MECHENG-450 Final Report

Automated Irradiance Mapping for Red and NIR emitting devices

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Team 15

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Summary

Our stakeholder in this project is our sponsor, JustLight. JustLight's goal is to popularize the use of Red Light Therapy as a non-invasive method for pain treatment. Their current product is the Sunflower, a device that can emit light in four different wavelengths and can be controlled by a mobile application. In order to measure the irradiation pattern and analyze the effectiveness of the Sunflower, JustLight is looking for an automated solution to map the irradiation in the red and near infrared spectrum from the Sunflower.

We determined the requirements and engineering specifications from our discussions with our project sponsor. Our project sponsor previously performed the irradiation mapping process manually, and the requirements are developed from the prior experience.

This research project will introduce a brand new 3d irradiance mapping mechanism. The target space will be cubically meshed into cartesian discrete data points while the attached radio spectrometer will be moved to those positions to make measurements. As a result, a 3D matrix would be created throughout the designated space by plugging those data points. The matrix will then be post-processed and finalized as output.

The final design was made based on an off-the-shelf 3D printer that can offer all the parts required while being considerably less expensive compared to sourcing individual parts. So an Ender-5-Plus 3D printer was chosen for customization. We validated our design by comparing the irradiance mapping results we obtained to measurements made by the optical component manufacturer Eypex. Overall, the obtained data matched with the reference data qualitatively and quantitatively.

We were able to design and build a product that meets the requirements and is able to be deployed and used in a product development environment. If we had more time and resources to better define the problem, we would further explore the potential future products of JustLight.

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Introduction

Our sponsor, Justlight[1], has developed the Sunflower device that utilizes red and near infrared light to penetrate deep into the human skin and stimulates the energy production part of the human cells, the mitochondria, in increasing the production of an energy substance called ATP.[2]The increased ATP production is used to facilitate additional cellular activity, which allows accelerated wound healing and tissue regeneration capabilities. Red/NIR light is chosen for the device as previous research has shown that light with wavelength of above 650 nanometers have significantly superior penetration capabilities when compared to light of other wavelengths around the visible spectrum.[3][4]

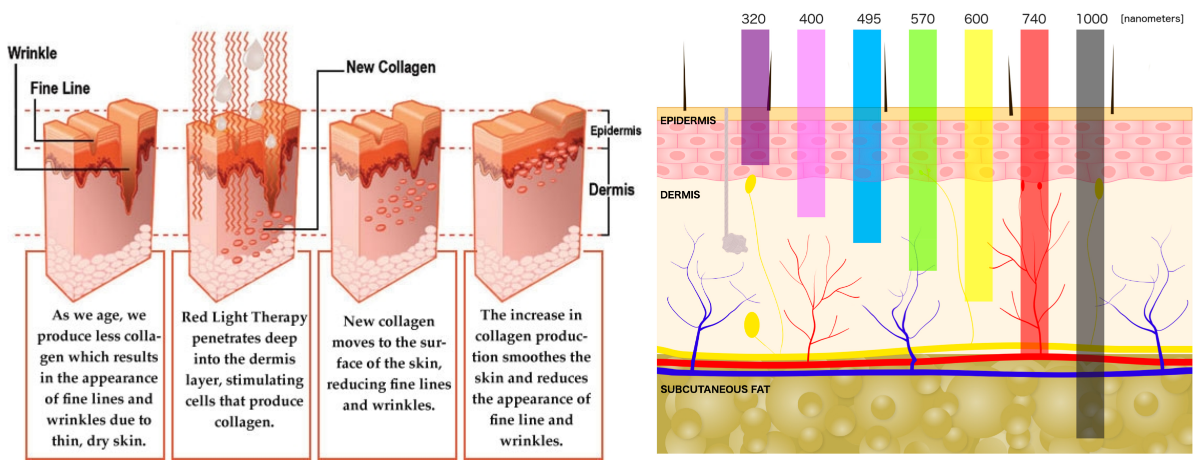


Figure 1. (left)The ability for red and NIR light to help cellular activity (right) The penetration capabilities for light at around visible spectrum

Red-light therapy can provide a wide range of benefits across the body, including short-term relief of pain for muscles, relax stiff joints, and reduce inflammation for non-open wounds. [5][6] The exact dosage of light required however. varies depending on the location of treatment, fatness of the user, the distance between the device and user, and more. Thus, it is required to obtain a calibration of the device under different working conditions in order to develop an algorithm that can help the user determine the optimal treatment time. This leads to the major goal of this project: to design a device that could provide a spatial irradiance map around the Sunflower device. The project would be considered successful if our device can deliver a detailed irradiance map measuring the light intensity across a range of wavelengths in the space surrounding the Sunflower device. [7] Currently there are no devices that can provide the capability of achieving this goal on the market and there is no research showing that a similar device is in development. The sponsor has previously attempted to make measurements with hand-held devices, but the spatial accuracy was proven to be too low and unreliable. [8] Therefore, this project was brought up to our team.

- **Intellectual Property**

  All team members signed the intellectual property agreement at the start of the semester and all intellectual property related to this project are transferred to our sponsor JustLight, pbc.

- **Design Process**

  Since our project have only one major goal and requires less consideration on other aspects of the design, we've decided to take a rather linear approach by using a solution-orientated stage-based model with cyclic activities on specific parts of the design.[11] We chose a stage-based model because this would allow us to rapidly come up with a feasible design solution within a short period of time, this would be extremely useful as the course have a very limited timespan. [12] Iterative cycles can be used on specific parts of the design to ensure the most ideal outcome on critical components. Solution-oriented strategies were considered superior because the major problem we are solving are very straightforward and do not require further decomposing. Additionally, after analyzing the problem, we were able to find several designs that solves essentially the same problem. We decided to base our design concept on those designs and tweak according to our project needs.

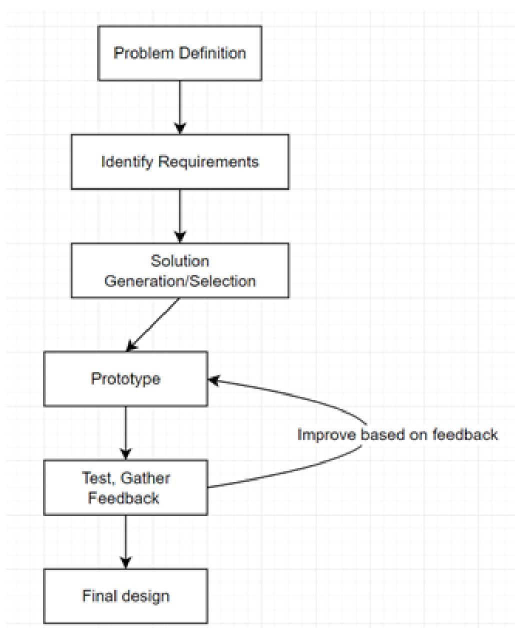


Figure 2. Final design process block diagram

This final design process we've developed as shown in Figure 2. looks the same as the one introduced to us in ME450 class. It looks the same because the characteristics of our project deemed that the design process will not be complicated. And for a rather simple process, there are already processes such as the one provided to us in class, that are proven to be extremely effective and versatile.[13][14]

- **Information Sources**

  For this project, we determined several reliable sources of information, including our sponsor's product website, email exchange and online meetings with sponsor, various search engines and databases, as well as the UM library. During our information gathering process, we found that the online search engine worked best for our team and we were able to obtain the majority of our information from there, and the rest was obtained from our sponsor and section instructor. So we did not engage with the librarian. We utilized software documentations extensively for our code libraries, such as Matplotlib and Numpy.

Requirements and Engineering Specifications

Table 1. List of specifications and requirements

Requirement	Specification	Importance
Measuring envelope	Measurement envelope larger than a 14" diameter sphere	High
Measuring resolution	Measurement linear resolution ≤ 2 mm	High
Ease of control	Mapping program can run automatically without operator intervention	High
Radiospectrometer interface	Control software for mapping device can interface with radiospectrometer and record data	High
Output format	Program can output data file containing a 3D matrix with irradiance spectrum measurements at each point	High
Device size	Device size < 20"x20"x20"	Low
Device weight	Device weight < 20 lbs	Low

The dimension and resolution requirements are based on the design of the Sunflower device and its intended use. The measuring envelope requirement stems from the intended operating range of the Sunflower device, and the resolution requirement is from the previous manual measuring experience. Ease of control is required for the device to fulfill its intended goal of reducing irradiation mapping time and effort, and the radiospectrometer interface is a continuation of the requirement, as any manual interface with the radiospectrometer will significantly complicate the process. A suitable output format is required in order for our sponsor to be able to process the data and gain usable information from the measurements. All of the above are requirements that must be met to satisfy the goal of the project, and share equal importances. We also decided that the device should be within a certain size and weight limit for ease of transport and storage, however, they are not important for our sponsor and do not be met for the device to be functional.

