

# Automatic Mirror for Plant Lighting

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# **1. Introduction**

## **1.1 Problem**

There are many situations where a person wants to grow a plant, but there isn't enough light where they want to grow it. An example of this is an apartment or room without a south-facing window, which would not provide enough direct sunlight for many plants. Another example is a garden or deck which was originally in the sun but became more shady as the surrounding trees grew. Many full-sun or partial-sun plants grown in these environments will have poor health or die due to the insufficient amount of sunlight they receive. Full-sun plants need at least 6 hours of direct sunlight while partial-sun plants need 3-6 hours of direct sunlight.

The inability to grow many plants in shady environments has negative impacts on mental health. A study from the National Library of Medicine has shown a link between indoor plants and decreased stress. Increasing the amount of plants that can be grown in indoor spaces would help to reduce the stress of the public. People would also likely be more satisfied with their living spaces as they would have more choices of which plants to grow. More fresh fruits and vegetables could also be grown in shady areas, since they are produced by full-sun plants. This would improve the physical health of the public by making nutritious and fresh food more widely available.

## **1.2 Solution**

We will build a device that uses a sun-tracking flat mirror to redirect sunlight towards the plant in a non-south facing window or other shady space. The device will be powered by a battery, which will allow it to be mounted outside of a window or be placed on a yard or deck. It will use a GPS

signal and compass to determine the time, location, and orientation of the device. This data will be used by a microcontroller to determine the position of the sun in the sky relative to the device. On setup, the device will be calibrated to reflect the sun at the desired angle, and the microcontroller will move the mirror to continue reflecting the sun at this angle. The mirror will be attached to a horizontal axle which will be connected by two supports to the base. The base will rotate to allow for rotation parallel to the ground and there will be a motor connected to the horizontal axle that allows for rotation perpendicular to the ground. The device will also use a light sensor to determine when it is night time or the weather is poor so that it can save energy. This device will be able to provide the extra sunlight that many plants need to thrive in shady spaces.

### 1.3 Visual Aid

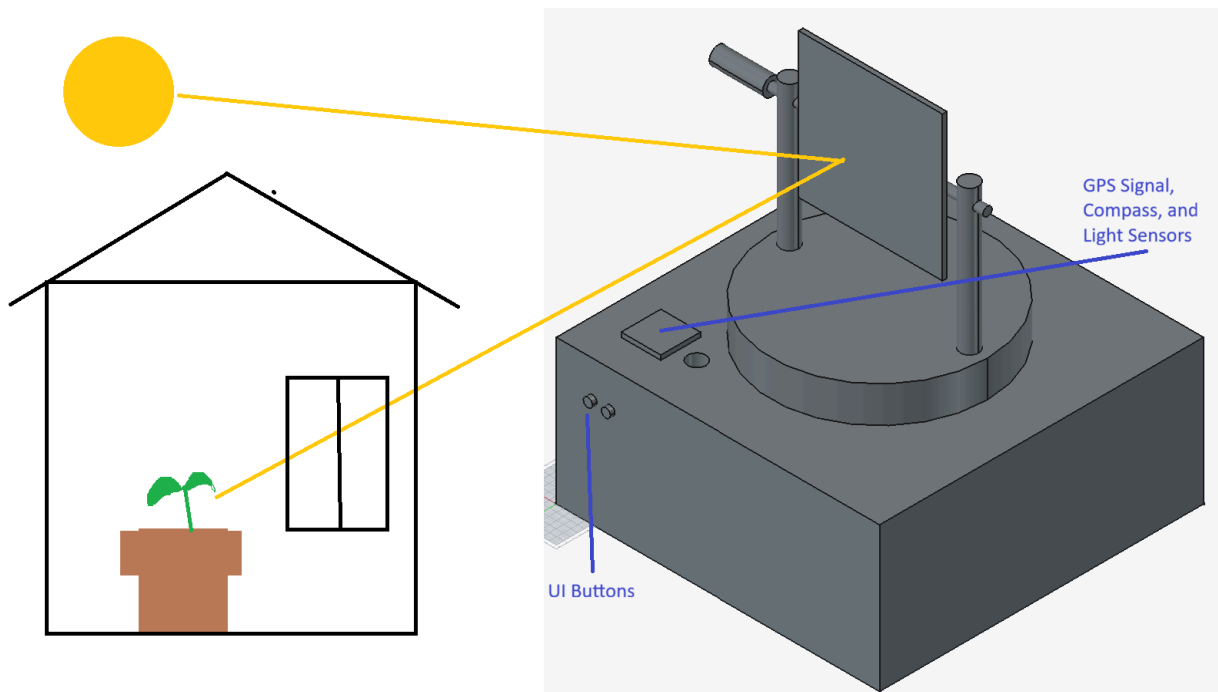


Figure 1: Visual Aid for Automatic Mirror Displaying Interactions with Environment

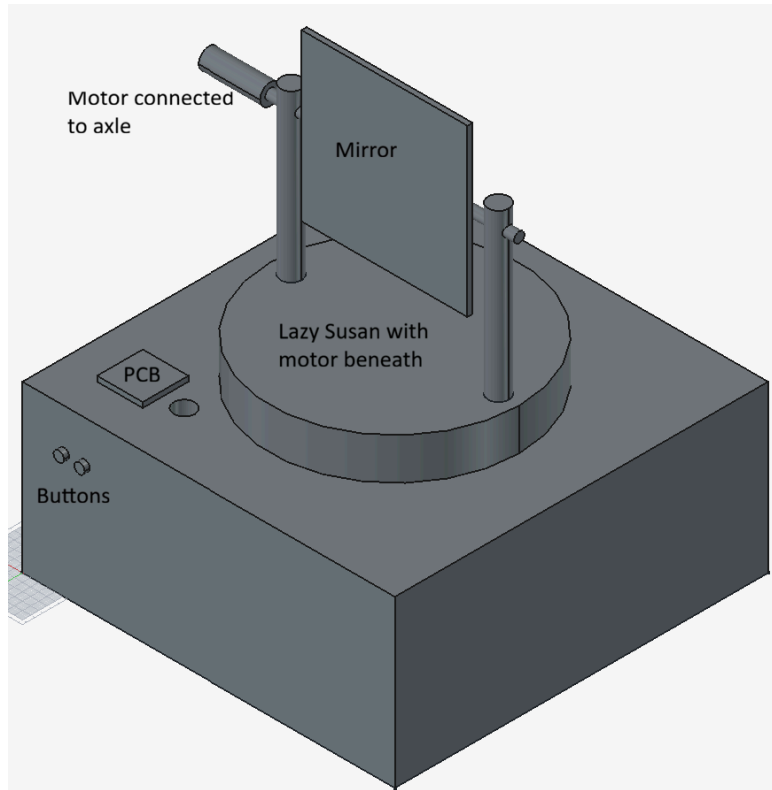


Figure 2: Visual Aid for Automatic Mirror with Labeled Components

#### 1.4 High-level Requirements List

In order to successfully redirect the sun to the plant in the shade, the project must exhibit the following characteristics.

