Sun Tracking Umbrella

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Abstract

The purpose of the sun-tracking umbrella is to provide the user with an optimal amount of shade throughout the day without the need for user management. The design consists of four main subsystems: power, control, sensing, and safety. These allow the umbrella's canopy to rotate 180° and tilt 45° off of the z axis in both a forward and backward direction to cover all degrees of motion needed. The final design consists of safety mechanisms including limit switches and fuses, meant to halt movement of the device should unexpected movements occur. Each high level requirement for the project is met and additional features such as a separate display screen and solar cell power are considered.

Contents

1. Introduction

When one is utilizing a patio umbrella throughout the day, it is inconvenient to require the user to manually adjust the canopy to ensure shading as the sun moves. This action requires accessibility of the user and interrupts activities occurring at and around the umbrella.

A solution to this issue requires knowing the location of the sun, or greatest incident light upon the umbrella, in order to adjust the positioning of the canopy to provide maximum shading upon the user. With the sun-tracking umbrella, fine adjustments to the canopy are done autonomously to create shade in the desired area, requiring no work by the user. This creates a hands-free experience that can be used by all patrons.

The design of the product is elaborated upon in Chapter 2, which goes into detail of each subsystem. The design consists of two motors: one to rotate the umbrella, and one to tilt the umbrella off the vertical axis. In terms of sensing, 9 photodiodes are used to track the sun throughout the day, allowing for an accurate assessment of where the umbrella should be located to maximize user comfortability. In addition to these two main components, the umbrella has a printed circuit board (PCB) that utilizes the voltage levels from the photodiodes to accurately adjust the motors in accordance with the sun. Chapter 3 then works to verify the functionality of each subsystem of the product.

Chapter 4 gives a brief overview of the timeline and cost analysis of the project, as well as areas for improvement upon both. The design works as intended and thus is able to respond to incident light by rotating and tilting the umbrella. Within Chapter 5, potential improvements to the design are considered, including the addition of extra safety features, fine tuning of photodiode amplification and interpretation by the microcontroller, and the addition of a solar cell array which would allow the design to be self-powered.

1.1 Block Diagram

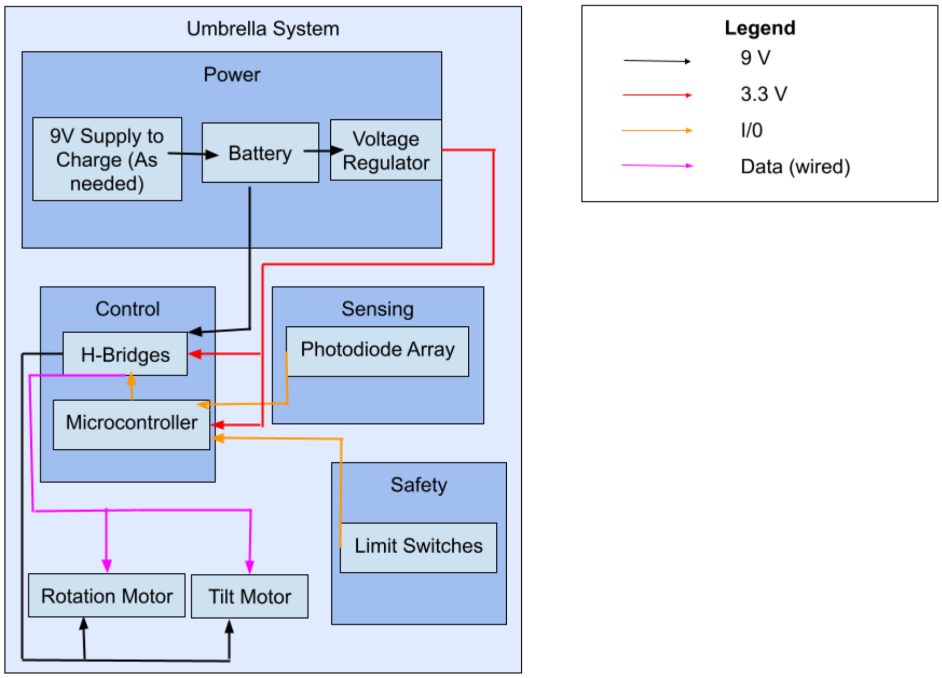

Figure 1. Block Diagram

Figure 1 shows a high level overview of the entire system as it was implemented. The original block diagram differs from this version in a few ways. Initially, there were plans to include solar cells in the power subsystem so that the final product could be fully self-sufficient. There was also the possibility of adding a display subsystem in order to show the user data and provide manual override options. These two aspects were ultimately removed from this version of the product to enhance focus on portions of the design that were necessary for overall functionality rather than additional features.

The final system includes four subsystems: power, control, sensing, and safety. The power subsystem needs to deliver power to all other subsystems at the specified voltage levels. The control subsystem takes in data from the sensing and safety subsystems and uses this to control the motors, as specified in the high level requirements. The sensing subsystem contains 9 photodiodes that detect light intensity across the canopy of the umbrella. Finally, the safety subsystem includes fuses and limit switches which limit current and override any motor movement if pressed.

1.2 Visual Aid

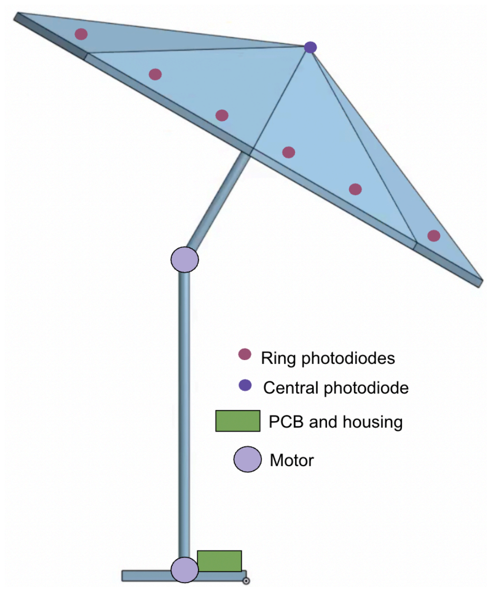

Figure 2. Visual Aid

Figure 3. Final Design Implementation

Figure 2 shows a visual aid to assist in understanding the block diagram from Figure 1. Figure 3 shows the final physical implementation of the scaled down version of the umbrella system. The photodiodes are placed evenly around the canopy of the umbrella, with the two motors rotating about the same axis both shown in the visual aid as well as the final design implementation.

1.3 High Level Requirements

In order to deem the design and implementation of this umbrella successful, all of the following high level requirements must be met:

1. The base motor and the tilting motor are able to rotate 180° around the z axis and 45° off of the z axis respectively. The motors must also be able to hold their position for at least 1 hour.
2. The photodiode array must detect differences in illumination such that a conservative voltage difference of 0.2V is seen for a difference of 30 lx in intensity.
3. The microcontroller must be able to iterate through 8 inputs (two 8:1 multiplexers with only 4 inputs used on each) and determine the largest gap in intensity, while comparing this to the maximum value seen from the 9th photodiode at the top of the umbrella.

2. Design

2.1 Power

The power subsystem includes an external battery, a barrel jack, and a voltage regulator. The purpose of this subsystem is to deliver power to all other subsystems of the umbrella at the proper voltage levels. The external battery is a 9V Duracell battery [11]. This enters the system through the barrel jack on the PCB, which then flows into the AZ1117-3.3 voltage regulator as shown in the schematic in Figure 4 [2]. Many of the components in the other subsystems required access to 3.3V, which this voltage regulator provides reliably.

A 9V battery was chosen over a higher voltage level, like 12V, due to simplicity and ease of use. Rather than working with large 12V batteries, similar to car batteries, using a smaller 9V battery provides the necessary power to both the motors and the PCB without compromising ease of operation. Additionally, having a lower voltage level battery comes with less safety hazards while still providing enough amp hours (Ah) for the system to run for extended periods of time. This proof is elaborated upon in Chapter 3.1 where verification of the 9V battery is tested and confirmed.

