Microcontroller-based Design a Supporting System for Irradiance, Temperature and Tilt Angle Conditioning of PV Performance Measurement

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Abstract— Several factors influence PV output, including irradiance, temperature, and panel tilt angle. Irradiance and tilt angle affect the Photovoltaic (PV) current, while temperature affects the PV voltage. To accurately measure the performance of PVs in the field, it is necessary to condition these three parameters. Therefore, a system should be created to condition these parameters. This research aims to develop a control and monitoring system based on the set point to condition irradiance, temperature, and tilt angle. This research started with system design, fabrication, and functionality testing with the black box method, sensor reading accuracy, and PV performance testing. The functionality testing results indicate that each test item can perform as expected. The sensor testing revealed 1%, 0.26%, and 1.8% errors for MLX90614, BH1750, and MPU6050, respectively. The system's performance was tested, and it was discovered that the input value, which is the setpoint of the three variables, i.e., irradiance, temperature, and tilt angle of the PV, can produce outputs that are almost the same as the input value, and the settling time is different to reach the setpoint of each parameter. PV performance measurement using this system can represent PV performance by conducting direct testing using direct sunlight.

Keywords—PV performance; irradiance; temperature; tilt angle; microcontroller

I. Introduction

Irradiance, temperature, and panel tilt angle greatly influence photovoltaic (PV) output [1]. Irradiance, temperature, and tilt angle affect the performance of PV in terms of current and voltage, as shown by the current (I) and voltage (V) curves. This curve shows the relationship between the voltage and current of the PV. Decreasing the irradiance value decreases current and voltage, but the most significant decrease occurs in current. However, if the temperature increases, the current increases, but the voltage decreases is the most significant change [2]. In addition to these two factors, additional factors that affect the output of the PV are the tilt angle of the PV and shading [3].

Several factors, such as the astronomical location of the panel installation site, the daily and yearly apparent motion of the sun, and the weather, affect the amount of irradiance received by the PV. System design requires the most appropriate panel tilt angle to obtain maximum solar radiation. Two angles have an impact on the PV mounting installation. The first is the angle of inclination of the PV concerning the horizontal plane, also known as the slope, and the second is the angle measured in the direction to the south, also known as the azimuth angle [4], [5], [6].

The field with the best radiation is produced by an angle of incidence (θ) close to zero. One way to achieve this is to use a sun tracker to observe how the sun moves continuously. However, such a system would consume a lot of energy, so it would not be economically beneficial [7]. Maximum voltage, current, power, and efficiency are achieved at an incident angle of 90° or, in other words, the light source is perpendicular to the PV [4]. Varying the irradiance, temperature, and tilt of the panel can give an idea of the PV's performance.

Researchers have conducted previous studies on regulating irradiance, temperature, and tilt angle. The development of a solar panel performance measurement simulator that can adjust two variables: irradiance and temperature is presented in [8]. The design of a PV simulator monitoring system that varies irradiance is given in [9]. The implementation of a microcontroller to vary the PV tilt angle was performed by [10]. The system for measuring PV performance by varying irradiance and temperature was conducted by [11].

However, none of the literature mentioned above has created a PV performance testing system that can vary three parameters: irradiance, temperature, and tilt angle. In this paper, a PV performance measurement system is proposed that can vary these three parameters. If the values are inputted as desired, this system will automatically set the lamp to emit light intensity equivalent to the inputted irradiance. The same applies to temperature and tilt angle.

This paper is expected to contribute to the development of a more complete PV performance testing system by adding other parameters that significantly affect PV performance. The selection of irradiance, temperature, and tilt angles proposed in this paper as variables to be varied is because these three variables significantly influence PV performance.

