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

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ADC Analog to Digital Converter

ADCS Attitude determination and control system

ATP Acquisiton, Tracking and Pointing

CCD Charge-Coupled Device

CSV Comma Separated Values

CTE Coefficient of thermal expansion

DAQ Data Acquisition System

FOV Filed of View

GSFC Goddard Space Flight Centre

LEO Low Earth Orbit

OPS Optical Position Sensor

PSD Position Sensitive Detector

PV Photovoltaic

RED Renewable Energy Demonstrator

SGP4 Simplified General Perturbations 4

SMPS Switch-Mode Power Supply

TIA Transimpedance Amplifier

TLE Two-line element set

VLC Visible Light Communication

WSN Wireless Sensor Networks

SMD Surface Mount Device

OpAmp Operational Amplifier

PCB Printed Circuit Board

PLA Polyactic Acid

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 exeed 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

The prototype will be composed of three parts: a stripboard containing the components for the amplification circuit, a 3D printed Photodiode enclosure which will allow placing

the photodiodes in the correct positions, as the photodiodes have the legs at a smaller distance than the stripboard, and need to be placed quite close to eachother, with the third part being the Arduino based DAQ. The third part to the

Sun Sensor Geometry and Aperture Design was decided to be in a T shape, providing an x-y layout with two photodiodes in the x direction and two photodiodes in the y direction. Combined with an aperture design that covers one half of each diode, as represented in Figure 4.1.

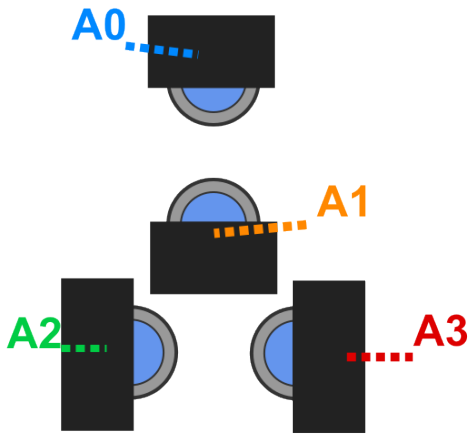

Figure 4.1.: Rough Diagram of Photodiode Array with Apertures

Component Selection

The components chosen for the design of the prototype are detailed below. They were first placed on a BreadBoard and tests were performed to ensure the functionality of the circuit before moving them to a stripboard which would ensure the components are phisically more stable and reduce the chance of faulty connectoins. Therefore, the same components were used for both BreadBoard and StripBoard prototyping. The circuit design and testing is gone into more detail in Section 4.1.2.

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 prohibitivly expensive and Surface Mount Device style (SMD), which would have been harder to prototype but would allow for much higher resolutions, while also complicating the

Table 4.1.: Components Used in Amplification Design

Component Type	**Comp. Part Name**	**Component Value**	**Amount**
Op-Amp	TI LM324-N	–	2
Photodiode	Hamamatsu S5971	–	4
Resistor	–	1 MΩ	4
Resistor	–	150 kΩ	4
Resistor	–	10 kΩ	4
Capacitor	–	1 μF	4
Stripboard	Veroboard	–	1
Screw terminal block	–	2-input	3

Table 4.2.: Components Used for DAQ System

Component Type	**Component Part Name**	**Component Value**	**Amount**
Microcontroller	Arduino Uno	–	1
Cable	USB cable	–	1
Computer	Laptop/Python	–	1

project due to the more complex nature of PSDs. 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 4.3.: 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 Isc	1.0 μA
Dark current Id (Typical)	0.07 nA[*3]
Dark current Id (Maximum)	1 nA[*3]
Cutoff frequency fc	0.1 GHz[*3]
Terminal capacitance Ct (f=1 MHz)	3 pF[*3]
Noise equivalent power NEP (V_R=10 V, λ=λ_p)	7.4×10^{-15} W/Hz$^{1/2}$

V_R = 10 V

Although the higher versions such as S5972-3 have better specifications, such as frequency cutoff of 1GHz and lower Dark current, these were not needed for our project, higher frequency cut off not needed due the static nature of the light source and dark current, while it could affect a case where one of the diodes is fully in the dark, a voltage offeset would be noticeable, but with a voltage resolution restricted by the Arduino DAQ

to 4.88mV/step, it was deemed acceptable:

$$\begin{aligned} V_{\text{offset-TIA}} &= I_d \times R_f \\ &= 0.07 \text{ nA} \times 1 \text{ M}\Omega \\ &= 70 \ \mu\text{V} \end{aligned} \tag{1}$$

$$\begin{aligned} V_{\text{offset-total}} &= V_{\text{offset-TIA}} \times \text{Gain}_{\text{post-amp}} \\ &= 70 \ \mu\text{V} \times 16 \\ &= 1.12 \text{ mV} \end{aligned} \tag{2}$$

Equation 2 above shows the final dark current would be a maximum of 1.12mV which is below what the ADC can detect.

The Operational Amplifier (OpAmp) choice was once again not a complicated choice due to the same arguments mentioned above re. photodiode selection: low frequency signal and reduced DAQ resolution. The LM324-N is a low-cost OpAmp which provides acceptable performance. The advantages in choosing this OpAmp is its ability to function

Table 4.4.: Operational Amplifier Specifications

Parameter	**Value**
DC Voltage Gain	100 dB
Unity Gain Bandwidth	1 MHz
Supply Voltage Range (Single)	3 V to 32 V
Supply Voltage Range (Dual)	±1.5 V to ±16 V
Supply Current	700 μA
Input Bias Current	45 nA
Input Offset Voltage	2 mV
Input Offset Current	5 nA
Input Common-Mode Voltage Range	Includes Ground
Differential Input Voltage Range	Equal to Supply Voltage
Output Voltage Swing	0 V to V^+ - 1.5 V

Internally frequency compensated for unity gain
Temperature compensated

on a Power Supply, it is rather cheap while still offering 1MHz Unity Gain Bandwidth and is recommended for DC Gain which the type of signal our project aims to amplify.

BreadBoard Testing

Once the circuit design was completed as seen in Figure 4.4, the components were placed on a BreadBoard to test the real circuit, as seen in Figure 4.2. There were several iterations, at first with only the Transimpedance Amplifier (TIA)- a design that when tested, resulted in a low Voltage output when testing with only the LED light from the

Renewable Energy Demonstrator (RED) testbench. This is due to the low light of LEDs. A decision was made to add a secondary amplification circuit which raised the Voltage to a maximum 5V as designed. Further details on design in Section 4.1.2. The final BreadBoard design can be found in Figure 4.2.

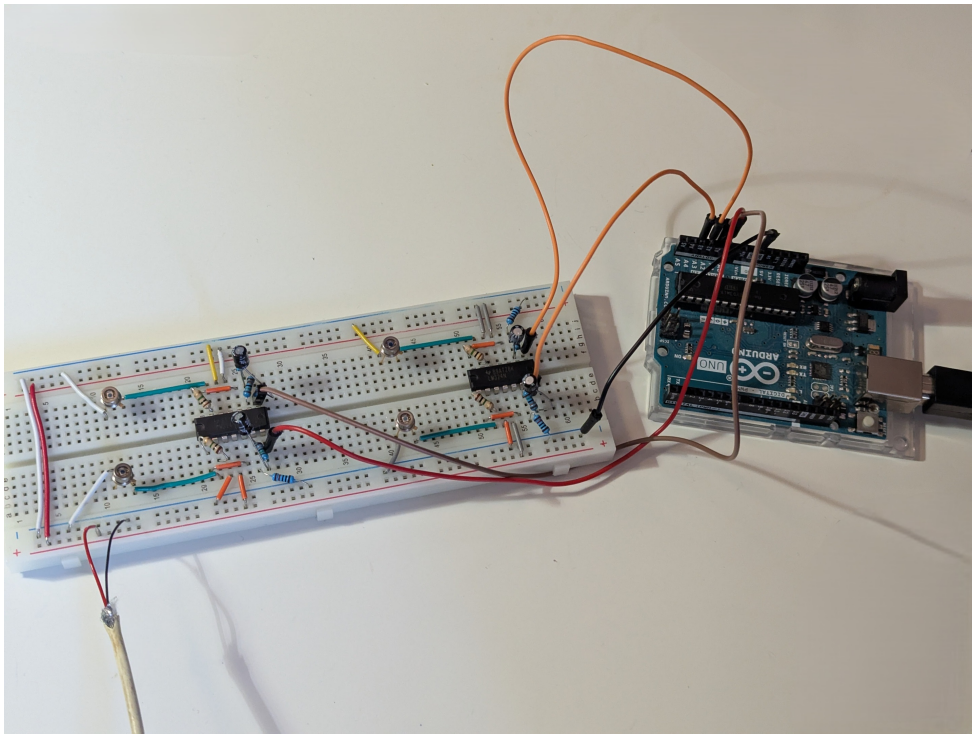

Figure 4.2.: Photo Of BreadBoard Prototype

Design Refinement

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

Stripboard Prototype Development

- Implementing design improvements was easy on a BreadBoard
- Fabricate improved aperture
- Enhance housing design

BreadBoard Testing

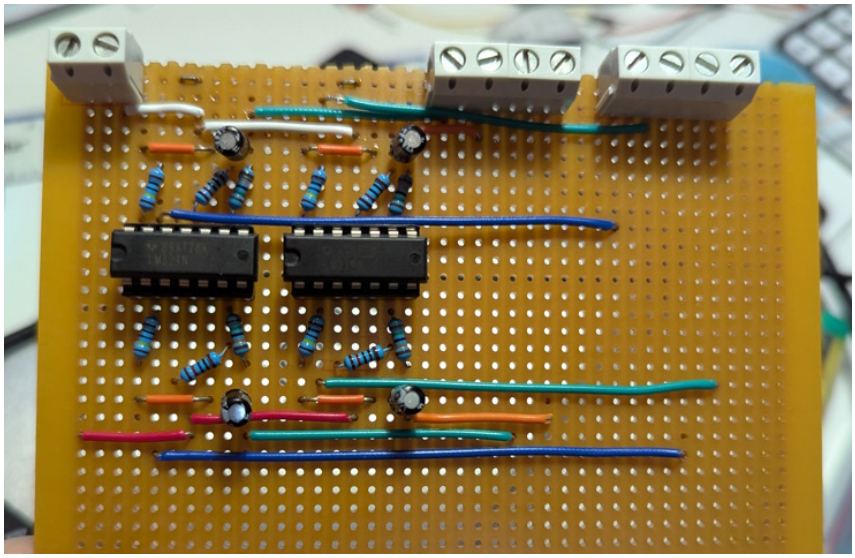

Figure 4.3.: Photo Of Stripboard Prototype

Comprehensive Testing

- Laboratory performance testing (angular accuracy, resolution)
- Improve Aperture
- Interface compatibility testing

Validation and Calibration

- Calibration procedure: match readings to simulation
- Create calibration fixtures
- Validate sensor performance against requirements

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. [2021KeiserFibreOptics]

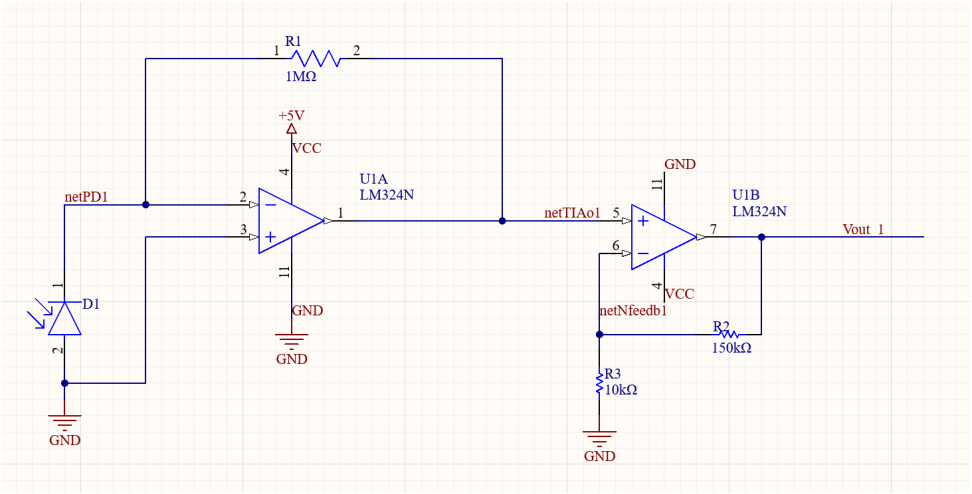

Figure 4.4.: TIA and Post Amplification Circuit in Altium Designer

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 Enclousure 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 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 4.5.

