Development of a Portable Electroluminescence Measurement System for Photovoltaic Modules

Handover Document

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1. Introduction

In this project, the team aimed to develop a portable electroluminescence (EL) measurement device based on the theory of eliminating noise through the process of modulation where a sequence of photos is taken where current is run through a solar panel (bright image) and where current is not run through a solar panel (dark image). This process is described below in Figure 1. This sequence is then used to deduct the dark images from the bright images which will result in an image where the only thing visible is something that was present in one image but not the other, which in this case will be the electroluminescence light emitted from the solar panel when current is run through it.

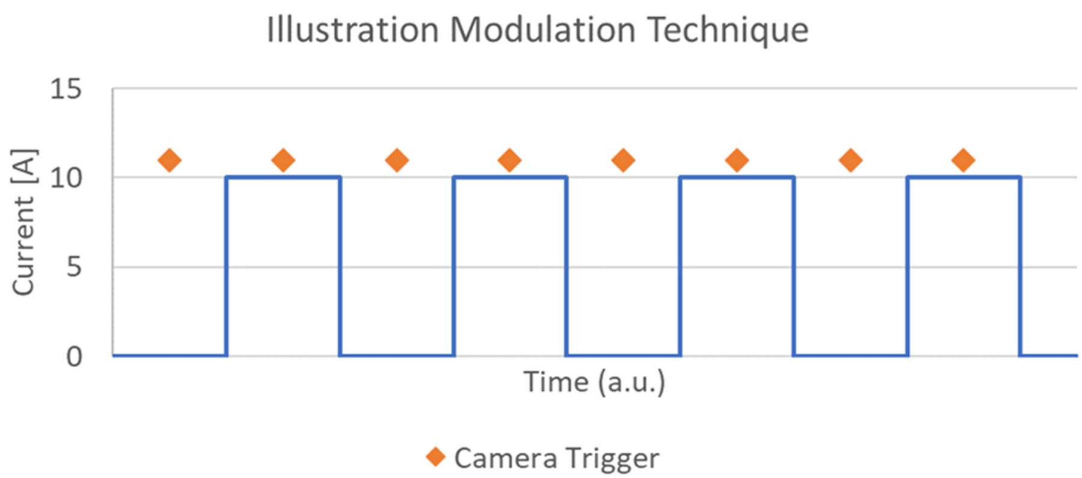

Figure 1: Modulation process of taking bright and dark photos.

Electroluminescence is a method that is widely used to identify inactive and/or defective cells in solar panels. This is done by running a current through the solar panel which results in the emission of light without heat due to the phenomenon known as electroluminescence. This light can then be captured through the use of an infrared camera. The image produced highlights the internals of a solar panel and is similar to how an x-ray is used to image a person’s bones.

To operate optimally, typical EL systems require specific conditions. These conditions include camera, temperature, and lighting requirements. The camera requirements include the type of sensors which are typically CDD or CMOS, resolution which are typically between 1 to 5 megapixels, and light sensitivity that includes dynamic range, exposure time, and wavelength which is typically 950nm to 1000nm. Next, the system requires an ambient temperature of between 20C to 25C. Lastly, the system requires a dark room for optimal capture of infrared images. To satisfy these requirements, typical EL systems are built using expensive cameras and have a large, dedicated room to meet the environmental requirements.

The EL system designed in this project is a portable system that can image only one solar panel at a time. As the design is a portable system, there is no guarantee that the external noise from the ambient temperature and light can be removed. Therefore, the system will have to account for these factors to produce an accurate estimation. The method to eliminate the external noise is as described previously where a sequence of images is taken. To achieve this, the system runs a specified current that meets the rating of the solar panel at a regular interval. Next, as the camera will need to be captured at the right moment where current is running through the solar panel, the capture needs to be timed correctly. This is managed using an algorithm on a Raspberry Pi. Furthermore, the Raspberry Pi is then used for the processing of the captured images. The algorithm and camera controls are complemented by a user interface that allows the user to easily define the input parameters and output of the resulting EL image.

For easy access to the work completed by the current team, the following links have been provided to the document and code repositories.