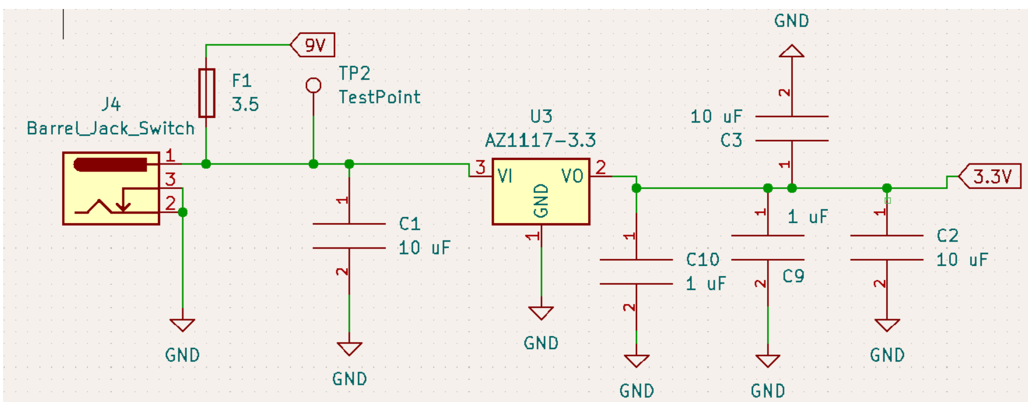

Figure 4. Power subsystem schematic of PCB

The voltage regulator and capacitor values were chosen based on which components were obtainable from the Electrical and Computer Engineering Building (ECEB) Electronics Services Shop, making for a cheaper design. This also ensured the ability to obtain components faster than if they were bought from a third party. The voltage regulator uses 22µF on the output side and 10µF on the input as defined in the datasheet [2].

2.2 Control

The control subsystem consists of the motor drivers and the microcontroller. The microcontroller is an ESP32-S3-WROOM-1 [10], with its connections shown in Figure 5, and outlined clearly in Table 10 in Appendix C. This microcontroller was chosen for its simplicity of programming as well as its built-in Wi-Fi/RF capabilities.

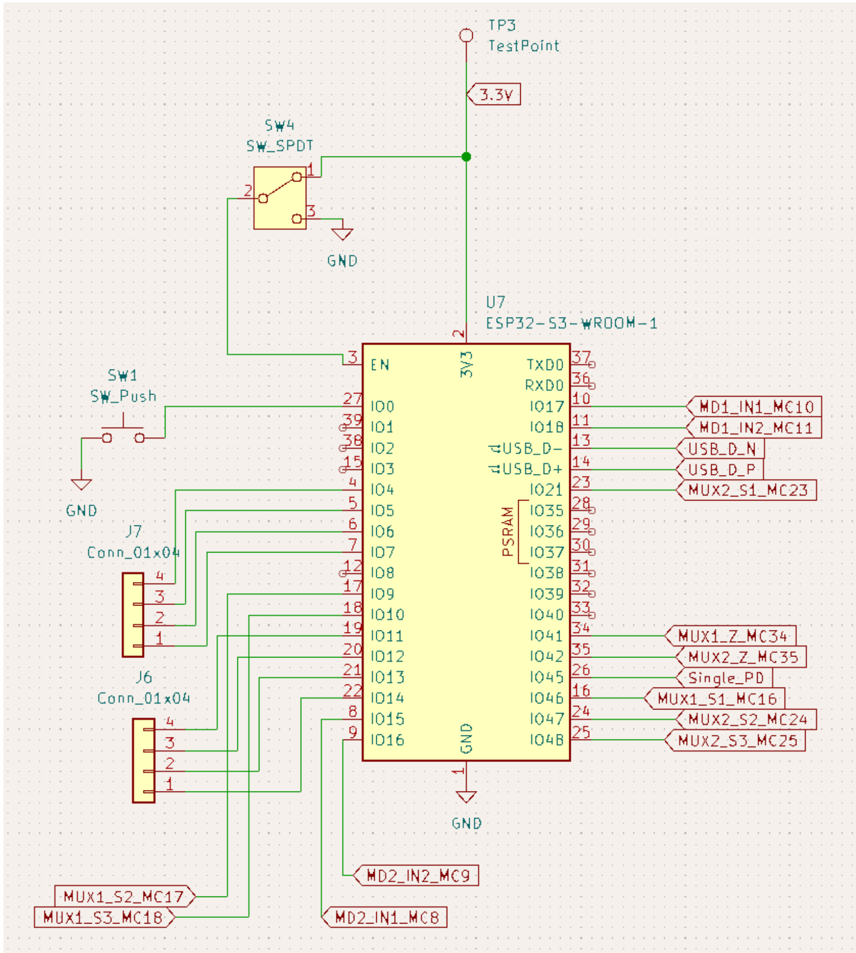

Figure 5. Microcontroller portion of control subsystem schematic of PCB

The only things needed to program the ESP32 are power and USB data positive and negative lines. Programming is completed through the use of a USB-C receptacle [18] which is connected in accordance with standard USB-C protocol. Proper functionality of the receptacle is determined by the resistors shown in Figure 6, which can either be pulled up or down, depending on whether or not the microcontroller is the host or peripheral device. In this case, the microcontroller on the PCB is considered to be a peripheral device, thus the resistors must be tied to ground. We do not draw any power from the USB-C connection as we wanted the ability to run the system unplugged from any laptop. All power to the control system comes directly from the power subsystem.

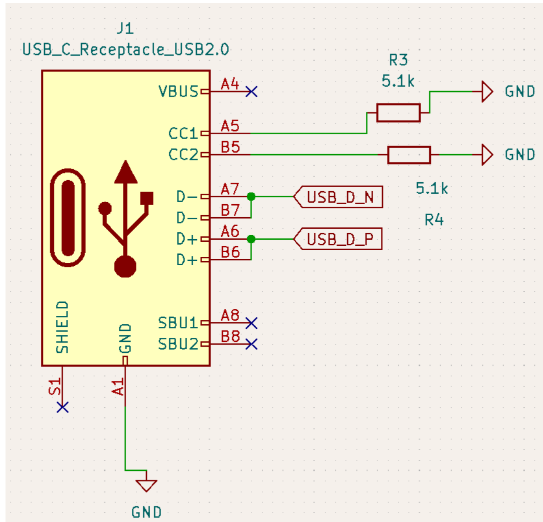

Figure 6. USB-C receptacle portion of control subsystem schematic of PCB

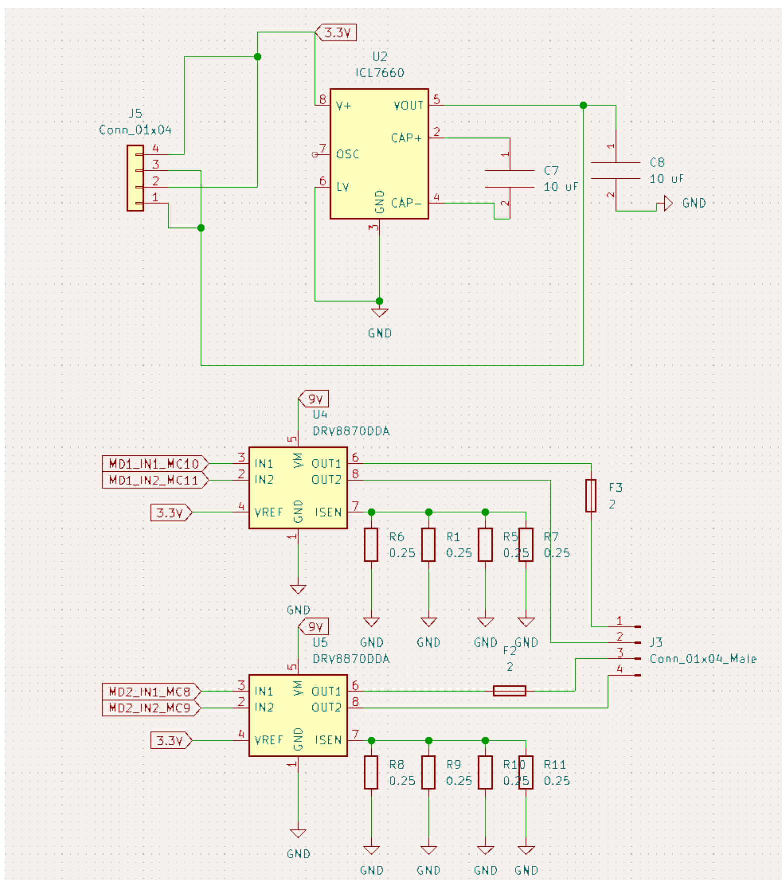

Figure 7. Motor control portion of control subsystem schematic of PCB

The motor control portion of the control subsystem, shown in Figure 7, consists of two DRV8870DDA motor drivers [8], in addition to an ICL7660 voltage inverter [17]. The motor drivers require motor voltage (VM), reference voltage (VREF), and two inputs from the microcontroller (IN1, IN2). The motor and reference voltages come directly from the power subsystem, at the 9V level and 3.3V level respectively. The inputs from the microcontroller are logical signals that control the H-bridges. Additionally, there is current regulation built into the motor drivers by connecting a low-value, high-power-rating resistor directly from the ISEN pin to ground. The details of this current limitation are explained further in Section 2.4.

