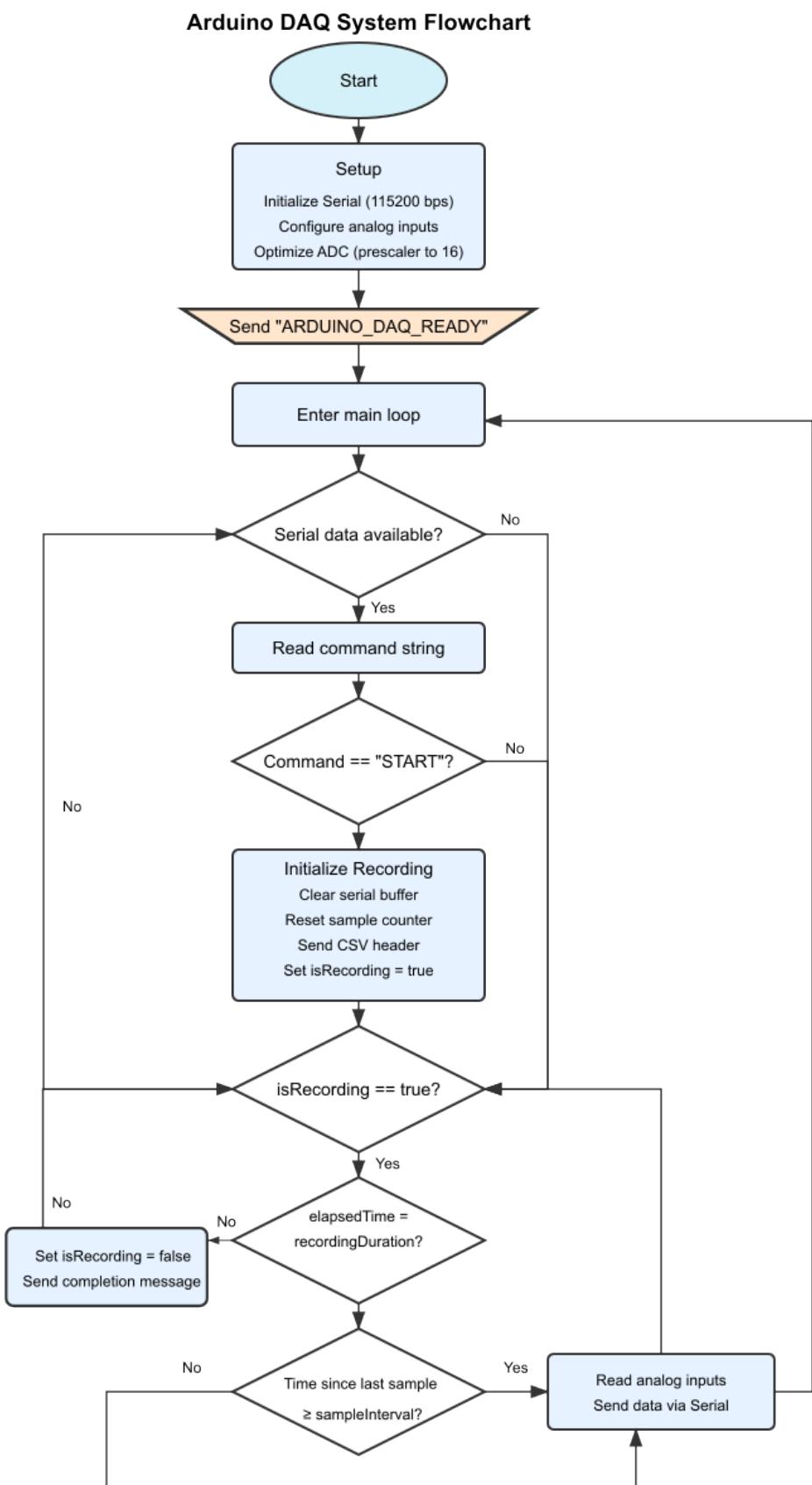


Figure 4.2.: Flowchart Arduino DAQ C++ program

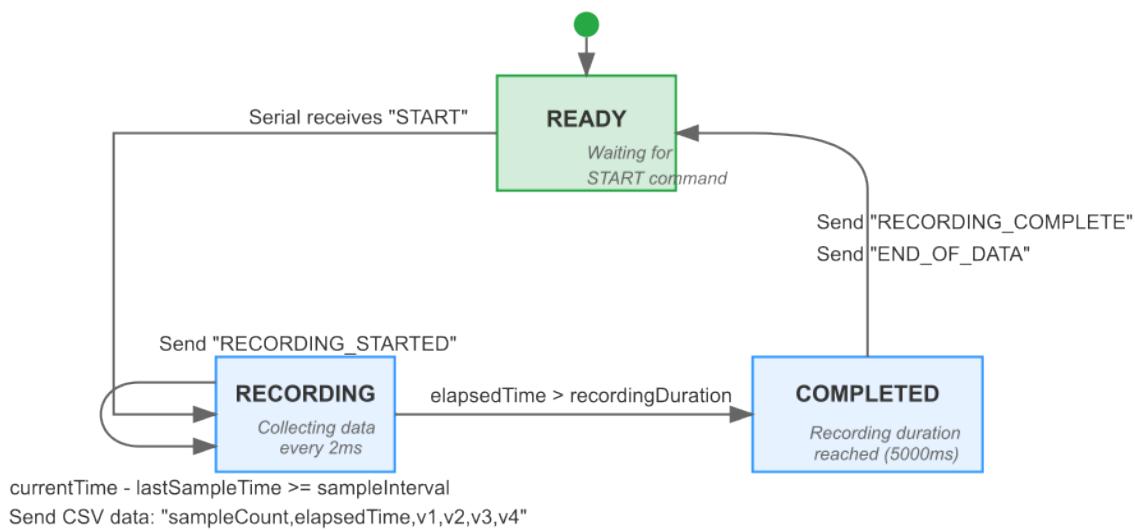


Figure 4.3.: FSM Arduino C++ LOOP

```

34     sampleCount++;
35     // Start each row with sample count and time of sample
36     String currentCSVrow = String(sampleCount) , string(
37     elapsedTime)
38     // Multiplex through all analog inputs
39     for (int = 0;i<4;i++){
40         //read raw values
41         rawValue = analogRead(analogInputs[i]);
42         // compute real value
43         voltage = rawValue * 5/1023
44         // add value to current row to send
45         currentCSVrow += String(voltage)
46     }
47     // Send completed row to PC
48     Serial.println(currentCSVrow)
49 }
50 }
51 // end recording
52 else{
53     state = notRecording
54     // tell PC recording finished
55     Serial.println("Recording_finished")
56 }

```

Listing 4.1: Arduino DAQ PseudoCode

Sampling Rate Details Several factors restrict the sampling rate:

Sample Interval Setting The most direct limitation is the `sampleInterval` constant set to 2ms in the code. It was meant to avoid having random sampling rates based on the number of computations required. This means samples are taken no more frequently than every 2 milliseconds (500 Hz theoretical maximum) of all four channels. The "jump" to sample the next channel is not limited in the code, but it will take 13 clock cycles, (ie. around 13 μ s at 1MHz ADC clock) to switch to the next channel.

ADC Prescaler Configuration The ADC prescaler is set to 16 (from the default of 128) with this line:

```
ADCSRA = (ADCSRA & 0xF8) | 0x04;
```

This increases the ADC clock to $16\text{MHz}/16 = 1\text{MHz}$. With each conversion taking 13 ADC clock cycles, the theoretical maximum sampling rate is about 76.9kHz for a single channel.

Serial Transmission Overhead Each sample requires formatting and sending data over serial:

```
String dataString = String(sampleCount) + "," + String(elapsedTime);
// ... format and add voltage values ...
Serial.println(dataString);
```

This string creation and serial transmission takes some time to process as mentioned earlier.

Serial Baud Rate The code uses 115200 bps, which limits how quickly data can be transmitted. Each sample in this format might be around 30-40 bytes, which means ~3000-3800 samples/second theoretical maximum throughput.

String Operations The use of the Arduino `String` class is memory-intensive and can cause fragmentation over time, potentially causing the slowdowns noticed during testing with larger timeframes (and longer strings).

Python Script

The digitized signal must be interpreted and saved on the PC. This is done via a python script which listens to the Serial port from the arduino. The signal then also required cleaning from RF interference discovered during testing. In Figure 4.4 a flowchart is produced showing the way the script works: after initial setup that sets up the Serial Communication, the script waits for a "DAQ_READY" signal from the Arduino. Once this is received, a csv file is created and the script sends a "START" signal which the Arduino interprets and starts sampling and sending the data. The script receives each line and saves it in the new CSV, and continues to record data until the Arduino sends a "RECORDING_COMPLETE" signal - which will happen when the recordingDuration is reached. At this point the python script performs the following post-processing steps:

The filter_and_save_data() function' purpose is mainly to correctly interpret the CSV. It takes a csv with the raw voltage values, saves them into a Pandas DataFrame for easier manipulation and sends each channel to the apply_lowpass_filter() function which will be described below. filter_and_save_data() pseudocode is produced in Listing 4.2.

```
1  FUNCTION filter_and_save_data(filename)
2      // Load data from CSV file into a table structure
3      data_table = READ_CSV(filename)
4
5      // Streamline the data by converting text to numbers
6      FOR EACH column IN data_table
7          CONVERT column values to numeric type
8          IF conversion fails for any value
9              REPLACE with NaN (Not a Number)
10     END FOR
11
12     // Remove any rows containing NaN values
13     REMOVE all rows with NaN values from data_table
14
15     // Calculate sampling frequency
16     time_differences = CALCULATE differences between consecutive time
17     values
18     typical_time_difference = FIND median of time_differences
19     sampling_frequency = 1000.0 / typical_time_difference // Convert ms
20     to Hz
21
22     // Process each data channel
23     channel_list = ["A0(V)", "A1(V)", "A2(V)", "A3(V)"]
24     FOR EACH channel_name IN channel_list
25         IF channel_name EXISTS in data_table
```

Python DAQ Script Flowchart

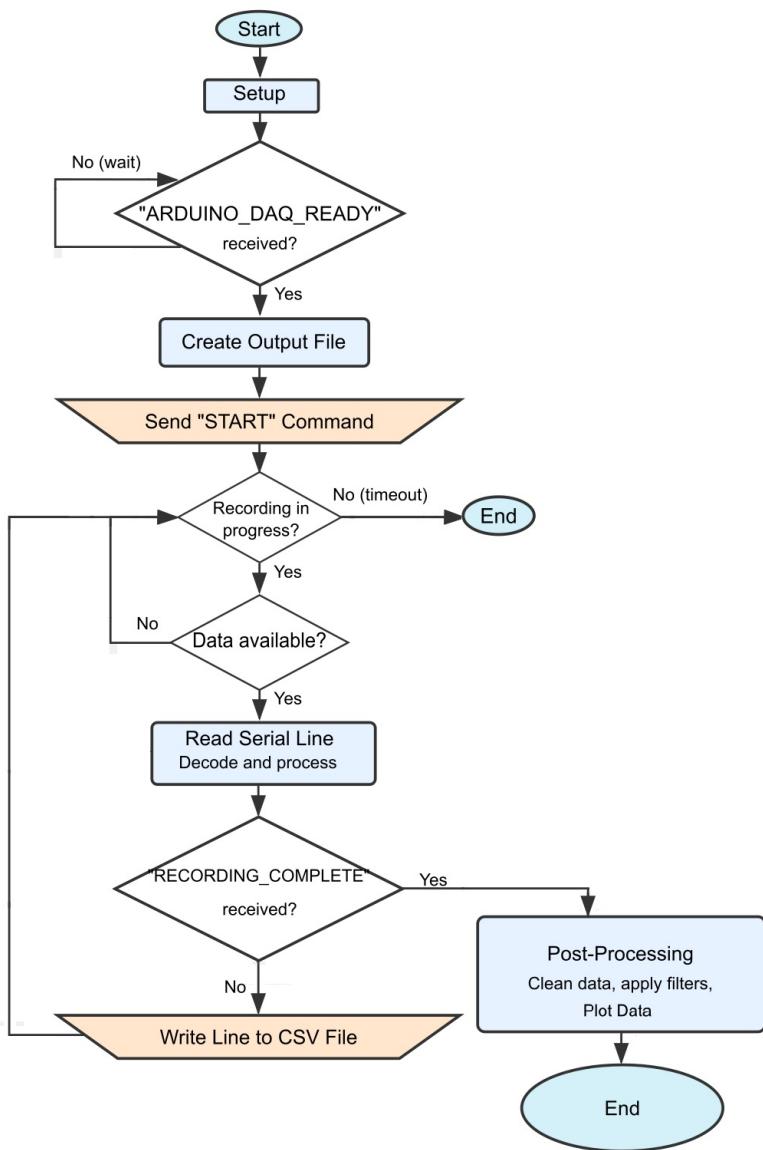


Figure 4.4.: Python Script Flowchart

```

25     filtered_values = APPLY_LOWPASS_FILTER(original_values,
26         sampling_frequency)
27         ADD new column named channel_name + "_filtered" with
28             filtered_values
29             END IF
30 END FOR
31
32 // Save results to new file
33 new_filename = REMOVE_EXTENSION(filename) + "_filtered.csv"
34 WRITE data_table TO new_filename
35
36 RETURN new_filename
37 END FUNCTION