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.

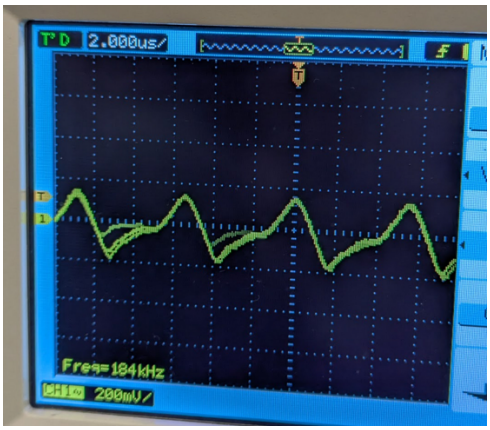

Figure 4.5.: Signal Noise Analysis, oscilloscope AC coupled

4.2.2. Design Approach

The characteristics of the signal being low frequency, combined with the requirement to read all four signals simultanously 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 immediatly 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 contnuous loop triggered after setup comletes. Inside the loop, two if statements check for instructions from the PC script. The

recording time limit is hardcoded as a global function. Figure 4.6 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 recoring, sends the last values to the Python script on the PC and a "recording_stopped" command. A FSM diagram is also available in Figure 4.7. 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):

$$f_{\text{ADC-default}} = \frac{f_{\text{CPU}}}{Prescaler_{\text{default}}} = \frac{16 \text{ MHz}}{128} = 125 \text{ kHz} \tag{3}$$

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

$$f_{\text{ADC-optimized}} = \frac{f_{\text{CPU}}}{Prescaler_{\text{optimized}}} = \frac{16 \text{ MHz}}{16} = 1 \text{ MHz} \tag{4}$$

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

$$T_{\text{conversion-default}} = 13 \times \frac{1}{f_{\text{ADC-default}}} = 13 \times \frac{1}{125 \text{ kHz}} \approx 104 \ \mu\text{s} \tag{5}$$

$$T_{\text{conversion-optimized}} = 13 \times \frac{1}{f_{\text{ADC-optimized}}} = 13 \times \frac{1}{1 \text{ MHz}} \approx 13 \ \mu\text{s} \tag{6}$$

Time required to sample all 4 analog inputs:

$$T_{\text{4channels-default}} = 4 \times T_{\text{conversion-default}} = 4 \times 104 \ \mu\text{s} \approx 416 \ \mu\text{s} \tag{7}$$

$$T_{\text{4channels-optimized}} = 4 \times T_{\text{conversion-optimized}} = 4 \times 13\ \mu\text{s} \approx 52\ \mu\text{s} \tag{8}$$

Maximum theoretical sampling frequency for all 4 channels:

$$f_{\text{sampling-max-default}} = \frac{1}{T_{\text{4channels-default}}} = \frac{1}{416\ \mu\text{s}} \approx 2.4\ \text{kHz} \tag{9}$$

$$f_{\text{sampling-max-optimized}} = \frac{1}{T_{\text{4channels-optimized}}} = \frac{1}{52\ \mu\text{s}} \approx 19.2\ \text{kHz} \tag{10}$$

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

$$f_{\text{sampling-actual}} = \frac{1}{2\ \text{ms}} = 500\ \text{Hz per channel} \tag{11}$$

Effective data rate across all channels:

$$\text{Data Rate} = 4\ \text{channels} \times 500\ \text{Hz} = 2000\ \text{samples/second} \tag{12}$$

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.

```
recordingDuration = 5000 // for how long to record in milliseconds

minSampleInterval = 2    // control how fast to sample to avoid
                         // relying on Arduino performance
// Initialize serial communication
```

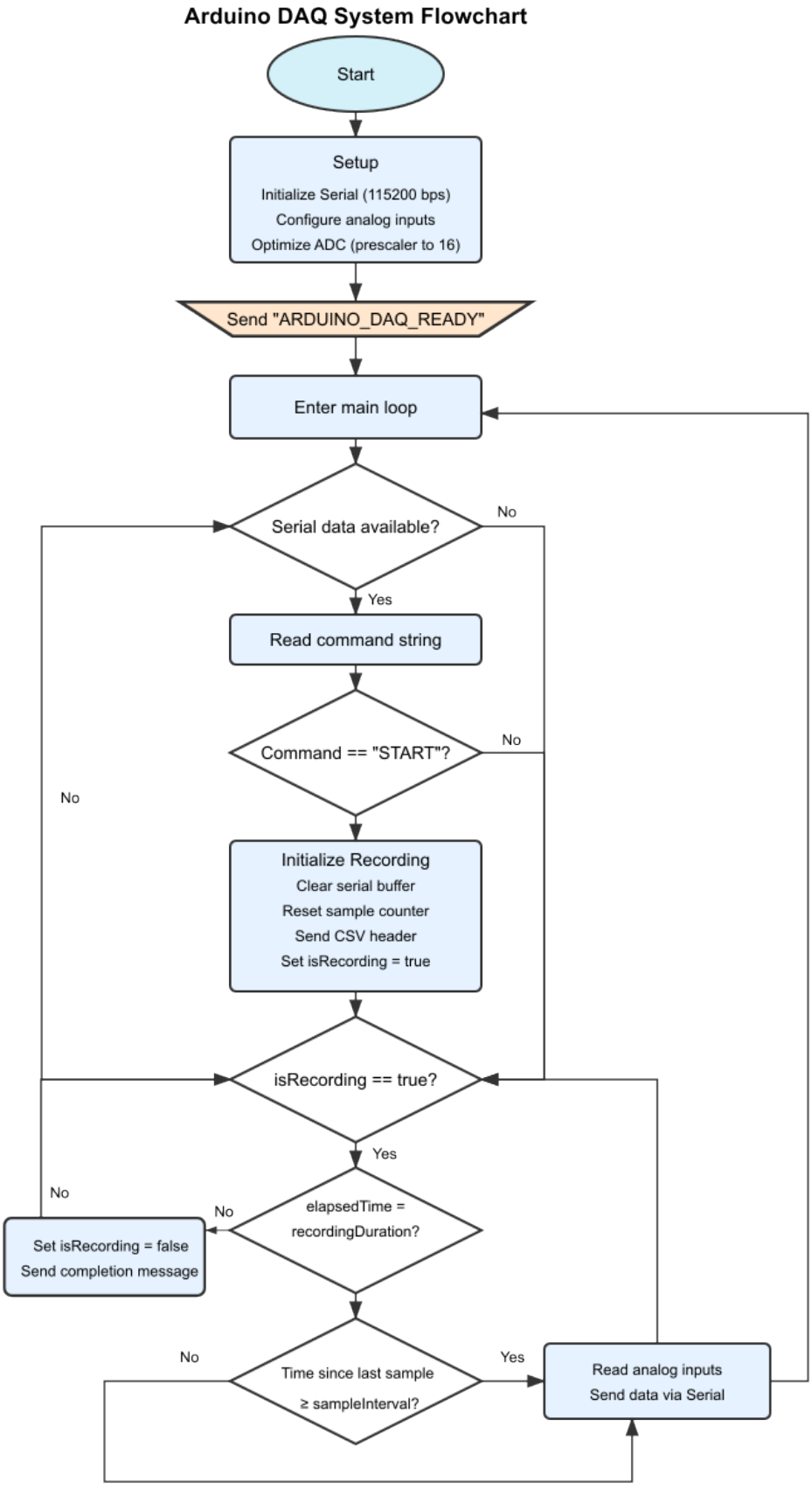

Figure 4.6.: Flowchart Arduino DAQ C++ program

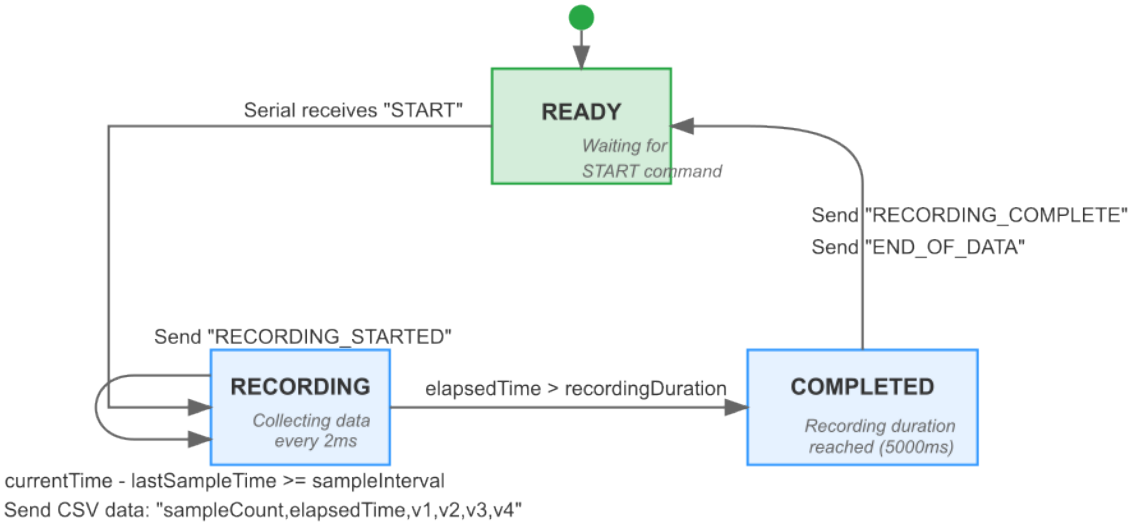

Figure 4.7.: FSM Arduino C++ LOOP

```
6  // Initialize analog inputs
7  // Setup ADC
8
9  // Infrom PC listening on Serial Connection: Arduino is ready to
    record
10 Serial.print("Arduino_DAQ_Ready")
11 // enter the loop
12 void loop(){
13   //listen for command from PC script:
14     String command = Serial.read()
15   //set system state
16   if (command == "START"){
17     // Send header of csv
18     Serial.println("Sample,Time(ms),A0(V),A1(V),A2(V),A3(V)")
19     // keep track of system state
20     state = recording
21     // keep time
22     startTime = currentTime()
23     // send confirmation
24     Serial.println("recording in progress")
25     }
26   // check if recording
27   if (state == recording){
28     // check if within recording period
29     currentTime = currentTime()
```

```
      elapsedTime = currentTime - startTime
      if(currentTime <= recordingDuration){
        // Also check not recording too fast
        if(currentTime - lastSampleTime >= minSampleInterval){
          sampleCount++;
          // Start each row with sample count and time of sample
          String currentCSVrow = String(sampleCount) , string(
  elapsedTime)
          // Multiplex through all analog inputs
          for (int = 0;i<4;i++){
            //read raw values
            rawValue = analogRead(analogInputs[i]);
            // compute real value
            voltage = rawValue * 5/1023
            // add value to current row to send
            currentCSVrow += String(voltage)
            }
          // Send completed row to PC
          Serial.println(currentCSVrow)
          }
        }
      }
  // end recording
  else{
    state = notRecording
    // tell PC recording finished
    Serial.println("Recording_finished")
    }
}
```