Concept Generation

We start with ideation based on problem definition, where a pool of diverse concepts were sketched and discussed from each team member. Then we filtered the solution pool by screening and evaluation. Impractical solutions were quickly eliminated where only eight strong solutions were selected as Table 1 shown. We also listed potential drawbacks based on the project requirements and specifications, as well as the availability of equipment. As we can see, three among the eight concepts were identified with problems:

Table 2. List of convergent solution concepts

Solution Concepts	Comment	Potential Drawbacks
Cartesian sample measuring model	Sampled in Cartesian coordinate	-
Sphere sample measuring model	Sampled in spherical coordinate	-
Cylindrical sample measuring model	Sampled in cylindrical coordinate	-
Handheld measuring	Choose point samples and measure manually	Limited accuracy
Sensor net model	Place multiple sensors around light source	Require multiple sensors
Software Simulation	Simulate the light source in software	-
Math model estimation	Create a mathematical model and estimate	-
Photo pixels analyses	Analyze the pictures from different directions	Require expensive equipments (IR camera)

Concept Selection Process

We select five among eight convergent solution concepts that have no potential drawback to be the final list of best solutions. To better estimate the performance of the filtered concepts, we created a rating scheme for feasibility and accuracy. Our criteria for judging feasibility was mainly based on estimated time consumption, team member's background knowledge, ease of data collection and ease of control. As we can see from Table 2, the Cartesian sample measuring model scored the highest in feasibility rating. The math model estimation method scored the lowest since our team members lack the potential background knowledge. Then we carried out the rating on accuracy based on position data accuracy, quantity of measured samples and background influences. We found out that the Cartesian sample model method scored the highest in both ratings while no potential drawback is discovered. This method stands out with easier data collection procedures and relatively higher accuracy. Each team member also reported substantial background knowledge regarding this method. Therefore, Cartesian sample measuring is picked as the best solution concept.

Table. 3 List of best solution concepts with ratings

Solution Concepts	**Feasibility**	**Accuracy**
Cartesian sample measuring model	4.5/5	4.5/5
Sphere sample measuring model	4/5	4.5/5
Cylindrical sample measuring model	4/5	4.5/5
Software Simulation	4/5	4/5
Math model estimation	3.5/5	3/5

Concept Description

Our final design concept is shown as Figure 3. below, A frame encloses linear railings on 3 dimensions, and 3 stepper motors each controls a degree of freedom, With the probe mounted on the innermost carriage, the actuation dimensions are shown as the transparent region below, being a cuboid of 14” * 14” * 20”

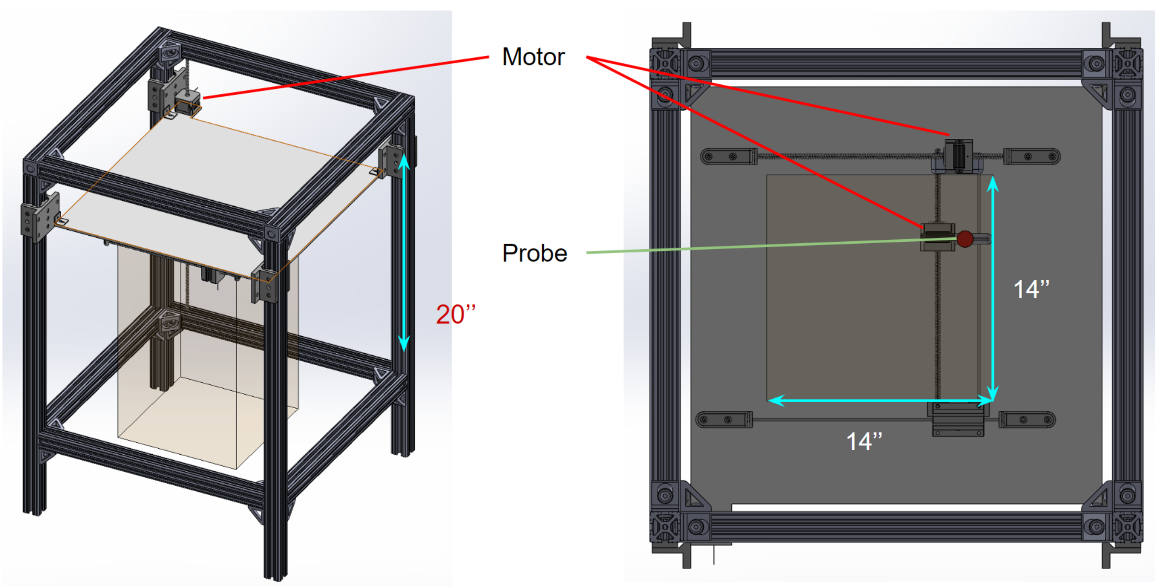


Figure 3. CAD model view (left) and bottom view (right), with orange transparent region indicating the probe’s actuation dimensions.

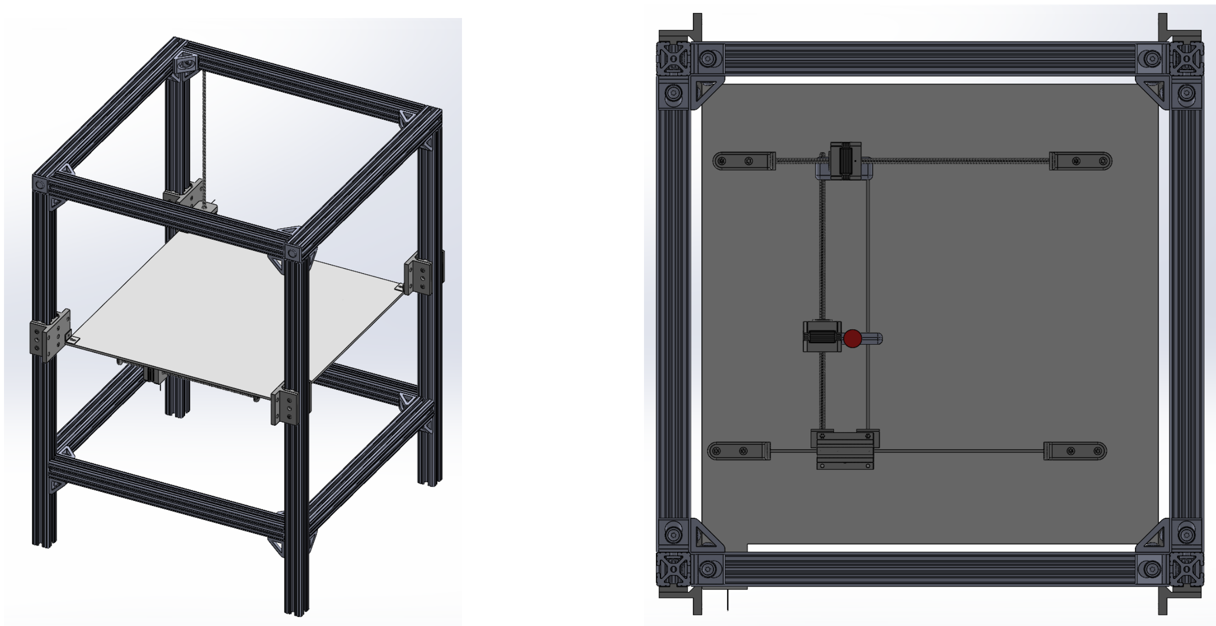


Figure 4. CAD model view (left) and bottom view (right), with the probe actuated to be compared with Figure. 3

As shown clearly in Figure 3&4. above, the spectroradiometer probe can actuate on 3 axes with a high degree of accuracy, this position can then be fed back to the controller software from the encoders embedded within the stepper motors. This forms the micropositioner necessary to perform high resolution measurements.

Engineering Analysis

During the process selecting the most optimal design, several issues were discovered and three were decided to be looked into further.

1. **The ability to perform measurements within the required envelope space**

   After reviewing the specifications and researching the characteristics of the Justlight product, it was determined that the data within the lobe shaped region (cross-section shown in Figure 5.) was most critical.