1) Landing Page:
https://u6283651.wixsite.com/luminescent
2) Document Repository:
https://anu365.sharepoint.com/sites/PortableELdeviceProject/Shared%20Documents/Forms/AllItems.aspx?csf=1&web=1&e=YKYAng&cid=f7faeba7%2D0d22%2D4ac3%2Da4c6%2Deac94488d29f&RootFolder=%2Fsites%2FPortableELdeviceProject%2FShared%20Documents%2FRepository%20Documents&FolderCTID=0x01200032ADF0DCE54BBE4A962468FDEB453A66
3) GitHub Repository:
https://github.com/V587MRZ/Portable-Electroluminescence-Measurement-System

2. Key Stakeholders

To understand who this project will affect and is affected by the team conducted a detailed stakeholder analysis and interaction plan. The main purpose of this process is to perform a requirements analysis of the desired product based on the needs of the identified stakeholders. The stakeholder of this project is detailed below in Table 1 and Figure 2.

Table 1: Stakeholder Identification, Description, and Interaction Plan.

Stakeholder	Description	Interaction Plan
Client	Project Client Marco and Hieu who provide funding and advice	Weekly meetings and remaining in frequent contact through the project coordinator
Design Team	The engineering team consisting of the 6 members that will work on this project	Weekly meetings and remaining in frequent contact through the use of a team chat channel
ANU	The university where this project is being undertaken who might be interested in the end result of this project	No interaction planned unless ANU takes interest in the project towards the end of project. Then the

		client and project team will discuss with the ANU
ANU Solarcar	The initial people who approached the client regarding the use of a portable EL system	Client is in contact with ANU Solarcar. Opportunities may arise to perform real-world test on ANU Solarcar's solar panels and will be organised by the client.
ANU PV Group	The research group the client operates in who might be interested in the end result of this project	No interaction planned, all handled via the client.
End User	The users of this system who desire to use an EL system on their solar panels	Only end user that may be interacted with is the ANU Solarcar, organised through the client.
Solar panel testing companies (i.e. PVLAB)	The companies that currently perform EL imaging who might be interested in expanding their market to portable EL imaging	No interaction planned due to early stage of project.
Competitors	Other companies who are currently producing or developing portable EL systems	No interaction planned. Research on competitor performed to undertake requirement benchmarking
Regulation bodies	The regulators who ensure that the product is safe for the end users	No interaction planned. Standards will be identified online and applied in the project
Solar panel manufacturers	The companies who make solar panels and might innovate the technology	No interaction planned. Team plans for frequent check up on manufacturers to identify any potential innovation in solar panels that may affect the project
Component Suppliers and Manufacturers	The companies where the components are sourced from	Items purchased from suppliers and manufacturers through the client. No further interaction planned.

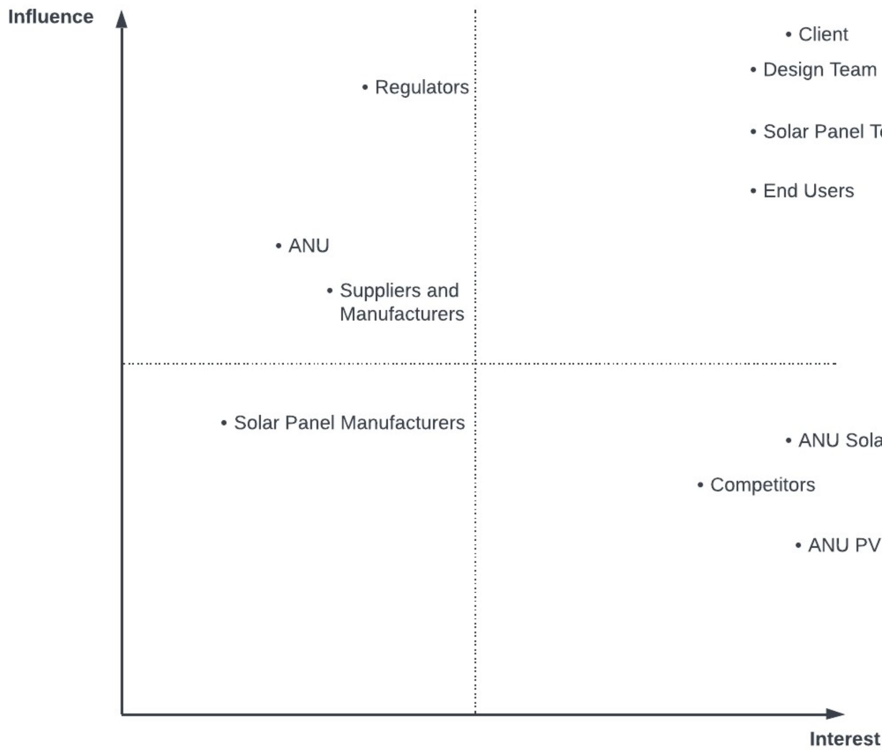

Figure 2: Influence-Interest Graph of the Identified Stakeholders.