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 13µs 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 16MHz/16 = 1MHz. 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 4.8 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
```

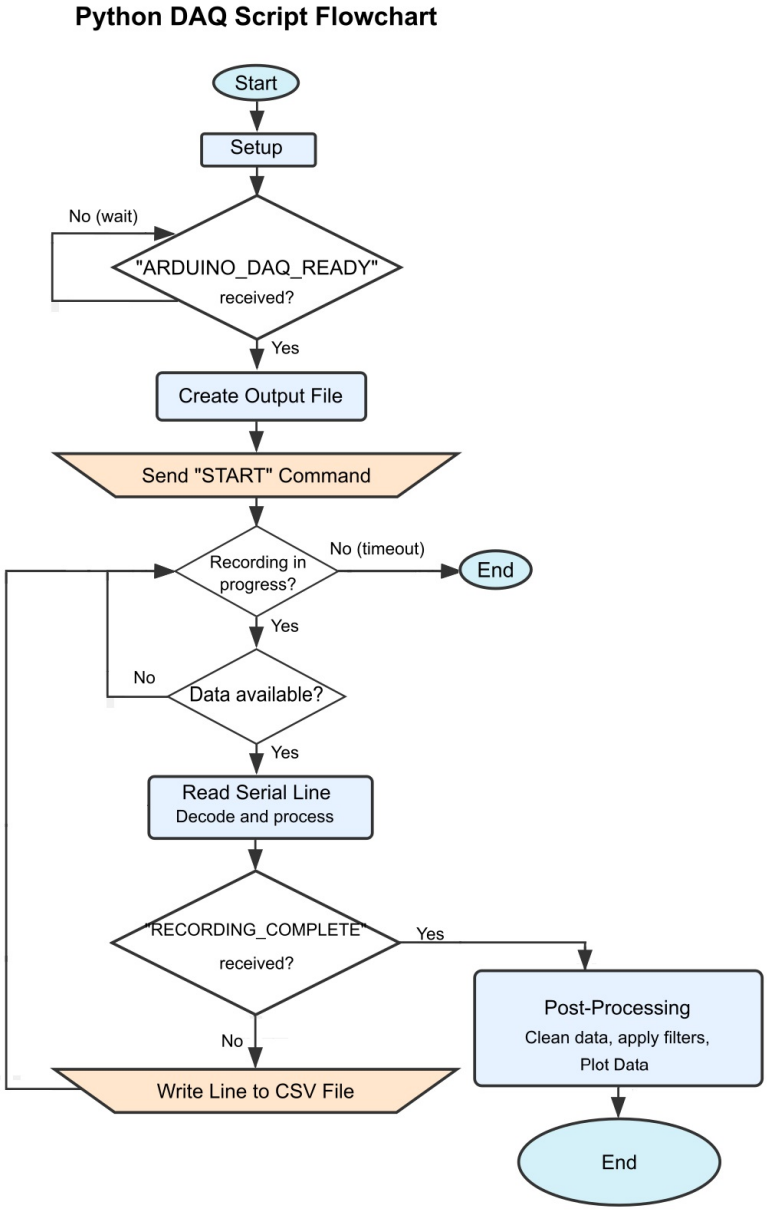

Figure 4.8.: Python Script Flowchart

```
  data_table = READ_CSV(filename)

  // Streamline the data by converting text to numbers
  FOR EACH column IN data_table
      CONVERT column values to numeric type
      IF conversion fails for any value
          REPLACE with NaN (Not a Number)
  END FOR

  // Remove any rows containing NaN values
  REMOVE all rows with NaN values from data_table

  // Calculate sampling frequency
  time_differences = CALCULATE differences between consecutive time
   values
  typical_time_difference = FIND median of time_differences
  sampling_frequency = 1000.0 / typical_time_difference  // Convert ms
   to Hz

  // Process each data channel
  channel_list = ["A0(V)", "A1(V)", "A2(V)", "A3(V)"]

  FOR EACH channel_name IN channel_list
      IF channel_name EXISTS in data_table
          filtered_values = APPLY_LOWPASS_FILTER(original_values,
   sampling_frequency)
          ADD new column named channel_name + "_filtered" with
   filtered_values
      END IF
  END FOR

  // Save results to new file
  new_filename = REMOVE_EXTENSION(filename) + "_filtered.csv"
  WRITE data_table TO new_filename

  RETURN new_filename
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 4.5. 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 relativly simple, due to the large frequency difference beteween 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 comunity. 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 4.9. 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.

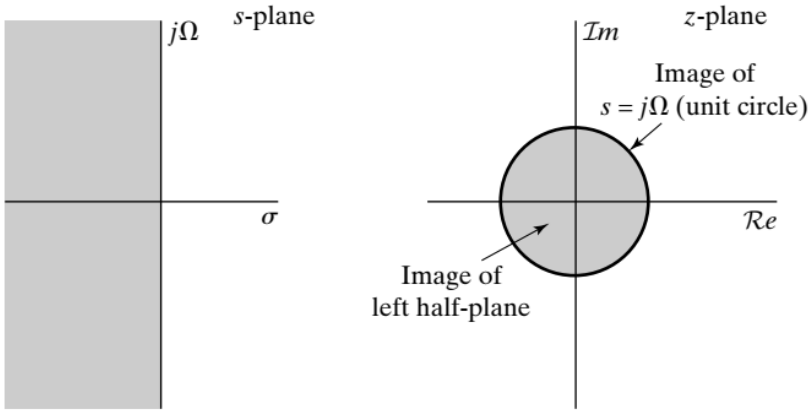

Figure 4.9.: Mapping of the s-plane onto the z -plane using the bilinear transformation [1, p.130]

The filter Frequency Response was reproduced in Figure 4.10 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 13.

$$H(e^{j\omega}) = \frac{b[0] + b[1]e^{-j\omega} + b[2]e^{-j2\omega} + b[3]e^{-j3\omega} + b[4]e^{-j4\omega}}{a[0] + a[1]e^{-j\omega} + a[2]e^{-j2\omega} + a[3]e^{-j3\omega} + a[4]e^{-j4\omega}} \tag{13}$$

```
from scipy import signal
FUNCTION apply_lowpass_filter(data, sampling_rate)
  // set hardcoded filter values
   cutoff_freq = 2;
   filter_order = 4;
  // calculate Nyquist Frequency and Normalized cut_off
  nyquist = 0.5 * sampling_rate;
  norm_cutoff = cutoff_freq / nyquist;
  // generate numerator b and denominator a polinomials
  b, a = signal.butter(filter_order, norm_cutoff, filterType = LOW);
  // filter the data
  filtered_data = filter(b,a,data);

  return filtered_data;
```

Listing 4.3: Python apply_lowpass_filter() PseudoCode

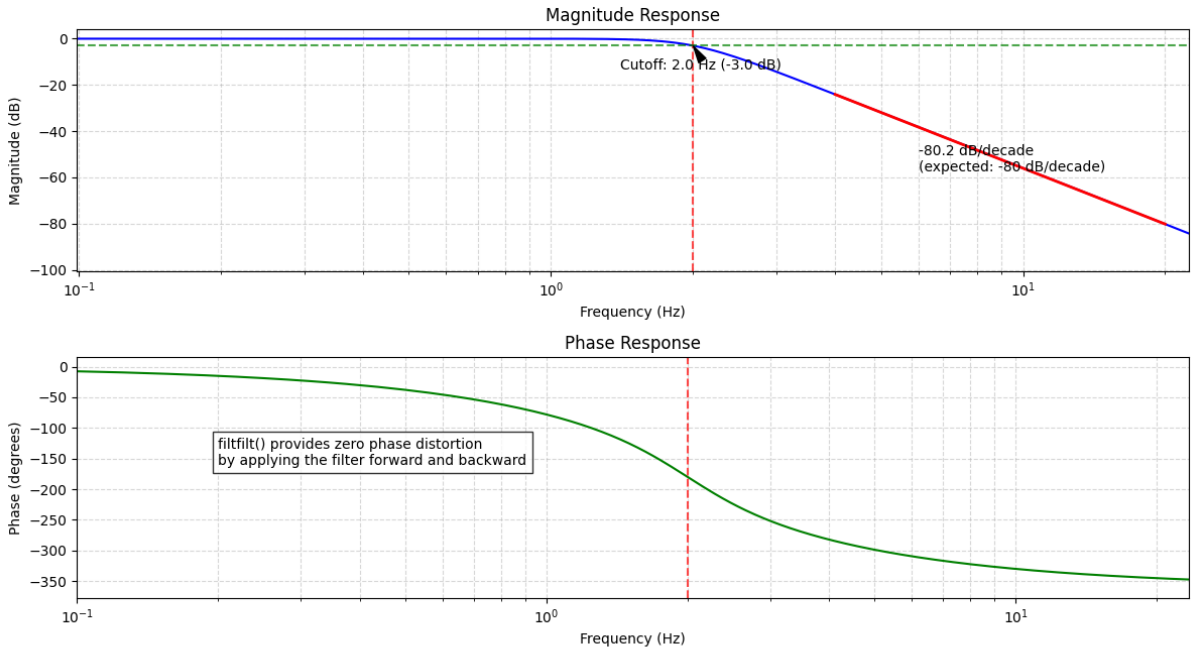

Figure 4.10.: Frequency Response of 4-pole Butterworth Low-Pass Filter (Cutoff: 2.0 Hz, Order: 4, Fs: 500 Hz)

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 4.5. 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 (14). 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.

$$\frac{x-a}{\alpha} = \frac{y-b}{\beta} = \frac{z-c}{\gamma} (= t) \tag{14}$$

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

$$t = \frac{\vec{n} \cdot \vec{P} - \vec{n} \cdot \vec{A}}{\vec{n} \cdot \vec{u}} \tag{15}$$

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 Militarty 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 $-240\,^{\circ}\mathrm{C}$ and the maximum is $260\,^{\circ}\mathrm{C}$. 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 resisters.