The motors [16] chosen require +3.3V and -3.3V to power the built-in encoders, so the voltage inverter was included to provide access to -3.3V from the +3.3V power rail. The motors were selected with input from the machine shop to take their expertise into consideration. The two main features of the motors that we looked for were a high gear ratio and a self-locking mechanism. The high gear ratio of the motors provides a very low output speed, 10rpm in this case. This contributes to keeping the entire system safe by ensuring that neither motor can spin aggressively fast and risk putting a user in harm's way. The self-locking feature of the motor allows the motors to keep their positions without requiring power, which keeps our power consumption to a minimum while ensuring the canopy will not move when movement is not desired.

2.3 Sensing

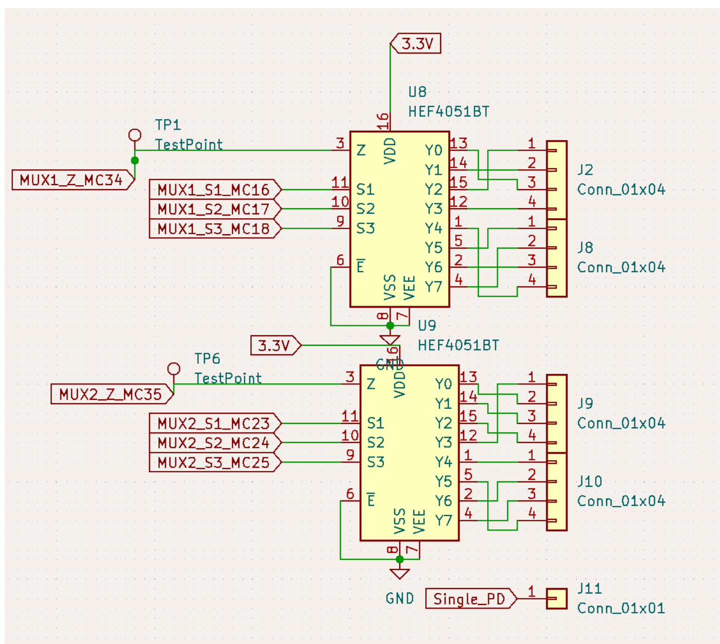

Figure 8. Multiplexer portion of sensing subsystem schematic of PCB

The sensing subsystem consists of the photodiodes on the umbrella and the software required to compare the received data. The final setup uses BPW34 silicon PIN photodiodes [14] reverse biased with 5V. The photodiodes are organized on the umbrella, as seen in Figures 2 and 3, with a resistor used to limit the voltage being input to the microcontroller. Limiting the voltage ensures that the inputs fall within a range accepted by the microcontroller. With the photodiodes reverse biased at 5V, a maximum current of 100µA can be produced, meaning that the attached resistor cannot exceed 33kΩ. However, due to our modified light source which produces significantly less lux incident on the photodiode, our design uses 100kΩ in order to ensure a voltage range large enough to be differentiated by the microcontroller. The outputs of the photodiode-resistor circuits are input to two separate 8:1 multiplexers (muxes), as shown in Figure 8.

The necessary software that is required to move the canopy was developed in C and flashed onto the microcontroller via USB-C connection. A photodiode, centered on the top of the umbrella, is used to determine when an optimal position has been reached. It does this by comparing its current reading to a preset maximum, determined to be approximately 0.54V, which corresponds to an analog read of 645. The center diode is polled after every move to see if it is within a specific range of that maximum voltage output. If it is out of range and a move is required, then all the photodiodes are polled in order to determine which two photodiodes across the canopy have the largest voltage difference.

The umbrella can only tilt on one plane so the system twists until the greatest difference (on opposite sensors) is across that plane. The difference between adjacent photodiodes, on the illuminated half of the umbrella, is used to determine which direction the motor needs to twist. Once it has reached the correct position, the difference between opposite sensors indicates which direction to tilt the umbrella. There is a built-in counter that tracks which two photodiodes initially had the greatest difference. If the same sensor starts the movement three times in a row, the software flags the system as adjusted in order to avoid the motors making repeated, small adjustments.

2.4 Safety

The sun-tracking umbrella is designed to be user-friendly; therefore, safety of the user is a large concern. The primary concerns for this product are sudden mechanical failure of the system as well as sudden movements of the system. The former concern is mitigated by utilizing motors that are able to support the umbrella weight at any allowed angle, with or without power from the power subsystem. Sudden movements are mitigated within the software by preventing the umbrella from moving more than three times per detected light intensity difference.

In order to ensure that the umbrella does not twist or tilt further than expected, limit switches are used to stop motor movement in specific directions. These limit switches also remove any possibility of wires being broken or disconnected due to overextension. There are four limit switches in the system. There are two per motor, kept on the umbrella with custom 3D printed mounts, which can be seen in Appendix F. They are placed to ensure the umbrella is only able to rotate 180º and tilt 45º off of the z axis in each allowable direction. The implementation of these sensors as part of the overall system is explored further in Chapter 2.5 through the discussion of the software developed.

The safety subsystem also consists of fuses which limit both the incident current to the PCB as well as the outgoing current to the motors. Each motor can handle up to 1.5A of current [8], thus 1.5A fuses were utilized on the PCB to ensure motor and user safety. Incident current is limited to a total of 3A to reduce damage to the PCB in the event that maximum current is pulled by both of the motors at the same time. This prevents any burnouts on the board should excessive current be pulled. Finally, there is also the current regulation within the motor drivers themselves, which is implemented by utilizing a reference voltage and resistance. The DRV8870DDA [8] limits outgoing current as defined by

$$I_{TRIP}[A] = V_{REF}\,[V] \,/\, (10 * R_{REF}\,[\Omega]) \qquad \text{Eq. 1}$$

Thus, if we want I_{TRIP} to be 1.5A, and V_{REF} as 3.3V (as this is easily accessible from the PCB), R_{REF} must be 0.22Ω. By utilizing 0.25Ω resistors from the Electronic Services Shop to reduce product cost, the motor driver successfully limits current going to the motor as 1.5A.

2.5 Software

The software was crucial in the implementation of our design as it controlled the movement of the system based on inputs from the photodiodes, limit switches, and encoders. A full software flowchart can be found in Appendix B. The software was flashed onto the microcontroller, which is powered directly from the power subsystem, rather than through the USB connection, allowing the system to run with no external attachments.

The code prioritizes twisting the umbrella as the tilting mechanism is constrained to one plane of movement. Two photodiodes are placed opposite each other on that axis and are assigned a designated position on both muxes. This is repeated until the eight photodiodes make a perimeter around the edge of the canopy. The code iterates through all mux entries to find the photodiode pair with the largest difference. If the pair found to have the largest difference is not the pair on the tilt axis, the program tests adjacent photodiodes on the perimeter of the umbrella in order to determine which direction to twist the system. If the largest difference is on the tilt axis, the sign of the difference determines which direction to tilt the umbrella.

The program also uses signals from limit switches in order to stop the movement of the motors when they are hit. The limit switches are implemented so each switch only stops the corresponding motor in that direction of motion. This allows the umbrella to use the other motor or move in the opposite direction even if a limit switch has been pressed.

Every time a move is initiated the encoder position is set to zero. The program then tracks the number of ticks that occurs as the motor moves and once the encoder has moved 200 ticks (approximately 10^{o}), the motor is stopped. It is important to note that the limit switches are an automatic interrupt, meaning they will stop movement regardless of how much the system has turned by that point.

In order to limit small, redundant movements, the program does not allow movement if the greatest difference was detected to be across the same photodiode pair for more than three cycles in a row. Additionally, the center diode is used to determine the optimal position by comparing the polled value to a known maximum. The movement of the system completely stops once the central photodiode reads a value within 0.01V of the known maximum, which corresponds to an analog reading of approximately 13.

3. Design Verification

3.1 Power

The requirements we determined to be necessary for full functionality of the power subsystem are listed in Table 6 of Appendix A. Many of the verifications for the power subsystem were done by simply probing different test points on the PCB with a multimeter.

The first two requirements listed in Table 6 ensure that the battery chosen provides the expected voltage to the circuit and that the voltage regulator properly steps down to the voltage level needed for most other subsystems. Probe measurements and setup are shown for the incoming 9V from the battery in Figure 9, and shown for the stepped down 3.3V in Figure 10.