Key Resources

Table 2: Key resources identified for the project.

Type	Description	Number of resources	Individuals/location	Comment
Human	Electrical engineers	2	Balaji, Bhargav	Designing the current regulator
	Software engineers	3	Yixin, Zhengdao, Levi	Designing the algorithm and the GUI
	Project manager	1	Andrew	Systems engineering and project overview
	Consultants	3	Chris, Marco, Hieu	
Technology	Computer		-	Electrical software, coding.
	Laboratories	2	Franklin lab ANU, Makerspace ANU	Soldering, testing
Finance	Clients	2	Marco, Hieu	Purchasing of required parts

3. Functional Breakdown and System Architecture

Based on the requirements of the system, the team determined the key functions that the system must be able to perform. Overall, 14 functions were detailed which can be seen below in the Functional Breakdown of the system in Table 2. With the requirements and functions of the system outlined, the team created a system architecture to develop a physical prototype of the system. This is shown below in the System Architecture Diagram in Figure 3. On this same diagram, the functional flow block diagram can also be observed.

Table 3: Functional Breakdown of the System.

ID	Name	Description
1.0	Initialise System	The EL systems starts and prepares for imaging functionality.
2.0	Present Input Options	The EL system presents all input options to the user relevant to begin imaging.
3.0	Accept and Store Inputs	The EL system receives and stores user input.
4.0	Ready Camera	The EL system prepares the camera for operation based on user inputs.
5.0	Set Current Limit	The EL system prepares the current source for operation based on user inputs.
6.0	Send Current Pulse to Solar Panel	The EL system sends current to the solar panel in a pulse pattern based on the user input.
7.0	Capture Images of Panel	The EL system captures images of the solar panel.
8.0	Send Images to Processing Unit	The EL system sends the captured images to the processing unit.
9.0	Store Images	The EL system stores the captured images on the processing unit
10.0	Process Images	The EL system processes the captured images using computer vision algorithms to produce the final image.
11.0	Store Final Image	The EL system stores the final image on the processing unit
12.0	Send Final Image to Display	The EL system sends the final image to the display
13.0	Display Image	The EL system outputs the final image to the user on the display.
14.0	Export all Images	The EL system is able to export both the raw images and the final processed image from the system.

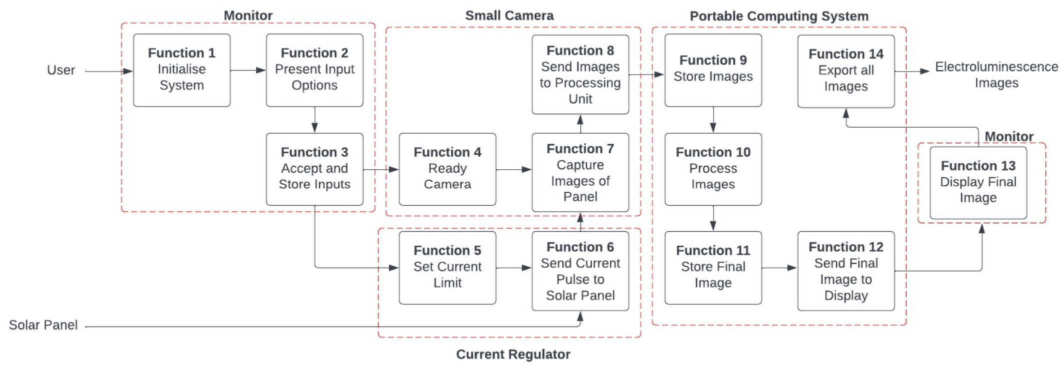

Figure 3: System Architecture and Functional Flow Block Diagram of the system.