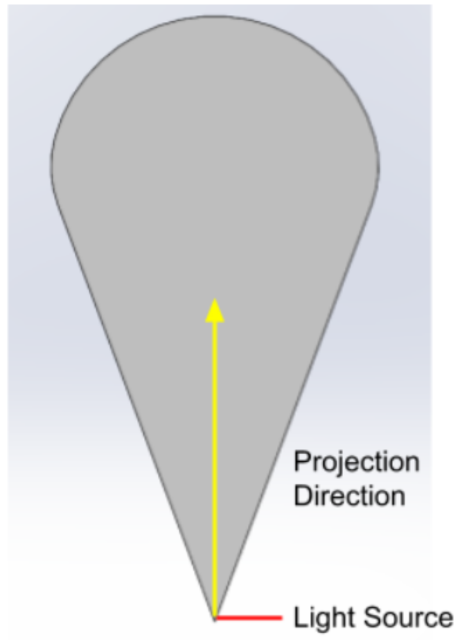
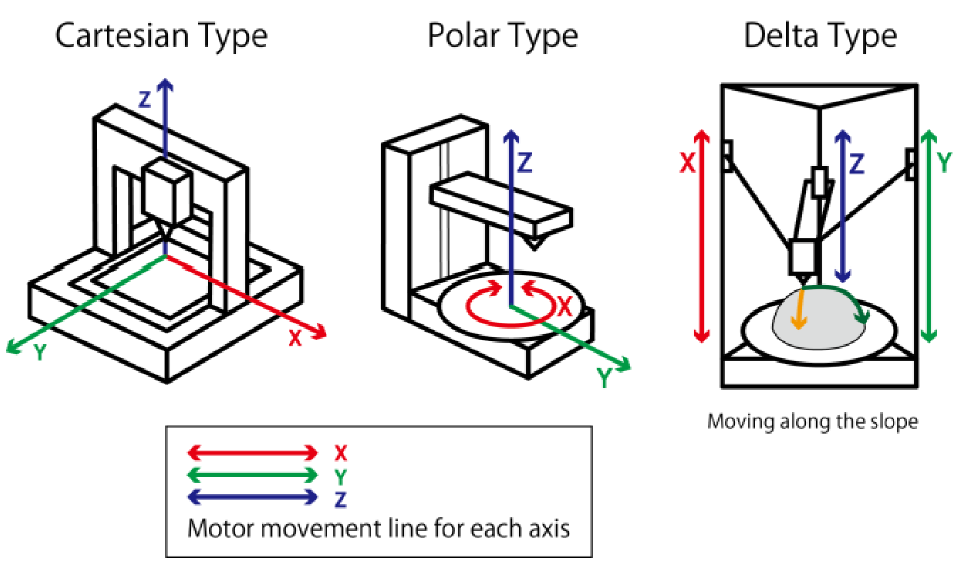


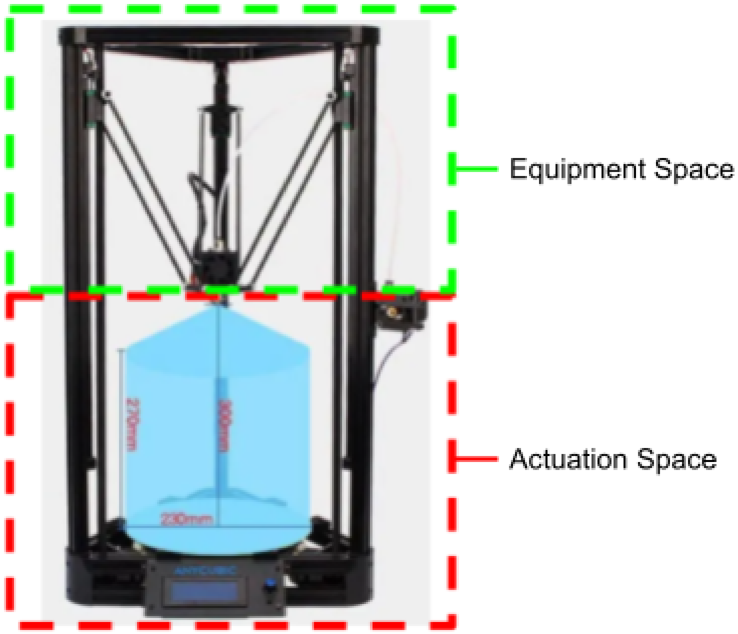
Figure 5. Cross-sectional view of the mapping region

And in order to contain that region, different architecture from commercially available 3D printers were conducted and their actuation dimensions were also researched. Three main type architectures, cartesian, polar, and delta type were found, with the cartesian type having a envelope of cuboid, polar type having a cylinder, and the delta type having a conical cylinder.



. [15][16]

Figure 6. Common architectures of 3D printers



[17]

Figure 7. Space composition of delta type 3D printer

After judging the pros and cons, we concluded that although the delta type has the best shape to enclose a lobe shape, its size, mainly the green part, which is the equipment portion, compared to the red usable space, makes it hard for us to control the machine's dimensions. Along with the fact that the delta type and polar type architecture poses additional encoding issues for positioning, it might cost us more time in tuning the machine. In the end, we decided to stick to a rather conservative approach and chose the cartesian type.

For the selected architecture, we would still need to determine the actuation dimensions. Both a theoretical method and a physical method were developed:

Theoretical: calculate the actuation space within the cad model

- Most visual way to approach before production
- Cost saving

Physical: measure the actuation distance when the prototype is built or when we have the actuator available.

- Late into the development phase
- Gain a better understanding of the capabilities of the device
- May reveal problems that are neglected within the cad model

The theoretical method was used initially, and a space of 10’’ * 10’’ * 20’’ was measured using the CAD model we’ve constructed, For the final design, we obtained a 3D printer kit that has a listed actuation dimension of 350 * 350’ * 400mm , further modifications expanded this envelope and it was able to reach a measuring envelope of a 14’’ sphere. This was measured both within our updated CAD model and confirmed using calipers on our actual prototype.

2. **How to ensure that the spectroradiometer acquires data accurately**

For engineering analysis, we focused on comparing the theoretical and actual behavior of the spectrometer. The first element we analyzed is the relationship between the angle of the incident light upon the receptor and the measured value. We expected to see a cosine relationship due to how the projected area of the receptor surface changes. Using the following experimental setup, we were able to collect a series of measurements with the receptor placed at different angles.

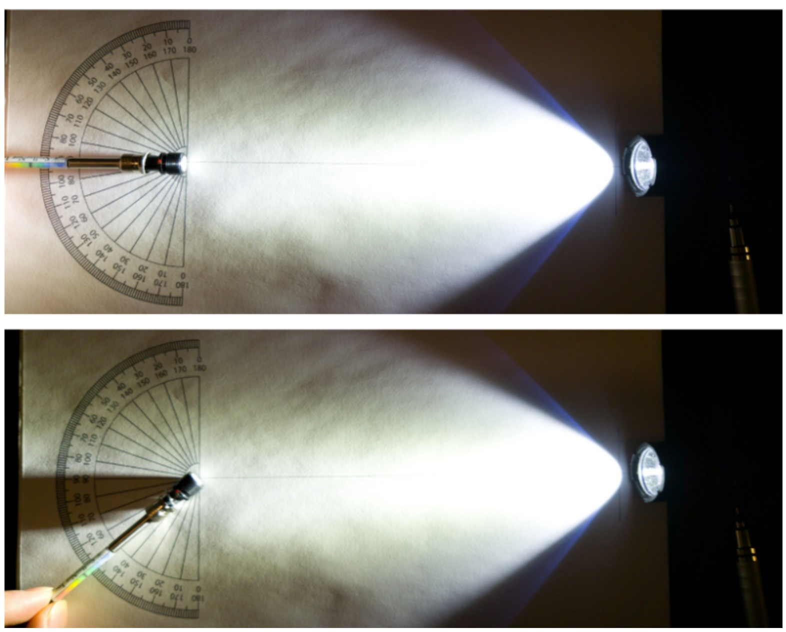


Figure 8. Experimental setup for measured value vs. incidence angle

Plotting the collected data with the theoretical model of cosine(theta), we obtain the following graph:

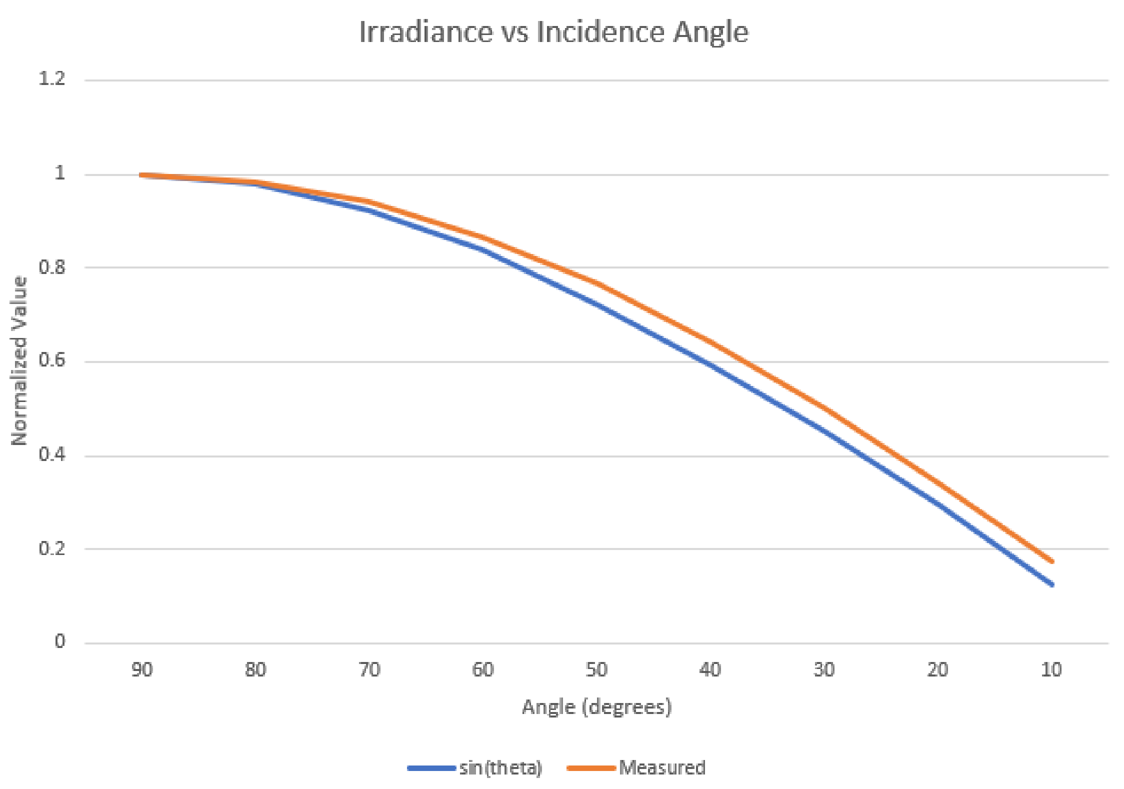


Figure 9. Results of irradiance measurements vs incidence angle

The two lines match closely, confirming the measured irradiance value indeed follows the cosine relationship with the incidence angle.

The second aspect of the analysis is the relationship between the measured irradiance and the distance between the irradiation source and the receptor. Using the view factor formula, we can obtain a theoretical relationship. However, the view factor formula is based on several assumptions that are not strictly true for our case. The view factor formula assumes the source is a diffused and even surface, while in our case, the LEDs we are measuring are located on the edge of the disk and form a ring. The LEDs also have a narrow beamwidth and focus most of the output in a narrow cone, instead of evenly in all directions. Despite the discrepancies, the theoretical model may still be sufficiently accurate, especially as the distance increases. We tested two irradiation sources, the actual Sunflower device, and an LED flashlight. We took measurements at different distances between the irradiation source and the receptor, from 2 inches to 24 inches, at 2 inch intervals. The results are presented in the graph below:

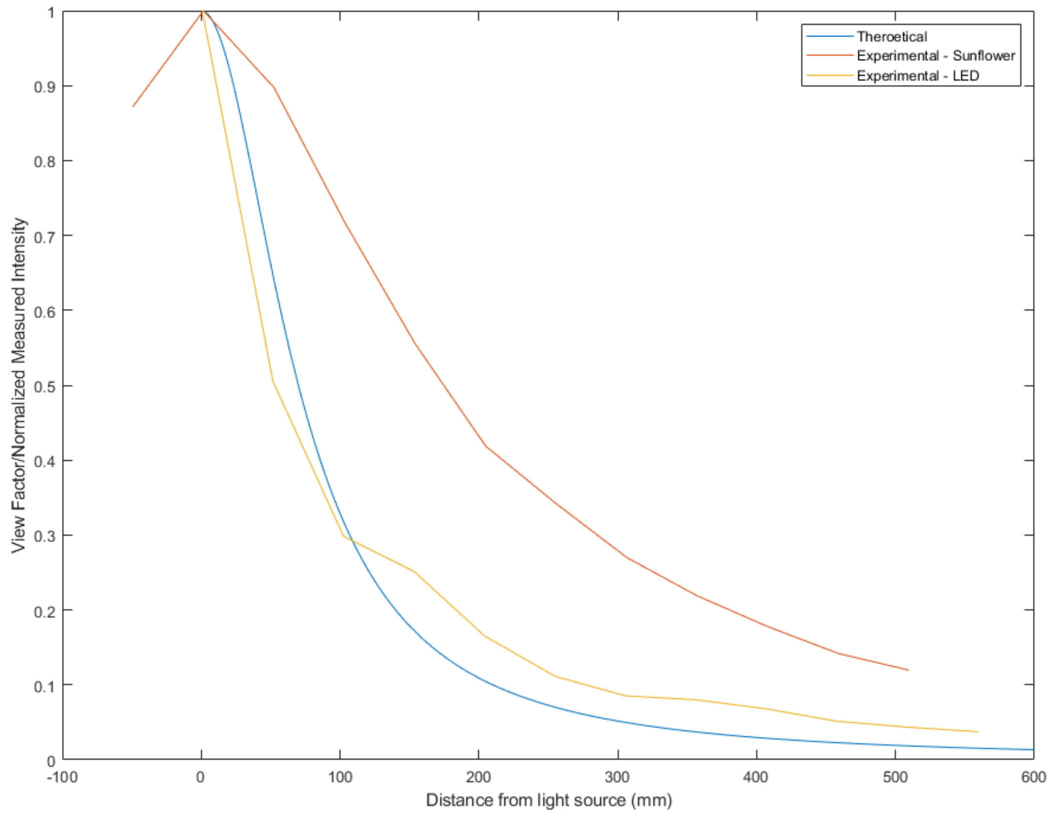


Figure 10. LED measured and estimated viewfactor vs distance from light source.

As expected, the LED follows the theoretical model closely, while the Sunflower results deviate somewhat from the model. We believe the previously discussed differences between the assumptions and the Sunflower design explains the discrepancies.

In order to build a complete model, we took into account the behaviors discussed above, as well as assumed a 20 degree half-power beamwidth of the Sunflower. Using Python, we were able to simulate and visualize the results:

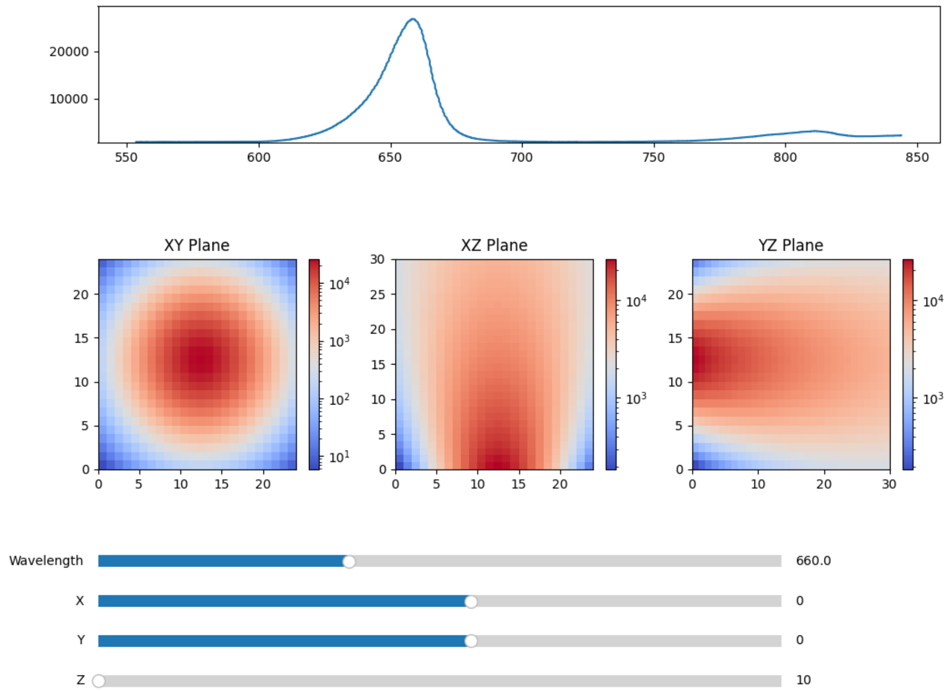


Figure 12. Visualized result

The graph shows the intensity in each plane using a log scale. We expect our actual measurements to have the general form of the above model, however, due to the difference between the Sunflower construction and the assumed ideal model, there will likely be differences especially at planes closer to the Sunflower.

3. Would there be any human interaction with the machine during the operation cycle?

It is expected that the final product would have multiple moving parts working asynchronously, and this may pose a working hazard if human interactions are required during the operation cycle. Similar to earlier issues, both a theoretical method and a physical method were developed:

Theoretical: have a simulation of the entire operation and observe if there are any circumstances that would require human interaction during the operation cycle of the machine.