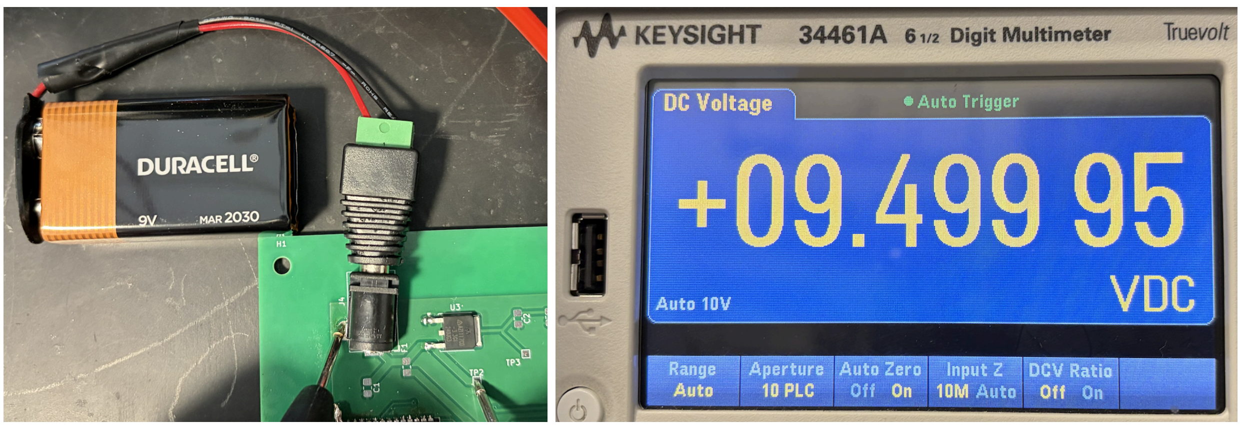

Figure 9. Probing setup and measurement of 9V supply

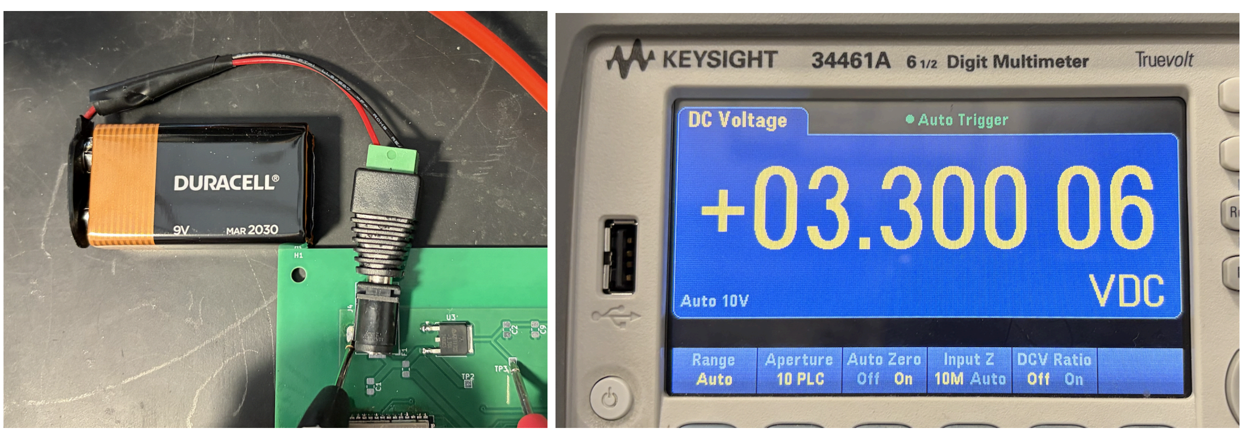

Figure 10. Probing setup and measurement of stepped down 3.3V supply

The third requirement ensures that the battery chosen will be able to power the system for a sufficient amount of time. We ran a load test on one of the batteries for one hour and recorded the voltage at the terminals every five minutes for the duration of the test. The results of this test are shown in Table 1. Since the voltage at the terminals stayed relatively constant, and above 9.5V for the full hour, it was determined that this power supply is sufficient to power the umbrella system as a whole. With this amount of power, the motor is able to hold its position for long periods of time (no power needed) and maneuver in small increments throughout a longer period of time since a constant, regulated load is able to be applied for an hour with no significant drop shown.

Table 1. Battery Longevity Test

Time Elapsed	**Battery Voltage (V)**	**Diode Voltage (V)**	**Calculated Current (mA)**
0 minutes	9.522	1.862	0.8418
5 minutes	9.580	1.863	0.8480
10 minutes	9.591	1.863	0.8492
15 minutes	9.593	1.863	0.8495
20 minutes	9.593	1.862	0.8496
25 minutes	9.593	1.862	0.8496
30 minutes	9.593	1.862	0.8496
35 minutes	9.593	1.862	0.8496
40 minutes	9.587	1.862	0.8489
45 minutes	9.583	1.862	0.8485
50 minutes	9.583	1.861	0.8782
55 minutes	9.580	1.861	0.8482
60 minutes	9.577	1.861	0.8479

3.2 Control

The control subsystem of the umbrella project has requirements and verification steps as outlined in Table 7 of Appendix A. Most verification processes are implemented through simple code segments which test functionality of the motors. With this, one knows that the motor drivers are operating properly, signals are being passed from the microcontroller to the encoders properly, and with two simple photodiodes, directional integrity can be tested as well. Figure 11 shows the physical implementation of the control subsystem on the PCB, where U4 and U5 are the motor drivers and U2 is the voltage inverter.

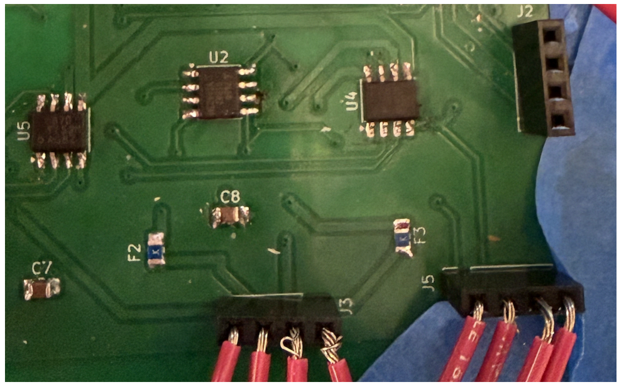

Figure 11. PCB Implementation of Control Subsystem

The first requirement of the control subsystem was the ability to move the motors in both the forward and reverse directions based on inputs from the microcontroller. This was verified by connecting a motor to one of the motor controllers and providing the correct power from the PCB, then using the ESP32 development board to send signals to the IN1 and IN2 pins of the motor controller appropriately. Upon testing we saw that the motor acted as expected, which allowed us to verify the first requirement.

$$\frac{6553\ ticks}{360\ deg} 10\ deg = 182\ ticks \approx 200\ ticks \qquad \text{Eq. 2}$$

The second requirement was the ability to move the motors in set increments of approximately 10^o. To confirm this, we first connected and powered both the motor and the encoder. Then, through a program meant to print the current number of encoder ticks to the serial monitor, we found that it takes 6553 encoder ticks for the motor to spin 360^o. This information was used to find the correct number of encoder ticks per 10^o movement, as shown in Eq. 2. Then, 200 ticks was set as the target for motion in all code segments that dealt with motor movement. This was verified during testing by ensuring that all motor movement happened in small increments.

3.3 Sensing

The requirements and verifications for the sensing subsystem are fully listed in Table 8 of Appendix A. The first requirement involves ensuring the photodiodes were biased such that for a 30lx difference in intensity, a 0.2V difference could be detected.

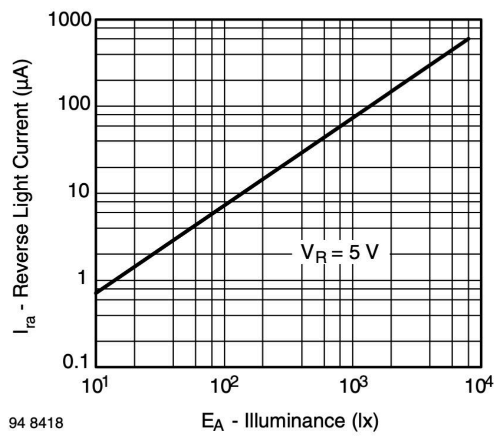

Figure 12. Current vs Illuminance

When considering a 30lx difference in intensity, the corresponding current output of a photodiode (when reverse biased at 5V) is 2µA, as shown in Figure 12. As per our requirement, this should correlate to a 0.2V difference to be read by the microcontroller. Using Ohm's Law, this requires a 100kΩ bias resistor, the placement of which can be seen in Figure 13.

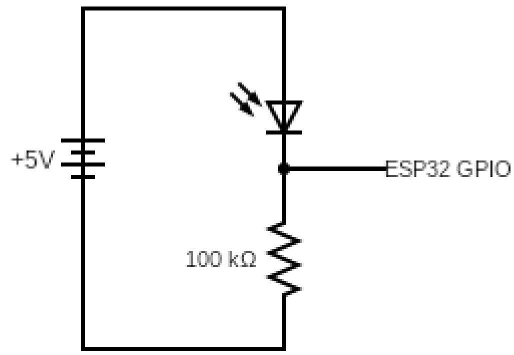

Figure 13. Example photodiode-resistor circuit

$$\frac{4095}{3.3\,V} = \frac{Analog\ Read}{Recorded\ Voltage} \quad \text{Eq. 3}$$

The system was set up to trigger motion on a 0.1V difference, which, as shown in Eq. 3, corresponds to an analog read of 125. Through testing, the 0.1V threshold was found to be a successful trigger point for motion. To ensure that all photodiodes would provide similar outputs, multiple photodiodes were tested under the same conditions. The results of these tests can be seen in Table 2, showing negligible differences between the two tested photodiodes.