4. System Prototype

We have created a portable electroluminescence measurement system for photovoltaic modules using the Raspberry Pi Camera module. This system prototype helps in capturing images of solar panels and analyzing any defects or variations in their performance.

To used touch screen to operate the portable EL system, the team designed a graphical user interface (GUI) as Figure 4 shows. The team selected Tkinter as the toolkit for design. It provides a powerful object-oriented interface to the Tk GUI toolkit and it is the most commonly used module for building GUI applications in Python due to its simplicity and availability. Tkinter makes it very easy to create windows, buttons, menus, text boxes, labels, and many other widgets. Our system prototype includes a user-friendly interface that allows users to choose between automatic and manual modes. In the automatic mode, the system captures images with predefined settings, while in the manual mode, users can adjust parameters such as waiting time, ISO, shutter speed, and resolution according to their needs.

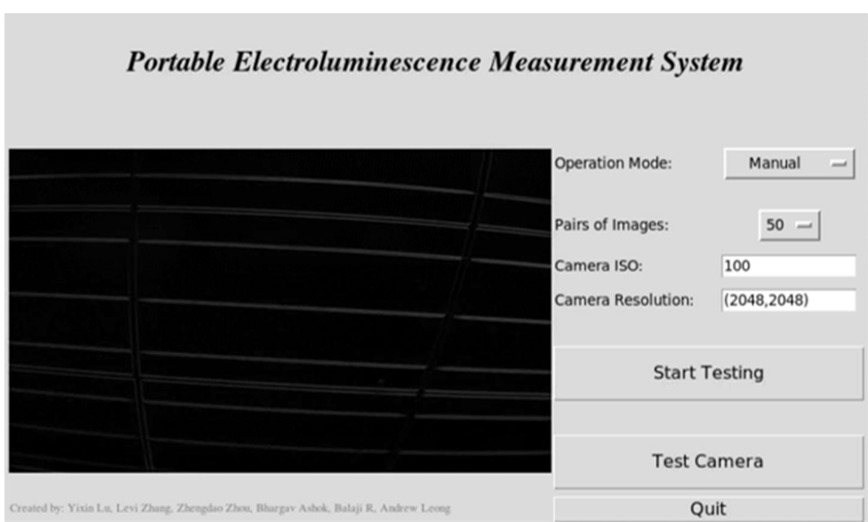

Figure 4: GUI Design for the Touch Screen

With our algorithm, we are able to obtain two raw images and calculate a difference image that highlights any areas of concern on the solar panel. This helps in identifying defects or variations in the performance of the panel. For the image capture and processing algorithm, functional tests and performance tests were run. The functional tests involved executing the entire script and checking if the resulting images were as expected. This was done manually by inspecting the images and automatically by comparing the output images to a set of expected images using a metric such as the structural similarity (SSIM) index. Performance tests involved measuring the time it took to execute the script and the memory it used. The script was then run with different inputs (number of photos, wait time, resolution, ISO) and the effects on performance was observed.

To vary the amount of current being passed to the panel, as well as controlling when to cut off the power supply to the panel to take the dark image, we have made a current regulating device. The requirements stated by the client were that the maximum current that needs to be passed to the solar panel is 10amps. Based on different panel sizes, the device should be able to adjust to current to the required rating and pass current to it. The following parts were used to create the current regulator.

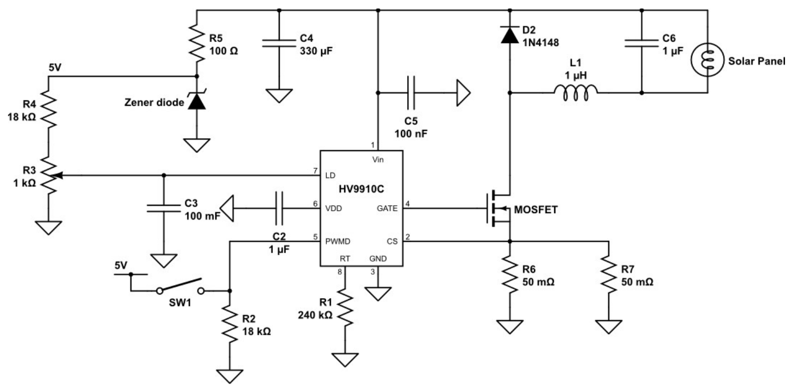

Figure 5: Final schematics of the current regulator device.