- Easy to neglect details or cases that could alter the observation
- May have unexpected situations that require human input

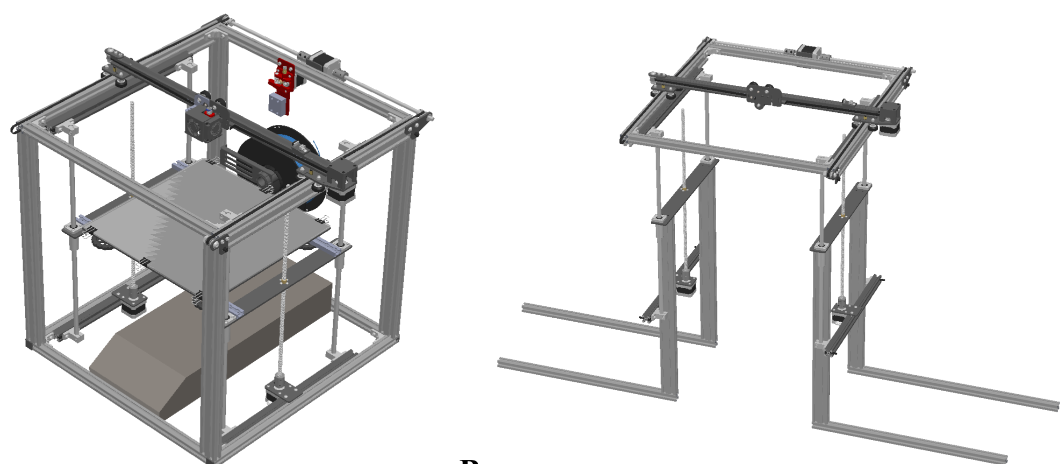
Physical: have a trial run after the prototype is built but leave the machine unpowered, check if there is any human intervention needed.

- Would be late in the development stage
- May require additional help or information from sponsor

After the development of the prototype, multiple operation cycles were performed as we needed measurement results. During the testing, it was found that the product had no issues performing autonomously and no human interaction was required during the measuring process. This eliminated the possibility of operators getting injured from this product. Additionally, since our product would not be facing the public and the sole user of the product would be our sponsor, Justlight, it is possible to communicate with them about this problem and resolve this issue from the user training side.

Final Design Description

Mechanical



A **B**

Figure 13. A. Original Assembly of the 3D printer (Ender-5-Plus)

B. Customized rig after reassembly

From our research it was found that purchasing an off-the-shelf 3D printer can offer all the parts required while being considerably less expensive compared to sourcing individual parts. So an Ender-5-Plus 3D printer was chosen for customization as this was the only consumer grade 3D printer that can achieve the required actuation range.

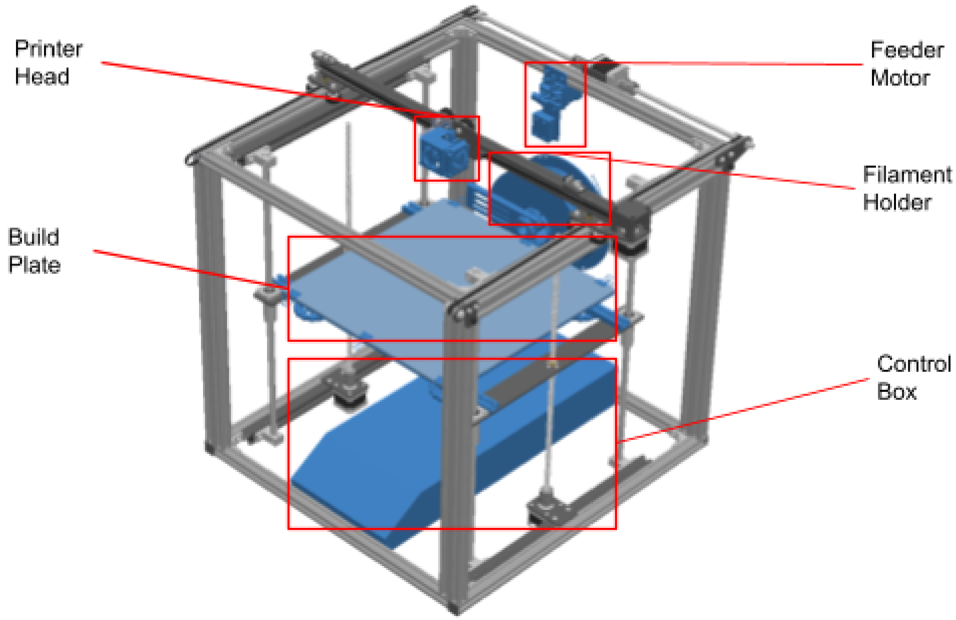


Figure 14. Parts removed from assembly

After receiving the product, a series of disassembly were performed as numerous components meant for 3D printing were no longer needed. This included the feeder motor, the filament holder, printer head, build plate, and the control box. The parts were taken apart carefully and some components were salvaged to be reused later in our customized setup, including the wires that lead to the motor and limit switches.

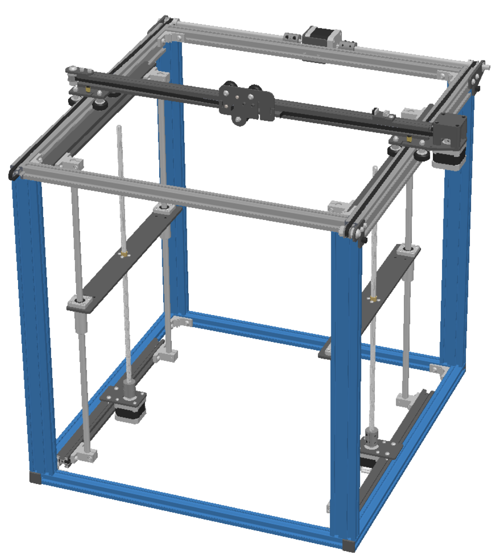


Figure 15. Assembly after the removal of unnecessary parts, with outer frame highlighted

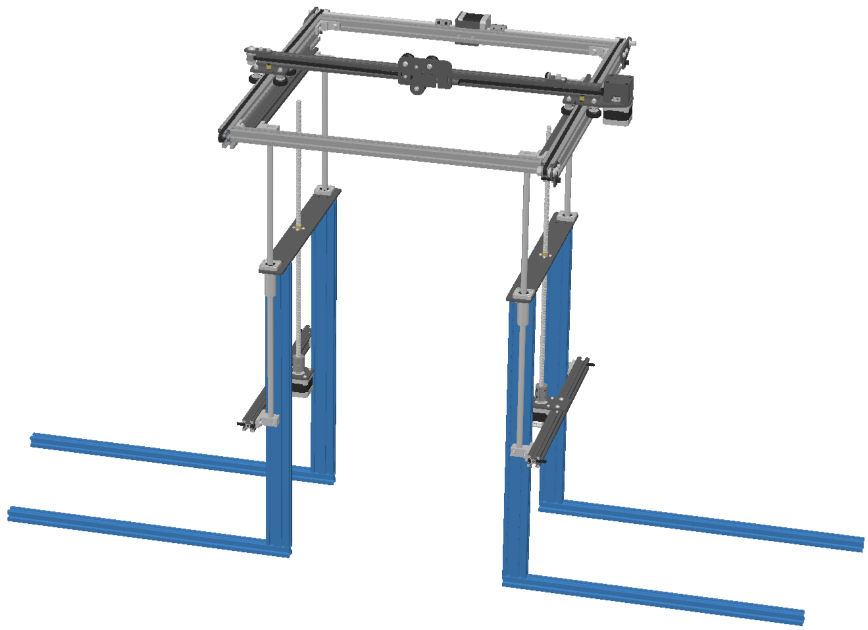


Figure 16. Outer frame was reconstructed and attached to the Y-axis platform to act as support and outriggers

Unlike our original design, which has all three degrees of freedom applied to the probe, this particular type of 3D printer has the Y-axis actuation applied to the building plate. This created additional challenges for the customization, but after analyzing the design of the printer, we were able to reutilize a portion of the outer frame, highlighted as blue in Figure 15. and reattach them to the Y-axis platform. This allowed the probe to regain all 3 degrees of actuation, as shown in Figure 16.

Electrical

The electrical development of this project is fairly simple, which is to achieve the precise movement of the probe. We use Tic controllers to communicate between software and motors, which enable us to control the motor using a micro-USB plug. As shown in Figure x, we use one Tic motor controller for the movement in one particular dimension. Therefore, we use a total number of 3 controllers corresponding to x, y and z axis movement. The controller wiring diagram is shown in Figure x. In our case, we use a 12V DC adapter to provide power and a breadboard to spread out the current. In order to achieve calibration and position reset, we also attached three limit switches along three dimensions. An arduino board is used to achieve the communication between the limit switch and the software. Figure x shows the wiring diagram of the limit switches and Figure x shows the final wired assembly.