```

Listing 4.2: Python filter_and_save_data() PseudoCode

The apply_lowpass_filter() function was created and integrated into the script once it was observed that the RED testbench used was introducing noise as seen in Figure 4.1. The benefit of using an already built testbench that could place the light at exact positions repeatedly, meant it would make sense to accept the noise and just filter the data, as the signal of interest was very low frequency while the noise was around 170kHz. The filter could be relatively simple, due to the large frequency difference between noise and signal. A 4th order Butterworth IIR filter was deemed acceptable and a low cut-off frequency of 1Hz or 2Hz was used for the static readings. This was found to be acceptable for the test involving light location at a frequency of 0.2Hz the transition of the light from one position to another was still visibly sharp. The post-processing is not the only reason light transition would not appear instantaneous on the Voltage graph, another reason is the amplification circuit which has a 1Hz cutoff frequency via the feedback capacitor on the secondary-amplification OpAmp circuit. The pseudocode of the function that creates the low-pass digital filter and filters the data is reproduced in Listing 4.3. The butter() function from the library signal is used, from the scipy package [6] which is a free and open source library offered to the scientific community. Before feeding the cutoff frequency to the filter, it is normalized to the Nyquist rate, which means it is between 0 (DC) and 1 (Nyquist frequency), and therefore the filter can be applied no matter the sampling rate. As Schafer and Oppenheim explain in "Discrete-Time Signal Processing" Third Edition: "The frequency scaling or normalization in the transformation from $X_s(j\Omega)$ to $X(e^{j\omega})$ is directly a result of the time normalization in the transformation from $x_s(t)$ to $x[n]$ " [1, p.171]. When creating a digital filter, this normalization becomes crucial because in the continuous-time domain, frequencies are measured in Herz and in the discrete-time domain, frequencies become relative to the sampling rate. The relationship between these two frequency domains is given by $\omega = \Omega T$, where:

- ω is the normalized digital frequency (radians/sample)

- Ω is the analog frequency (radians/second)
- T is the sampling period (seconds)

However, when implementing IIR filters like the Butterworth filter used for our purpose, the bilinear transformation is employed to convert from the continuous-time domain to the discrete-time domain. This transformation introduces frequency warping, where the relationship between the analog and digital frequencies becomes:

$$\omega = 2 \arctan(\Omega T_d / 2)$$

where T_d is the sampling period. This nonlinear relationship compresses the infinite analog frequency range $(-\infty, \infty)$ into the finite digital frequency range $(-\pi, \pi)$. The warping effect is more pronounced at higher frequencies, meaning that in our case it would not be noticeable [1, p.529-530].

A critical property of the bilinear transformation is stability preservation. In the analog domain, a stable system has all poles in the left half of the s-plane reproduced in Figure 4.5. The bilinear transformation maps the entire left half of the s-plane to the interior of the unit circle in the z-plane. This ensures that the 4-pole Butterworth filter, which is stable in the continuous-time domain, remains stable when converted to its discrete-time equivalent.

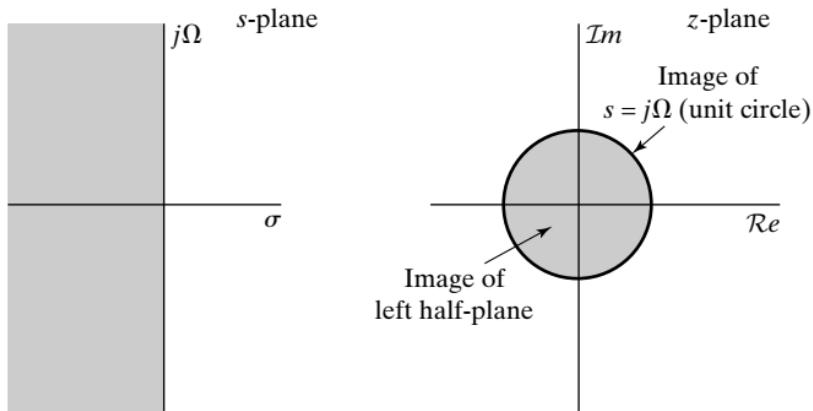


Figure 4.5.: Mapping of the s -plane onto the z -plane using the bilinear transformation [1, p.130]

The filter Frequency Response was reproduced in Figure 4.6 using the `scipy.signal.freqz()` method. The actual implementation uses `filtfilt()` which applies the filter twice, effectively doubling the filter order [7]. This affects the transition steepness and phase response. The Discrete-Time Transfer Function is reproduced in Equation 11.

$$H(e^{j\omega}) = \frac{b[0] + b[1]e^{-j\omega} + b[2]e^{-j2\omega} + b[3]e^{-j3\omega} + b[4]e^{-j4\omega}}{a[0] + a[1]e^{-j\omega} + a[2]e^{-j2\omega} + a[3]e^{-j3\omega} + a[4]e^{-j4\omega}} \quad (11)$$

```

1  from scipy import signal
2  FUNCTION apply_lowpass_filter(data, sampling_rate)
3      // set hardcoded filter values
4      cutoff_freq = 2;
5      filter_order = 4;
6      // calculate Nyquist Frequency and Normalized cut_off
7      nyquist = 0.5 * sampling_rate;
8      norm_cutoff = cutoff_freq / nyquist;
9      // generate numerator b and denominator a polinomials
10     b, a = signal.butter(filter_order, norm_cutoff, filterType = LOW);
11     // filter the data
12     filtered_data = filter(b,a,data);
13
14
15     return filtered_data;

```

Listing 4.3: Python apply_lowpass_filter() PseudoCode

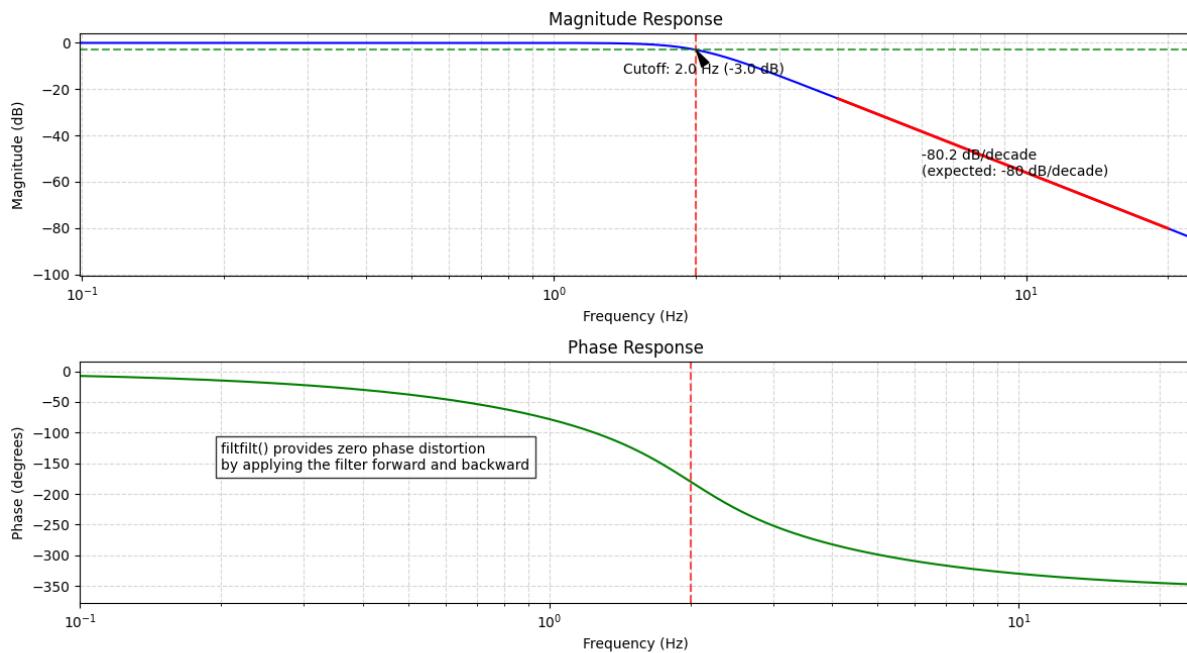


Figure 4.6.: Frequency Response of 4-pole Butterworth Low-Pass Filter (Cutoff: 2.0 Hz, Order: 4, Fs: 500 Hz)

4.2.4. Testing Strategy

The testing was done incrementally with each new version of the program, many tests were carried out as the development was dependent on both C++ code on the Arduino

and the Python script on the PC to somewhat work together. At first the C++ program was tested by listening to the output in the Serial Monitor of the Arduino IDE and sending commands the same way. Debug Serial.println() lines were used to ensure the loop on the Arduino was in the correct state. Once the C++ program seemed to somewhat work as intended, the Python script was implemented to send / receive.

4.2.5. Evaluation of design

The design was tested iterartivly while making changes to the code with a signal generator at first to simulate a stead known input signal and compare readings on the Arduino IDE Serial Monitor. Once the Python script was fully working, tests were performed again for the python script's ability to read the values sent correctly. An issue was identified where sometimes the Arduino would send the column headers not at the beggining of the CSV and these lines had to be cleaned manually. This could be due to Serial buffer issues but was not investigated. Later an attempt was made to perform the cleaning programatically by creating a function in the script to do so.

4.3. Renewable Energy Demonstrator Testbench

For testing the capability of the Sun Sensor to correctly detect the location of the light source, a test bench was required that could reliably place the location of the light at a precise location repeatedly. For this purpose we used a project built by our colleagues in the European Project Semester year 2021/22 who createad just such a device intended for demonstrating renewable energy creation live [8]. Their device was able to demonstrate the energy levels created by a Photovoltaic (PV) cell by light emited at different angles. The light emission would change location based on time of day and the PV cell readings would show the difference in energy. Futher the PV cell was controllable by a joystick to point the PV Cell at the optimum angle for the highest energy capture. For our project, the arch and LED strip were used for outputing light from different angles.

Analysis of High Frequency Noise in AC-DC Power Supply

Interference structure of around 170kHz with 400mV peak-to-peak was detected on the signal being received while the RED testbench was on as shown in Figure 4.1. This noise could be generated by several factors in the AC power supply used by the RED testbench:

1. **Switching frequency harmonics** — If it's a switch-mode power supply (SMPS), the fundamental switching frequency or its harmonics might be causing the noise. Many SMPS operate in the 50–200,kHz range.