1. **Position Calculations:** The device should be able to calculate the position of the sun in the sky within 1 degree of error at any time of the day and location. It should also be able to calculate the position of the target point after set-up to within 2 degrees of error. Using the sensor data to correctly determine the positions of the sun and target points is the first step to redirecting the sun.
2. **Movement Accuracy:** The device should be able to redirect the light from the sun to the target point at any time of the day as long as the reflection angle is realizable within 5

degrees of error. It should also be consistent and keep the target point illuminated for more than 90% of the time.

3. **Power Efficiency:** The device should save power by not adjusting if the reflection angle is not realizable within 5 degrees of error or the light level is below 500 lux. The device should be able to operate for at least a day on a single battery charge.

## 2. Design

### 2.1 Block Diagram

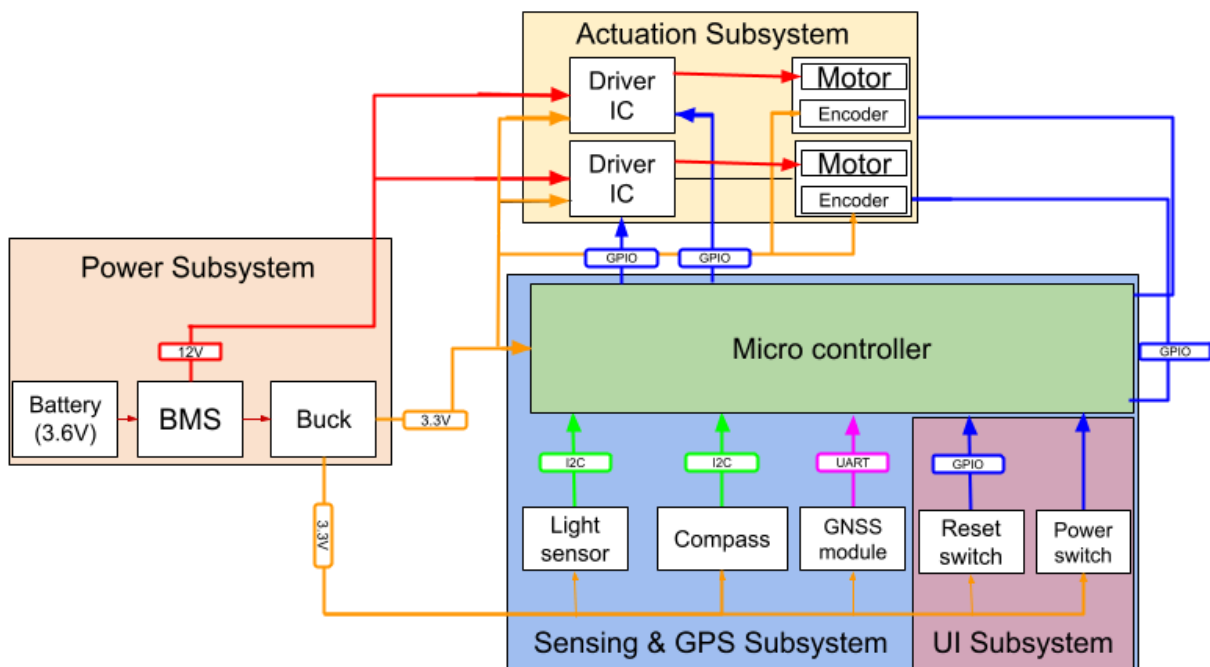
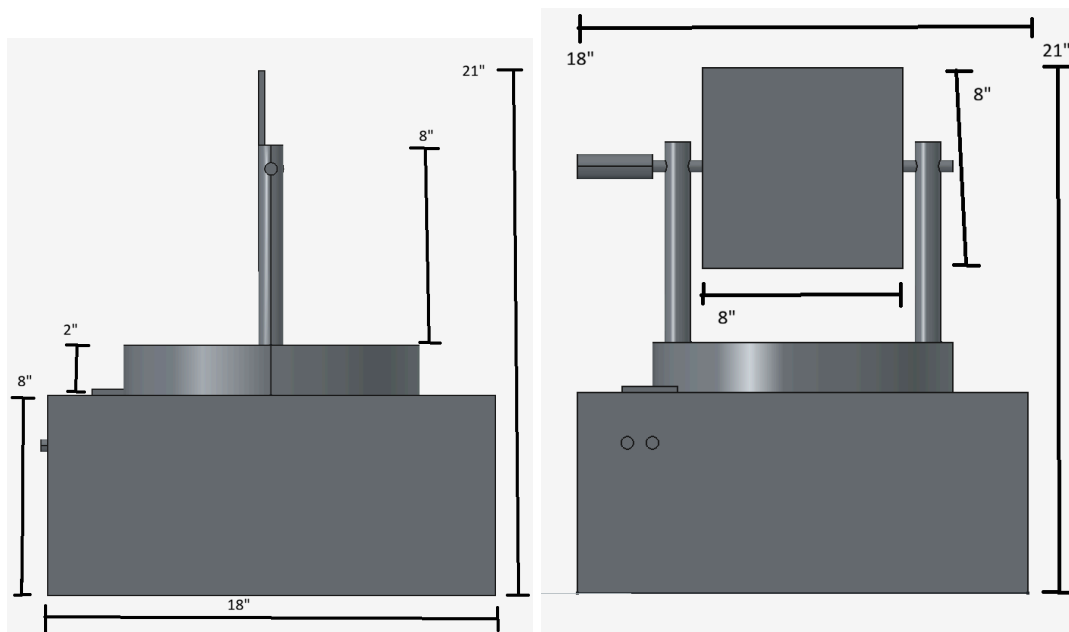


Figure 3: High level block diagram for Automatic Mirror

The system is built around a microcontroller that coordinates five subsystems. The power subsystem uses a rechargeable 14.4 V lithium-ion battery pack with a battery management system that protects against unsafe conditions such as overcharging, over-discharging, short circuits, and overheating. The pack drives the motors directly, while a regulator provides 3.3 V for the electronics. The actuation subsystem uses two motors with position feedback to rotate an

8" × 8" mirror horizontally and vertically, aiming reflected sunlight at the plant. The sensing and GPS subsystem measures ambient light, the device's compass heading, and its location and time using a GPS module with an external antenna. From this information, the microcontroller calculates where the sun is and how to angle the mirror, then moves the motors into position. Finally, the user interface provides a power switch to turn the system on and off and a reset switch to restart it.