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 resisters made from aluminium, and the PCB being made of polyimide. Then a

convection of 22 °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 °C. Each of the components have their respective temperatures when operating. Finally, two tests will be conducted using 200 °C and −200 °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.

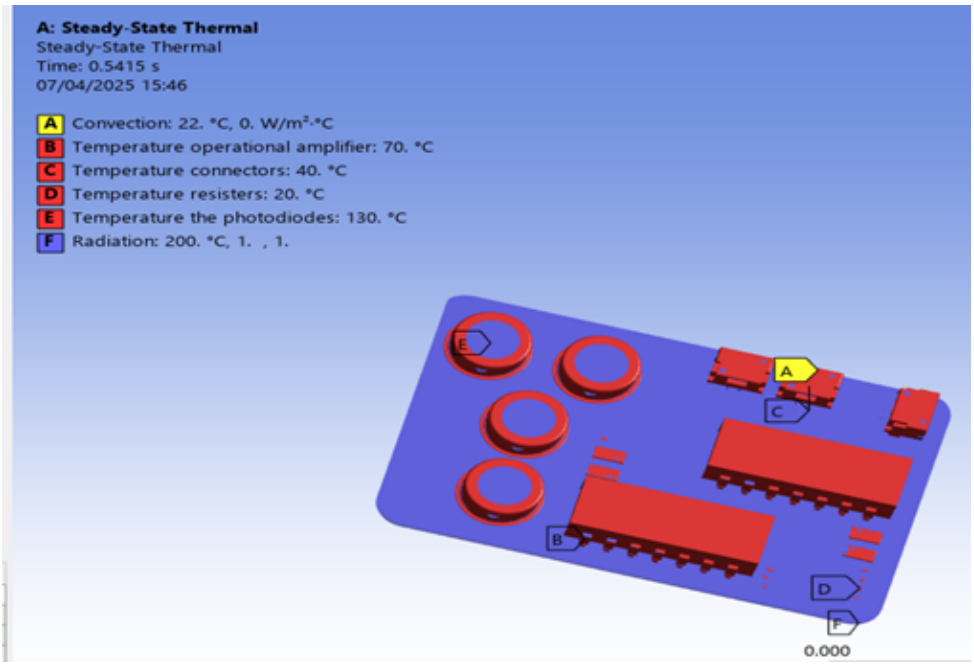

Figure 4.11.: PCB model with Parameters applied

4.6.3. Thermal results

4.6.4. Finite Analysis Evaluation 1 - Under 200 °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 4.12 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.

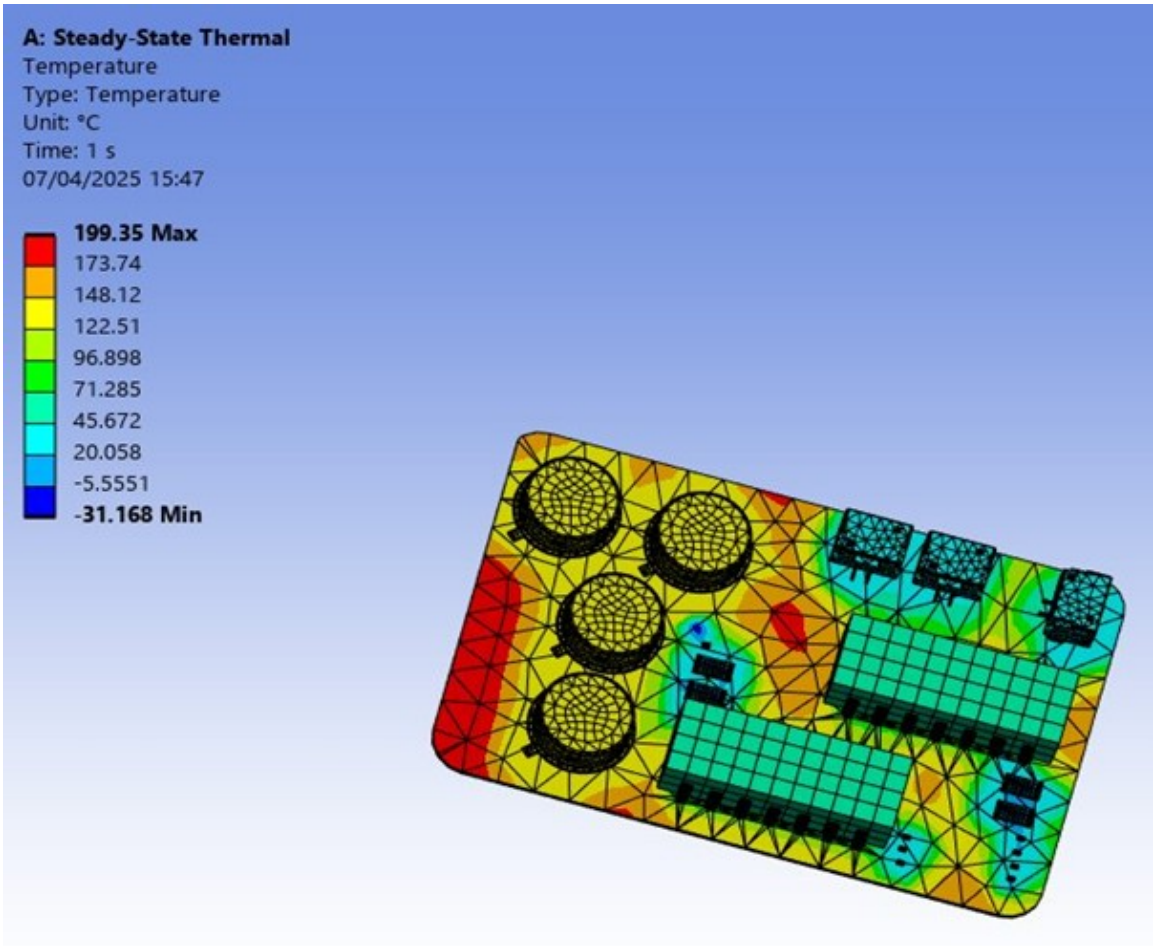

Figure 4.12.: Results under 200 °C radiation

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 4.13 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.