Table 2. Photodiode Readings

	Photodiode 1			**Photodiode 2**		
Light Source Distance from Photodiode	1 inch	2 inches	> 3 inches	1 inch	2 inches	> 3 inches
Analog Read Value	187	81	0	179	83	0
Voltage Difference	0.15V	0.065V	0V	0.144V	0.066V	0V

Additionally, Table 2 provides insight into the second requirement for the subsystem. With the same bias resistor, the two photodiode circuit outputs were within an analog read of 8 and, from Eq. 3, an acceptable 0.06V of each other. This allowed us to use the same value of resistor for each sensor as differences between devices did not create a large difference in the readings.

The use of the central photodiode was verified during operation as the motors did not move when the reading from that sensor was within 0.01V of the maximum. As seen in Figure 14, any voltage reading above 0.53V initiated a "Halt" in the software. These readings also give some insight into the success of the sensitivity achieved as the system is able to read and react to voltage changes on the scale of 0.01V.

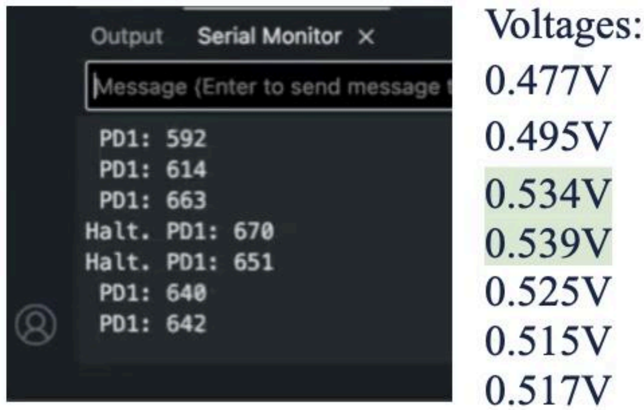

Figure 14. Outputs from Polling the Center Diode

The verification of the third requirement was also achieved during operation. The photodiodes, when illuminated, initiated the correct movements. The system would not move after the same photodiode pair had seen the largest difference three times in a row.

3.4 Safety

As safety is an important aspect of any engineering project, having redundancy within these systems is imperative. This is shown within this project through multiple ways of current limitation as well as numerous physical limitations for the moving portions of the umbrella. To ensure that these features work well, the limit switches were tested for functionality by ensuring that movement of the system stopped when a given limit switch was triggered. We also checked that the motor was still able to move in the opposite direction and that the other motor was unaffected by the limit switch being pressed. The exact requirements and verification procedures can be found in Table 9 of Appendix A.

Additionally, although the fuses were not tested directly, we have not had any instances where fuses have needed to be replaced. We do expect that the current limitations of the motor drivers work as specified in the datasheets as well, thus these aspects are not directly tested for functionality. This is also due to the fact that we were not able to pull more than 1A to the motors at any given time, even with large amounts of torque applied, such as the tilting mechanism being unable to pull the canopy back up from a steep angle.

4. Costs and Timeline

4.1 Parts and Labor

Table 3. Part Costs

Part	Manufacturer	Individual Cost ($)	Quantity Required	Component Cost ($)
Photodiodes	N/A (Eshop)	0.43	9	3.87
9V Battery	Duracell	6.99	2	13.98
Limit Switch	N/A (Eshop)	0	4	0
PCB: Toggle Switch	C&K	1.14	1	1.14
PCB: USB-C Receptacle	GCT	0.78	1	0.78
PCB: Motor Driver	Texas Instruments	2.09	2	4.18
PCB: Voltage Inverter	Renesas Electronics Corporation	2.35	1	2.35
PCB: Fuse	Vishay	0.67	3	2.01
PCB: Multiplexer	Nexperia USA Inc.	0.67	2	1.34
PCB: Resistor	N/A (Eshop)	0	10	0
PCB: Capacitor	N/A (Eshop)	0	6	0
PCB: Microcontroller	Espressif Systems	0	1	0
PCB: Voltage Regulator	Diodes Incorporated	0	1	0
PCB: Tactile Switch	N/A (Eshop)	0	1	0
Umbrella	N/A	0	1	0
Base and Turning Mechanism	ECEB Machine Shop	0	1	0
Motors	Fafeicy	19.28	2	38.56
Total				**68.21**

A cost analysis of the components required for one sun-tracking umbrella is shown in Table 3. For components alone, the cost of one umbrella system is shown to be $68.21, totalling less than half of the allotted budget of $150 per design project for the course.

Graduates from the University of Illinois Department of Electrical and Computer Engineering with Electrical Engineering degrees make on average $90,000 per year [15]. There are approximately 260 working days in a year, so this salary is around $45/hour. Assuming 30 hours for electrical design, 10 hours for mechanical manufacturing, 20 hours for electrical manufacturing, and 30 hours for software development, this totals to $45*2.5*90 = $10,125.00 for the design and manufacturing of one sun-tracking umbrella.

Taking both the components as well as labor into account, one may conclude the total cost of this project to be shown in Table 4 below.

Table 4. Total Cost

Student Labor	Parts	Machine Shop Labor	Total
3*10,125 = $30,375	$68.21	20 hours	$30,443.21

4.2 Timeline

Shown in Table 5 is a work schedule that we followed throughout the semester.

Table 5. Work Schedule

Week	Task(s)
10/6	Complete PD comparison breadboard design (Megan) Complete breadboard demo (all) Teamwork evaluation 1 (all) 1st PCB order complete (Sarah) Write design document (Dora, all) Receive motors and deliver parts to machine shop (Dora) Order PCB parts (Sarah)
10/13	Order battery and solar cells (Dora) 2nd round PCB order (Sarah) Begin writing software for and testing motors Pick up all self service parts (all) Have functional breadboard with dev board comparator implemented (all)
10/20	PCB redesigns for third PCB round (all) Write main comparator -> motor movement software
10/27	Complete breadboard design 2 (all) Combine comparator and motor software and test
11/3	Third PCB Order (Sarah) Individual progress reports (all) Begin testing for all requirements/verifications listed above (all)
11/10	Fourth PCB Order (Sarah) Prepare for mock demos (all)
11/17	Mock Demos Team contract assessment Assemble sensors on umbrella
11/24	Work on final presentation Work on final paper
12/1	Complete testing (all) Final Demo Present Mock Presentation Write Final Paper
12/8	Present Final Presentation Submit Final Paper Turn in lab notebook Lab Checkout

5. Conclusion

Most aspects of this project can be considered a success. Teamwork was consistent and thorough throughout the semester. Communication was constant and work was allotted in order to accommodate each team member's schedules through each week. Problems were addressed head-on and the necessary time was put in to complete the functionality of the project.

5.1 Accomplishments

There were many aspects that went well throughout the design and manufacturing process of this project. Notably, the power, safety, and software subsystems worked as expected. In detail, for the power subsystem, this includes the proper voltage levels being provided by the battery as well as stable voltage supply after voltage regulation on the PCB. Within safety, this includes the limit switches always stopping motor movement only in their respective direction. For software, this is mainly shown in the functionality of the system as a whole, and the intersection of all physical subsystems.

Although not mentioned directly, control and sensing saw major improvements throughout the semester. Sensing intricacies were addressed even if not shown to be perfect throughout the project and controlling of the motors became more reliable as testing of the software was concluded.

5.2 Uncertainties

Our two major uncertainties were the motors and the PCB functionality. The motors recommended to us do not have a datasheet, meaning it took longer than expected to learn motor control. This included extra tests in order to utilize the encoder and provide the motor accurate power. Ultimately, basic encoder count was achieved but more precise motor control would require additional time or motors. Additionally, with unexpected PCB delays and issues with KiCAD footprints, there was not enough time to accomplish the desired amount of testing before implementing the second half of the project. This resulted in the final PCB requiring jumper wires to function properly. There were also some other minor issues that may have been avoided had there been more diligent tests done on the earlier rounds of PCBs. Despite these complications, acceptable solutions were found that allowed us to move forward with the project. The PCB was fully functional by the final demonstration and was a great lesson in adaptability and perseverance.

5.3 Ethical Considerations

The ethical considerations that we focused on in this project are IEEE I.1 and II.9 [19], both aligning with ensuring the safety of others. To ensure no ethical breaches, we have ensured maximal safety precautions. A large concern was the umbrella possibly moving too quickly. This concern was avoided by choosing a motor that had a very high gear ratio to limit the motor speed to 10rpm. Additionally, an issue we considered was the possibility of the tilt motor not being able to hold the weight of the umbrella, causing it to fall if it tilted too much. This was accounted for by choosing a motor that is self-locking, ensuring that no power is needed to hold the motor at any given position. Finally, the limit switches associated with the tilt motor do not allow for motion past the 45^o mark, which gives an extra level of safety for the user.