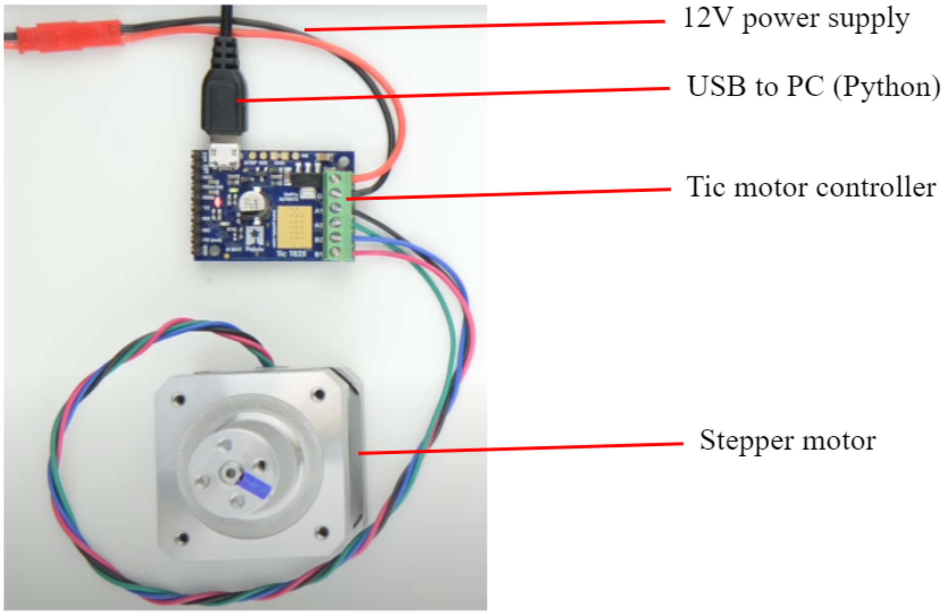


Figure 17. Connection of Tic motor controller

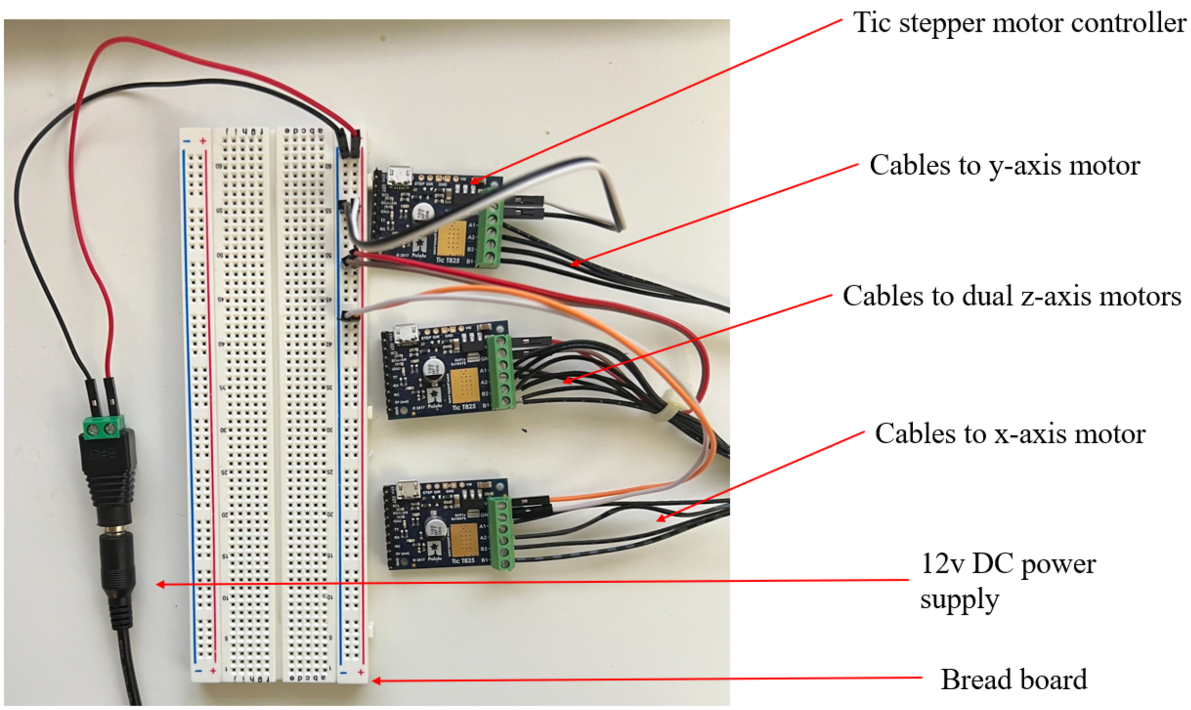


Figure 18. Tic-controller wiring diagram

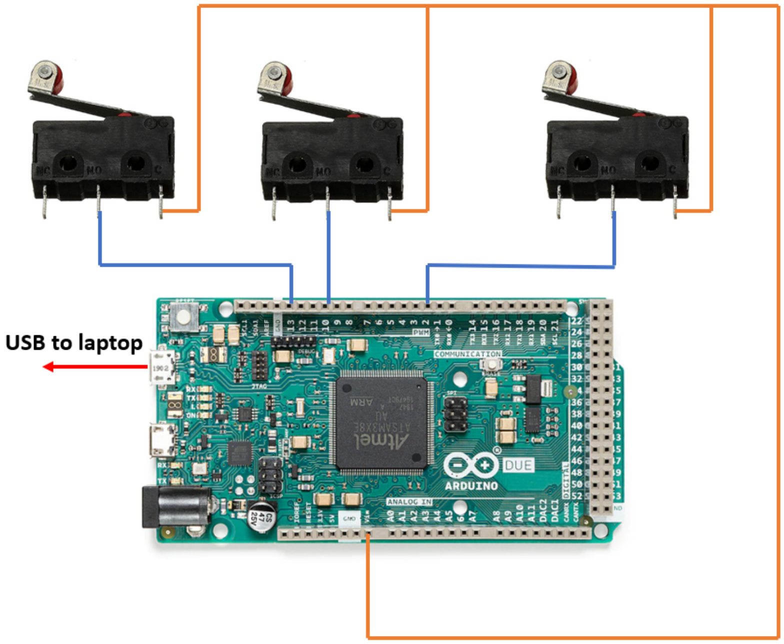


Figure 19. Limit switch wiring diagram

Figure 20. Wired final assembly

Software

Several pieces of programs are written for this project, for data collection, data visualization, and data exporting. All programs are written in Python using open source libraries and software, with the exception of the StellarNet spectrometer driver, which was obtained from StellarNet.

The data collection program controls the positioner and interfaces with the Spectrometer. The program takes several arguments, most notably the resolution and measurement size, and controls the movement of the positioner. The software upon launch first commands the stepper motors to home their positions by touching off on the limit switches on each axis. This ensures the repeatability of the measurements and avoids crashing. Once the homing procedure is completed, the program proceeds to the data recording process. The receptor is moved to each coordinate of interest, and when the positioner is at the expected coordinate, the program takes a snapshot of the spectrometer measurement and saves the data. It then repeats for all the coordinates and compiles a 4D matrix consisting of the spectrum at each position, and saves the data to the local computer. The receptor is then moved back to its initial position and ready for another measurement run. The workflow of the data collection program is shown below:

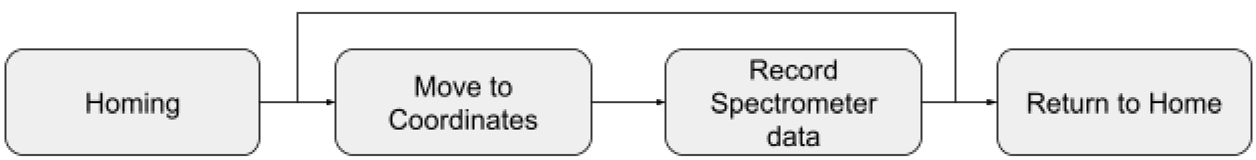


Figure 21. Workflow of data collection program

The data visualization program takes the data recorded by the previous program, and generates an interactive visualization of the data. The user can choose the wavelength and coordinates of interest, and the program will show the corresponding data at the selected wavelength and coordinates. The top figure shows the spectrum at the coordinate, while the lower figure shows the three planes that intersect with the chosen coordinates. The image below demonstrates how the program works with a measured dataset.