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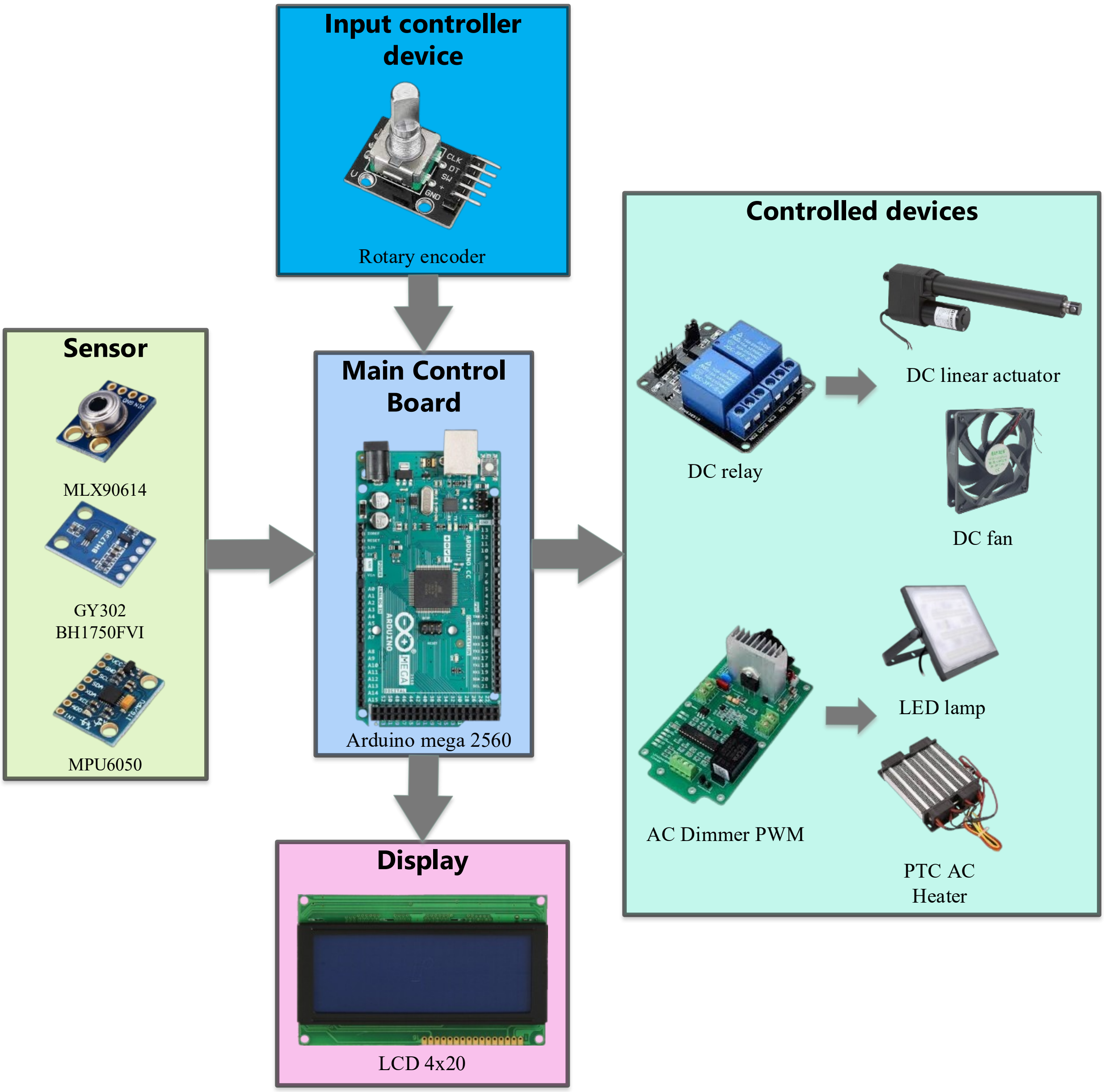


Figure 1. The system architecture

This paper is organized into four sections. Section 1 is the introduction, which discusses the background, literature review, and objectives. Section 2 of this paper is the method. This section covers hardware and software architecture design and how to test the system. Section 3 presents the results of the system tests that have been carried out and discusses them. Section 4 concludes this paper.