2. **Poor filtering** — Inadequate output filtering (insufficient capacitance or poor quality capacitors) can allow switching noise to appear on the output.
3. **Improper design of magnetics** — Issues with the transformer or inductor design could cause ringing or oscillations.
4. **Resonance in the circuit** — Parasitic capacitance and inductance forming a resonant circuit at around 170,kHz.
5. **Control loop instability** — PWM controller instability can cause oscillations.
6. **Ground loops or poor PCB layout** — Improper grounding or PCB layout can create noise paths. [9]

To avoid spending time diagnosing and trying to repair the testbench, an easier solution was reached: performing digital filtering of the acquired signal in post processing. Due to the signal of interest being close to DC - frequencies much lower than 1Hz, and the noise being high frequency, around 175kHz, a simple digital Butterworth filter with a cutoff frequency at around 1-2 Herz was found to be a good solution.

The only remaining issue was that this noise would sometimes trigger the internal components of the testbench, unintentionally triggering the button press from the control interface that was changing the light position, but it happened so rare that it was not a major concern.

4.4. Software Model

4.4.1. Introduction

A Python model was constructed to provide a simulation of the movement and intersection of rays from a movable source to evaluate sensor performance and compare these results with practical experiments. The model allows for a number of configurable parameters:

- The trajectory of the light source 3D space, which moves in configurable discrete increments.
- The placement of any number of sensors and apertures, including their dimensions.
- The form of the output data, including as a static, or animated graphic.

Affording flexibility for the model to simulate any sensor topology under a variety of conditions.

4.4.2. Theory and Concept

The system is modelled in 3D space, consisting of planes and lines. Each line is defined by vectors representing position and normal direction, $\vec{A} = (a, b, c)$ and $\vec{u} = (\alpha, \beta, \gamma)$. The planes are defined by the vectors $\vec{P} = (l, m, n)$ and $\vec{n} = (\lambda, \mu, \nu)$, respectively.

Ray projection, from a source plane to a sensor plane, is modelled using the parametric equation of a 3D line (12). This allows each ray to be described in terms of a parameter t , which enables the calculation of the intersection points between the light rays and the sensor plane.

$$\frac{x - a}{\alpha} = \frac{y - b}{\beta} = \frac{z - c}{\gamma} (= t) \quad (12)$$

Where the intersection coordinates (x, y, z) occur within a target area, a hit occurs, representing illumination.

For any given combination of source plane, and sensor plane, the t parameter is calculated using the Line-Plane Intersection equation

$$t = \frac{\vec{n} \cdot \vec{P} - \vec{n} \cdot \vec{A}}{\vec{n} \cdot \vec{u}} \quad (13)$$

4.5. Material Analysis and Selection

4.5.1. Material Selection and Requirements

External Factors

Extreme Temperature Variations

Ionizing Radiation

Internal Factors

Mechanical Stresses

Outgassing and Vacuum

4.5.2. PCB Material Selection

High-Tg FR-4

Polyimide

Alumina

PTFE(Teflon)

Copper Foils

Kapton

Material Selection for PCB

4.5.3. CubeSat Chassis Material

Aluminium 6061- T651

Aluminium 7075

6061-T651 vs 7075

Emerging Materials and Future Trends

4.5.4. Quality Assurance and Reliability Standards in Space PCB Manufacturing

NASA Standards

ESA Standards

IPC Standards

US Military Standards(MIL-SPEC)

4.6. Thermal Analysis of the PCB

4.6.1. Hypothesis

The purpose of the thermal analysis is to validate that the Polyimide PCB and the components can operate under the space conditions. The operational temperature of Polyimide minimum is -240°C and the maximum is 260°C . If the components are within the operational temperature range, then it is validated to be operational under dynamic heat conditions, however if it exceeds it, then the PCB material, and the PCB design with the component locations must be altered and reworked. It is expected that the

photodiodes area of the PCB to have the most thermal activity, with the lowest thermal activity occurring to the resistors.

4.6.2. Thermal Analysis Parameters

After a PCB CAD model is designed and material selection is completed, the thermal analysis for the PCB can now be conducted. The PCB CAD model was imported into ANSYS workbench using steady-state thermal analysis and a mesh was applied generated to the model to influences the accuracy and convergence of the simulation. Each off the components have their respective materials applied to the model, such as the photodiode with silicon and aluminium, connectors being made of copper, nickel, zinc, amplifiers and resistors made from aluminium, and the PCB being made of polyimide. Then a convection of $22\text{ }^{\circ}\text{C}$ was applied to the side of the PCB to simulate the transfer of heat of the PCB from the shuttlecraft it is housed in, assumingly room temperature of the spacecraft is the same as on Earth, it would be $22\text{ }^{\circ}\text{C}$. Each of the components have their respective temperatures when operating. Finally, two tests will be conducted using $200\text{ }^{\circ}\text{C}$ and $-200\text{ }^{\circ}\text{C}$ of radiation applied to the entire PCB model to simulate when the PCB is facing to the sun, and when the PCB is in the shadows of celestial bodies respectively.

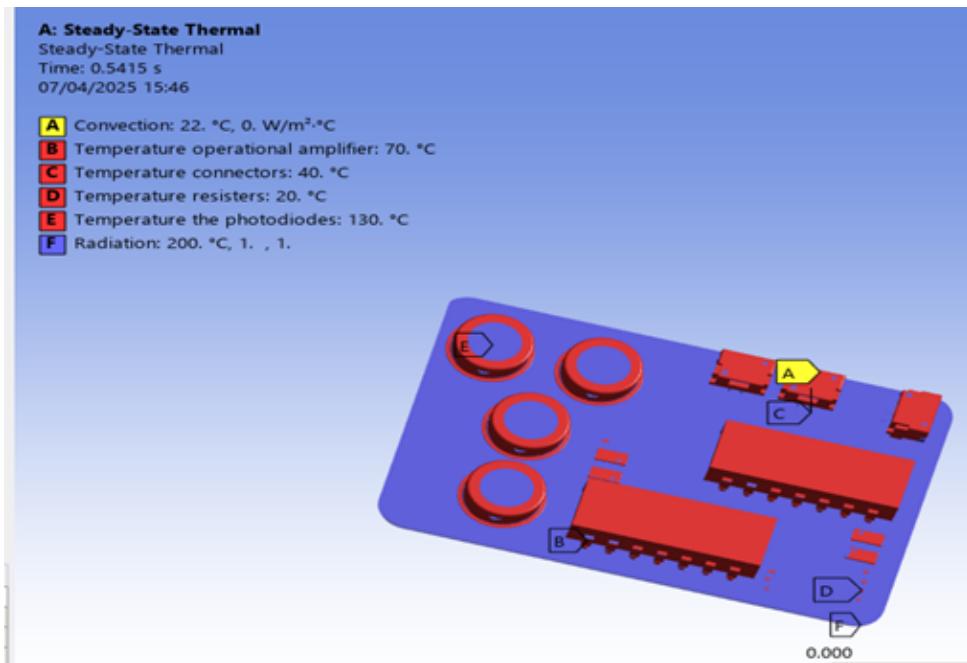


Figure 4.7.: PCB model with Parameters applied

4.6.3. Thermal results

4.6.4. Finite Analysis Evaluation 1 - Under $200\text{ }^{\circ}\text{C}$ in space

The results for the PCB when facing towards the sun depicts the most heat being towards outside of the photodiodes area and the cooler parts are around the other components. As

Figure 4.8 shows the maximum temperature experienced is 199.35°C and the minimum temperature is -31.168°C , this shows that the PCB can be operable when facing towards the Sun.

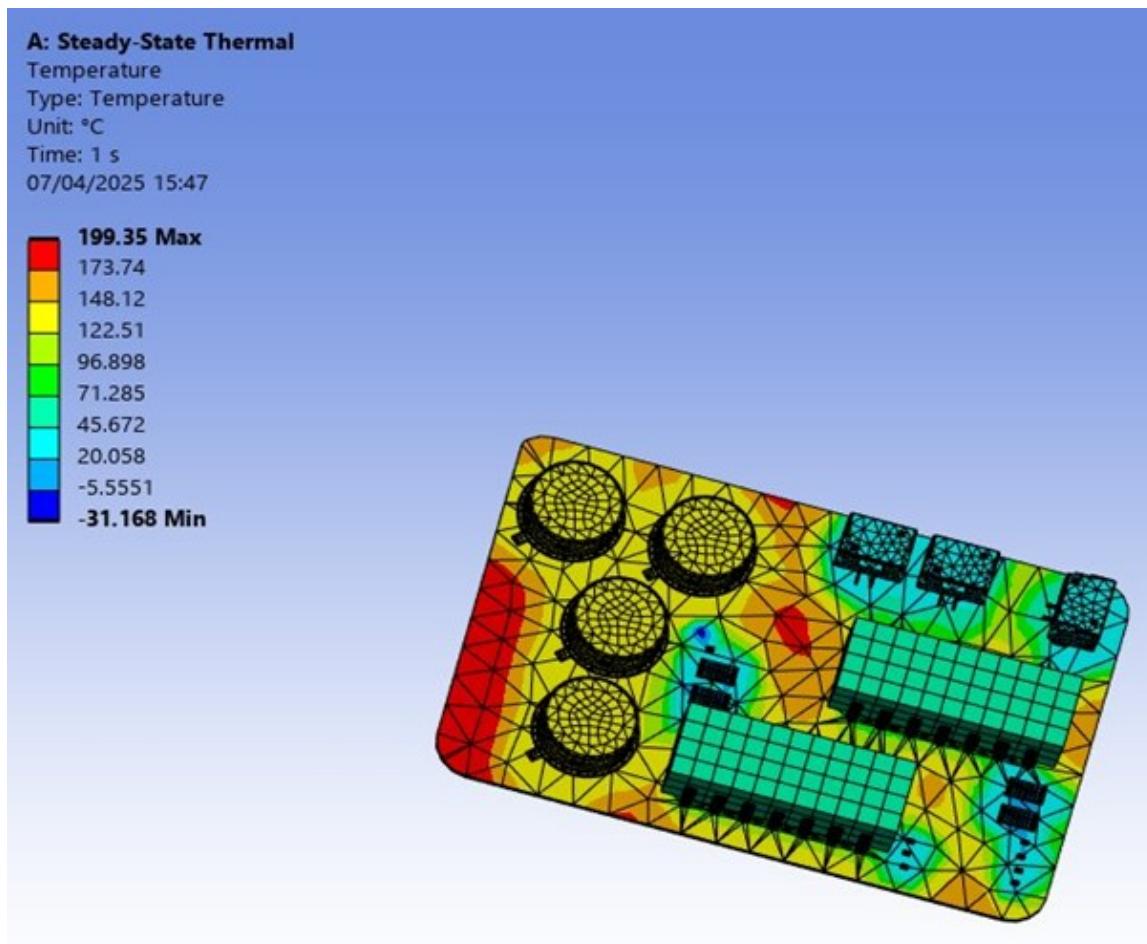


Figure 4.8.: Results under 200°C radiation

Finite Analysis Evaluation 2 - Under -200°C in space

The results for the PCB, when it is in the shadows of a celestial body depicts the most heat coming from the photodiodes themselves which is to be expected as it creates the most heat in the PCB components followed by the amplifiers then connectors. As Figure 4.9 shows the maximum temperature experienced is 136°C and the minimum temperature is -173.83°C , this shows that the PCB can be operable when in the shadow of a celestial body.