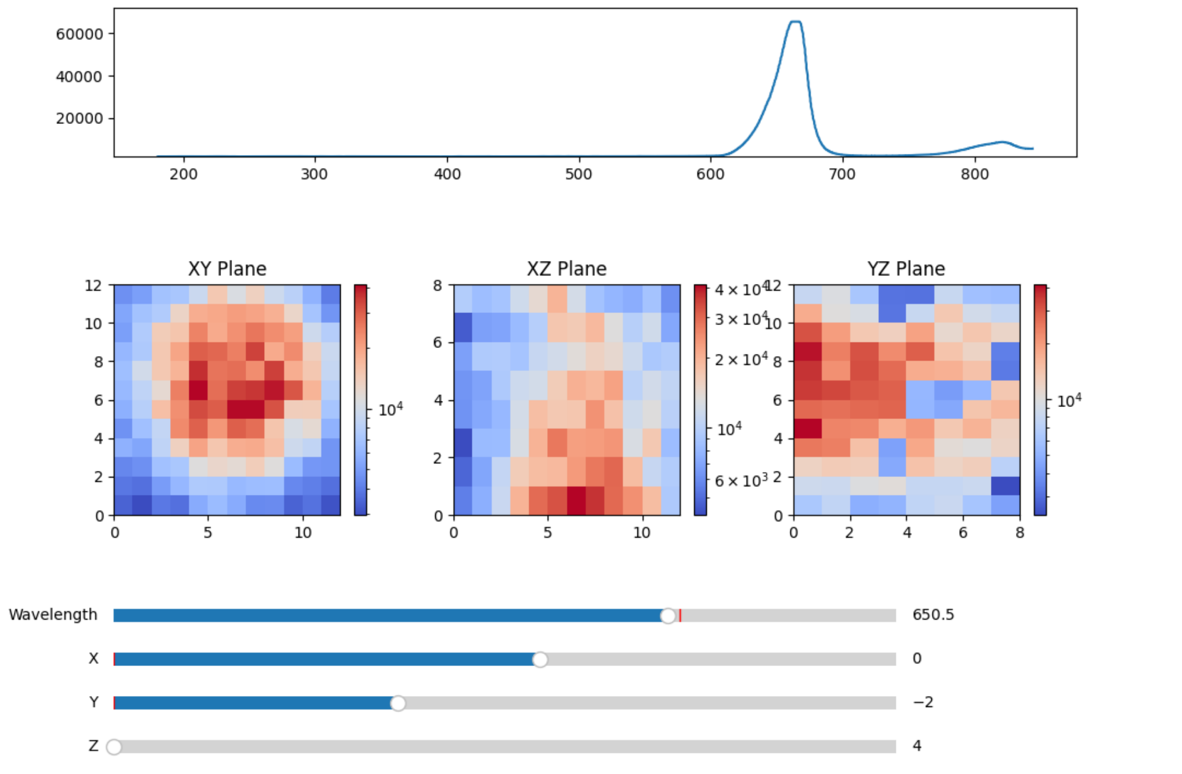


Figure 22. Interactive visualization of data

This program heavily utilizes the *Numpy* and *Matplotlib* Python libraries. Further visualization functionalities can be added to this program to match the needs of the engineering team at JustLight.

Another program is written to export the measured data to a more universal format, such as a .csv file. This program takes a previously recorded data file, and takes in the chosen coordinates and spectrum, and outputs a 2D matrix in a .csv format. This allows the file to be used in programs such as Excel and Matlab according to the needs of JustLight. The example below shows a set of data visualized in 3D using the *surf* function in Matlab.

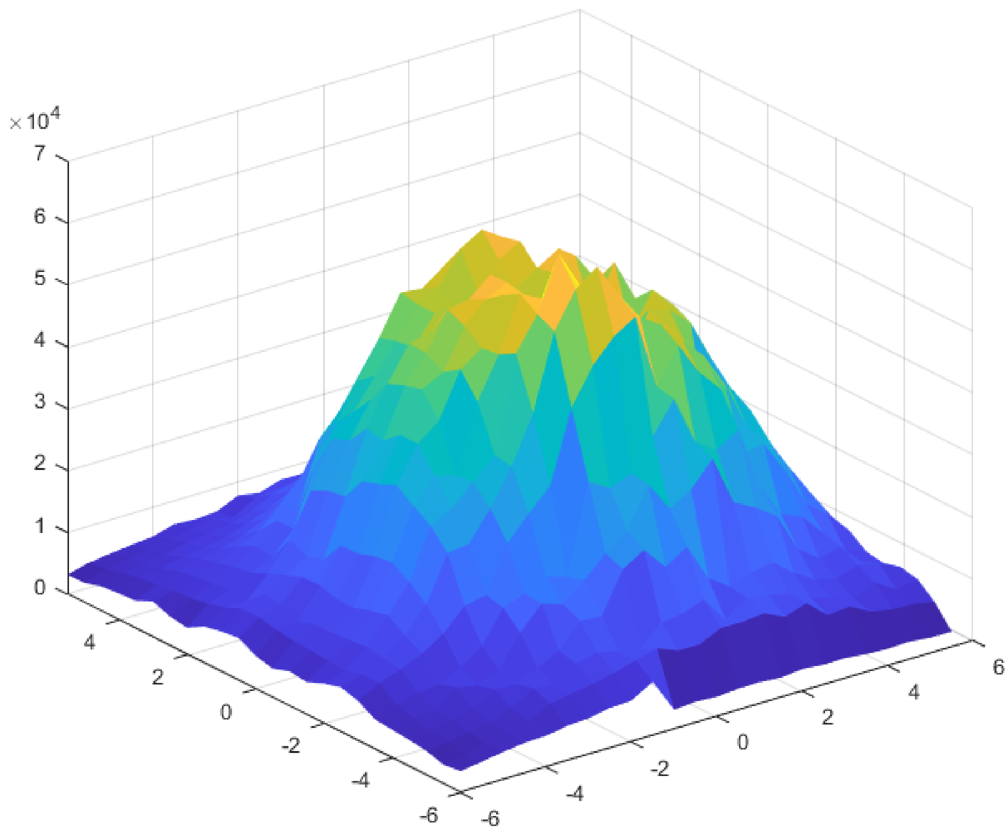


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Figure 23. 3D visualization of irradiance intensity in one plane using the *surf* function in Matlab.

Verification and Validation

We validated our design by comparing the irradiance mapping results we obtained to measurements made by the optical component manufacturer Eypex.

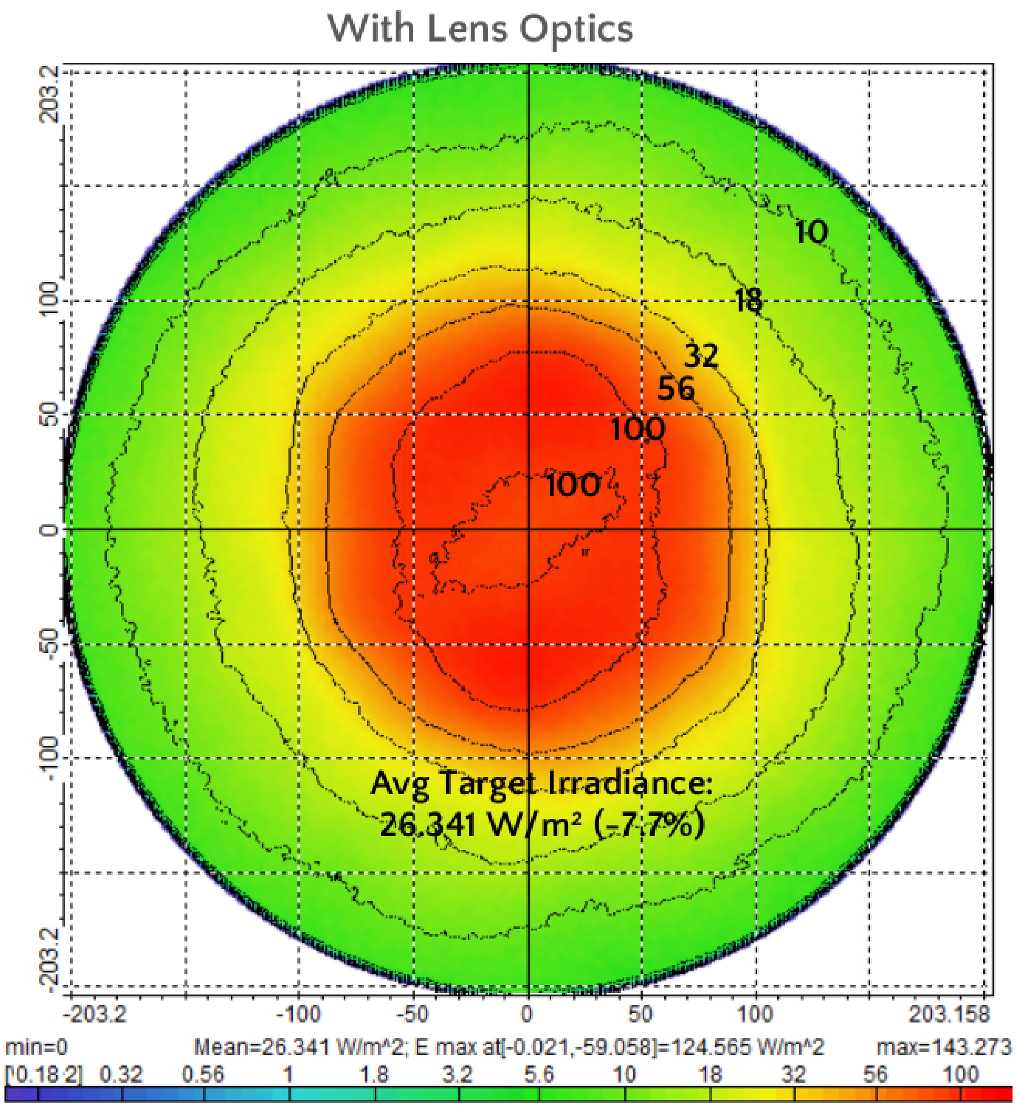

Figure 24. Irradiance map measured by Erpex for 660nm 4" from lens with lens optics.