Table 4: Parts used in the circuit with details of most parts.

Part	Description	Rating
HV9910C	The main chip that acts as the regulator.	15V-450V, max temp of 125°C
Resistor R1	Resistor that connects to pin 8 of the chip (RT)	240 kΩ
Resistor R2	Resistor that is used to step down the voltage to 5V	18 kΩ
R3 (potentiometer)	Help adjust the amount of current required.	1kΩ
Resistor R4	Connected to the potentiometer	18kΩ
Resistor R5		17kΩ
Resistor R6	A surface mount style resistor	50mΩ
Resistor R7	A surface mount styled resistor	50mΩ
Capacitor C1	Connects to pin 6 of the chip (VDD)	1 μF
Capacitor C2	Connects to pin 7 (LD) of the chip	0.1 μF

Capacitor C3		330 μF, 63V
Capacitor C4	Connects to pin 1 (Vin) of the chip	0.1 μF
Capacitor C5	Added before current enters the panel	1 μF
Zener diode		-
Switch	Normal 5V switch to activate the circuit	-
MOSFET	Used to connect the chip to the circuit and panel	100V, 45A rating
Diode D2	Schottky styled rectifier	100V, 20A
Inductor L1	Toroidal styled inductor	380μH

Using these parts, the first prototype of the circuit was built, which can be seen below.

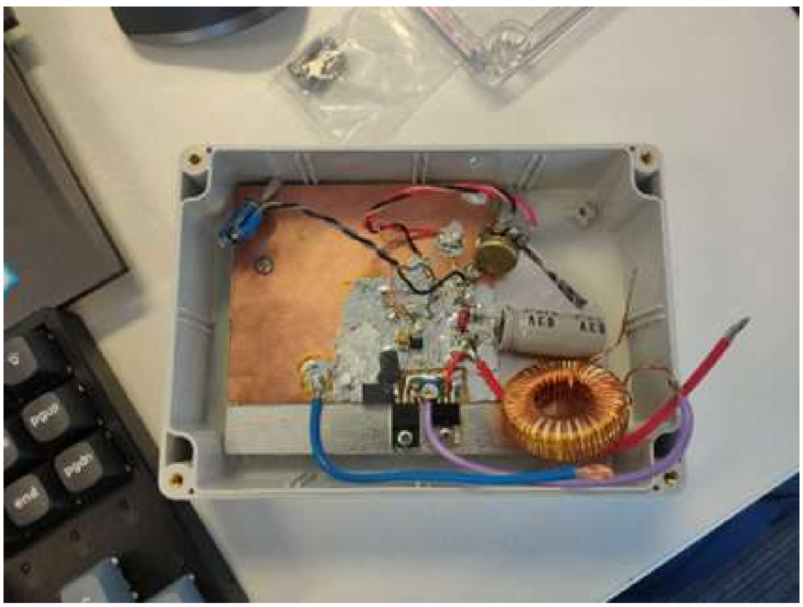

Figure 6: The final circuit of prototype 1 current regulator

In terms of the current regulating device, the first prototype was able to pass 30V and 9.5 amps of current in our initial testing.

Graphical User Interface: To used touch screen to operate the portable EL system, the team designed a graphical user interface (GUI). The team selected Tkinter as the toolkit for design. It provides a powerful object-oriented interface to the Tk GUI toolkit and it is the most commonly used module for building GUI applications in Python due to its simplicity and availability.

Radio Frequency Communication:

In terms of the communication between the Raspberry Pi controller and the current regulator circuit, an RF module was integrated into the system. The RF module has two components, a transmitter and a receiver. The transmitter circuit is able to transfer an input signal to radio wave and send that out through an antenna. Then the receiver is able to intercept that radio wave through another antenna, and convert the radio wave to an output signal, which is ideally same as the input signal of transmitter. The RF module implemented in this project is the Linx LR-433 RF module, which is designed to send and receive radio waves with 433.92MHz frequency. The transmitter board is attached to, and powered, by the Raspberry Pi controller. Furthermore, the Raspberry Pi is designed to send a periodic step signal through the GPIO function, as the indicator for triggering current regulator (i.e., send logic-high signal to switch on the current supply to solar panel, vice versa). The receiver board is attached to the current regulator circuit. It is power by two AAA batteries for the purpose of reducing circuit complexity. It is designed to output either logic-high (3.3V) or logic-low (0V) signal, for the purpose of switching the current supply on and off.