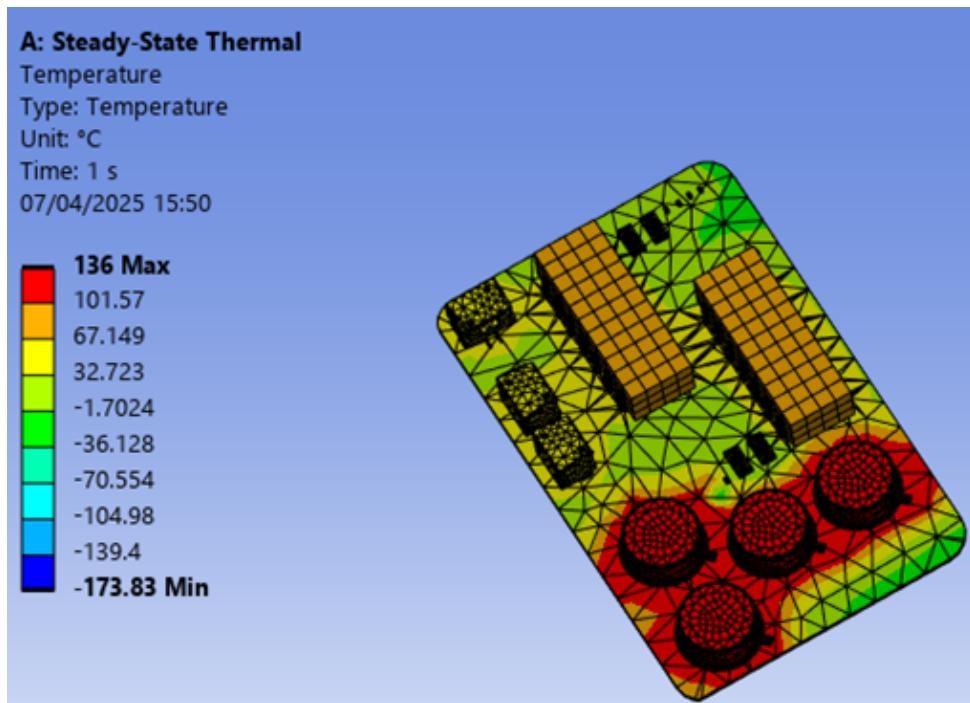


Figure 4.9.: Results under -200°C radiation

4.6.5. Results Evaluation

The results shown for both under 200°C and -200°C radiation shows that the PCB is operable under the harsh thermal conditions in space. That validates the design of the PCB and their component placements, and the material selection. The polyimide having about a clearance when facing the sun at 60°C and when in the shadows of a celestial object at -66°C shows that it would not be on the brink of melting or freezing during operation. The next step would be analysis the stresses and forces at work in space, unfortunately, a mechanical analysis of the stress cannot be conducted because it requires further work with the complete work of the entirety of the CubeSat chassis and all the power source such as the solar panels.

4.7. CubeSat Chassis Design

For the purposes of visualization, there were 2 potential designs for the CubeSat chassis. The CubeSat chassis were design dependant on where the PCB would be mounted. The first CubeSat chassis design was taken from GrabCAD.com and an aperture is mounted to this design to show where they would be mounted. The second CubeSat chassis was based on a design found online and recreated as much as possible, however this did not have any measurements given so dimensions were assumed.

4.7.1. CubeSat Chassis Design 1

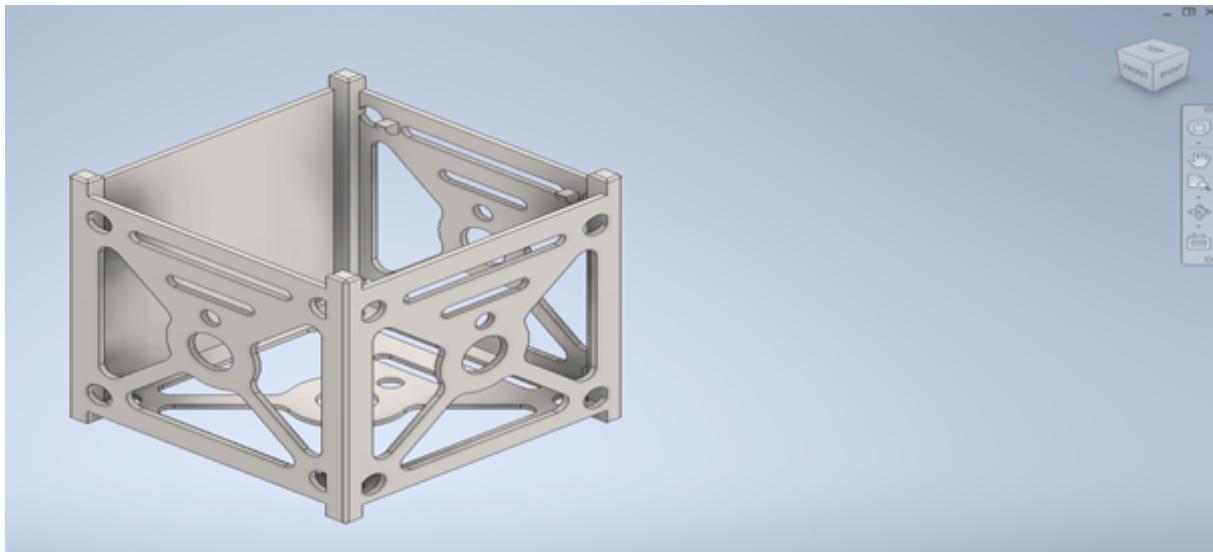


Figure 4.10.: Front view of the first CubeSat chassis design

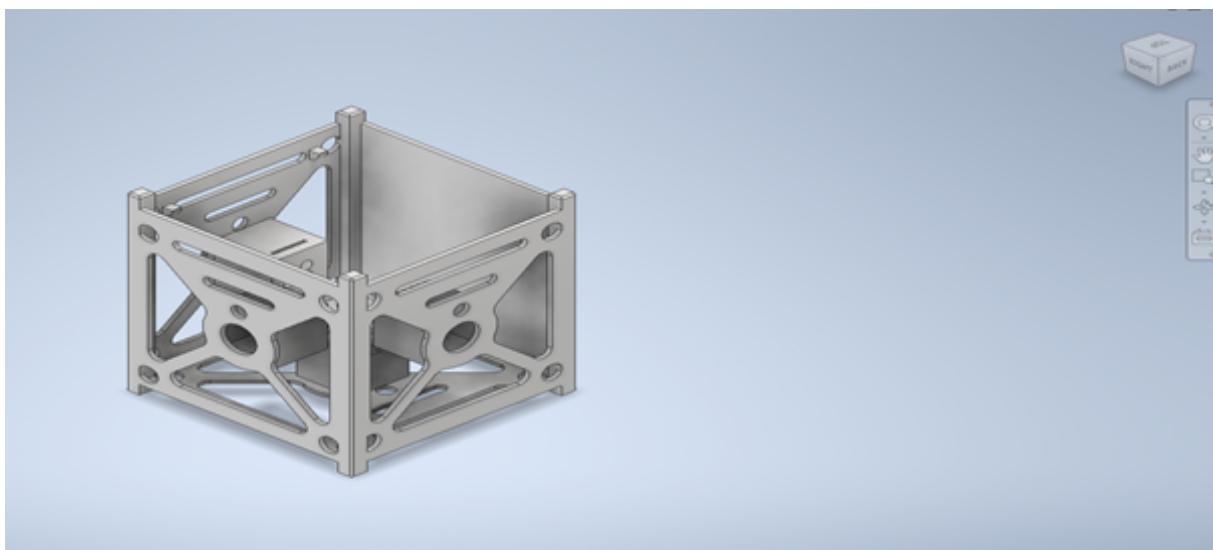


Figure 4.11.: Angular view of the first CubeSat chassis design

The first design taken from <https://grabcad.com/library/cubesat-1u-5> as seen in Figure 4.10 has exposed holes made to allow for easy removal, the circular holes at the centre are to let the light to expose to the aperture where the PCB photodiodes are located. The software used to show these are AutoCAD Inventor, with a different angle and the aperture shown in Figure 4.11.

4.7.2. CubeSat Chassis Design 2

The second hypothetical design is a much more basic skeleton frame made to house the aperture as seen below in Figure 4.12 and Figure 4.13.



Figure 4.12.: Front view of 1U Cubesat Skeleton Chassis



Figure 4.13.: Angular view of 1U Cubesat Skeleton Chassis

This was recreated in inventor with rough estimation on the thickness of the PCBs and skeletons itself and the apertures. The PCBs are mounted on top of each other compared to being the aperture housing the PCB mounted on each side of the CubeSat, the PCB cannot be more than 96×96 mm. As seen below in Figure 4.14 and Figure 4.15, are the CubeSat Chassis with and without the PCBs, additional angles and drawings are found in the appendix.