II. METHOD

A. Design of Hardware Architecture

The designers divide the hardware system into three major sections: sensors, the main control board, and controlled devices. The sensor section uses three sensors: MLX90614, GY302 BH1750FVI, and MPU6050. The main control board is an Arduino Mega 2560. In the controlled device section, there are DC relays to regulate linear actuators and DC fans and AC PWM Dimers to regulate LED lights and PTC heaters. Additional devices include a Rotary Encoder to select the input menu and a 4x20 LCD to display and monitor irradiance parameters, temperature, and tilt angle. A design of hardware architecture shown in Figure 1.

1) Arduino Mega 2560

Arduino Mega 2560 is the main development board, and an ATmega2560 is the processing chip. There are 54 sets of digital I/O ends (14 sets can be PWM output), 16 sets of analog input ends, four sets of UART (hardware serial ports), and an instruction cycle of 16 MHz. Because there is a boot loader, the programs can be downloaded directly via USB without needing external programmers. The power can be supplied directly from a USB or an AC-to-DC adapter [12].

2) MLX90614

The MLX90614 monitors an object's temperature without touching it, using emissivity and radiation. Emissivity is a coefficient that indicates how well an object emits infrared light compared to a theoretically ideal black body. MLX90614 uses this radiation to calculate the object's temperature. During production, the manufacturer calibrates MLX90614 with black matter with an emissivity of 99.9%, which is regarded as E = 1 [13].