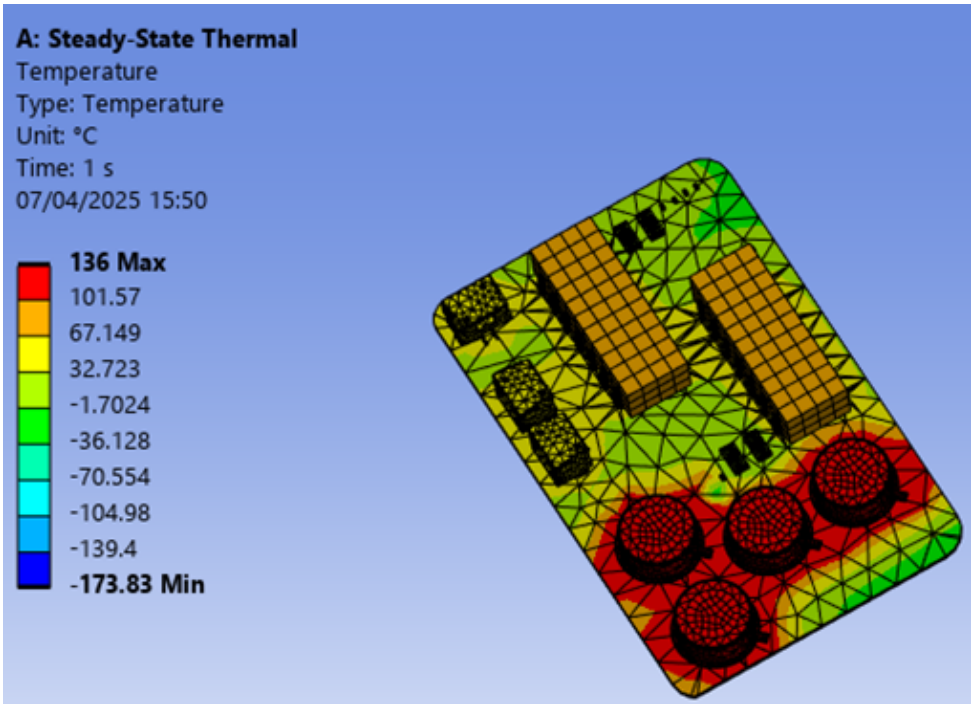

Figure 4.13.: Results under −200 °C radiation

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

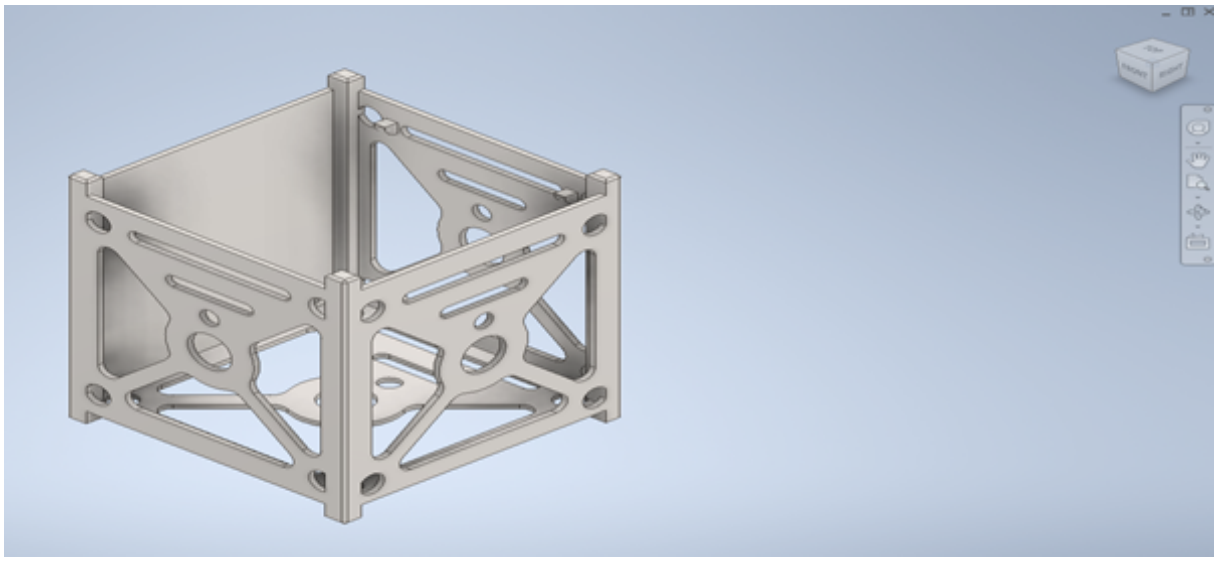

Figure 4.14.: Front view of the first CubeSat chassis design

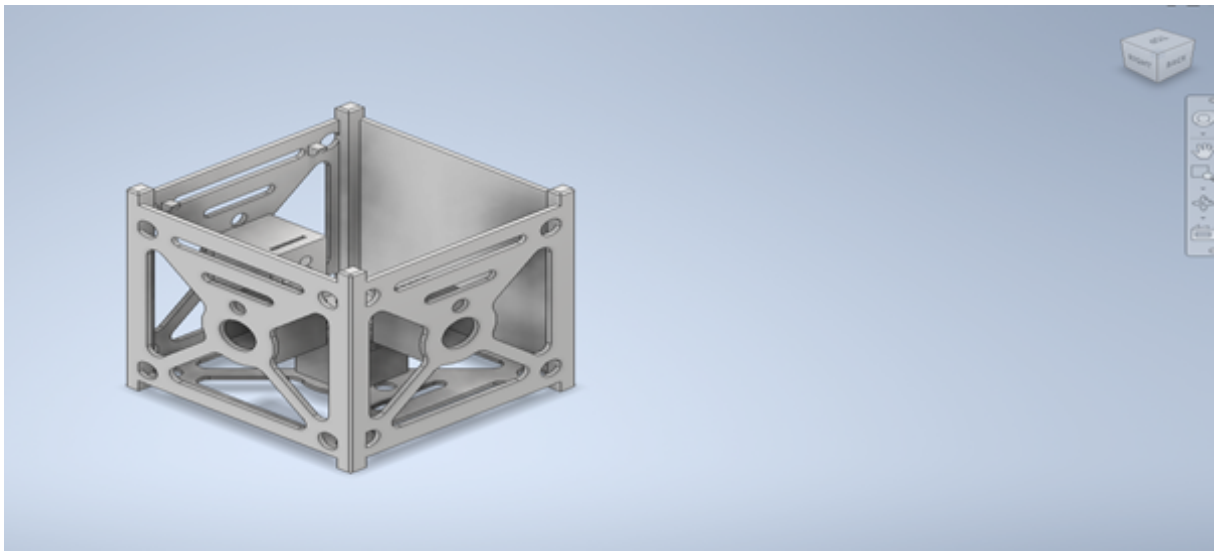

Figure 4.15.: Angular view of the first CubeSat chassis design

The first design taken from `https://grabcad.com/library/cubesat-1u-5` as seen in Figure 4.14 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 4.15.

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 4.16 and Figure 4.17.

Figure 4.16.: Front view of 1U Cubesat Skeleton Chassis

Figure 4.17.: 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 4.18 and Figure 4.19, are the CubeSat Chassis with and without the PCBs, additional angles and drawings are found in the appendix.

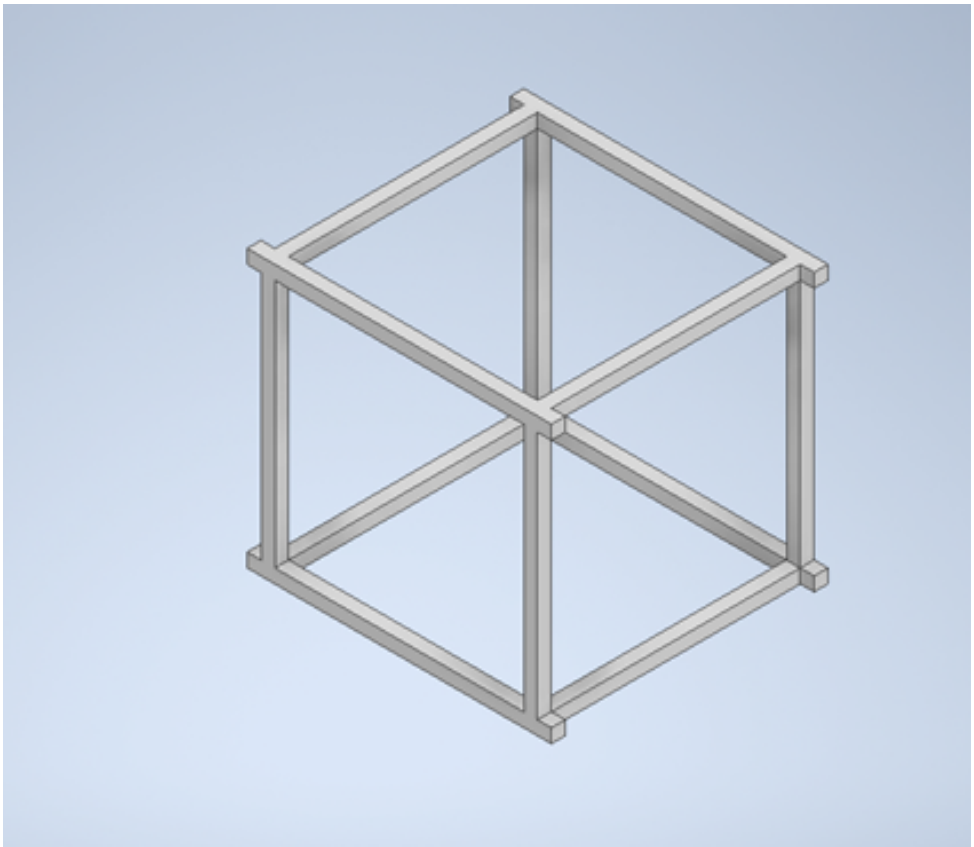

Figure 4.18.: Second chassis design without PCBs

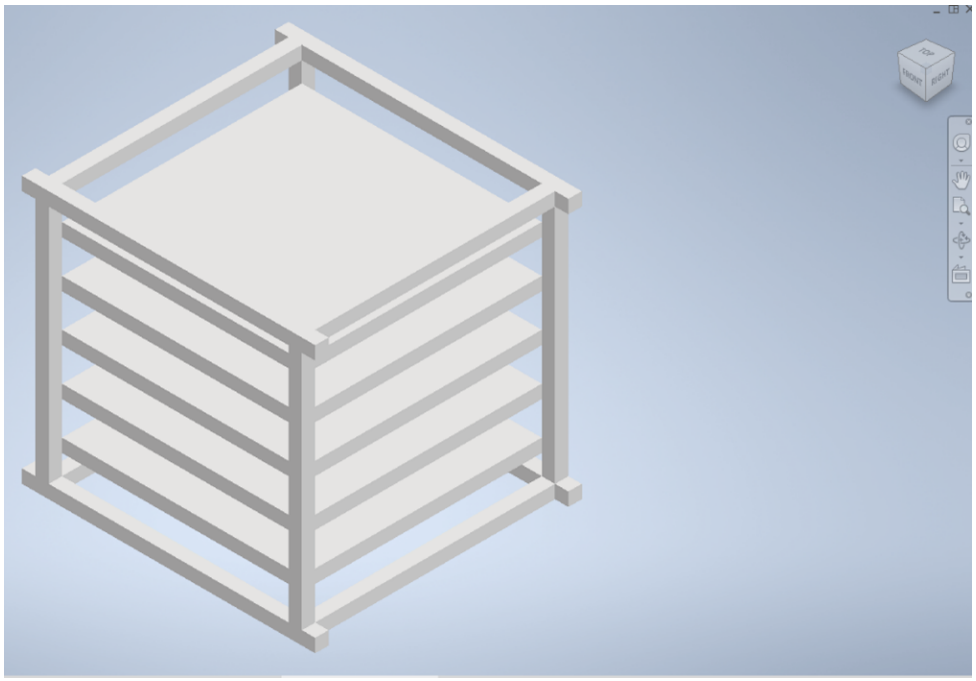

Figure 4.19.: Chassis with the aperture

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

SNR!

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.

5.2. 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 enlosure.

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).