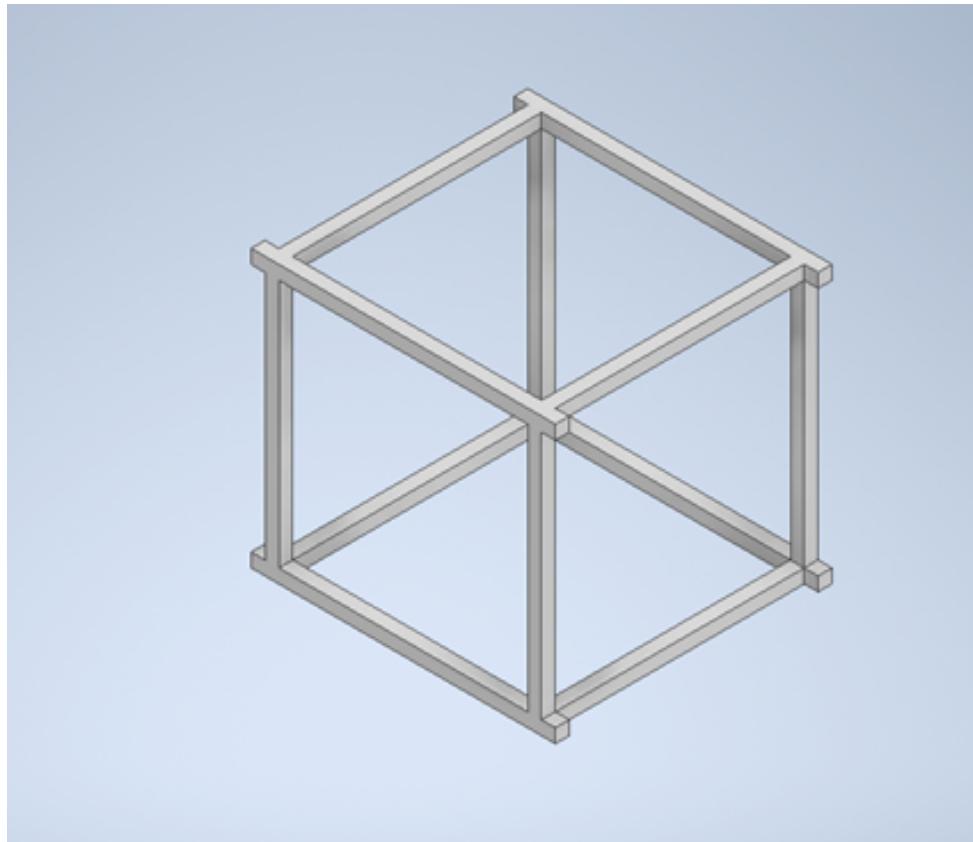


Figure 4.14.: Second chassis design without PCBs

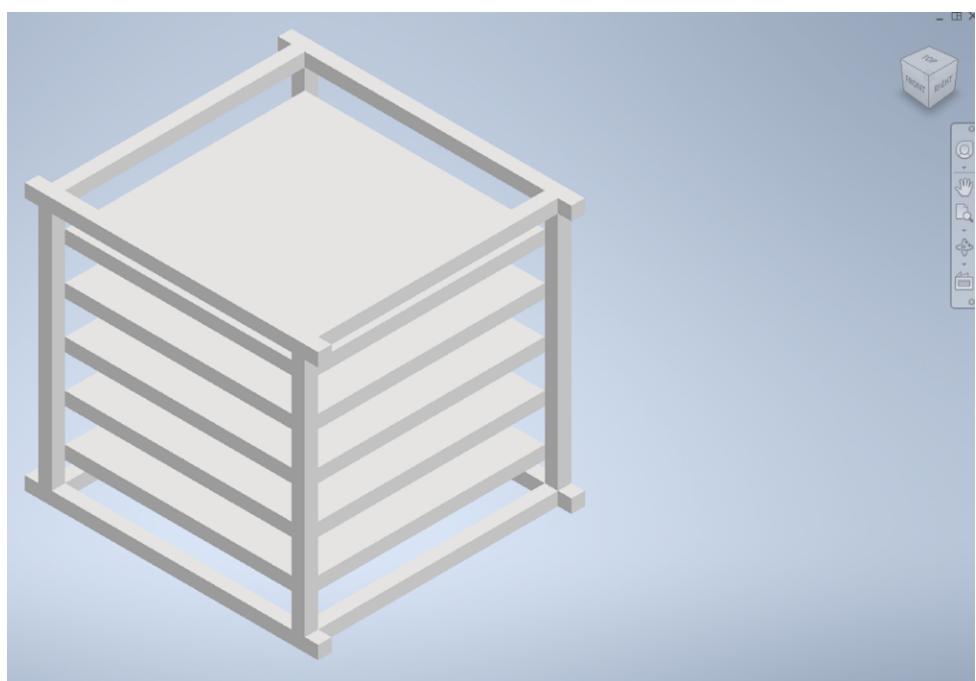


Figure 4.15.: Chassis with the aperture

5. Results

5.1. Sensor Characterization

TO FINISHTO FINISHTO FINISHTO FINISHTO FINISHTO FINISHTO FINISH focus on the fundamental properties and performance of your photodiodes themselves, distinct from the other subsections. Here are some key elements that would belong specifically under SensorCharacterization:

Basic Photodiode Electrical Characteristics:

Dark current measurements Junction capacitance I-V characteristics in different lighting conditions Spectral response profiles (sensitivity vs. wavelength)

Individual Sensor Benchmarking:

Performance comparison between the 4 photodiodes (matching/differences) Responsivity measurements (A/W) Quantum efficiency calculations Detection threshold levels

Response Linearity:

Measurements showing linear range of the photodiodes Saturation point characterization Recovery time from saturation

Temperature Dependency:

Performance drift with temperature Baseline shift measurements Temperature compensation data

Aging/Stability Tests:

Long-term drift measurements Repeatability of measurements over time

This section should focus on the inherent properties of the photodiodes themselves - essentially providing the baseline characterization data that underpins all the other analysis. The other sections then build on this foundation by examining how these sensors perform when integrated into the complete system with amplification, angular positioning, enclosure effects, etc.

5.1.1. Functional Requirements

5.1.2. Design Approach

5.1.3. System Architecture

As shown in Figure the system architecture consists of various components.

5.2. Amplification Performance

This section provides results of the amplifier performance.

5.3. Photodiode Angular Response

This section discusses the results of the response of the solar sensor to angular changes of the light source.

5.4. Enclosure Effectiveness

This section discusses the effectiveness of the Photodiode enclosure.

5.5. Data Acquisition System Evaluation

This section provides results related to the Arduino DAQ.

5.6. System Performance Analysis

5.6.1. Operational Constraints Identified

5.6.2. Environmental Factors Impact

5.6.3. System Stability and Repeatability

5.6.4. Recommendations for Improvement

5.7. Comparative Analysis

This section compares the simulation with the prototype results.

5.7.1. Breadboard vs. Stripboard Results

5.7.2. Iteration Improvements Analysis

5.7.3. Performance Against Design Requirements

The performance ...

5.7.4. Design Evolution Assessment

The what now?

5.8. System Limitations And Considerations

This section discusses the limitations and future work.

5.8.1. Angle accuracy

6. Conclusions

7. Future Work

Mention: methods to avoid detecting sun reflections off the moon and earth (such as light intensity or light source width if possible).

Bibliography

- [1] A. V. Oppenheim and R. W. Schafer, *Discrete-Time Signals and Systems*. India: Pearson, 2013.
- [2] J. Puig-Suari and C. Turner, “Development of the standard cubesat deployer and a cubesat class picosatellite,” 2001.
- [3] K. S. Balaji, B. S. Anand, P. M. Reddy, V. C. B, M. D. P. Lingam, and V. K, “Studies on attitude determination and control system for 1u nanosatellite,” *ICCPCT*, pp. 616–625, 2023.
- [4] I. Lopez-Calle and A. I. Franco, “Comparison of cubesat and microsat catastrophic failures in function of radiation and debris impact risk,” *Scientific Reports*, vol. 13, no. 1, -01-07 2023.
- [5] Atmel, “Atmega328p 8-bit avr microcontroller with 32k bytes in-system programmable flash datasheet,” 2015. [Online]. Available: https://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-7810-Automotive-Microcontrollers-ATmega328P_Datasheet.pdf
- [6] T. S. community, “butter scipy v1.15.2 manual.” [Online]. Available: <https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.butter.html#scipy.signal.butter>
- [7] ——, “filtfilt — scipy v1.15.2 manual,” 2025. [Online]. Available: <https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.filtfilt.html>
- [8] N. I. Shopov, S. Hannisse, and S. Gupta, “Renewable energy demonstrator (red),” Glasgow Caledonian University, Tech. Rep., 2022.
- [9] G. L. G. Burbui, U. Reggiani, and L. Sandrolini, “Prediction of low-frequency electromagnetic interferences from smps,” *IEMC*, vol. 2, pp. 472–477, 2006.

A. Appendix - DAQ Code

A.1. Arduino DAQ full code

A.1.1. Arduino C++ Code

```
1  /*
2   * Reads 4 analog inputs (0-5V) for recording_dur seconds
3   * Streams data to PC while recording
4   */
5   // change to true to print debug messages on Serial Monitor
6   // printing debug lines impacts transmission speed and messes csv
7   // do not leave on during measurements!
8   bool debug = false;
9
10  const int analogInputs[] = {A0, A1, A2, A3};
11
12
13  // set up the global variables
14  unsigned long start_time;
15  const unsigned long recording_dur = 5000; // 25 seconds in
milliseconds (ENSURE python code is greater than this)
16  unsigned long last_sample_time = 0;
17  const unsigned long min_samp_interval = 2; // Sample every 2ms (
adjust for stability)
18  bool recording = false;
19  int sample_count = 0;
20
21 void setup() {
22     // serial communication at 115200 bps
23     Serial.begin(115200);
24
25     // Set pins as input
26     for (int i = 0; i < 4; i++) {
27         pinMode(analogInputs[i], INPUT);
28     }
29
30     // Optimize ADC for faster sampling
31     // Set ADC prescaler to 16 (default is 128)
32     //
```

```

33     // Bit: 7:enable; 6: initiate a conversion 5:
34     //
35     ADCSRA = (ADCSRA & 0xF8) | 0x04;
36
37     // Wait for serial connection to establish
38     delay(1000);
39
40     // Send ready message
41     Serial.println("ARDUINO_DAQ_READY");
42 }
43
44 void loop() {
45     // Check if we received a command
46     if (Serial.available() > 0) {
47         String command = Serial.readStringUntil('\n');
48         command.trim();
49
50         if (command == "START") {
51             if(debug) Serial.println("received START command");
52
53             // Clear any remaining data in serial buffer
54             while (Serial.available()) {
55                 Serial.read();
56             }
57
58             // Reset sample counter
59             sample_count = 0;
60
61             // Send header once
62             Serial.println("Sample,Time(ms),A0(V),A1(V),A2(V),A3(V)");
63
64             // Start recording
65             recording = true;
66             start_time = millis();
67             last_sample_time = start_time;
68
69             // Send confirmation
70             Serial.println("RECORDING_STARTED");
71         }
72     }
73
74     // If we're recording, collect and send data immediately
75     if (recording) {
76         if(debug) Serial.println("Recording!");
77         unsigned long currentTime = millis();
78         unsigned long elapsed_time = currentTime - start_time;
79

```

```

80     // Check if we're still within the recording period
81     if (elapsed_time <= recording_dur) {
82         if(debug) Serial.println("elapsed time << duration");
83         // Only sample at the specified interval
84         if (currentTime - last_sample_time >= min_samp_interval) {
85             last_sample_time = currentTime;
86
87             // Increment sample counter
88             sample_count++;
89
90             // Start building the output string
91             String data_string = String(sample_count) + "," + String(
92             elapsed_time);
93
94             // Multiplex through the four inputs sequentially
95             for (int i = 0; i < 4; i++) {
96                 if(debug) Serial.println("reading input: " + String(i));
97                 int raw_value = analogRead(analogInputs[i]);
98                 float voltage = raw_value * (5.0 / 1023.0);
99                 data_string += "," + String(voltage, 3);
100            }
101
102            // Send the complete data string at once
103            Serial.println(data_string);
104        }
105    } else {
106        // End of recording
107        recording = false;
108
109        // Send notification that recording is complete
110        Serial.println("RECORDING_COMPLETE");
111        Serial.print("SAMPLES_COLLECTED:");
112        Serial.println(sample_count);
113        Serial.println("END_OF_DATA");
114    }
115}
116

```

Listing A.1: C++ Code on Arduino

A.1.2. PC-side Python Serial Receive Script

```

1 import serial
2 import time
3 import matplotlib.pyplot as plt
4 import pandas as pd

```

```

5      import os
6      import numpy as np
7      from scipy import signal
8
9      def apply_lowpass_filter(data, fs):
10         """Apply a 4-pole low-pass Butterworth filter with 5Hz cutoff"""
11         cutoff_freq = 2.0
12         filter_order = 4
13
14         nyquist = 0.5 * fs
15         normal_cutoff = cutoff_freq / nyquist
16         # analog=False implies bilinear Transformation
17         b, a = signal.butter(filter_order, normal_cutoff, btype='low',
18         analog=False)
19         filtered_data = signal.filtfilt(b, a, data)
20
21     return filtered_data
22
23     # Load data from CSV, apply a 4-pole low-pass filter, and save the
24     # filtered data
25     def filter_and_save_data(filename):
26
27         # Read the CSV data to pandas DataFrame
28         # It knows what are the column names
29         df = pd.read_csv(filename)
30
31         # Clean the dataframe - convert all columns to numeric
32         for col in df.columns:                      # v - write NaN where it
33             can't convert to number (in teh data, not column names)
34             df[col] = pd.to_numeric(df[col], errors='coerce')
35
36         # remove rows with NaN (not a number)
37         df = df.dropna()
38
39         # Samples not at exact distance from each other
40         # Calculate the sampling frequency (median of differences)
41         # numpy.diff to get the difference between samples
42         time_diffs = np.diff(df['Time(ms)'])
43         # numpy.median to get the median
44         median_time_diff = np.median(time_diffs) # in milliseconds
45         fs = 1000.0 / median_time_diff # Convert to Hz
46
47         # Filter each analog channel:
48         # ID column head for each channel
49         analog_channels = ['A0(V)', 'A1(V)', 'A2(V)', 'A3(V)']
50         # take each channel one at a time
51         for channel in analog_channels:

```

```

49         # if name matches a column name
50         if channel in df.columns:
51             # add a new column _filtered , and send the array
52             # containing all the raw values to
53             # have them filtered , and save them in the new _filtered
54             # column
55             df[f"{channel}_filtered"] = apply_lowpass_filter(df[
56             channel].values , fs)
57
58             # Save the pandas Dataframe with filtered columns to a new CSV
59             file
60             filtered_filename = f"{os.path.splitext(filename)[0]}_filtered.
61             csv"
62             df.to_csv(filtered_filename , index=False)
63
64             return filtered_filename
65
66             #
67             # Plot the DAQ data with original and filtered signals overlapped
68             #
69             def plot_data(filename):
70
71                 # Read the CSV data with pandas
72                 df = pd.read_csv(filename)
73
74                 # Initialize an empty list to store our analog channel names
75                 analog_channels = []
76
77                 # Look through all column names in the DataFrame
78                 for col in df.columns:
79                     # the column name starts with 'A'
80                     if col.startswith('A'):
81                         # the column name ends with '(V)'
82                         if col.endswith('(V)'):
83                             # the column name does NOT contain '_filtered'
84                             if '_filtered' not in col:
85                                 # add this column name to our list
86                                 analog_channels.append(col)
87
88                 # Create color cycle for different channels
89                 colors = ['blue' , 'green' , 'red' , 'purple']
90
91                 # Create a single plot with all channels overlapping
92                 plt.figure(figsize=(14, 8))
93
94                 # Plot original data (semi-transparent)
95                 for i, channel in enumerate(analog_channels):

```

```

91         color = colors[i % len(colors)]
92         plt.plot(df['Time(ms)'], df[channel], label=f'{channel}
93 Original',
94             linewidth=1.5, alpha=0.4, color=color, linestyle='--'
95 )
96
97     # Plot filtered data (solid lines)
98     for i, channel in enumerate(analog_channels):
99         filtered_channel = f'{channel}_filtered'
100        if filtered_channel in df.columns:
101            color = colors[i % len(colors)]
102            plt.plot(df['Time(ms)'], df[filtered_channel], label=f'{channel} Filtered',
103                 linewidth=2.5, color=color, linestyle='--')
104
105    # Set the y-axis range from 0 to 5V
106    plt.ylim(0, 5)
107
108    # Add labels and title
109    plt.xlabel('Time (ms)')
110    plt.ylabel('Voltage (V)')
111    plt.title('Arduino DAQ - 4-Channel Readings with 4-Pole 5Hz Low-
112 Pass Filter')
113    plt.legend()
114    plt.grid(True)
115
116    # Add data summary
117    duration = df['Time(ms)'].max() - df['Time(ms)'].min()
118    sample_count = len(df)
119    sample_rate = sample_count/(duration/1000) if duration > 0 else
120    0
121
122    info_text = f'Data summary:\n' \
123                f'Duration: {duration:.1f} ms\n' \
124                f'Samples: {sample_count}\n' \
125                f'Sample rate: {sample_rate:.1f} Hz\n' \
126                f'Filter: 4-pole Butterworth, 5Hz cutoff'
127
128    plt.figtext(0.02, 0.02, info_text, fontsize=10,
129                bbox=dict(facecolor='white', alpha=0.8))
130
131    # Save the plot
132    plot_filename = f'{os.path.splitext(filename)[0]}_plot.png'
133    plt.savefig(plot_filename, dpi=300, bbox_inches='tight')
134
135    # Show the plot
136    plt.tight_layout()

```

```

133     plt.show()
134
135     def main():
136
137         # ASk if to plot or measure
138         what_to_do = int(input("Record new measurement (1) or plot
existing (2): "))
139
140         # User selected to plot old csv
141         if(what_to_do == 2):
142             plot_data(input("Insert the name of the csv: "))
143
144
145         # User selected to record new measurement
146         elif(what_to_do == 1):
147             # Use a default port (COM3 for Windows, modify as needed)
148             default_port = "COM3" # Change to match your system
149
150             print(f"Using port: {default_port}")
151
152             # Configure serial port
153             try:
154                 ser = serial.Serial(default_port, 115200, timeout=2)
155                 print("Connected to Arduino!")
156             except serial.SerialException:
157                 print(f"Error: Could not open port {default_port}")
158                 print("Please modify the default_port variable in the
script.")
159             return
160
161             time.sleep(2) # Wait for Arduino to reset
162
163             # Flush buffers
164             ser.reset_input_buffer()
165             ser.reset_output_buffer()
166
167             # Wait for Arduino ready
168             print("Waiting for Arduino to be ready...")
169             ready = False
170             timeout = time.time() + 10 # don't wait too long
171
172             while not ready and time.time() < timeout:
173                 line = ser.readline().decode('utf-8', errors='ignore').
strip()
174                 if line == "ARDUINO_DAQ_READY":
175                     ready = True
176                     print("Arduino is ready!")

```

```

177
178     if not ready:
179         print("Timed out waiting for Arduino. Make sure it's
properly connected.")
180         ser.close()
181         return
182
183     # Create a filename for this recording session
184     filename = f"arduino_daq_data_{time.strftime('%Y%m%d_%H%M%S
')}.csv"
185
186     print(f"Starting data recording to {filename}...")
187     print("Press Ctrl+C to stop if needed.")
188
189     with open(filename, 'w', newline='') as file:
190         # Send start command
191         ser.write(b"START\n")
192
193     recording = True
194     data_lines = 0
195
196     # Start time for timeout
197     start_time = time.time()
198     timeout_duration = 15 # seconds
199
200     while recording and (time.time() - start_time) <
timeout_duration:
201         if ser.in_waiting:
202             line = ser.readline().decode('utf-8', errors='
ignore').strip()
203
204             if "RECORDING_COMPLETE" in line:
205                 recording = False
206                 print("Recording complete!")
207             elif "END_OF_DATA" in line:
208                 pass
209             elif line:
210                 # Write the line to the file
211                 file.write(line + '\n')
212                 data_lines += 1
213
214             # Show progress occasionally
215             if data_lines % 100 == 0:
216                 print(f"Recorded {data_lines} data
points...")
217
218         # Close the serial port

```

```

219         if ser.is_open:
220             ser.close()
221             print("Serial port closed.")
222
223             print(f"Recorded {data_lines} lines of data.")
224
225             # Process the data
226             print("Applying filters to data...")
227             filtered_filename = filter_and_save_data(filename)
228             print(f"Filtered data saved to {filtered_filename}")
229
230             print("Generating plot...")
231             plot_data(filtered_filename)
232             print("Done!")
233
234         else:
235             print("Wrong Choice. Goodbye!")
236             exit()
237     if __name__ == "__main__":
238         try:
239             main()
240         except KeyboardInterrupt:
241             print("\nProgram terminated by user.")

```

Listing A.2: Python Serial Receive Script

B. Appendix - Software Model Code

B.1. Section 1 Title

B.1.1. subsectiontitle

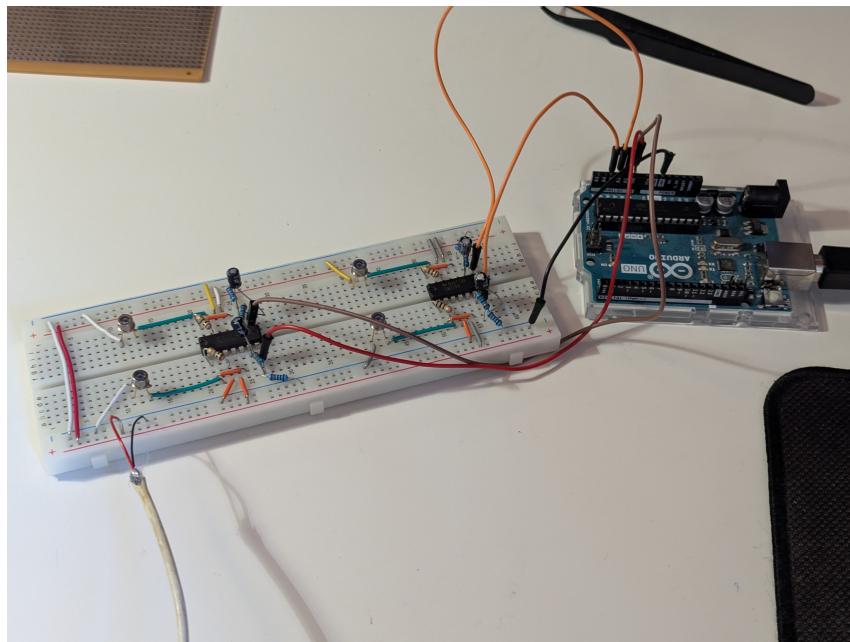
B.2. Section 2 Title

B.2.1. subsectiontitle

C. Appendix - Photos of Lab Work

C.1. Prototype Images

C.1.1. BreadBoard Prototype



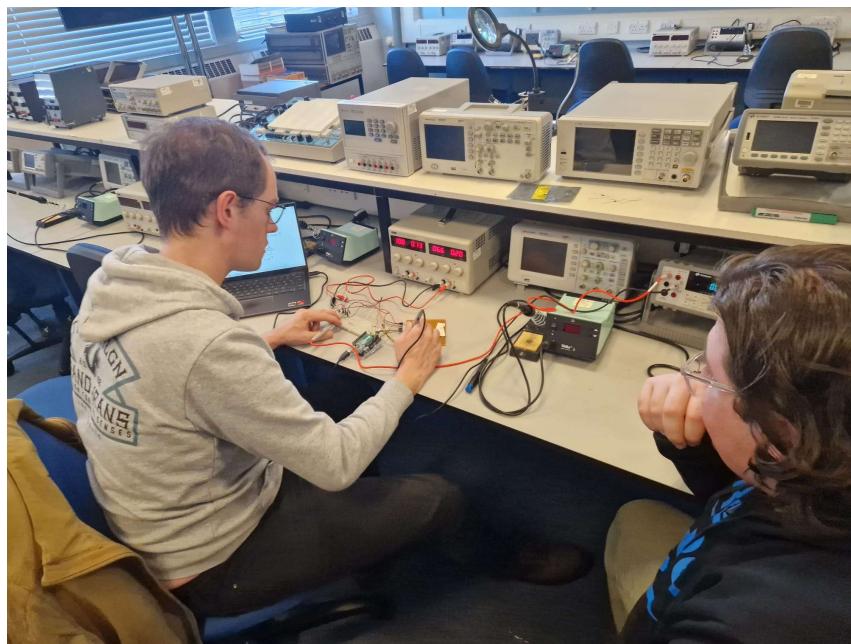
Initial BreadBoard Prototype of the Photodiode Circuit