As shown in Fig. 6, the connection is made in pairs, where the transmitter is attached to Raspberry Pi and receiver is attached to the current regular's MOSFET chip. The port GPIO 7 on the Raspberry Pi was used to generate the triggering step signal. In specific, the GPIO port sends out X+0.1 seconds-long logic-high signal and X+0.1 seconds-long logic-low signal in sequence, where X is a user input that determines the responding period for the current regulator (5 seconds). In that case, as described above, the RF receiver will output a 3V-peak step signal at the same frequency, to switch on/off the current supply to solar panel. The connection between each component is made with Dupont wires soldering.

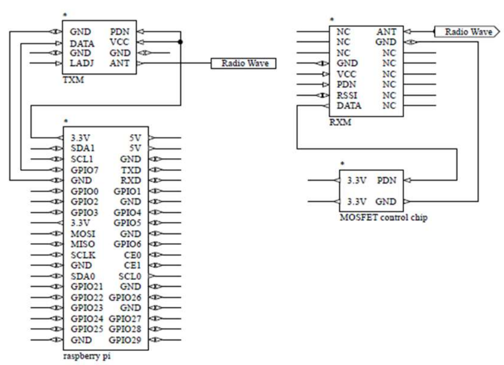

Fig. 6. RF module connection details.

The designed system was finally evaluated against the requirements of the system. This was done through technical performance metrics derived from the requirements. The evaluation is detailed below in Table 5. It is worth noting that the criteria for waterproof, windproof, and scratchproof are for the final product of the system. However, the system is currently in prototype 2 and will continue to be iterated on. Therefore, these requirements cannot be satisfied at this stage of the project. Based on the evaluation, the system is performing as expected and within reason with the only exception being the amount of external lighting noise the system can operate in. The issue should be resolved in the future by utilising a light filter on a better quality camera.

Table 5: Technical Performance Metric

TPM	DoI*	Metric	Target		Current Status	Score	Testing method
			Min	Max			
Measurable number of panels per time	+	Total number	1	-	1	1	Number of current regulator outputs
Weight	-	Kg	0	18.5	5.5	1	Weighing system
Daily Operable Time	+	Hours per day	8	-	9.76	1	Based on power consumption of Raspberry Pi (1250mA), Display (550mA), and Camera (250mA) connected to 20000mAh battery.
Initialisation Time	-	Minutes	10	15	5	1	Timed Testing
Lifespan	+	Years	1	-	1	1	Lowest warranty of components
Waterproof	-	IP rating	65	69	NA	NA	System still in prototype phase, not finalised with proper casing
Windproof	-	Beaufort Wind Force Scale	6	10	NA	NA	System still in prototype phase, not finalised with proper casing
Scratchproof	-	Mohs Scale	5	10	NA	NA	System still in prototype phase, not finalised with proper casing
Measurement Time for 50 pairs	-	Minutes	20	30	5	1	Timed testing
Pixels Per Inch	+	PPI	160	300	133	0.85	Based on resolution of Raspberry Pi display
Number of user input	-	Total Number	5	8	4	1	Counted inputs on GUI
Lead time for parts	-	Days	3	14	8	1	Longest lead time of components (due to low stock)
Cost	-	AU dollars	1500	1800	1319.38	1	Summed cost of used components

Maximum operable lighting conditions	+	Lux	6000	8000	500	0.1	Measured using lux meter in a dimly lit room
Maximum operable terrain conditions	+	Slope degree	35	45	NA	NA	Tripod selection not finalised as still in prototype phase

Detail Timeline:

The development of the system prototype followed the following timeline:

Week 2: Requirement Gathering and Planning: We defined the requirements for the system prototype, including the desired functionality and modes of operation. The research on how to initiate the electrical design started.

Week 4: initial build of the proposed electrical circuit was created on LT spice and ready for simulations. Alternatively, the search for finding ideal parts available to purchase and acquire had started.

Week 6: Code Development: We wrote the necessary code in Python, utilizing the PiCamera library and OpenCV for image processing operations. The code was structured into separate functions for modularity and reusability. The electrical circuit was successfully simulated in the software and the first draft of the procurement list was generated and sent to the client.