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A. Appendix - DAQ Code

A.1. Arduino DAQ full code

A.1.1. Arduino C++ Code

```
/*
* Reads 4 analog inputs (0-5V) for recording_dur seconds
* Streams data to PC while recording
*/
// change to true to print debug messages on Serial Monitor
// printing debug lines impacts transmission speed and messes csv
//  do not leave on during measurements!
bool debug = false;

const int analogInputs[] = {A0, A1, A2, A3};


// set up the global varialbes
unsigned long start_time;
const unsigned long recording_dur = 5000; // 25 seconds in
milliseconds (ENSURE python code is greater than this)
unsigned long last_sample_time = 0;
const unsigned long min_samp_interval = 2; // Sample every 2ms (
adjust for stability)
bool recording = false;
int sample_count = 0;

void setup() {
  // serial communication at 115200 bps
  Serial.begin(115200);

  // Set pins as input
  for (int i = 0; i < 4; i++) {
    pinMode(analogInputs[i], INPUT);
  }

  // Optimize ADC for faster sampling
  // Set ADC prescaler to 16 (default is 128)
  //
```

```
33      // Bit: 7:enable; 6: initiate a convertion 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(
    elapsed_time);
92
93            // Multiplex through the four inputs sequentially
94            for (int i = 0; i < 4; i++) {
95              if(debug) Serial.println("reading input: " + String(i));
96              int raw_value = analogRead(analogInputs[i]);
97              float voltage = raw_value * (5.0 / 1023.0);
98              data_string += "," + String(voltage, 3);
99            }
100
101           // Send the complete data string at once
102           Serial.println(data_string);
103         }
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
```

```
    import os
    import numpy as np
    from scipy import signal

    def apply_lowpass_filter(data, fs):
        """Apply a 4-pole low-pass Butterworth filter with 5Hz cutoff"""
        cutoff_freq = 2.0
        filter_order = 4

        nyquist = 0.5 * fs
        normal_cutoff = cutoff_freq / nyquist
        # analog=False implies  bilinear Transformation
        b, a = signal.butter(filter_order, normal_cutoff, btype='low',
    analog=False)
        filtered_data = signal.filtfilt(b, a, data)

        return filtered_data

    # Load data from CSV, apply a 4-pole low-pass filter, and save the
    filtered data
    def filter_and_save_data(filename):

        # Read the CSV data to pandas DataFrame
        #  It knows what are the column names
        df = pd.read_csv(filename)

        # Clean the dataframe - convert all columns to numeric
        for col in df.columns:                  # v - write NaN where it
     can't convert to number (in teh data, not column names)
            df[col] = pd.to_numeric(df[col], errors='coerce')

        # remove rows with NaN (not a number)
        df = df.dropna()