## 2.2 Physical Design



Figures 4 & 5: Side View and Front View of Automatic Mirror with Dimensions

The Automatic Mirror frame consists of a mirror connected to a horizontal axle on two supports with a Lazy Susan beneath them, and a base below the Lazy Susan. The base contains the batteries in their container, a motor connected to the Lazy Susan, and buttons for the user to interact with. The PCB is on top of the base and is connected to the motors, buttons, and batteries. There is also a motor connected to the horizontal axle that allows the mirror connected to the axle to rotate. The mirror is an 8in by 8in square and the overall device is around 18in by

18in by 21in. The dimensions and shape of the supports and base may change, as we are working with the ECE machine shop to create the frame. The dimensions in this diagram are meant to give the device a sense of scale and are not final except for the mirror itself.

## **2.3 Power Subsystem**

The power subsystem consists of three main components: batteries, a battery management system (BMS), and a buck converter. Four 18650 battery cells connected in series serve as the power source for the entire circuit. We chose to use four 18650 battery cells in series to provide enough voltage to the motor without a boost converter, and to ensure that 3.3V could be provided with only a buck converter. A BMS module will be attached between the battery and the rest of the system to isolate the battery from the circuit in order to protect circuit elements and prevent overcharge and overdischarge of the battery. The output of the BMS module will then be used to provide the motors with around 12V DC, as these components require the highest voltage. The BMS output is also connected to a buck converter to ensure steady 3.3V DC supply for the sensors, encoders, and microprocessor. The power subsystem must be able to provide the correct amount of voltage to the components of the other subsystems, and it must be able to provide enough current during high-demand processes like moving the motors. If this subsystem fails, the other subsystems may not receive enough power to operate, or they could receive too much which could damage their electrical components. The requirements for this subsystem are meant to ensure correct connection of its components and adequate voltage and current supply to the other subsystems.

| Requirements                                                                                                                                                                                                                                                                                                                                                                           | Verification                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>The BMS can shut off power within 500us in a short-circuit event to prevent components from being damaged due to excessive heat.</p>                                                                                                                                                                                                                                                | <p>A spare BMS will be connected to a lab power supply and a lab e-load. An oscilloscope is connected to the e-load and the power supply to measure the voltage input to the BMS and the voltage output by the BMS. The e-load is then used to simulate a short circuit and the time taken for the BMS to respond is determined from the oscilloscope. The oscilloscope connected to the power supply can also indicate if the power supply shut its power off before the BMS responded.</p>                                                                                                                   |
| <p>The BMS is able to output current equal to at least 90% of the battery's maximum current rating, but it does not output current greater than the current limit of the battery. The rated discharge current of the batteries is 20A while our circuit should not require more than 3A, so this will also determine if our BMS provides enough current for the device to operate.</p> | <p>A spare BMS will be connected to a lab power supply and a lab e-load. An oscilloscope is connected to the e-load and the power supply to measure the voltage input to the BMS and the voltage output by the BMS. The e-load is then used to simulate a resistor and its resistance is decreased until the BMS disconnects the circuit due to too much current. The current in the circuit when the BMS responds can be recorded from the e-load display and analyzed. The oscilloscope connected to the power supply can also indicate if the power supply shut its power off before the BMS responded.</p> |
| <p>When the motors demand the maximum 1.66 A current draw from the BMS, the BMS output voltage does not drop below 4.7V. This is because the motor can operate below 12V, but the 3.3V buck converter needs at least 4.7V to operate.</p>                                                                                                                                              | <p>An oscilloscope is set up to record the voltage output by the BMS. The microcontroller sends a command to the drivers to run the motors disconnected from the frame at their rated current of 0.83 A each. After 1s, the oscilloscope is read to determine if the minimum voltage output by the BMS stays above 4.7V.</p>                                                                                                                                                                                                                                                                                   |
| <p>The BMS outputs the same voltage as the series of batteries within 10% variation when they are connected.</p>                                                                                                                                                                                                                                                                       | <p>An oscilloscope is used to measure the voltage of the series of batteries and the voltage output by the BMS. These two voltage measurements are then compared to see if they vary by less than 10%.</p>                                                                                                                                                                                                                                                                                                                                                                                                     |
| <p>The buck converter outputs 3.3V DC with 10% variation respectively when connected to the powered BMS.</p>                                                                                                                                                                                                                                                                           | <p>An oscilloscope is used to measure the output voltage of the buck converter. The maximum and minimum voltage is inspected to</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |

|  |                                                              |
|--|--------------------------------------------------------------|
|  | determine if the output voltage stays within 10% of 3.3V DC. |
|--|--------------------------------------------------------------|

Table 1. Requirements and verifications for power subsystem

## 2.4 Actuation Subsystem

The actuation subsystem consists of two sets of DRV8871 circuits and DC gear motors. The DC gear motor receives an average of around 12V DC from the batteries, and the current to the motor is controlled by the DRV8871 circuit. The DRV8871 circuit is powered by 3.3V DC from the buck converter. This circuit receives GPIO signals (pulses) from the microcontroller, which causes it to send a pulse of current to the motor. This pulse of current causes the motor to apply a torque in a direction. Encoders that are integrated in the motor units will also be connected to the micro controller through GPIO pins, providing position feedback of the elements that are attached to the motor shafts. The encoders will be powered from 3.3V DC supply. If this system does not function correctly, light may not be accurately redirected to the plant even if the other subsystems work properly. The actuation subsystem must be able to move the motors correctly based on the signals sent from the microcontroller to the DRV8871 circuit over GPIO. The motor encoders must also send accurate signals to the microcontroller over GPIO to ensure the position of the mirror can be correctly measured.