5.4 Future Work

In the future, adapting the system to be functional outside, in direct sunlight, would be a main priority. Due to weather in the winter months, testing in the direct sun was not an option. This would change the associated resistance on each sensor as they would need to be scaled down in order to ensure a valid voltage was passed into the microcontroller with an acceptable amount of sensitivity. Time constraints also limited some of the desired features that could be implemented. One being an external display that allows users to view data that is being wirelessly transmitted from the PCB. This display would also include a setting for manual adjustment so the user could adjust the system as they wanted. Finally, this product would also need to be scaled to a full sized patio umbrella. It would require additional photodiodes in order to account for the large canopy. It would also need different motors that could handle the heavier system and the additional torque. New motors would also allow us to implement more motor control through PWM signals or equivalent methods.

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Appendix A. Requirement and Verification Tables

Table 6. Requirements and Verifications of Power Subsystem

Requirements	**Verification Procedure**
The battery must be able to provide 9V +/- 1.0V and up to 3A to the barrel jack of the printed circuit board.	- Ensure proper connection between barrel jack and adapter - Utilize test point to probe for incoming power information - Verify that voltage readings are 9V +/- 1 V - Verify that current readings are < 3A +/- 0.25A
The buck converter must provide 3.3V +/- 0.2V and at least 500mA of current.	- Ensure proper connection between barrel jack and adapter - Utilize test point to probe buck converter output power information - Verify that the voltage reading is 3.3V +/- 0.2V - Verify that the current reading is at least 500mA

The battery must be able to provide an average of 9V +/- 1V for a minimum of 1 hour. Current may vary.	- Ensure proper connection between battery and load
	- Run load test using LED load for 60 minutes
	- Verify that voltage remains above 8.0V for the duration of the test
	    - Record voltage readings every 5 minutes to ensure consistent power supply
	    - Record current supply to ensure true power distribution

Table 7. Requirements and Verifications of Control Subsystem

Requirements	**Verification Procedure**
H-Bridges are able to move motors in the forward and reverse directions based on signals received from the microcontroller.	- Program the microcontroller such that a signal is sent to each h-bridge to rotate the motors forward at 10rpm in order to confirm motor speed - Run said program on the microcontroller and verify that motors are running at 10rpm +/- 1rpm in the forward direction - Once prior verification is complete, program the microcontroller such that a signal is sent to each h-bridge to rotate the motors backwards at 10rpm - Run backwards movement program on the microcontroller and verify that both motors are running at 10rpm +/- 1rpm in the reverse direction
H-Bridges must be able to move the motors a set rotation to within 10°.	- Ensure proper connection to motors from h-bridges and verify movement functionality prior to testing rotation accuracy - Program the microcontroller to tell the h-bridges to rotate a set amount - Ensure that starting position is at a stationary point of measurement - the edge of a table or marked surface - Rotate the motors a set amount and use a protractor to verify rotation accuracy to within 10° (+/- 2.5°) of supposed position - Read encoder values to ensure rotation is accurately completed (approximately 200 ticks per 10°)

Table 8. Requirements and Verifications of Sensing Subsystem

Requirements	**Verification Procedure**
PDs on opposite sides detect a difference of 0.2V with a difference in intensity of 30 lx.	- Manually illuminate the photodiodes in a dark room and record the output of the photodiodes prior to connecting them to the PCB - Run the same test in a lit room and ensure the same sensitivity is maintained - Probe the outputs of the PCB to ensure that the corresponding changes match the difference in intensity detected
PDs/system have a tolerance that determines whether "best case" scenario was reached.	- Adjust the connected resistor during manual testing so the voltage output at the same intensity is as close as possible for each photodiode - The system does not poll the photodiodes when the center photodiode is within 0.01 of maximum recorded voltage output
The system does not adjust more than three times in a row for the same photodiode pair.	- Ensure that all but one pair of photodiodes are completely blocked from all incident light - Take a 30 lumen device (such as a phone flashlight), and illuminate one half of the photodiode pair - Verify that the control subsystem effectively moves the umbrella based on the incident light - Take the same 30 lumen device and illuminate the other half of the photodiode pair (the photodiode opposite the one previously used) - Verify that the control subsystem effectively moves the umbrella based on the incident light - Repeat steps 2 - 4 - Verify that the control subsystem DOES NOT make any changes to the umbrella state as this will be comparing the same photodiodes more than 3 times and making adjustments accordingly, which is NOT desired

Table 9. Requirements and Verifications of Safety Subsystem

Requirements	**Verification Procedure**
Limit switches successfully halt all motor movement in the specified direction when the mechanism hits 180/45 degrees as described in the motor requirements.	- Ensure proper functionality of motor movement with photodiode input - Shine phone flashlight on photodiode to induce motor movement in a constant direction - Hold phone flashlight over photodiode to ensure movement through degree of motion of mechanism - Ensure movement halts when the limit switch is reached - Take flashlight away from photodiode and reintroduce light to ensure motor does not continue movement when at movement limit (repeat for all limit switches)
Fuses successfully limit current going to motors at 1.3A as this is the	- Ensure proper functionality of motor movement - Attempt to drive motor at high torque to induce high current pull from the PCB

maximum rating for the motors.	- Ensure fuse trips and/or current does not surpass 1.3A for an individual motor (repeat for second motor/fuse set)