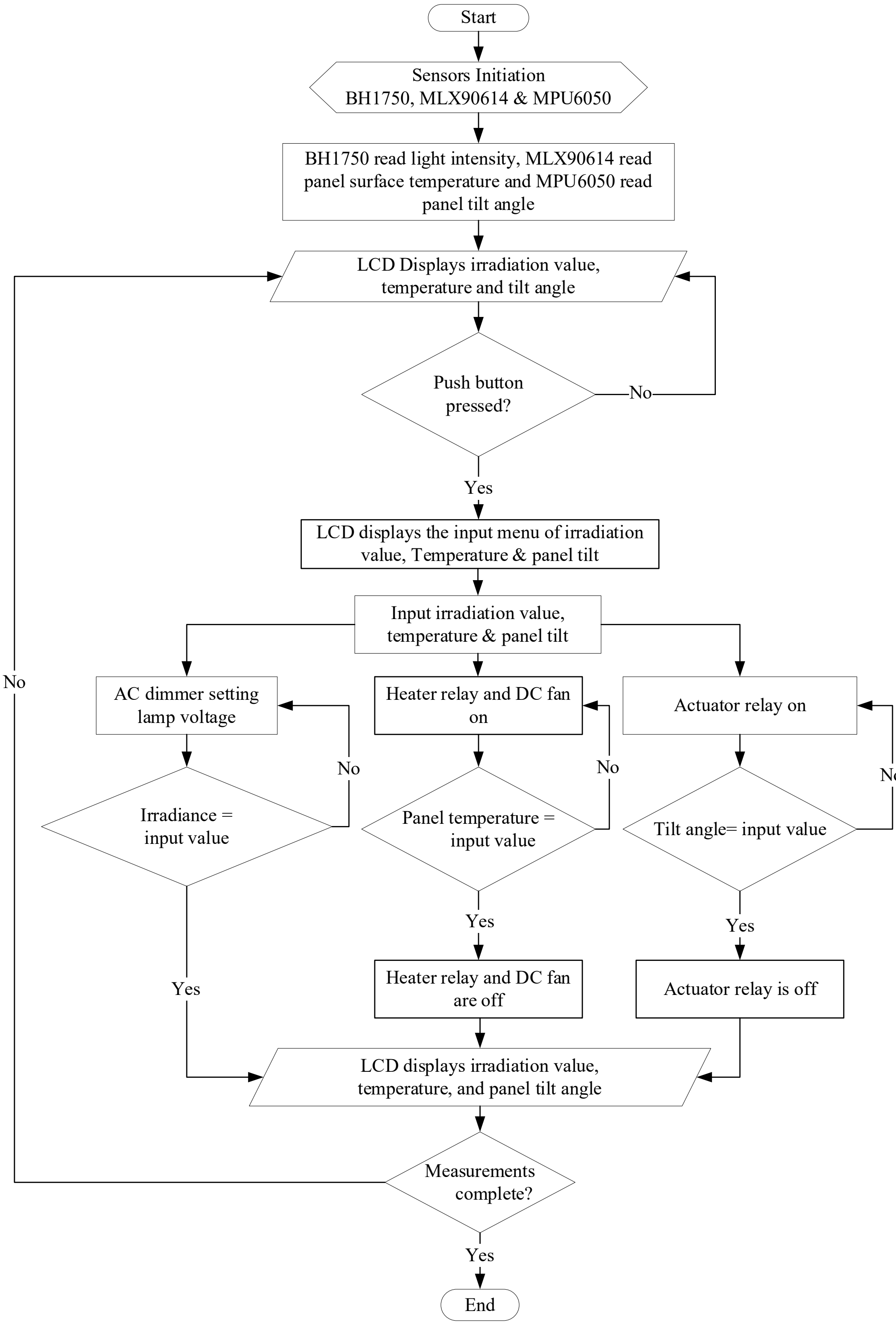


Figure 2. Flowchart of control and monitoring system.

3) GY302 BH1750FVI

The GY-302 module is a board that includes a BH1750 sensor, an appropriate voltage stabilizer, capacitors, and pull-up resistors for the I2C line [14]. The GY-302 module is a popular solution that is employed in a variety of applications, including the management of runway edge lamps by drone [15], [16].

The sensor operates with a supply voltage of 3-5 V and has a resolution of 16 bits (working range 1 to 65535 lx). Communication takes place over the I2C bus, and the ADDR pin allows the modification of the address from 0x23 to 0x5C after selecting a high or low state. The sensor measures light intensity in lux units with an accuracy of 1 lx in H-resolution mode (120 ms between successive readings) and 4 lx in L-resolution mode (16 ms) [17].

4) MPU6050

The MPU6050 sensor is an electronic module that can determine tilt angle using data from the integrated accelerometer and gyroscope sensors. This sensor also includes a temperature sensor, which can measure ambient temperature. Applications requiring angle information commonly utilize the MPU6050 sensor with this functionality [18].

B. Design of Software Architecture

The software design of this system is arranged in the form of a flowchart and consists of a series of instructions that will be embedded in the Arduino Mega 2560 microcontroller, as shown in Figure 2. The series of instructions is made in the C++-based Arduino IDE. Based on this figure, the Arduino Mega first initiates the sensor, and then the sensor reads each parameter according to the type of parameter being measured. The reading results are displayed on the LCD. To input the setpoint of light intensity, temperature, and tilt angle. It is done by pressing the push button and selecting the menu on the LCD by turning the Rotary Encoder. After inputting the setpoint of the PV's light intensity, temperature, and tilt angle, the Arduino will activate the AC dimmer and relay to activate the lights, heaters, fans, and actuators. After the setpoint is met, the AC dimmer and relay will turn off.

C. Sensor Accuracy Testing

This assessment aims to determine the accuracy levels by analyzing the performance indicators of the sensors, specifically MLX90614, MPU6050, and BH1750, measured in terms of error. The test involves comparing the sensor readings with those of specialized measuring instruments such as the Solar Power Meter, Thermogun, and Inclinometer, which measure irradiance, temperature, and tilt angle. The measurement data is then compared to calculate the error by [19].

$$Error = \frac{|x_0 - x|}{x} \times 100\% \quad (1)$$

where x_0 measurement result of the sensor and x measurement result of the measuring conventional instrument.