| Requirements                                                                                                      | Verification                                                                                                                                                                                                                                                                                                                                                    |
|-------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Signals from the microcontroller should be able to cause the DRV8871 circuit to supply PWM voltages to the motor. | Connect the DRV8871 to the microcontroller, the motor and the power subsystem. Command forward rotation for 2s, brake (IN1 = IN2 = 1), then command reverse for 2s. Probe OUT1 and OUT2 with a two-channel oscilloscope to confirm the output polarity reverses, and check that the encoder count increases during forward motion and decreases during reverse. |
| Each DRV8871 drives its motor at the motor's                                                                      | Mount the motor on the frame, or load its                                                                                                                                                                                                                                                                                                                       |

|                                                                                                                                                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| rated operating point (12 V average, approximately 0.83 A load current) for 5 minutes continuously without thermal shutdown or current-limit chopping. | shaft so it draws approximately 0.83 A. Set the PWM duty cycle so the average motor voltage is 12 V, measured with a DMM across the motor terminals. Measure the motor current with a DC current probe to confirm approximately 0.83 A. Run the motor for 5 minutes while monitoring OUT1 and OUT2 on the oscilloscope, and confirm that the output never stops (no thermal shutdown) and shows no chopping (current stays below the current limit).                                                                                                                                                                                                          |
| The encoders should be able to measure the orientation of the motors within 0.5 degrees of error.                                                      | Only the encoder is powered by the power subsystem and the rest of the motor is off. An oscilloscope is connected to the encoder's output to count the number of voltage pulses sent to the microcontroller. A marker is added to the motor shaft and body and they are aligned. The motor shaft is then rotated one full time until the markers align again, and the number of voltage pulses sent to the oscilloscope is measured. This number of pulses is compared to the number of pulses corresponding to a 360 degree rotation for the reduction ratio of the motor.                                                                                   |
| The microcontroller should be able to rotate each motor to a target orientation within 1 degree of error when connected to the frame.                  | The actuation subsystem is fully connected and the motors are connected to the frame. An oscilloscope is connected to the encoder's output to count the number of voltage pulses sent to the microcontroller. The microcontroller sends a run command to the DRV8871 until the microcontroller detects that it has reached its target position. The number of pulses from the encoder on the oscilloscope is then used to compare to verify the accuracy of the rotation. If the encoders were found to be accurate in the previous requirement, this should be a valid way to determine the accuracy of the motor rotation due to the microcontroller input. |
| When the motors are attached to the frame, they should be able to rotate a full 270 degrees in their movement range.                                   | The actuation subsystem is fully connected and the motors are connected to the frame. Both motors are manually positioned at one end of their movement range. The                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |

|  |                                                                                                                                                                                                                                 |
|--|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | microcontroller then sends a command to both motors to rotate 270 degrees. The resulting motion is observed to ensure the frame allows for a sufficient range of motion and that there are no problems with the motor function. |
|--|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table 2. Requirements and verifications for actuation subsystem

## 2.5 Sensing & GPS Subsystem

This subsystem includes the microcontroller, light sensor, compass, GNSS module, and an antenna. The GNSS module measures the position of the device and the time of day to calculate the position of the sun in the sky relative to the device. The GNSS also has an antenna with a complicated implementation, which is explained more below the requirements. This subsystem then uses equations to determine where the mirror should be focused to redirect light to the target point. The microcontroller sends signals to the DRV8871 in the actuation subsystem to move the mirror to the position that it calculated, and it receives signals from the encoders in the actuation subsystem to ensure that the mirror moves to this position. The light sensor also shuts down the device to save power if there is not enough light to be redirected to the plant. If this subsystem does not function correctly, the device will not redirect the sun to the correct target point. It could also cause the motors to move too much or the device to keep running at night or in bad weather, which could cause too much power consumption.

| Requirements                                                                                  | Verification                                                                                                                                                                                                                                                                  |
|-----------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| RF path should be able to provide accurate signal to the GNSS module.                         | RF impedance matches the values shown below when analyzed by a Precision LCR Meter in the lab. When the device is powered and the GNSS module is connected to the microcontroller, the microcontroller should be able to receive valid GNSS data on the I <sup>2</sup> C bus. |
| The light sensor shall measure ambient light within $\pm 15\%$ of a reference lux meter, from | Place the sensor and a reference lux meter side by side at 5 light levels across that range.                                                                                                                                                                                  |

|                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| dim indoor light (~10 lux) to bright outdoor light (~10,000 lux).                                                                                                  | At each level, compute the percent error between the sensor reading (read over I <sup>2</sup> C) and the reference, and confirm all errors are within $\pm 15\%$ .                                                                                                                                                                                                                                                                                   |
| The 3-axis magnetometer shall report the device's heading within $\pm 2^\circ$ of true magnetic heading after calibration, including while the motors are running. | Calibrate the MMC5983MA . Then, using a reference compass, rotate the device through 8 headings (every $45^\circ$ ) and record the reported heading at each, first with the motors off and then with both motors at full duty cycle. Confirm all errors are within $\pm 2^\circ$ .                                                                                                                                                                   |
| The microcontroller should be able to calculate the position of the sun in the sky relative to the device within 1 degree of error.                                | The device should be powered by the power subsystem and all sensors should be checked for correct functionality. The true position of the sun in the sky can be determined using an online source for the exact time and location of the device. The device will then be powered on and the position of the sun calculated by the microcontroller will be compared to the true position of the sun to see if the result is within 1 degree of error. |
| The microcontroller should be able to calculate when the reflection angle is not realizable within 5 degrees of error.                                             | When the microcontroller is provided with a test target point and position of the sun, it should calculate if the angle of reflection is not realizable. If the requirements that the target point is correct within 2 degrees of error and that the sun's position is correct within 1 degree of error are met, then the reflection angle will be correctly identified as not realizable within 5 degrees of error.                                 |

Table 3. Requirements and verifications for sensing & GPS subsystem

Below is the conceptual diagram highlighting the RF receiver/ antenna side for the GNSS module.

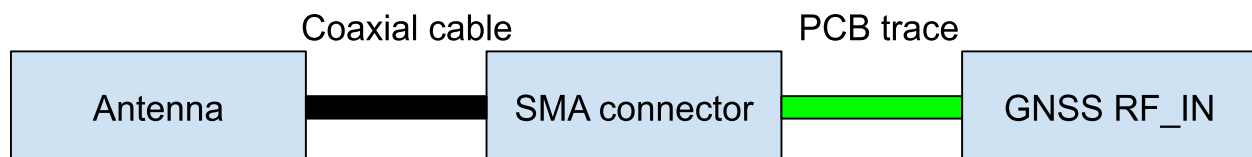


Figure 6. Configuration of GNSS signal path

The GNSS signal that was received by the external antenna is passed down to coaxial cable, SMA connector and then RF\_IN pin of the GNSS module through the PCB trace to. Since the frequency of the GNSS signal that is received by the antenna is 1575Mhz, the wavelength of the signal can be calculated with the equation below, using effective permittivity of 2.8.

$$v_p = \frac{c}{\sqrt{\epsilon_{eff}}} \approx \frac{3 \times 10^8}{\sqrt{2.8}} \approx 1.8 \times 10^8 \text{ m/s}, \quad \lambda_g = \frac{v_p}{f} \approx 114 \text{ mm}$$

As a rule of thumb, a trace longer than about 10% of the signal's wavelength cannot be treated as a lumped element and must instead be analyzed as a transmission line. Here, 10% of 114 mm is 11.4 mm. This is a significant length compared to the PCB's dimensions of up to 100 mm × 100 mm, so depending on component placement, the RF trace could easily exceed it. Thus, PCB traces should be designed as a transmission line and impedance matching between the elements have to be considered.