By exporting one of our measurement runs at 4" and 660nm as a .csv file and importing the data to Matlab, we are able to create a similar plot.

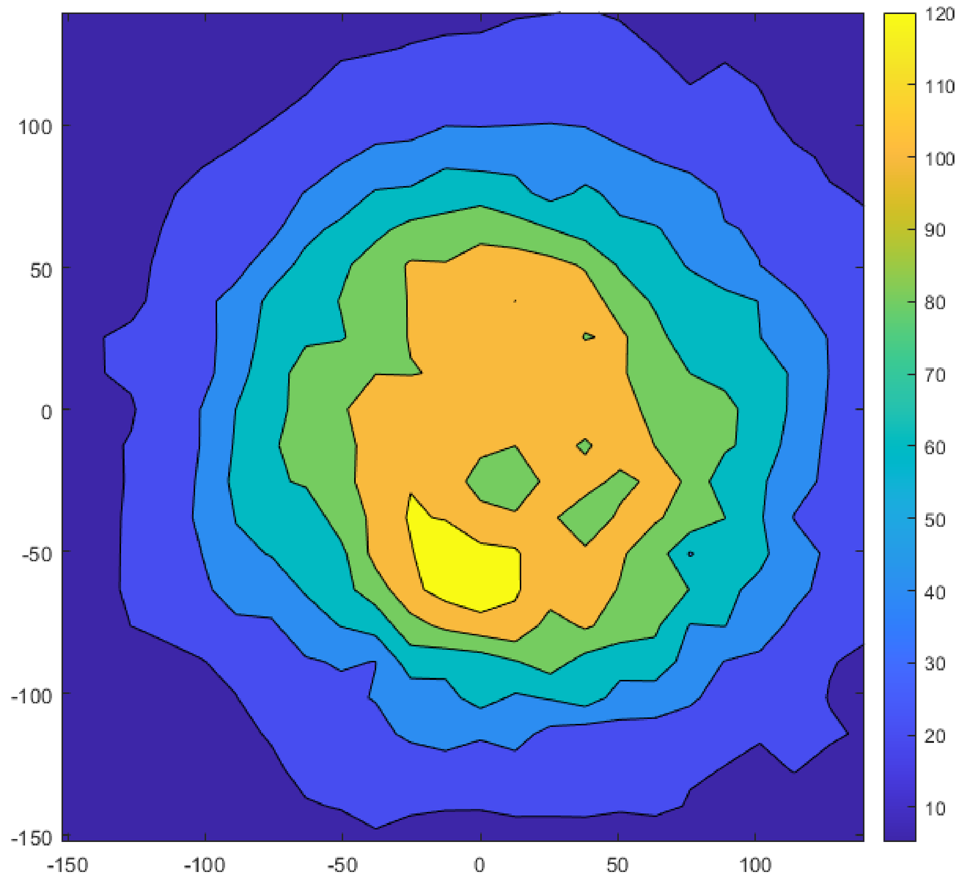

Figure 25. Irradiance map measured using our project for 660nm 4” from lens with lens optics, at a resolution of 2 measurements per inch.

The two plots generally have the same features. Noticeably, the pattern of the irradiance appears to be lengthened in the y direction, instead of being perfect concentric circles. However, due to the lack of interpolation and a lower resolution, our data appears to be less smooth. This could be improved by using a higher resolution during the measurement and interpolating data for visualization. Using the scale and contour lines provided by the Erpex measurement, we can also qualitatively compare the two measurements. Our measurement is calibrated against the Eypex measurement by scaling the center value to 100 W/m^2.

Table. 4 Data provided by the original manufacturer and results acquired from our product are compared and shown below in W/m^2

Distance from center	0 mm	50 mm	100 mm	150 mm
Eypex	100	100	32	18
This project	100	93	40	17

The maximum value from Eypex is 125 W/m^2 at (0, -60). Our recorded maximum value is 140 W/m^2 at (-13, 40).

Overall, the two sets of data match each other qualitatively and quantitatively. Therefore, we determined that our device is sufficiently validated for its intended use.

Discussion

We were able to design and build a product that meets the requirements and is able to be deployed and used in a product development environment. If we had more time and resources to better define the problem, we would further explore the potential future products of JustLight, so we can design the device to accommodate a broader range of devices, and not just the SunFlower. We would also further analyze whether the current resolution requirement is appropriate, and if a lower resolution is acceptable. This would allow us to further simplify the device and reduce cost. We would work closely with JustLight and spend more time discussing their future plans and their current development process in order to better define the problem.

In terms of our design, we are generally satisfied with its performance, however, there are several places where it could be improved. In order to measure the entire environment at a high resolution, the process takes a long time. Using a design that will allow for a faster movement of the receptor and having a more optimized motion control program could speed up the process. The current design is limited by the maximum speed of the stepper motors. Attempting to run the receptor at a higher speed leads to skipping steps and inaccurate or failed measurements, therefore a simple improvement could be to use faster motors. The program's user interface could also be improved. For example, a GUI could be made, so that the measurement program is more intuitive to use compared to directly editing the Python code to make changes.

Reflection

1. For our final product, since our product only directly interacts with our sponsors from JustLight, pbc, the impact on public health, safety and welfare are negligible. From our current information, we believe that our sponsor has no intent to put this product alone on the commercial market, therefore it will not have any benefit to the global marketplace.

However, this product does provide detailed calibration data for our sponsor's product, which could in turn provide better therapy results for their customers. It is also possible that there are others who could be affected by our project, especially from the effect of the device's manufacturing and disposal. Our project is limited in quantity and scale, hence the effect is minimized. However, we intend to take this into consideration during our design process and minimize any negative impact. We could achieve this by choosing recyclable material and components from sustainable sources, and possibly reusing unused components from other projects. Some of these costs may affect the performance of the device negatively, and therefore will require additional cost and benefit analysis. The minimum amount of tools required for this project are a set of allen wrenches, which were included in the 3D printer assembly kit.

2.
    a. The teammates had a relatively low cultural, identity and workstyle difference compared to other teams, this allowed us to understand each other more easily and plan schedules without much conflict. However, two of our teammates also major in electrical engineering, this granted us more possibilities and more expertise in the related field, which helped us greatly on this project.
    b. Our sponsor shared a similar educational background with the team members, and most of them have taken this particular course. Having the knowledge about the workflow and the time limit for this course allowed them to show great understanding during the development process and plan accordingly.

Recommendations

From our experience designing and using our device, we have the following recommendations:

1. The device should be handled with care and ensure the wires do not disconnect or break.
2. Measurement resolution and envelope should correspond to the actual needs, as excessive resolution and envelope will lead to a long runtime and slower data processing.
3. Sunflower's thermal throttling should be taken into consideration when running a measurement program. We noticed the Sunflower to automatically reduce power output after extended runtime, which would interfere with the results.
4. Routine maintenance should be performed on the mechanical components.
5. Program efficiency may be improved, such as by allowing the measurements to be taken when the receptor is traveling in both directions.

Conclusion

For this product, our team designed and built a mechanism that can provide high resolution red/NIR irradiance mapping within a spatial field.we went through literature review and gathered data from multiple sources and developed numerous possible solutions. After going through a detailed analysis of the concepts, we chose our final design and adapted the design accordingly to the requirements and specifications. We were able to deliver a product that can reach all the requirements made from the sponsor within the timeframe.

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Appendixes

Bill of Materials

Item	Quantity	Price per item /$	Total price /$
Wall Power Adapter: 12VDC, 5A, 5.5×2.1mm Barrel Jack, Center-Positive	1	23.25	23.25
DC Barrel Jack to 2-Pin Terminal Block Adapter	1	1.95	1.95
Stepper Motor: Unipolar/Bipolar, 200 Steps/Rev, 42×48mm, 4V, 1.2 A/Phase	1	26.95	26.95
Tic T825 USB Multi-Interface Stepper Motor Controller	4	51.95	207.80
Creality Ender 5 Plus 3D Printer	1	569.00	569.00
Total (tax included)			874.19

Manufacturing Plan