D. System Performance Testing

The method used in this research is to use black box testing. This method is one of the system testing methods that use the black box as a technique for testing that focuses on the output results in the program by giving input values and finding errors through five parameters, which are functions, interfaces, data structures, application performance, as well as initialization and termination [20]. The test carried out is to see whether the system's functionality, both hardware and software, can work as expected. Table I presents this system test scenario.

TABLE I. SYSTEM TESTING SCENARIO

No.	Input	Scenario
1	MLX90614	PV temperature reading
2	BH1750	Light intensity reading
3	MPU6050	PV tilt angle reading
4	Relay	Setting on and off the DC fan, AC heater, and DC actuator
5	AC Dimmer	Setting the light intensity
6	LCD 20x4	Display sensor measurements in real-time and as an HMI
7	Rotary Encoder	HMI display settings for inputting data

III. RESULTS AND DISCUSSION

A. Implementation

The results of the system implementation are presented in Figure 3. The 4x20 LCD is placed on the outside, making it easier to input values and monitor measurement results. On the outside, there is also a Rotary Encoder and Push Button. The microcontroller, MLX90614, MPU6050, and BH1750 are placed on the PV holder, and the actuator is connected to the PV holder. These components are located inside the box.

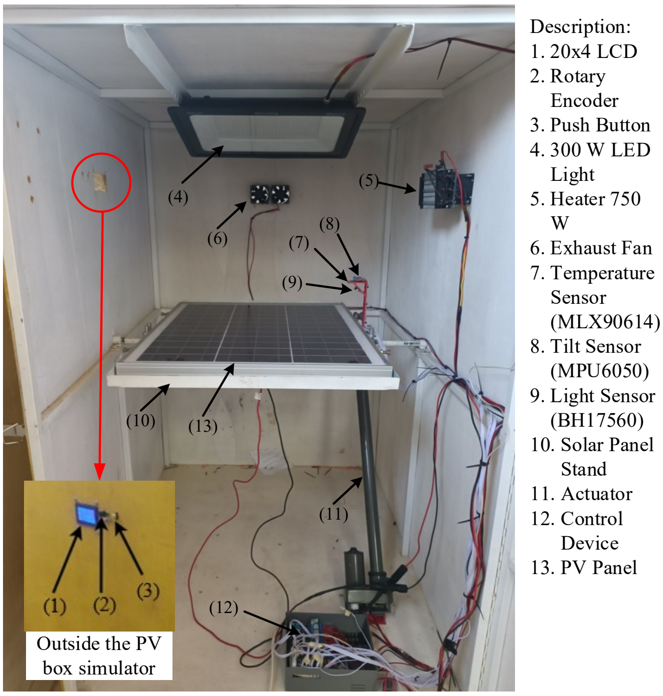


Figure 3. Hardware implementation

B. Sensor Accuracy

The test results of the temperature sensor (MLX90614), tilt angle sensor (MPU6050), and light intensity sensor (BH1750) against the Solar Power Meter for BH1750, Thermogun for MLX90614, and Inclinometer for MPU6050 are presented in Table II and Table III respectively. Error is obtained using (1). The average reading error on the light sensor is 1.46%, the temperature sensor is 1%, and the tilt sensor is 1.88%.