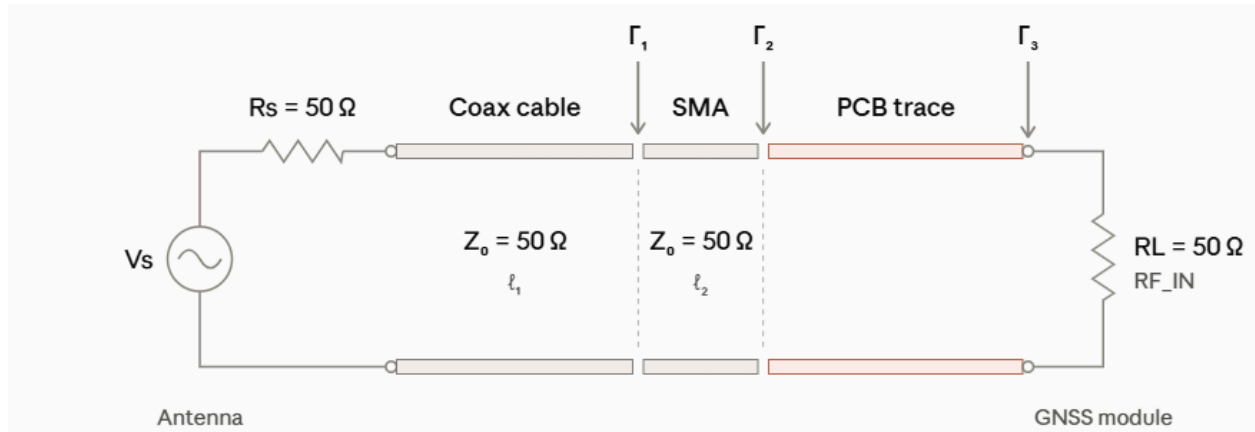
Below is a chart showing the characteristic impedance of the elements that are related to the GNSS signal path.

| Name                | Characteristic impedance [ $\Omega$ ] | Source                           |
|---------------------|---------------------------------------|----------------------------------|
| Anetenna            | 50                                    | <a href="#">Datasheet</a> page 2 |
| SMA connector       | 50                                    | <a href="#">Datasheet</a> page 1 |
| GNSS module (RF_IN) | 50                                    | <a href="#">Datasheet</a> page 7 |

Table 4. Characteristic impedance of antenna, SMA connector and GNSS module

Figure below shows the transmission-line equivalent of the GNSS RF signal path. The active antenna is modeled as a source with a 50  $\Omega$  output impedance. The coaxial cable, SMA connector, and PCB trace are modeled as cascaded transmission-line sections, each with a characteristic impedance of 50  $\Omega$ , and the RF\_IN pin of the GNSS module is modeled as a 50  $\Omega$

load.



$$\Gamma_1 = \frac{Z_{0,\text{SMA}} - Z_{0,\text{coax}}}{Z_{0,\text{SMA}} + Z_{0,\text{coax}}} = 0, \quad \Gamma_2 = \frac{Z_{0,\text{trace}} - 50}{Z_{0,\text{trace}} + 50}, \quad \Gamma_3 = \frac{R_L - Z_{0,\text{trace}}}{R_L + Z_{0,\text{trace}}}$$

Figure 7. Transmission line equivalent of GNSS signal path

Where  $\Gamma$  represents the reflection coefficient. Since the goal is to deliver all the signal that was received by the antenna,  $\Gamma_3$  and  $\Gamma_2$  have to equal 0. Thus, characteristic impedance of the PCB trace  $Z_{0,\text{trace}} = 50 [\Omega]$ .

To achieve the characteristic impedance of 50 [ $\Omega$ ], PCB trace that connects the RF\_IN pin of the GNSS module and the SMA connect will be fabricated as coplanar waveguide with shielding vias, as shown in the figure below.

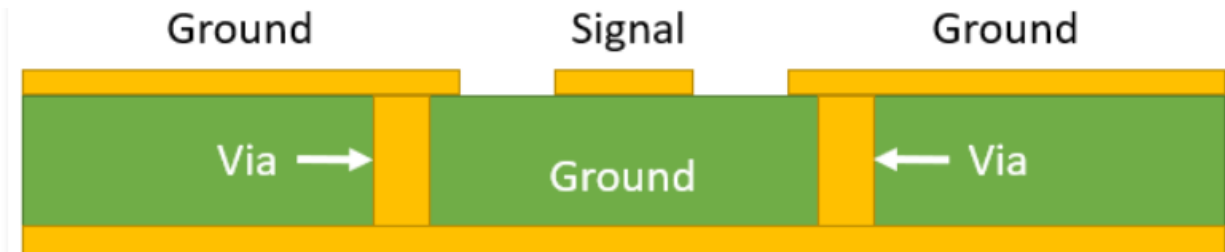
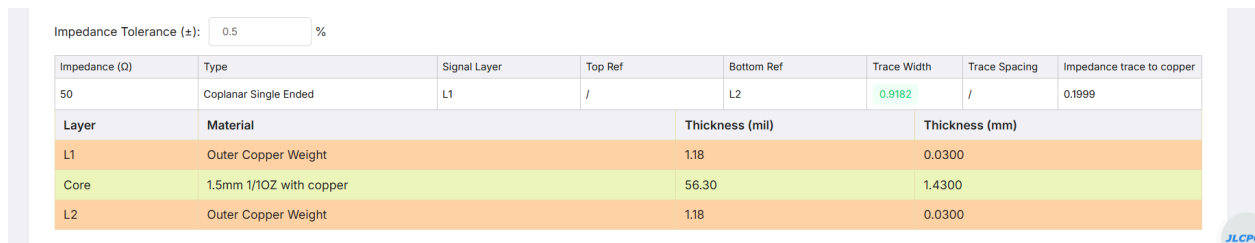