Break week 1: The final procurement list was created and approved by the client. The purchase was made by the end of the week.

Week 7: The final parts were received at the end of the week, a bit of delay but all components arrived and was ready for building.

Week 8: Testing and Debugging: We conducted extensive testing of the code to ensure proper functionality and address any bugs or issues. We verified the image capture, grayscale conversion, difference calculation, and average difference image generation. The building of the current regulator circuit had started, with some new iterations and possibility of more components required.

Week 10: The current regulator circuit was completed with initial testing done. The testing of the current regulator and the software team together was done, and our first initial test was performed successfully.

Week 11: Preparation of detailed code comments and documentation to explain the functionality, usage, and parameters of the system prototype. The demonstration of the entire project was presented to the client and the system validation test was also run.

Week 12: Connection of the battery to the system, making the system truly portable without the need of having a lab power supply. Final review of documents and repository with small updates to the website.

Our system prototype has achieved several significant milestones during the 12 weeks that were given to us. It improves efficiency by streamlining the image capture and analysis process, reducing manual effort. The system is also portable, allowing measurements to be taken in various conditions. It offers flexibility and customization, empowering users to adjust settings based on their specific requirements. The average difference image generated by the system provides a clear visual representation of any variations or defects in the solar panel. Additionally, the user-friendly interface makes it easy for anyone to use, regardless of their technical expertise.

Detailed cost

Part	Source	Cost
HV9910C	Element 14	$ 0.80
Resistor	Recycled part	$ 0.00
Capacitor	Recycled part	$ 0.00
Diode	Recycled part	$ 0.00
Switch	Recycled part	$ 0.00
MOSFET	Element 14	$ 3.05
Inductor	Element 14	$ 7.07
Copper clad board	Element 14	$ 8.46
Battery	Client	$ 500.00
RF Eval Kit	Client	$ 170.00
Raspberry Pi Touchscreen	Client	$ 130.00
SmartiPi Touch 2	Client	$ 55.00
SmartiPi Touch 2 Back cover	Client	$ 22.00
Polycarb enclosure	Client	$ 27.00
RaspberryPi HDMI Cable	Client	$ 10.00
MC4TO4MM Test lead	Client	$ 90.00
Anderson Plug for battery	Client	$ 15.00
RaspberryPi Power supply	Client	$ 17.00
Lens small	Client	$ 45.00
Lens large	Client	$ 85.00
Raspberry Pi HQ camera	Client	$ 85.00
32 GB SD Card	Client	$ 25.00
HQ Camera Mount	Client	$ 11.00
FlexCable 1m	Client	$ 13.00
	Total	$ 1319.38

5. Key Decisions Made and Issues Faced

During the development of our portable electroluminescence measurement system prototype, we encountered several key decisions and challenges. Here are some of the major ones:

Current Regulator Part Selection: Decision: The parts were selected based on the LT spice schematic. The decision was validated by results and graphs from LT spice that showed 10A of current being safely passed. However, as the part was being built there were certain challenges that we faced. Issue: Limited access and availability of components. Certain components were not available on Element 14 or had long delivery time. Decision: To ensure we completed the project within the given timeline, we used spare parts from old computers by recycling them for our circuit. Therefore, we were required to iterate the circuit the accommodate parts available. For example, we were unable to procure a surface mounted 25mΩ resistor, hence we found two 50mΩ resistors (resistor 6 and 7) and connected them in parallel. Decision: to use a potentiometer instead of a voltage regulator, the reason was because the client wanted to be able to control the current flowing through the panel so that the connection could be made to various sizes of solar panels with different current rating. Further decisions made and the support provided to making them have been highlighted in the Table below.

Part	Decision	Support
HV9910C	The chip that reduces the voltage and controls the current flowing through the solar panel	Suggested by electrical expert Chris, validated by LT spice
Resistor	To reduce the voltage where necessary and ensure that a high voltage power source can be used	The chip, potentiometer and switch operate at a low voltage compared to the high voltage power supply
Capacitor	To use capacitor where necessary to help reduce current amplitude	Validated by LT spice results
Diode	Alternative load to help current flow through the circuit	Validated by HV9910C Datasheet
Switch	To break circuit when not in use or complete circuit when in use	Needed for RF link connection to control circuit from GUI
MOSFET	To help current pass from the chip to the solar panels safely	Suggested by client and validated by HV9910C Datasheet
Inductor	To reduce ripple current in the circuit	Suggested by electrical expert Chris, validated by LT spice

Image Format Selection: Decision: We opted to capture images in the YUV format instead of the traditional RGB format. This decision was made to leverage the unique advantages of YUV, such as better colour representation and efficient storage. Issue: Working with the YUV format required additional effort in converting the captured data to grayscale for further analysis.