C.1.2. Building the Prototype

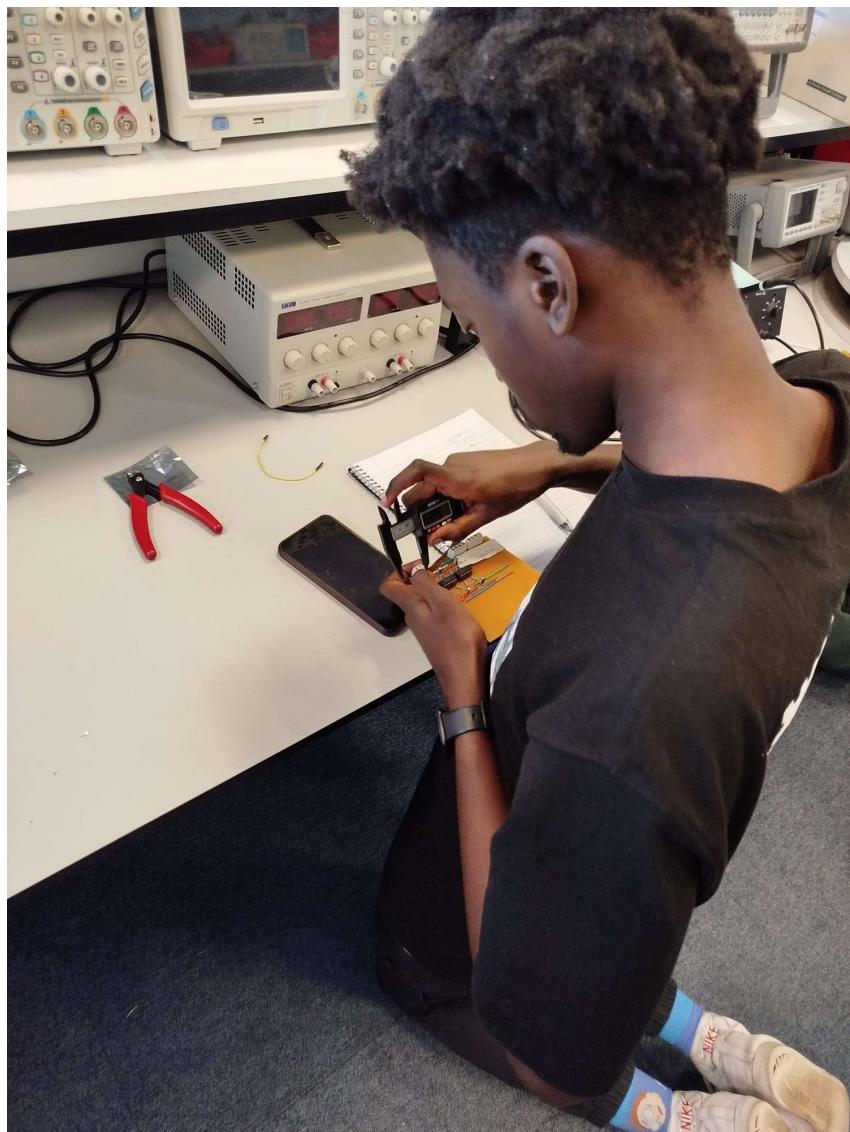
C.1.3. Prototype Testing

C.1.4. RED testbench

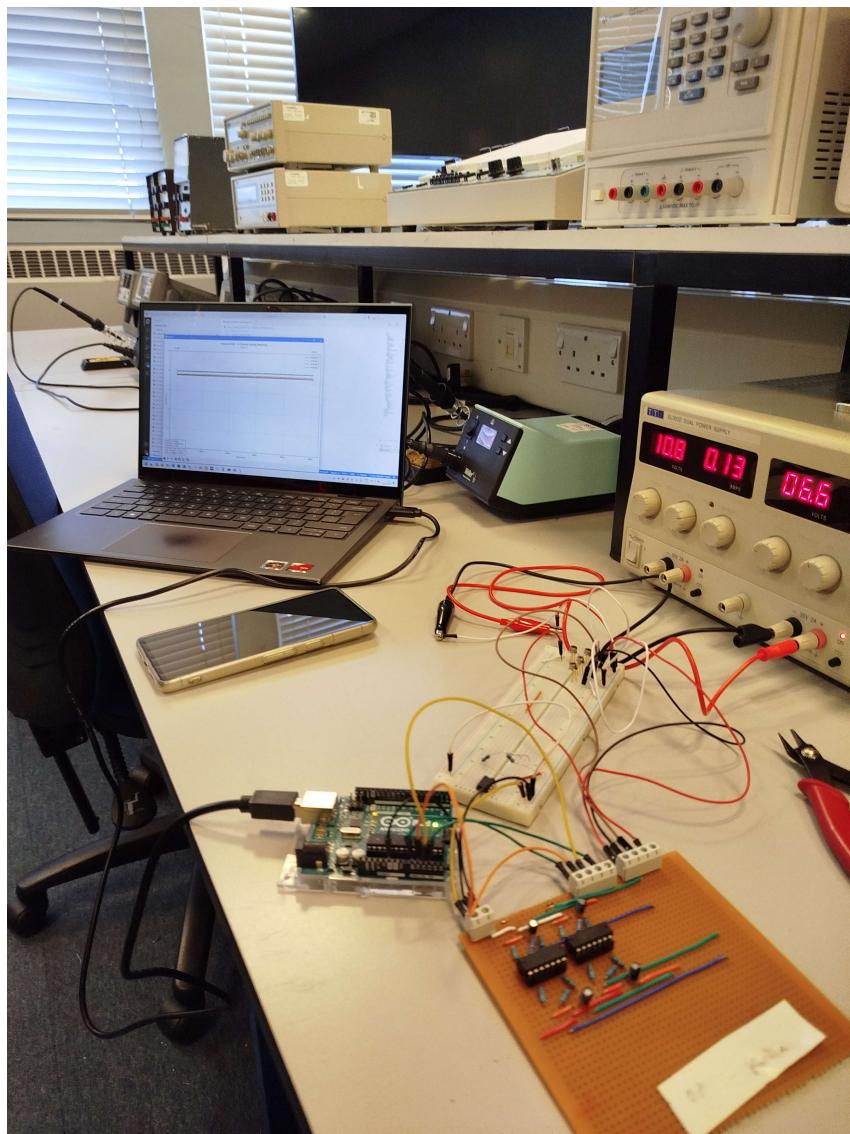
C.1.5. Solar Lab Prototype Testing



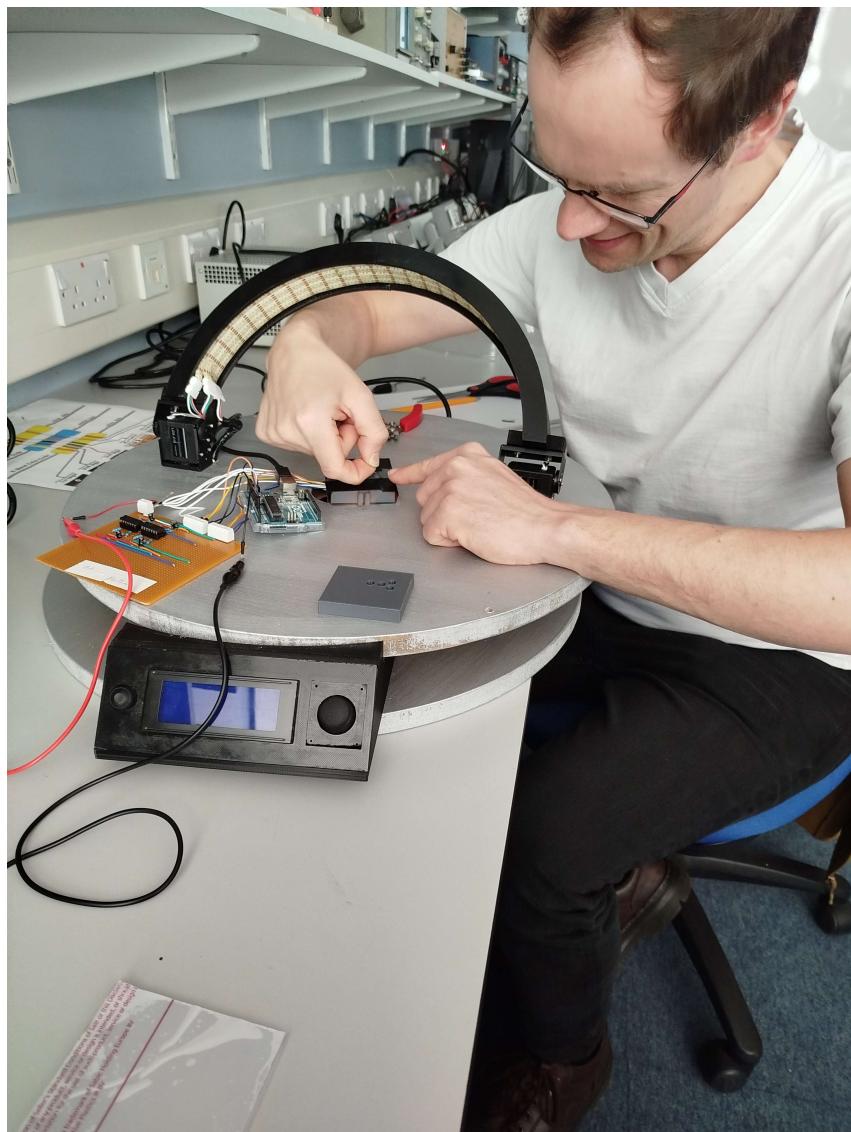
Lab Work for the Prototype (session 1)



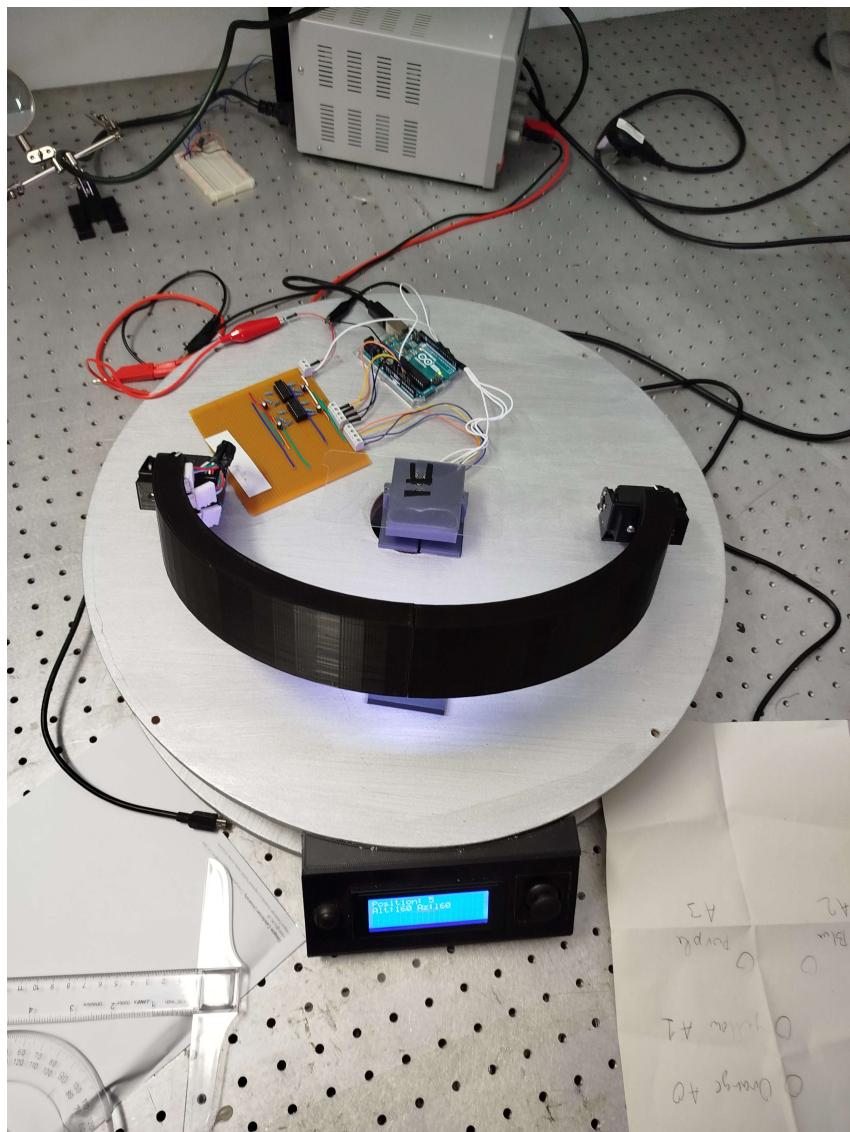
lab Work for the Prototype (session 2)