        # Samples not at exact distance from each other
        # Calculate the sampling frequency (median of differences)
        # numpy.diff to get the difference between samples
        time_diffs = np.diff(df['Time(ms)'])
        # numpy.median to get the median
        median_time_diff = np.median(time_diffs)  # in milliseconds
        fs = 1000.0 / median_time_diff  # Convert to Hz

        # Filter each analog channel:
        # ID column head for each channel
        analog_channels = ['A0(V)', 'A1(V)', 'A2(V)', 'A3(V)']
        # take each channel one at a time
        for channel in analog_channels:
```

```
            # if name maches a column name
            if channel in df.columns:
                # add a new column _filtered, and send the array containing all the raw values to
                # have them filtered, and save them in the new _filtered column
                df[f"{channel}_filtered"] = apply_lowpass_filter(df[channel].values, fs)

        # Save the pandas Dataframe with filtered columns to a new CSV file
        filtered_filename = f"{os.path.splitext(filename)[0]}_filtered.csv"
        df.to_csv(filtered_filename, index=False)

        return filtered_filename

    #
    # Plot the DAQ data with original and filtered signals overlapped
    #
    def plot_data(filename):

        # Read the CSV data with pandas
        df = pd.read_csv(filename)

        # Initialize an empty list to store our analog channel names
        analog_channels = []

        # Look through all column names in the DataFrame
        for col in df.columns:
            # the column name starts with 'A'
            if col.startswith('A'):
                #  the column name ends with '(V)'
                if col.endswith('(V)'):
                    # the column name does NOT contain '_filtered'
                    if '_filtered' not in col:
                        # add this column name to our list
                        analog_channels.append(col)

        # Create color cycle for different channels
        colors = ['blue', 'green', 'red', 'purple']

        # Create a single plot with all channels overlapping
        plt.figure(figsize=(14, 8))

        # Plot original data (semi-transparent)
        for i, channel in enumerate(analog_channels):
```

```
            color = colors[i % len(colors)]
            plt.plot(df['Time(ms)'], df[channel], label=f'{channel} Original',
                     linewidth=1.5, alpha=0.4, color=color, linestyle='-')

        # Plot filtered data (solid lines)
        for i, channel in enumerate(analog_channels):
            filtered_channel = f"{channel}_filtered"
            if filtered_channel in df.columns:
                color = colors[i % len(colors)]
                plt.plot(df['Time(ms)'], df[filtered_channel], label=f'{channel} Filtered',
                         linewidth=2.5, color=color, linestyle='-')