Figure 8. Coplanar structure of the waveguide with shielding vias

Considering JLCPCB's minimum trace spacing of 0.1 mm for 2-layer boards, the gap between the signal trace and the coplanar ground will be set to 0.2 mm. This provides a 100% margin over the manufacturing limit, avoiding the risk of shorts between the signal and ground and reducing the effect of etching variation on the characteristic impedance. With this gap, the JLCPCB impedance calculator gives a trace width of 0.918 mm for a 50  $\Omega$  characteristic impedance, as shown in the figure below.



| Impedance ( $\Omega$ ) | Type                  | Signal Layer | Top Ref | Bottom Ref | Trace Width | Trace Spacing | Impedance trace to copper |
|------------------------|-----------------------|--------------|---------|------------|-------------|---------------|---------------------------|
| 50                     | Coplanar Single Ended | L1           | /       | L2         | 0.9182      | /             | 0.1999                    |

| Layer | Material                | Thickness (mil) | Thickness (mm) |
|-------|-------------------------|-----------------|----------------|
| L1    | Outer Copper Weight     | 1.18            | 0.0300         |
| Core  | 1.5mm 1/10Z with copper | 56.30           | 1.4300         |
| L2    | Outer Copper Weight     | 1.18            | 0.0300         |

Figure 9. Trace width calculation done within JLC PCB portal

## 2.6 User Interface Subsystem

This subsystem includes the start button, the reset button, and the microcontroller. The reset button is used to calibrate the device, which allows it to determine position of the target point from the device's current position and the calculated position of the sun. The power button turns the device off, which could help it save power if it's not in use. Both buttons are connected to the microcontroller by GPIO and are accessible from the outside of the frame. If this subsystem does not work, the user will not be able to correctly set the target point for light reflection, which will cause the device to be inaccurate.

| Requirements | Verification |
|--------------|--------------|
|--------------|--------------|

|                                                                                                                                                |                                                                                                                                                                                                                                                                                                                                                                                                                     |
|------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| The power button can turn the device on and off.                                                                                               | The device is fully connected with the power subsystem able to supply power and the power button is pressed. A multimeter is then used to measure if power is supplied to the microcontroller, motors, and sensors. The power button is then pressed again to turn the device off. A multimeter is used again to measure if power is still supplied to the microcontroller, motor, and sensors.                     |
| The reset button starts the calibration process and the microcontroller calculates the position of the target point within 2 degrees of error. | The device is fully connected and the power subsystem is able to supply power. Measure a target point relative to the device using a protractor and position the device so that the center of the sun's reflection is on the target point. Once the reset button is pressed, observe the target point calculated by the microcontroller and determine if it is within 2 degrees of error of the known target point. |

Table 5. Requirements and verifications for user interface subsystem

## 2.7 Tolerance Analysis

One of the major challenges to successfully operating the sunlight redirecting mirror is the angular accuracy with which the mirror can be positioned. Errors can originate from the motors, mechanical backlash, mirror mounting, and uncertainty in calculating the position of the Sun. Since the design reflects sunlight to a relatively small target from a distance, these errors can be magnified considerably as the distance between the target and the mirror increases.

According to the law of reflection, the angle of incidence equals the angle of reflection. Therefore, rotating the mirror by a factor of  $\Theta$  will cause changes to both the incidence and reflection angle causing the reflected sunlight to change by  $2\Theta$ . Similarly, if the mirror has an angular positioning error  $\epsilon_p$ , then the resulting reflected beam error is

$$\Theta_b = 2\epsilon_p$$

However, this error is only considering one axis of rotation. The positioning system consists of both azimuth and elevation axes. Therefore, the total beam error depends on the combined error of both motors rather than either axis independently. Assuming the azimuth and elevation errors are independent and sufficiently small, the combined reflected beam error can be calculated by the root sum square of both values

$$\epsilon_{\text{combined}} = \sqrt{(\epsilon_{\text{azimuth}})^2 + (\epsilon_{\text{elevation}})^2}$$

From which we can compare the following values

| Per-Axis Error ( $\epsilon_p$ ) | Combined Error ( $\epsilon_c$ ) | Beam Error ( $\Theta_b$ ) |
|---------------------------------|---------------------------------|---------------------------|
| $\pm 5^\circ$                   | $\pm 7.07^\circ$                | $\pm 14.1^\circ$          |
| $\pm 3^\circ$                   | $\pm 4.24^\circ$                | $\pm 8.49^\circ$          |
| $\pm 2^\circ$                   | $\pm 2.83^\circ$                | $\pm 5.66^\circ$          |
| $\pm 1^\circ$                   | $\pm 1.41^\circ$                | $\pm 2.83^\circ$          |

Table 6. Per-axis, combined, and reflected beam error comparison

So if each motor is controlled within a  $\pm 3^\circ$  tolerance we get under  $\pm 5^\circ$  of combined error and a beam error of less than  $\pm 9^\circ$ .

At a target distance L, the distance between the intended beam target and the deviation is calculated by

$$x = L \tan(2\epsilon)$$

Where  $\epsilon$  is the combined error.

With a  $\pm 5^\circ$  tolerance and varying distance we get the following deviations

| Mirror to plant distance (L) | Beam Deviation (x) |
|------------------------------|--------------------|
| 0.3 m                        | 5.3 cm             |
| 0.5 m                        | 8.8 cm             |

|        |         |
|--------|---------|
| 0.75 m | 13.2 cm |
| 1.0 m  | 17.6 cm |
| 2.0 m  | 35.3 cm |

Table 7. Beam deviation at the target versus mirror-to-plant distance for a  $\pm 5^\circ$  combined error

This table alone shows us that a  $\pm 5^\circ$  tolerance is enough for short distances, but becomes less reliable as the distance increases.