TABLE II. COMPARISON OF TEMPERATURE AND IRRADIANCE SENSOR WITH CONVENTIONAL INSTRUMENTS

Temperature (°C)		Irradiance (W/m²)		Error (%)	
MLX90614	Thermo-gun	BH1750	Solar Meter	Tempe-rature	Irradi-ance
29.33	29.10	10.07	10.10	0.79	0.29
33.21	32.90	40.06	40.13	0.94	0.18
37.23	37.60	70.24	70.52	0.98	0.41
40.09	40.80	100.16	100.57	1.74	0.41
43.13	42.90	120.55	120.51	0.54	0.04
Average				1.00	0.26

TABLE III. COMPARISON OF TILT ANGLE SENSOR WITH CONVENTIONAL INSTRUMENTS

MPU6050 (°)	Inclinometer (°)	Error (%)
20	20.30	1.50
15	15.21	1.40
10	10.11	1.10
5	5.12	2.40
0	0.20	NA
-5	-5.11	2.20
-10	-10.3	3.00
-15	-15.21	1.40
-20	-20.31	1.55
Average		1.82

Note: + PV tilt angle is clockwise, - PV tilt angle is counterclockwise

According to reference [19], measuring instruments are categorized by size of accuracy into three groups: precision tools (<0.5%), work tools (± 1-2%), and rough measuring instruments (>3%). Based on this classification, the sensor used for measuring temperature, tilt angle, and light intensity has an average maximum error of 1.88, placing it in the category of work measuring instruments. Therefore, using sensors in this system can effectively replace conventional measuring instruments.

C. System Performance Testing

The software test focuses on the input value measured by the microcontroller, including sensor measurement data. The software uses the LCD to display the sensor measurement results and control the integrated hardware. Table IV shows the results of software testing. The results of the tests provided are as expected. Hardware testing includes heater, DC fan, LED lights, and actuators. The results of this test are shown in Table V. Based on the table, all test results provide results as expected.

The system performance measurement is conducted by comparing the setpoint and measuring the time taken to reach the setpoint of each parameter, i.e., irradiance, temperature, and tilt angle, to the value displayed on the LCD. The test results are presented in Table VI for irradiance, Table VII for temperature, and Table VIII for tilt angle. An increase of 10 W/m^2 takes an average time of 0.11 s. Temperature takes longer than irradiance, with the average time for a rise of 5 °C, from 30 °C to 50 °C is 33.63 s. As for the tilt angle, the average time required to increase every 5° is 1.3 s for clockwise and 1.59 s for counterclockwise.

The temperature sensor, MLX90614, has a maximum error of 1.74 %. This value is almost the same as in [21], where the highest error of the sensor reading is 1.8 %. Based on the measurements taken, the light intensity sensor obtained a maximum error of 0.41 %. The light sensor used is BH-1750, which gives accurate values compared to other sensors [22]. Meanwhile, the tilt sensor using MPU6050 has a maximum error of 0.31°. In a previous study by [23] the accuracy of this sensor is ±1.5°, and in [24] maximum error is 0.31°.

The results of PV performance testing using this system are shown in Figure 4. Based on the figure, it is found that irradiance affects both voltage represented by the Open Circuit Voltage (Voc), and current represented by the Short Circuit Current (Isc). The higher the irradiance , the greater the voltage and current generated by the PV. Meanwhile, the higher temperature will decrease the voltage and increase the current. This condition has been previously revealed by [2] stating that a decrease in irradiance leads to a decrease in PV current and voltage, but the current is a significant decrease. However, if the temperature increases, the voltage drops significantly, but the current experiences a slight increase.

TABLE IV. SOFTWARE BLACKBOX TESTING RESULT

No.	Test Item	Expected Results	Actual Result	Remark
1.	Display sensor readings	Display the sensor reading result: 1. Irradiance 2. PV surface temperature 3. PV tilt angle	Can display sensor readings on the LCD: 1. Irradiance 2. Panel surface temperature 3. Panel tilt angle	Success
2.	Main Setting	Each option on the menu has a specific value that can be inputted	Can input the value of irradiance, temperature, and panel tilt angle with a specific value	Success
3.	Save settings data	The setpoint value can be saved	Setpoint is successfully saved and can be reopened	Success