Exposure and Shutter Speed Settings: Decision: We provided users with the flexibility to manually set the exposure and shutter speed parameters to achieve the desired image quality and capture the necessary details. Issue: Determining the optimal exposure and shutter speed settings can be challenging, especially for users with limited knowledge in photography. Providing clear guidelines and examples in the system documentation can help the handover team avoid any confusion.

Testing and Debugging: Decision: We allocated a significant amount of time for testing and debugging to ensure the functionality and reliability of the system prototype. Issue: Testing image capture, conversion, and difference calculation algorithms required careful analysis and verification to ensure accurate results. The handover team should thoroughly test each component of the system to ensure its proper functioning.

Key issues faced and how the handover team can avoid them:

Performance Optimization: Issue: Processing and analysing a large number of images can be computationally intensive and time-consuming. This can result in slower performance and delays in delivering results. Solution: The handover team should explore optimization techniques, such as parallel processing or image down sampling, to improve the system's performance. They can also provide recommendations for hardware upgrades or optimizations to enhance processing speed.

User Interface and Documentation: Issue: The user interface and documentation play a crucial role in the system's usability and understanding. Inadequate documentation or a poorly designed user interface can lead to confusion and difficulties in operating the system. Solution: The handover team should prioritize creating comprehensive and user-friendly documentation that clearly explains the system's functionality, modes of operation, and parameter settings. They should also consider conducting user testing to identify any potential usability issues and address them proactively.

Heating of Current Regulator: Issue: The Diode and Mosfet heated up to greater than 100 degrees Celsius. The issue was investigated and observed to be due to high inductance in the circuit particularly from connection between the chip (CS) and a 25mΩ. Solution: To lower the inductance in the resistor, we used a different type of resistor which was not as long but instead a surface mount resistor.

6. Recommended Next Steps

The team were able to create two main prototypes with groundworks on the code and the electrical circuit being created. In this section, the team details on what more can be done to the project.

1. Capture 12-Bit Images:

The current system prototype captures images in the YUV format, but our next step is to modify the code to capture 12-bit raw images. This will allow us to capture higher-quality and more detailed images, enhancing the accuracy of our analysis. We will update the camera settings and configure the Raspberry Pi Camera module to capture raw data. By incorporating the necessary modifications, we can ensure that the system captures and processes images with a higher bit depth, leading to improved measurement precision.

2. **Develop a More Portable and Reliable Box:**

To enhance the system's durability and protect the devices from dust and water, our next step is to design and construct a more robust and portable enclosure. The box will be specifically engineered to house the Raspberry Pi, PiCamera module, and other associated components securely. It will feature appropriate seals and shielding to prevent dust and water ingress, ensuring the system's reliability in various environmental conditions. Additionally, the enclosure will be designed to be lightweight and compact for easy transportation and deployment.

3. **Implement Power Management:**

Power management is a crucial aspect of a portable system. In our next step, we will integrate power management features into the system to optimize power consumption and ensure reliable operation. This may involve the use of efficient power regulators, battery backup systems, and intelligent power control mechanisms. By implementing effective power management, we can prolong the system's runtime and make it more practical for field applications.

4. **Creating a PCB board**

The current circuit is built on a prototyping board, after the final circuit is developed, the circuit can be modelled on a PCB program such as KiCAD and sent to a PCB maker in order to create a final PCB board which can be used.

5. **Higher rating current.**

The current regulator is built to handle 10Amps of current. Since panel technology is increasing drastically, and there is so much more improvements being made to solar panels, having a regulator that can handle more than 10 amps can help future proof the product.

By focusing on these next steps, we aim to enhance the functionality, portability, reliability of our portable electroluminescence measurement system. These improvements will enable us to provide a more comprehensive and practical solution for analysing solar panel performance in a wide range of applications and settings.