To calculate beam width there are two factors. One is the physical dimensions of the mirror and the second is the apparent angular diameter of the sun. Using an 8" x 8" square mirror and a  $0.53^\circ$  angular diameter for the sun we can approximate the additional angular spread for the beam as

$$D_{\text{Sun}} = L \tan(0.53^\circ)$$

Adding this additional width to the effective mirror beam width gives us the total illuminated region for the reflected sunlight

$$D_b \cong D_{\text{eff}} + L \tan(0.53^\circ)$$

For example, with an 8" mirror we get 20.3 cm width plus the angular spread at 0.5 m results in an illuminated region of

$$D_b \cong 20.3 \text{ cm} + 0.5 \tan(0.53^\circ)$$

$$D_b \cong 20.8 \text{ cm}$$

Now to calculate the maximum beam movement before the beam will miss the plant we consider the plant width  $D_p$  and the beam width  $D_b$ . The target plant may have varying widths and be bigger or smaller than the beam width itself. Therefore, calculating the maximum beam movement will focus on keeping the center of the reflected beam on the plant. With a plant width

of  $D_p$  the maximum allowable movement of the beam is half of the width before the center moves away from the plant. Combining this with the earlier deviation formula we get the relation

$$L \tan(2\epsilon) = D_p / 2$$

With which we can now solve for the allowable tolerance at a given distance

$$\tan(2\epsilon) = D_p / 2L$$

$$2\epsilon = \tan^{-1}(D_p / 2L)$$

$$\epsilon_{\max} = (1/2)\tan^{-1}(D_p / 2L)$$

At a distance of 0.5 m and a plant width 15 cm we get

$$\epsilon_{\max} = (1/2)\tan^{-1}(15 / 2(50))$$

$$\epsilon_{\max} = 4.27^\circ$$

So a maximum allowable tolerance of  $\pm 4.27^\circ$  which is very close to the preliminary proposed tolerance of  $\pm 5^\circ$ .

The mirror must also be placed in an unobstructed line of sight to the sun and to the plant. If the mirror is placed within the shadow of an object then no direct sunlight is available to redirect to the plant. For an object of height  $H$  and the elevation of the sun  $E_s$  we can calculate the approximate shadow length of the object as

$$L_{\text{shadow}} = H / \tan(E_s)$$

For example, an object 3 m high with the sun at a  $30^\circ$  elevation produces a shadow approximately 5.2 m long, and 11.2 m long at  $15^\circ$  elevation. So the mirror in these situations must be placed farther away from the shadow and the plant in order to receive sunlight. However, doing so also increases the required angular positioning accuracy. This creates a tradeoff between access to direct sunlight and angular tolerance.

The analysis therefore shows that the mirror is best suited for short-distance or window based plants where the mirror can be placed in a position where it can access a path of direct sunlight and the plant. Testing will be conducted to determine the actual motor and mirror positioning error and compare it to the maximum allowable tolerance.

### 3. Cost and Schedule

#### 3.1 Cost Analysis

##### Labor:

Quote from Research Lab Machine Shop: 20hrs x \$56.12/hr = \$1,122.40

Assume each partner works on project for 15 hrs per week for the next 6 weeks

Assume \$20/hr wage since this is common for interns who are also college undergraduates

Estimated cost of group labor: 3 x 15hrs x 6 x \$20 = \$5,400.00

Total Labor Cost: \$1,122.40 + \$5,400 = \$6,522.40

##### Parts:

| Description                                              | Manufacturer              | Quantity | unit price | Extended price | Link                                                                     |
|----------------------------------------------------------|---------------------------|----------|------------|----------------|--------------------------------------------------------------------------|
| Samsung 25R 18650 2500mAh 20A Battery                    | Samsung SDI               | 4        | \$4.99     | \$19.96        | <a href="#">Samsung 25R 18650 2500mAh 20A Battery</a>                    |
| 18650 Series Parallel Connection DIY Lithium Battery Box | LUORNG                    | 1        | \$9.95     | \$9.95         | <a href="#">18650 Series Parallel Connection DIY Lithium Battery Box</a> |
| BQ7790500PW                                              | Texas Instrument          | 1        | \$1.99     | \$1.99         | <a href="#">BQ7790500PW</a>                                              |
| ERJ-2RKF1001X                                            | Panasonic Industry        | 3        | \$0.10     | \$0.30         | <a href="#">ERJ-2RKF1001X</a>                                            |
| C0603C104K5RACTU                                         | KEMET                     | 7        | \$0.14     | \$0.98         | <a href="#">C0603C104K5RACTU</a>                                         |
| CL10A105KB8NNNC                                          | Samsung Electro-Mechanics | 3        | \$0.14     | \$0.42         | <a href="#">CL10A105KB8NNNC</a>                                          |
| NCU15XH103F6SRC                                          | Murata Electronics        | 1        | \$0.10     | \$0.10         | <a href="#">NCU15XH103F6SRC</a>                                          |
| RMCF0402FT10K0                                           | Stackpole Electronics Inc | 1        | \$0.10     | \$0.10         | <a href="#">RMCF0402FT10K0</a>                                           |
| RC0603JR-073M3L                                          | YAGEO                     | 1        | \$0.10     | \$0.10         | <a href="#">RC0603JR-073M3L</a>                                          |
| CRGCQ0402J1M0                                            | TE Connectivity Passive   | 2        | \$0.10     | \$0.20         | <a href="#">CRGCQ0402J1M0</a>                                            |