Appendix B. Software Flowchart

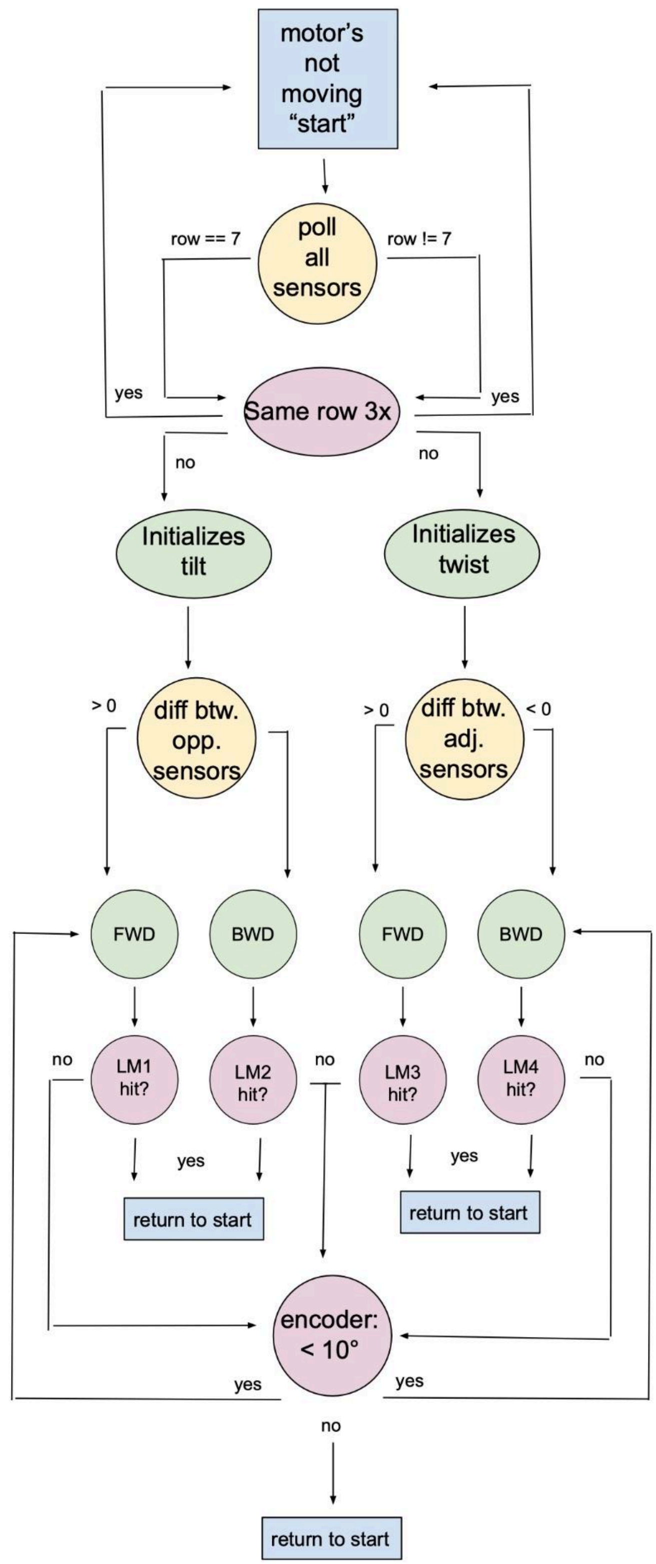

Figure 15. Full software flowchart

Appendix C. Pin Configuration

Table 10. Pin Usage on ESP32-S3-WROOM-1

Name	Pin #	Function	Name	Pin #	Function
GND	1	GND	IO14	22	Limit switch 4 (input)
3V3	2	Power Supply	IO21	23	Mux 2 S2 (output)
EN	3	Enable	IO47	24	Mux 2 S1 (output)
IO4	4	Motor 1 Encoder A (input)	IO48	25	Mux 2 S0 (output)
IO5	5	Motor 1 Encoder B (input)	IO45	26	Unused (strapping pin)
IO6	6	Motor 2 Encoder A (input)	IO0	27	Unused (strapping pin)
IO7	7	Motor 2 Encoder B (input)	IO35	28	Unused
IO15	8	Motor 1 Forward (output)	IO36	29	Unused
IO16	9	Motor 1 Reverse (output)	IO37	30	Unused
IO17	10	Motor 2 Forward (output)	IO38	31	Unused
IO18	11	Motor 2 Reverse (output)	IO39	32	Unused
IO8	12	Unused	IO40	33	Unused
IO19	13	USB_D-	IO41	34	Unused
IO20	14	USB_D+	IO42	35	Unused
IO3	15	Mux 1 S2 (output)	RXD0	36	Unused
IO46	16	Unused	TXD0	37	Unused
IO9	17	Mux 1 S1 (output)	IO2	38	Mux 1 Output (input)
IO10	18	Mux 1 S0 (output)	IO1	39	Mux 2 Output (input)
IO11	19	Limit switch 1 (input)	GND	40	GND
IO12	20	Limit switch 2 (input)	EPAD	41	GND
IO13	21	Limit switch 3 (input)			

Appendix D. Sunlight Proof

Table 11. Necessary quantities

	Beam diameter	Half Angle	Solid Angle	Beam Intensity	Illuminance
2.5 cm away	0.08m	58°	2.95sr	45.7cd	7.312 per cm^2
5 cm away	0.105m	46.5°	1.95sr	69.2cd	2.768 per cm^2

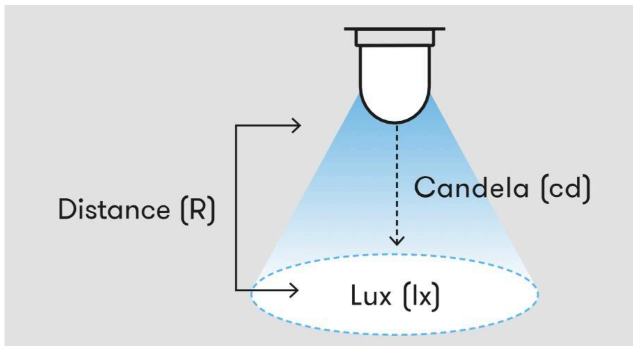

Figure 16. Lux calculation diagram [21]

Beam Angle from Measurements:

1. $distance\ (d)\ =\ 0.05m\ \&\ beam\ diameter\ (s)\ =\ 0.105m$
   Since the beam forms a cone from a single point, the half angle defines the angle from the centerline to the rim of the beam:
   $half\ angle\ geometry\text{: } tan(\frac{\theta}{2})\ =\ \frac{s}{2d}\ =\ \frac{0.105}{2\cdot 0.05} = 1.05$
   $\frac{\theta}{2}\ =\ arctan(1.05)\ \simeq\ 46.5°$
2. $distance\ (d)\ =\ 0.025m\ \&\ beam\ diameter\ (s)\ =\ 0.08m$
   $half\ angle\ geometry\text{: } tan(\frac{\theta}{2})\ =\ \frac{s}{2d}\ =\ \frac{0.08}{2\cdot 0.025} = 1.6$
   $\frac{\theta}{2}\ =\ arctan(1.6)\ \simeq\ 58°$

Solid Angle of the Beam:

For a cone: $\Omega\ =\ 2\pi(1\ -\ cos(\frac{\theta}{2}))$

1. $cos(46.5°)\ \simeq\ 0.69$
   so $\Omega\ =\ 2\pi(1\ -\ 0.69)\ \simeq\ 1.95sr$
2. $cos(58°)\ \simeq\ 0.53$
   so $\Omega\ =\ 2\pi(1\ -\ 0.69)\ \simeq\ 2.95sr$

Lumes:

$\varphi\ =\ 450\ lumens$ and on average, 30-50% make it to the desired surface. Assuming a 30% transfer rate:
$\varphi beam\ =\ 0.3\ \cdot\ 450\ =\ 135lm$

1. $beam\ intensity\ (candela)\ =\ \frac{\varphi beam}{\Omega} = \frac{135}{1.95} =\ 69.2cd$
2. $beam\ intensity\ (candela)\ =\ \frac{\varphi beam}{\Omega} = \frac{135}{2.95} =\ 45.7cd$

Illuminance:

1. $distance\ to\ table\ (d)\ =\ 0.05m\ so\ d^2\ =\ 0.0025$

   $Illuminance\ \simeq \frac{cd}{d^2}\ =\ \frac{69.2}{0.0025} = 27,680$

   $E\ =\ 27,680\ lx$

2. $distance\ to\ table\ (d)\ =\ 0.025m\ so\ d^2\ =\ 0.000625$

   $Illuminance\ \simeq \frac{cd}{d^2}\ =\ \frac{45.7}{0.000625} = 73,120$

   $E\ =\ 73,120\ lx$

Table 12. Illuminance based on source

Source	Illuminance
Flashlight: 2 inches away	27,680
Flashlight: 1 inch away	73,120
Bright Sunlight [20]	> 110,000
Typical Overcast Day [20]	1-2,000

Holding the same ratio, a 66kΩ would result in the same sensitivity. However, as a safety precaution, since the maximum current output is 1mA, the new bias resistor cannot exceed 3.3kΩ. Additional features like a low pass filter and smoothing out the readings would help the sensitivity with the limited bias resistor.