        # Set the y-axis range from 0 to 5V
        plt.ylim(0, 5)

        # Add labels and title
        plt.xlabel('Time (ms)')
        plt.ylabel('Voltage (V)')
        plt.title('Arduino DAQ - 4-Channel Readings with 4-Pole 5Hz Low-Pass Filter')
        plt.legend()
        plt.grid(True)

        # Add data summary
        duration = df['Time(ms)'].max() - df['Time(ms)'].min()
        sample_count = len(df)
        sample_rate = sample_count/(duration/1000) if duration > 0 else 0

        info_text = f"Data summary:\n" \
                    f"Duration: {duration:.1f} ms\n" \
                    f"Samples: {sample_count}\n" \
                    f"Sample rate: {sample_rate:.1f} Hz\n" \
                    f"Filter: 4-pole Butterworth, 5Hz cutoff"

        plt.figtext(0.02, 0.02, info_text, fontsize=10,
                    bbox=dict(facecolor='white', alpha=0.8))

        # Save the plot
        plot_filename = f"{os.path.splitext(filename)[0]}_plot.png"
        plt.savefig(plot_filename, dpi=300, bbox_inches='tight')

        # Show the plot
        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
```

```
            if ser.is_open:
                ser.close()
                print("Serial port closed.")

            print(f"Recorded {data_lines} lines of data.")

            # Process the data
            print("Applying filters to data...")
            filtered_filename = filter_and_save_data(filename)
            print(f"Filtered data saved to {filtered_filename}")

            print("Generating plot...")
            plot_data(filtered_filename)
            print("Done!")

        else:
            print("Wrong Choice. Goodbye!")
            exit()
    if __name__ == "__main__":
        try:
            main()
        except KeyboardInterrupt:
            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

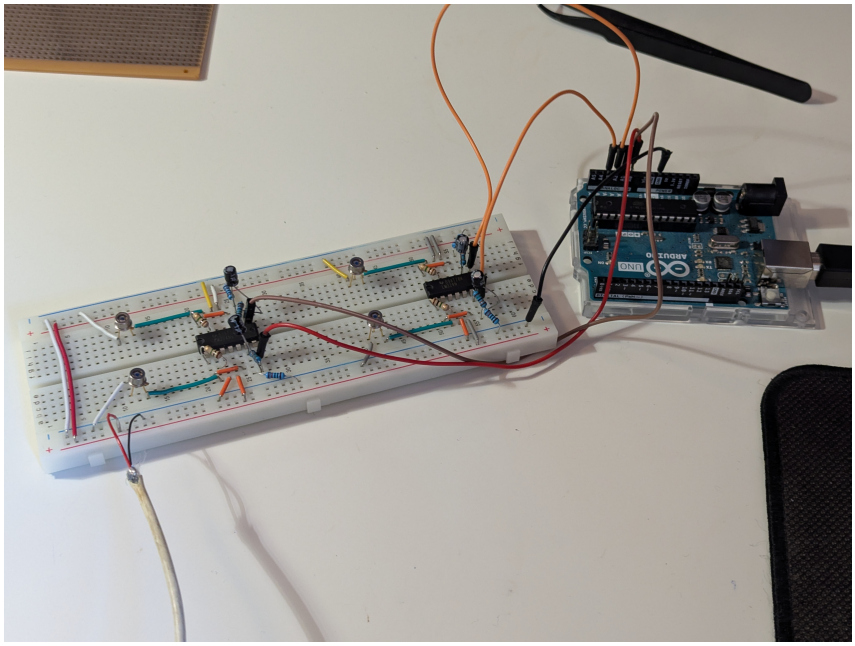
B.2. Section 2 Title

B.2.1. subsectiontitle

C. Appendix - Photos of Lab Work

C.1. Prototype Images

C.1.1. BreadBoard Prototype



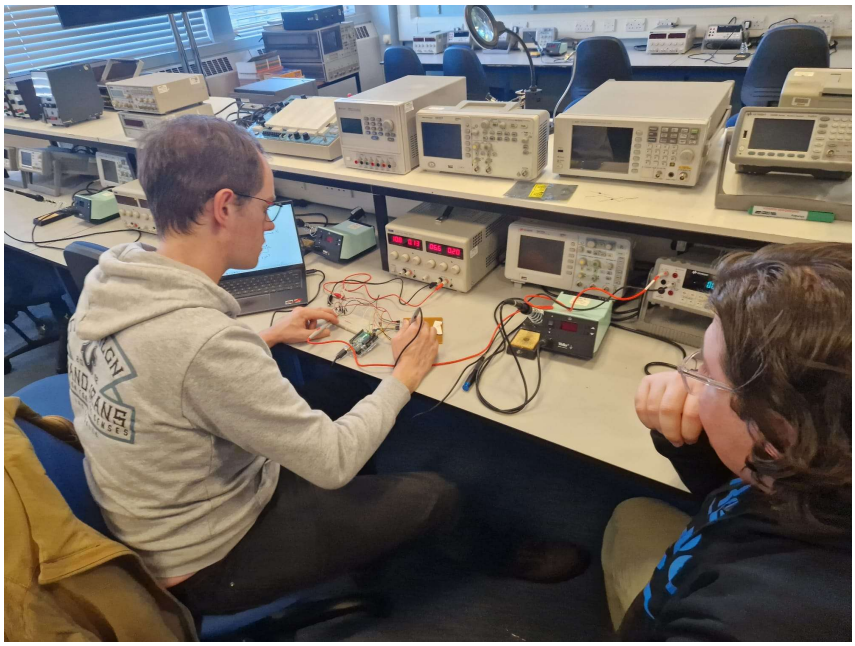
Intial BreadBoard Prototype of the Photodiode Circuit

C.1.2. Building the Prototype

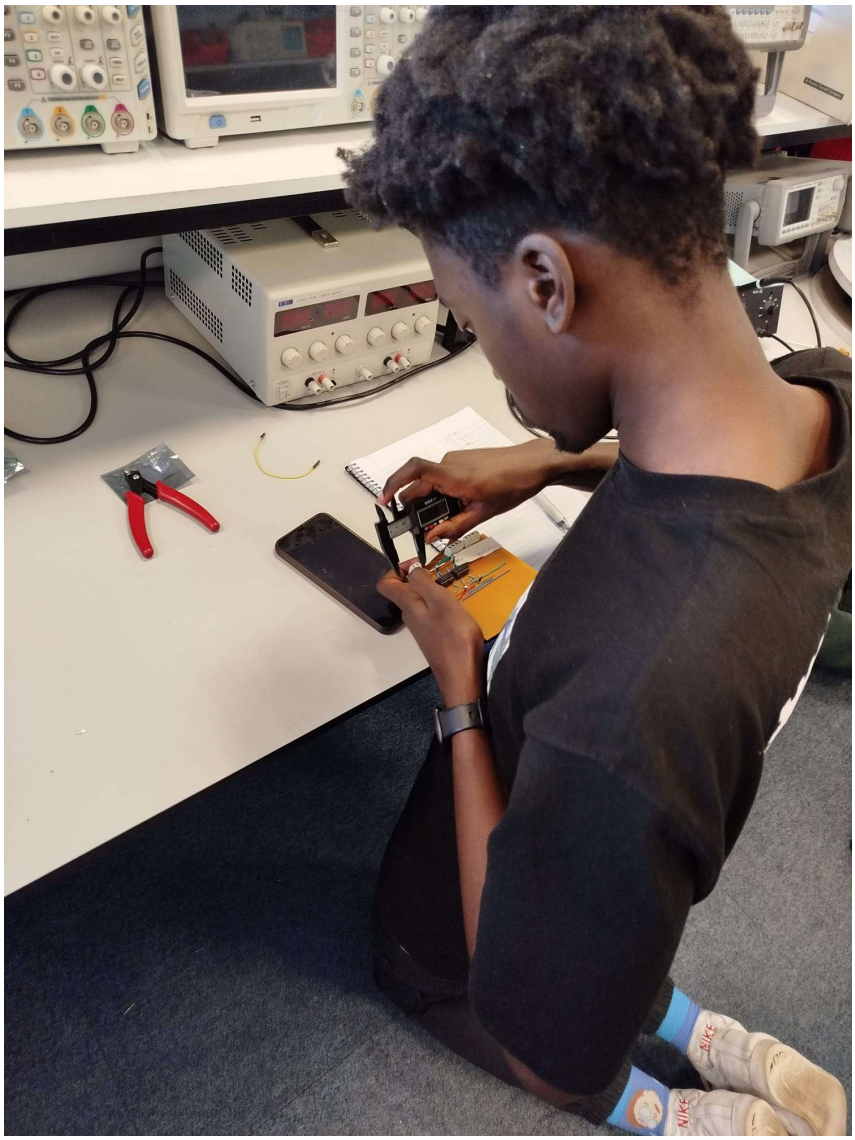
C.1.3. Prototype Testing

C.1.4. RED testbench

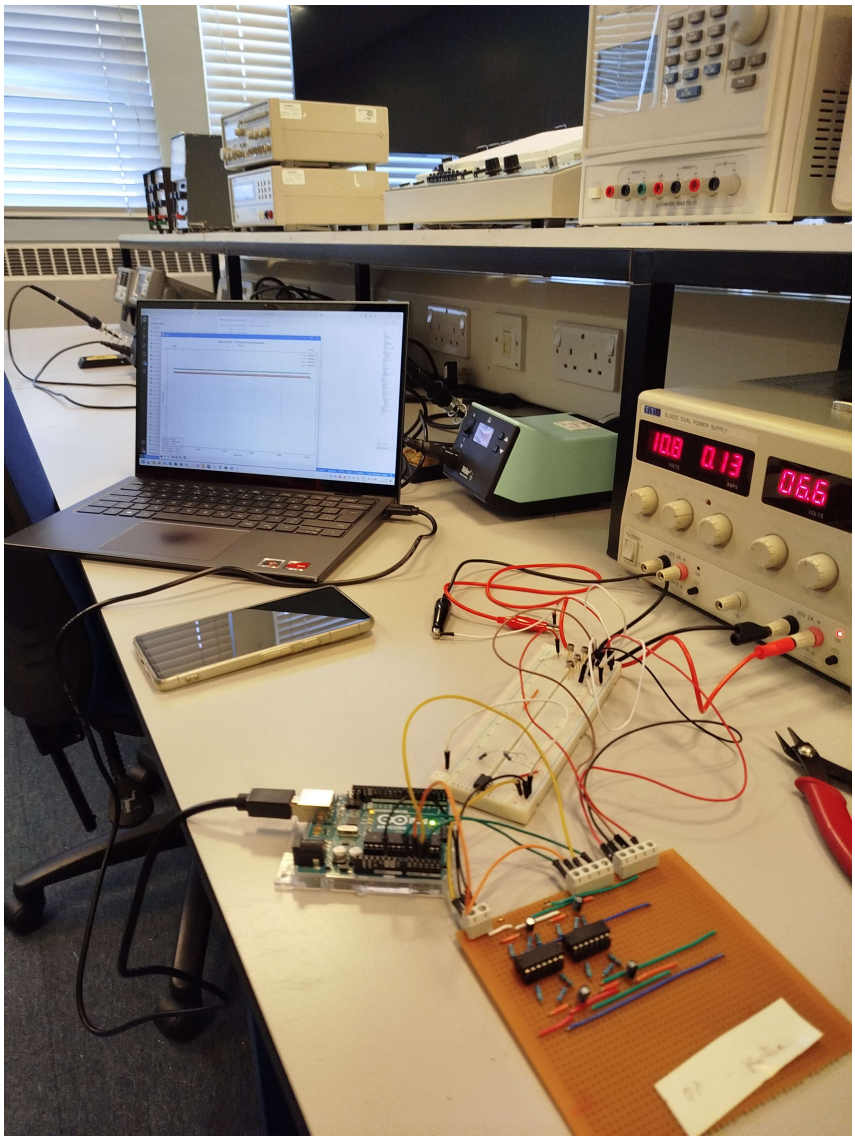
C.1.5. Solar Lab Prototype Testing



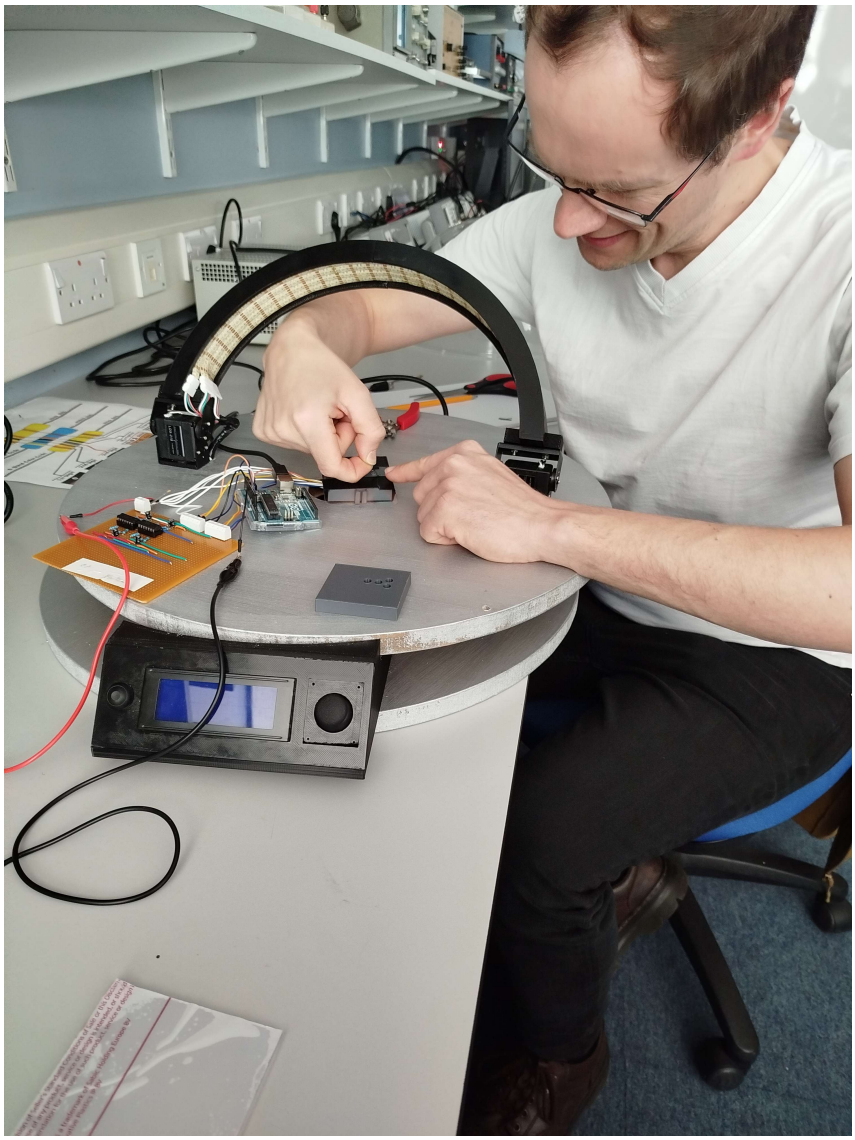
Lab Work for the Prototype (session 1)



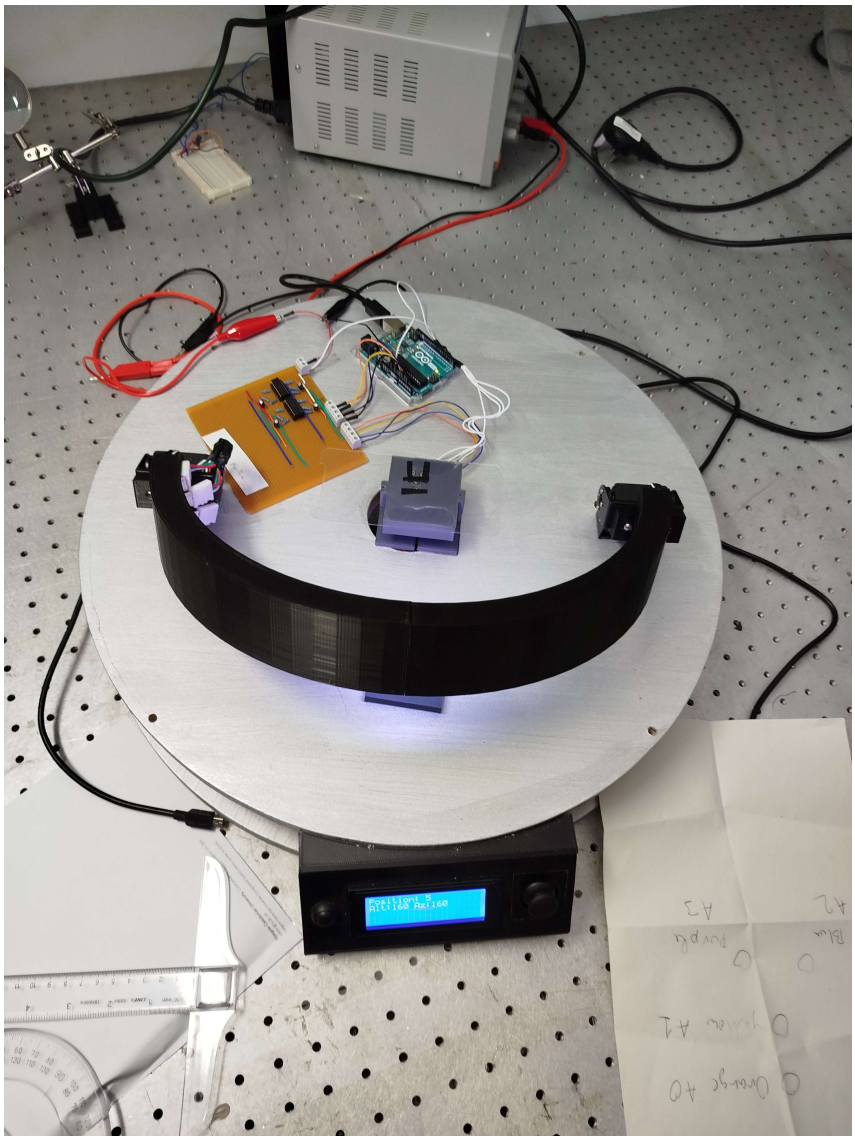
lab Work for the Prototype (session 2)



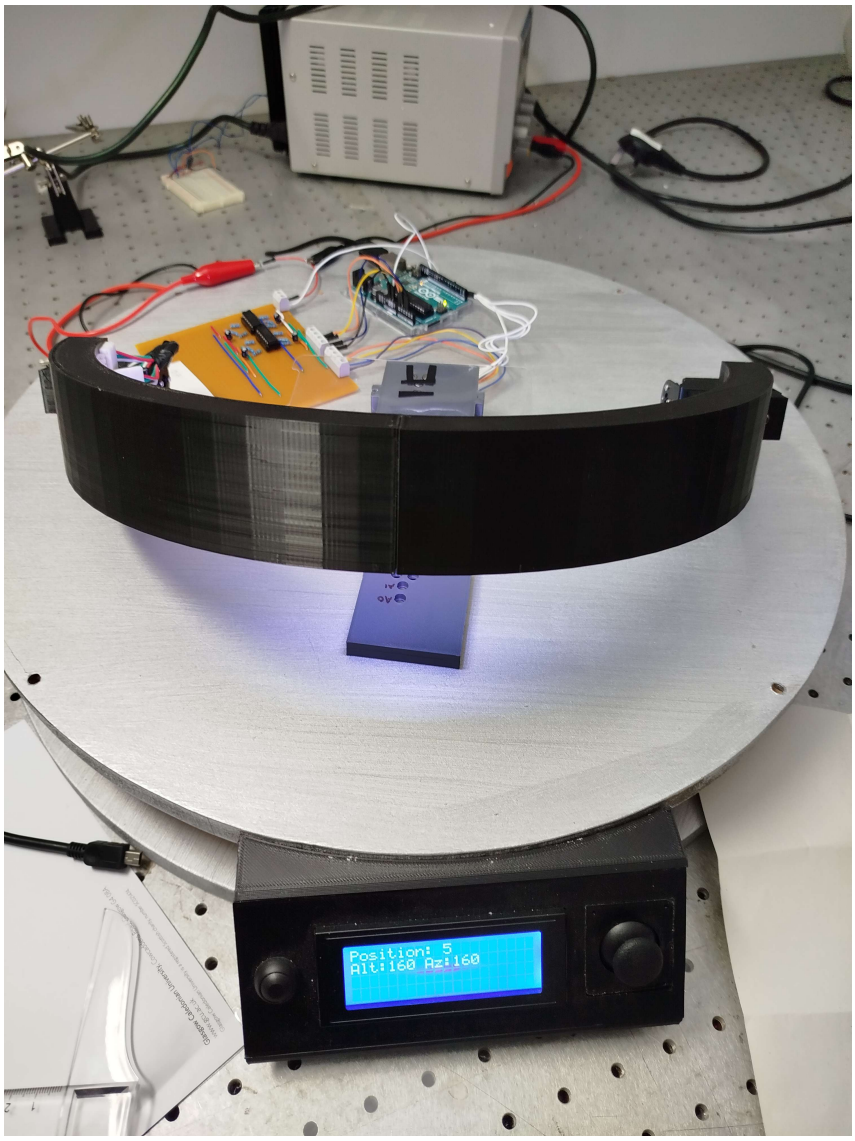
First Lab Test of the Prototype



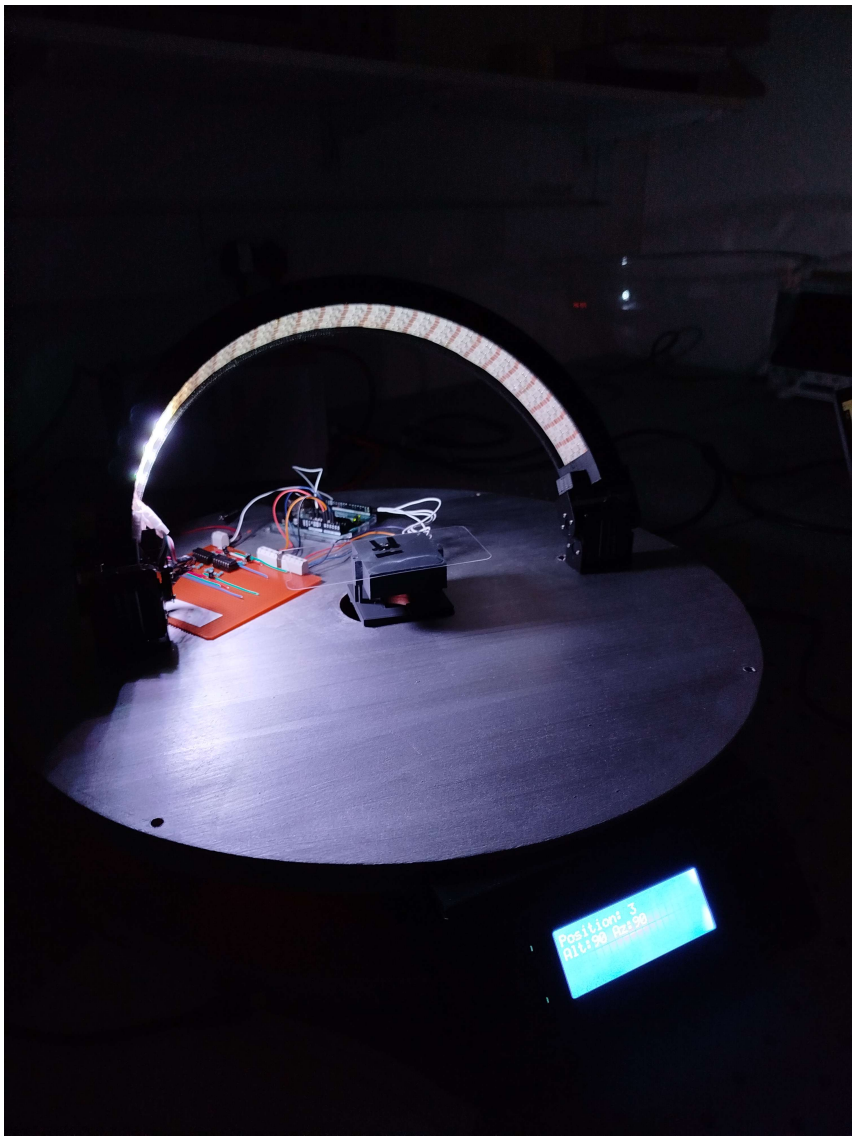
RED Testbench 1



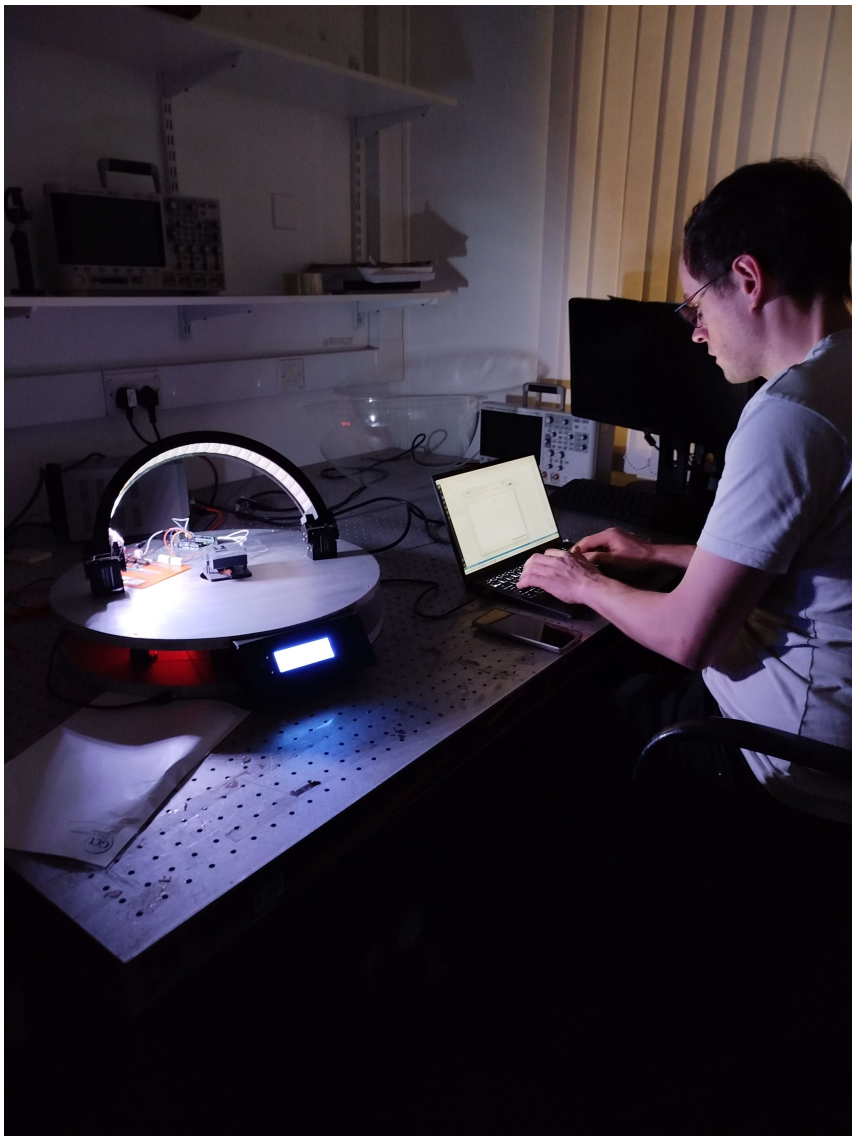
Solar Lab Test of the Prototype 1



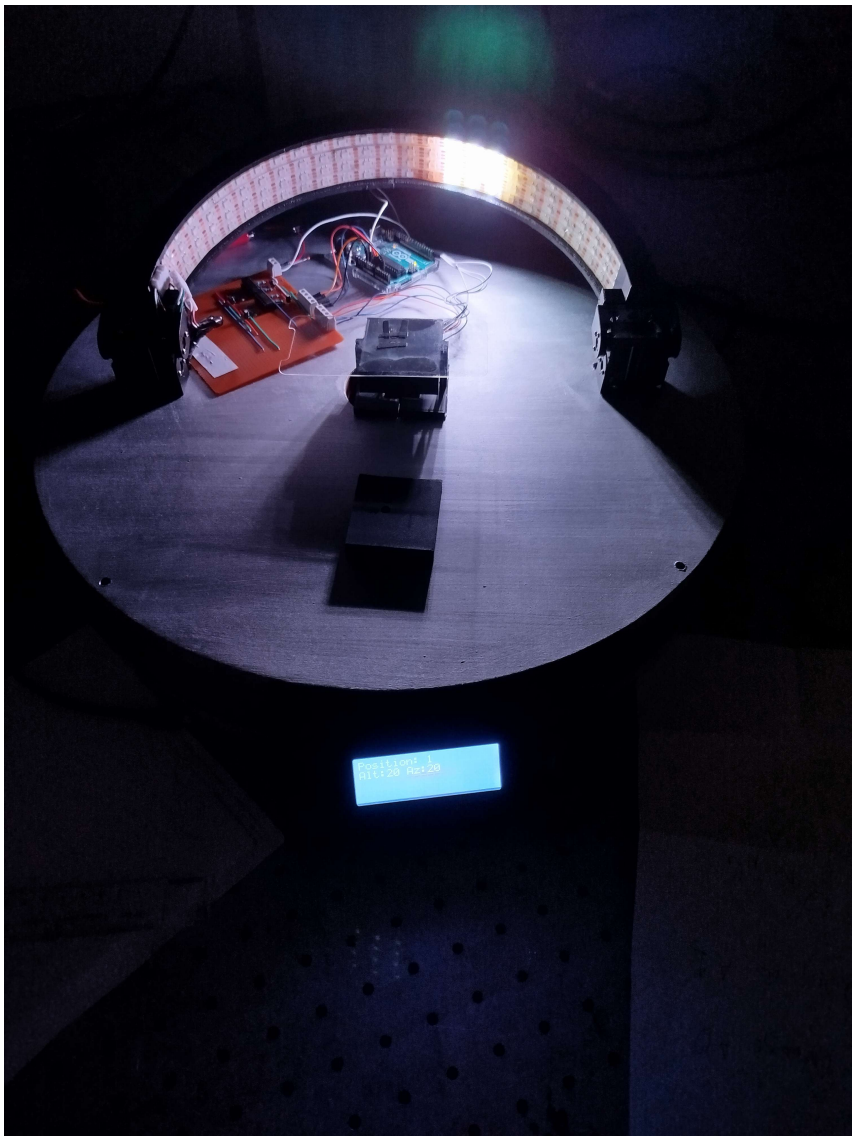
Solar Lab Test of the Prototype 2



Solar Lab Test of the Prototype 3



Solar Lab Test of the Prototype 4



Solar Lab Test of the Prototype 5