|                                           | Product                                         |   |              |                 |                                                           |
|-------------------------------------------|-------------------------------------------------|---|--------------|-----------------|-----------------------------------------------------------|
| RC0402JR-074K7L                           | YAGEO                                           | 1 | \$0.11       | \$0.11          | <a href="#">RC0402JR-074K7L</a>                           |
| CHV2512-JW-106ELF                         | Bourns Inc.                                     | 1 | \$0.51       | \$0.51          | <a href="#">CHV2512-JW-106ELF</a>                         |
| RMCF0805FT453K                            | Stackpole Electronics Inc                       | 1 | \$0.10       | \$0.10          | <a href="#">RMCF0805FT453K</a>                            |
| WFCP06121L000FE66                         | Vishay Dale                                     | 1 | \$0.48       | \$0.48          | <a href="#">WFCP06121L000FE66</a>                         |
| LM1117DTX-3.3/NOPB                        | Texas Instrument                                | 1 | \$1.21       | \$1.21          | <a href="#">LM1117DTX-3.3/NOPB</a>                        |
| MPTAC10V106KBT                            | Newark Electronics                              | 7 | \$0.25       | \$1.76          | <a href="#">MPTAC10V106KBT</a>                            |
| DRV8871DDAR                               | Texas Instruments                               | 2 | \$2.98       | \$5.96          | <a href="#">DRV8871DDAR</a>                               |
| SI4056DY-T1-GE3                           | Vishay Siliconix                                | 3 | \$1.47       | \$4.41          | <a href="#">SI4056DY-T1-GE3</a>                           |
| GA25-370 Gear Motor DC with Speed Encoder | Hyuduo                                          | 2 | \$20.98      | \$41.96         | <a href="#">GA25-370 Gear Motor DC with Speed Encoder</a> |
| VEML7700-TT                               | Vishay Semiconductor Opto Division              | 1 | \$0.92       | \$0.92          | <a href="#">VEML7700-TT</a>                               |
| RMCF0402FT2K20                            | Stackpole Electronics Inc                       | 2 | \$0.10       | \$0.20          | <a href="#">RMCF0402FT2K20</a>                            |
| MMC5983MA                                 | Memsic Inc.                                     | 1 | \$3.32       | \$3.32          | <a href="#">MMC5983MA</a>                                 |
| CRG0805F2K7                               | TE Connectivity Passive Product                 | 2 | \$0.10       | \$0.20          | <a href="#">CRG0805F2K7</a>                               |
| MAX-M10S-00B                              | u-blox                                          | 1 | \$11.42      | \$11.42         | <a href="#">MAX-M10S-00B</a>                              |
| RC0201FR-0733RL                           | YAGEO                                           | 6 | \$0.10       | \$0.60          | <a href="#">RC0201FR-0733RL</a>                           |
| CL10B103K08WPNC                           | Samsung Electro-Mechanics                       | 1 | \$0.11       | \$0.11          | <a href="#">CL10B103K08WPNC</a>                           |
| RMCF1206FT10R0                            | Stackpole Electronics Inc                       | 1 | \$0.10       | \$0.10          | <a href="#">RMCF1206FT10R0</a>                            |
| LQG15HN27NJ02D                            | Murata Electronics                              | 1 | \$0.10       | \$0.10          | <a href="#">LQG15HN27NJ02D</a>                            |
| AN_GPS_A002                               | Suzhou Maswell Communication Technology Co. Ltd | 1 | \$20.95      | \$20.95         | <a href="#">AN_GPS_A002</a>                               |
| RFPC-SMA28-F                              | GCT                                             | 1 | \$1.89       | \$1.89          | <a href="#">RFPC-SMA28-F</a>                              |
| STM32G071CBT6                             | STMicroelectronics                              | 1 | \$4.24       | \$4.24          | <a href="#">STM32G071CBT6</a>                             |
| GRM188R61E475KE11D                        | Murata Electronics                              | 1 | \$0.24       | \$0.24          | <a href="#">GRM188R61E475KE11D</a>                        |
| PV5S24018                                 | E-Switch                                        | 2 | \$5.83       | \$11.66         | <a href="#">PV5S24018</a>                                 |
| 8"x8" Unbreakable Small Mirrors           | VXKZF                                           | 1 | \$9.99       | \$9.99          | <a href="#">8"x8" Unbreakable Small Mirrors</a>           |
|                                           |                                                 |   | <b>total</b> | <b>\$156.54</b> |                                                           |

Table 8. Cost estimate for parts

Total Cost: \$6,522.40 + \$156.54 = \$6,687.94

### 3.2 Schedule

| Week of | Team Objective   | KIM                                             | BELL                                  | TRIGO                                  |
|---------|------------------|-------------------------------------------------|---------------------------------------|----------------------------------------|
| 10/5    | Finish schematic | Finish schematic for power, actuation subsystem | Finish schematic for sensor subsystem | Finish schematic for MCU, UI subsystem |

|       |                                                          |                                                  |                                                     |                                             |
|-------|----------------------------------------------------------|--------------------------------------------------|-----------------------------------------------------|---------------------------------------------|
| 10/12 | Breadboard demo, Finish PCB design, submit order for PCB | Finish PCB design for power, actuation subsystem | Finish PCB design sensor subsystem                  | Finish PCB design MCU,UI subsystem          |
| 10/19 | Finish building casing and physical structure of design  | Check for PCB compatibility (RF)                 | Check for PCB compatibility (Sensor)                | Check structural integrity, mirror mounting |
| 10/26 | Source parts / solder parts                              | Integrate Sensor, Actuation related parts        | Integrate passive, BMS, batteries                   | Code software for MCU                       |
| 11/2  | Progress demo                                            | Feedback, improvement on RF, power and actuation | Feedback, improvement on sensors, HW integrity      | Feedback, improvement on software           |
| 11/9  | Debug, improvement                                       | Debug on HW (power RF, actuation)                | Debug on HW (sensor and MCU)                        | Debug on SW                                 |
| 11/16 | Mock demo, presentation                                  | Make presentation for RF, power and actuation    | Make presentation for sensor and MCU integration    | Make presentation for SW, logic, I/O        |
| 11/23 | Fall break                                               | Fall break                                       | Fall break                                          | Fall break                                  |
| 11/30 | Final demo                                               | Final scrutiny check for RF, power and actuation | Final check for sensors, calibration, HW integrity  | Final check on SW, bugs, edge cases         |
| 12/7  | Final paper                                              | Draft report on RF, power and actuation          | Draft report for sensors, calibration, HW integrity | Draft report on SW integration and MCU      |

Table 9. Schedule and workload distribution among individuals

## 4. Ethics, Safety, and Societal Impact

Aligned with the IEEE Code of Ethics, the team has a responsibility to prioritize public safety and communicate honestly of the capabilities and limitations of the system. The project will be tested in various lighting conditions and the documentation will clearly state that the device supplements natural sunlight rather than guaranteeing plant health.

During the development and testing of the device, there are several safety hazards that must be considered. Some electrical hazards include short circuits and improper wiring that could damage the components or create a fire risk. Mechanical hazards include pinch points from the rotating gears and platform, which can cause minor injuries while operating. Since the mirror

concentrates and redirects sunlight this also creates an optical hazard of glare or potentially a fire hazard if improperly aimed.

To reduce these risks, the team will follow established electrical safety practices such as insulation, proper wiring, and verification of the connections before powering on the system. Mechanical components will be mounted securely with help from the university's machine shop. Testing will be conducted with care to keep hands and other objects clear from moving parts. The mirror will be tested in a controlled environment aimed away from people and materials susceptible to combustion.

The project will follow and comply with the safety principles outlined in the university's laboratory safety policies, including the required safety training completed by team members. In addition, other useful guidelines are the NFPA 70 or the National Electrical Code with core goals of reducing injury, property damage, and economic loss resulting from fires and hazards. The OSHA laboratory electrical and mechanical safety guidelines which require proper equipment grounding, regular inspection of cords, and avoiding circuit overloading. Also basic electrical protection such as insulating and limiting the current to prevent potential injury. Following these standards help minimize the risk of electrical, mechanical, and optical hazards throughout the project's development.

## **5. Citations**

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