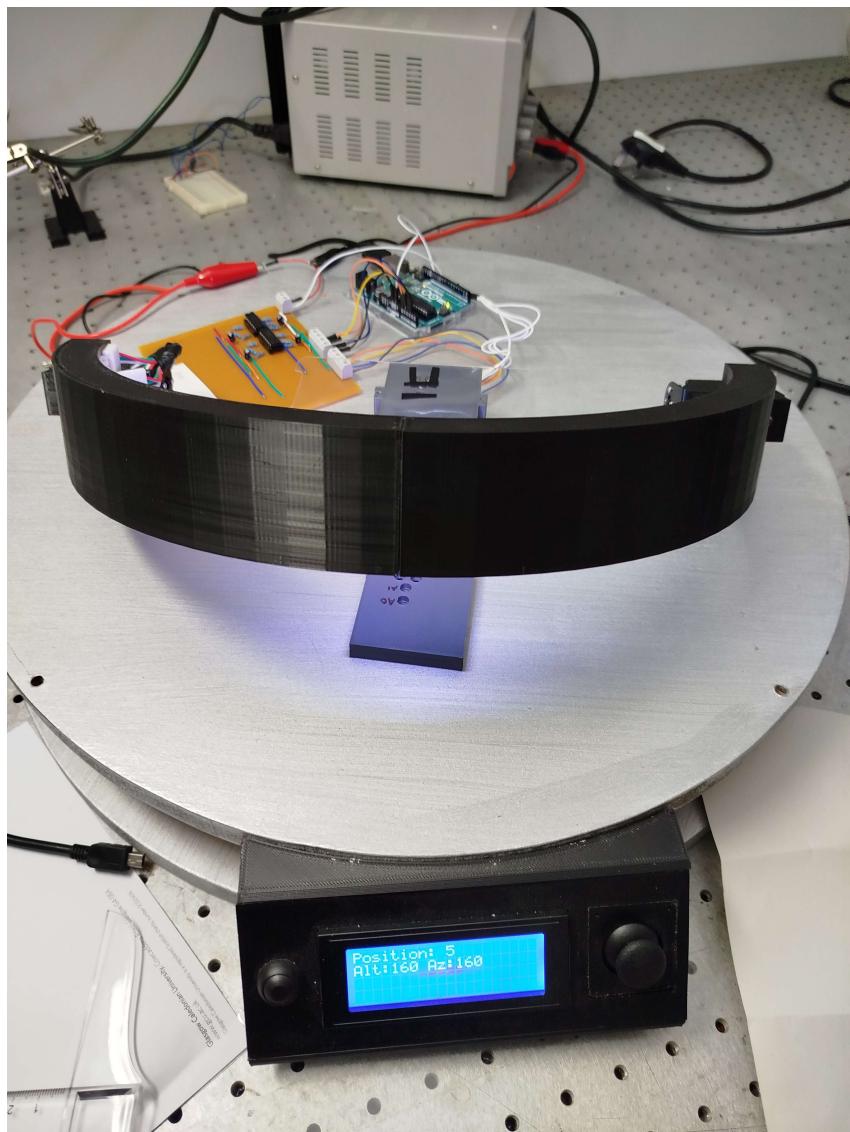
First Lab Test of the Prototype



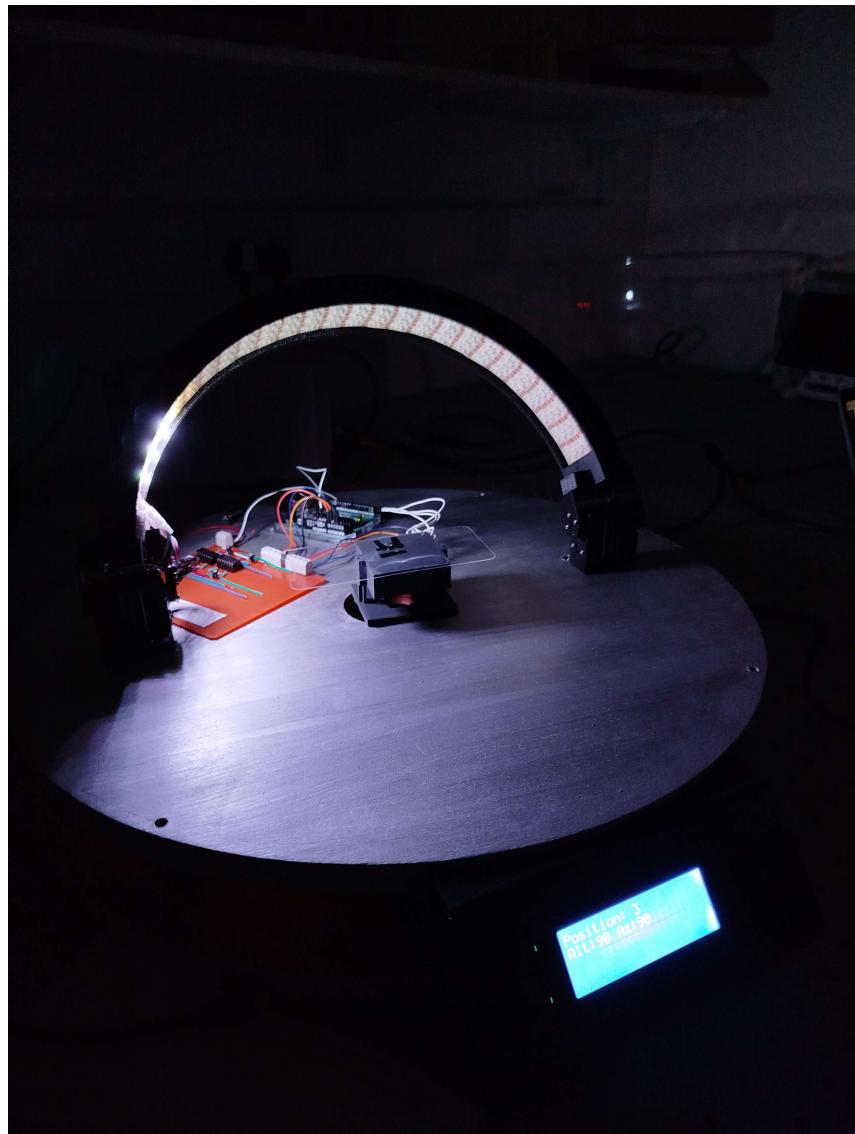
RED Testbench 1



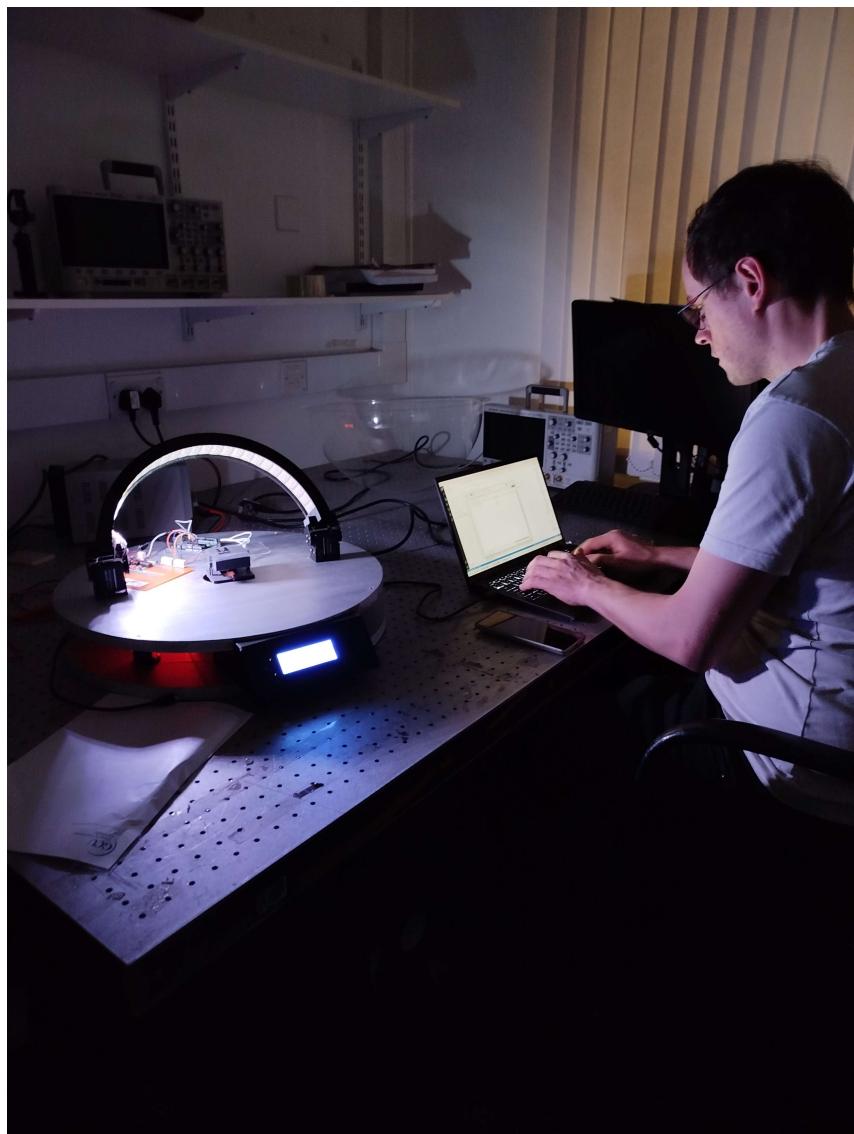
Solar Lab Test of the Prototype 1



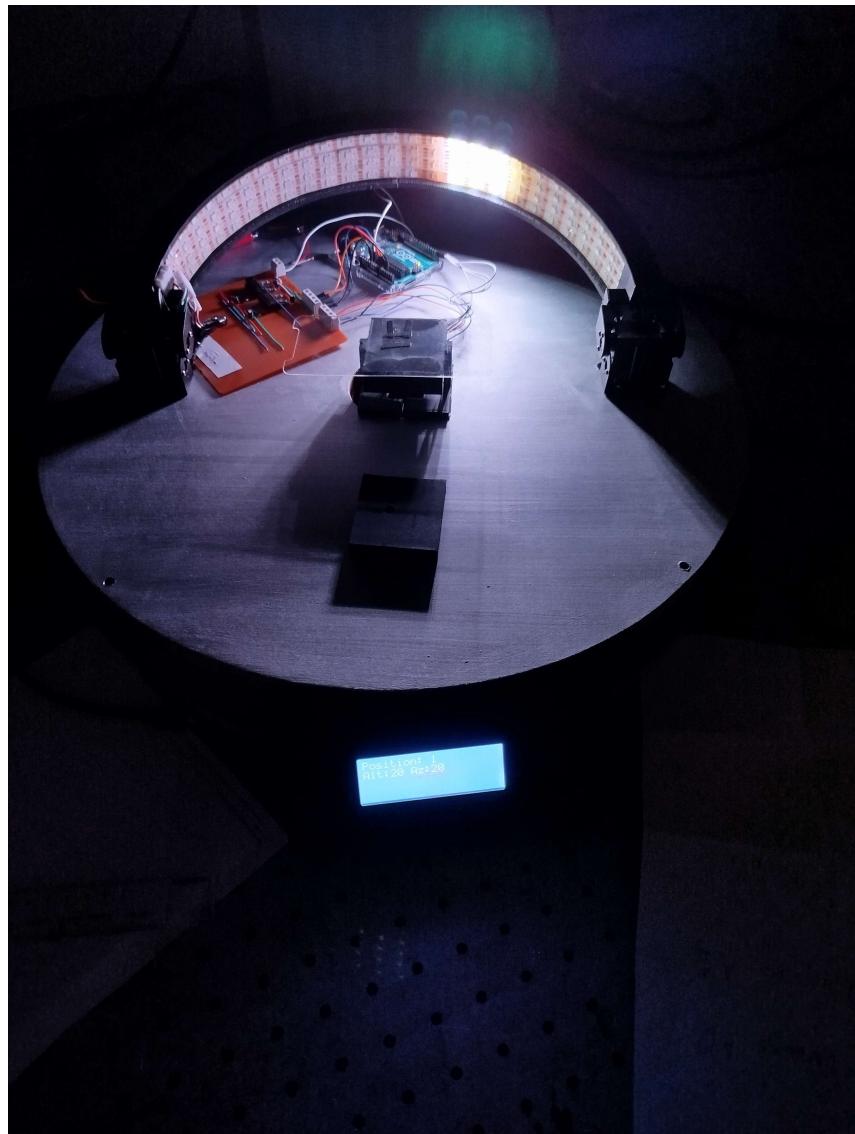
Solar Lab Test of the Prototype 2



Solar Lab Test of the Prototype 3



Solar Lab Test of the Prototype 4



Solar Lab Test of the Prototype 5