Appendix E. Full PCB Schematic and Layout

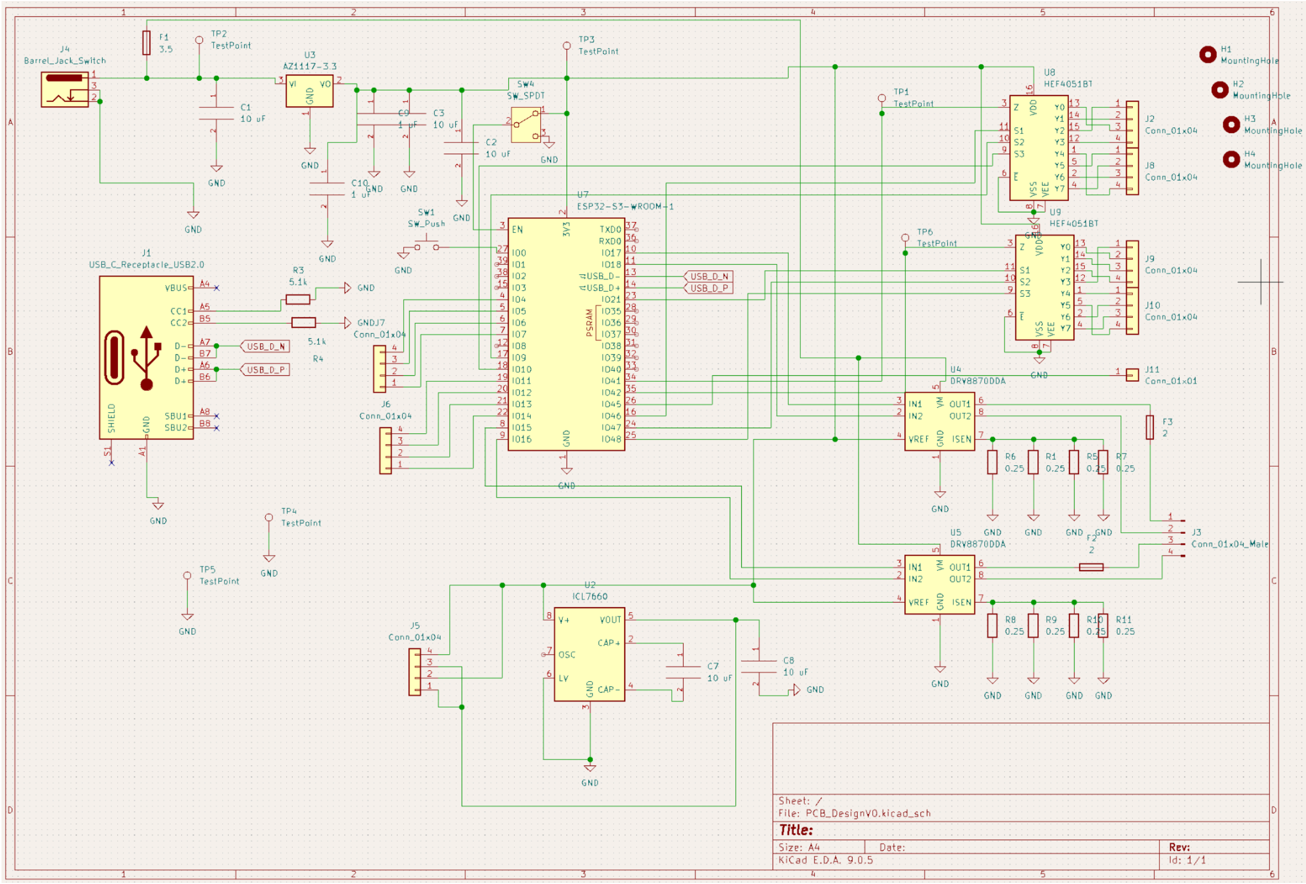

Figure 17. Full PCB Schematic

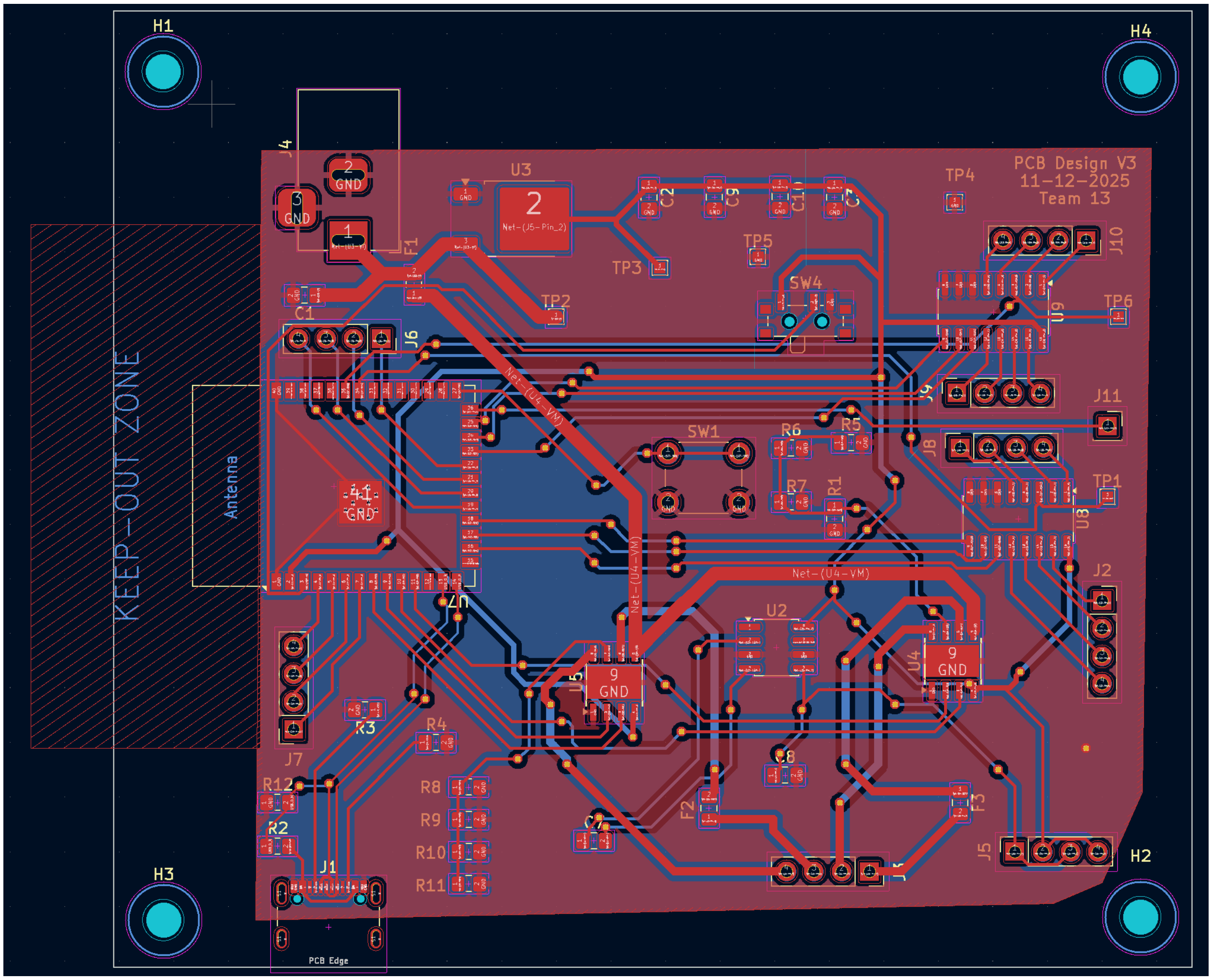

Figure 18. Full PCB Layout

Appendix F. Limit Switch Mount CAD

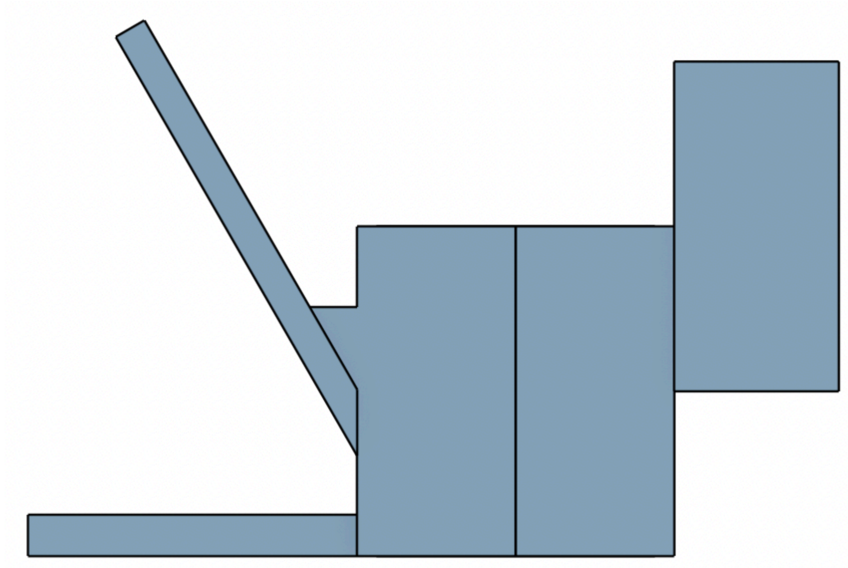

Figure 19. Limit switch mount (front view)

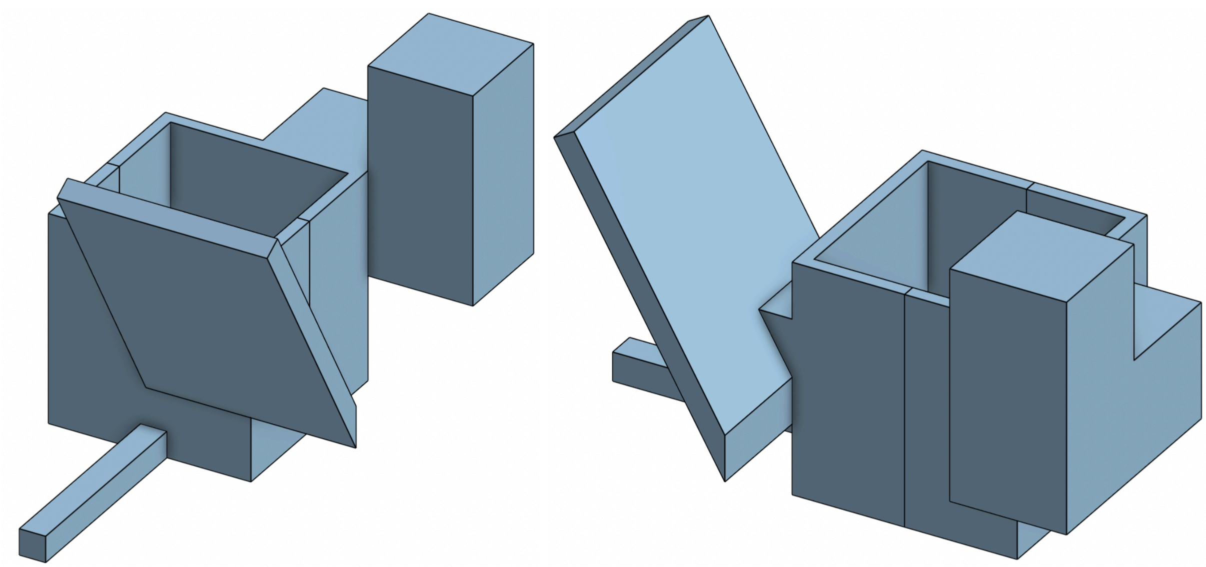

Figure 20. Limit switch mount (isometric views)