TABLE V. HARDWARE BLACKBOX TESTING RESULT

No.	Test Item	Expected Results	Actual Result	Remark
1.	Light sensor BH1750 measures light intensity	The sensor can read the light intensity in lux units to be converted into W/m2 unit	The sensor reads the light intensity value in lux and has been converted to W/m^2.	Success
2.	Temperature sensor MLX90614 measures temperature	PV temperature sensor	The sensor reads the temperature of the PV	Success
3.	MPU6050 tilt angle sensor reads the tilt angle value on the PV stand	The sensor can read the tilt angle of the PV mount in units of degree	The sensor reads the temperature of the tilt angle value of the PV mount in degrees	Success
4.	Controlling lamp voltage with AC dimmer	The light intensity of the lamp can be controlled according to the setpoint	The lamp can produce varying irradiance according to the setpoints given, namely 0 W/m^2, 30 W/m^2, 60 W/m^2, 90 W/m^2, 120 W/m^2, and 130 W/m^2	Success
5.	Controlling the temperature with an AC heater and DC fan	The temperature on the simulator can be varied and maintained according to the input setpoint.	The heater can produce temperatures according to the setpoints given, namely 30 °C, 35°C, 40 °C, 45 °C, and 50 °C, and maintain the temperature	Success
6.	Controlling the tilt angle of the PV stand using actuators	The tilt angle of the PV mount can be adjusted according to the input set value.	The actuator moves automatically forward and backward to move the PV mat until it gets a slope value from the MPU6050 sensor reading that matches the given set value	Success
7	Controlling the HMI display to select input data	The user can select the parameter input menu as desired	Users can select the input menu to input the irradiance setpoint, temperature, and tilt angle of the PV	Success

TABLE VI. COMPARISON OF SETPOINT TO IRRADIANCE MEASUREMENT RESULTS

No.	Setpoint (W/m²)	Measurement Result (W/m²)	Settling Time (s)
1.	10	10.03	1.30
2.	20	20.03	1.42
3.	30	30.07	1.56
4.	40	40.07	1.63
5.	50	50.03	1.70
6.	60	60.23	1.79
7.	70	70.41	1.88
8.	80	80.26	1.97
9.	90	90.23	2.14
10.	100	100.40	2.28
11.	110	110.23	2.36
12.	120	120.44	2.47
13.	130	130.50	2.58

TABLE VII. COMPARISON OF SETPOINT TO TEMPERATURE MEASUREMENT RESULTS

No.	Setpoint (°C)	Measurement Result (°C)	Settling Time (s)
1.	30	30.23	12.54
2.	35	35.37	27.84
3.	40	40.20	48.25
4.	45	45.23	82.64
5.	50	50.23	147.2

TABLE VIII. COMPARISON OF SETPOINT TO TILT ANGLE MEASUREMENT RESULTS

No.	Setpoint (°)	Measurement Result (°)	Settling Time (s)
1.	20	20.30	5.21
2.	15	15.21	4.08
3.	10	10.11	2.80
4.	5	5.12	1.43
5.	0	0.20	0
6.	-5	-5.11	1.51
7.	-10	-10.3	3.09
8.	-15	-15.21	4.71
9.	-20	-20.31	6.38

Note: + PV tilt angle is clockwise, - PV tilt angle is counterclockwise

PV performance testing at various tilt angles is presented in Figure 5. According to this figure, Isc decreases as the PV tilt angle increases. This condition occurs because the light is not perpendicular to the plane of the PV surface, causing the light falling on the PV surface to decrease. Solar energy transformed into solar PV panels depends mainly on surface tilt angles relative to the horizontal plane and the PV module's azimuth angle orientation. The azimuth and tilt angle affect the solar PV panel on their peak power production, economic value, total energy production, rate structures, electricity market prices, etc [25].

Figure 6 shows how irradiance and temperature affect PV efficiency. PV efficiency decreases with decreased irradiance. Increasing the temperature to a standard range of 25 (°C) will reduce PV efficiency. This condition is due to low irradiance, which reduces the current produced by the PV, and an increase in temperature over the standard temperature causes a decrease in the voltage produced by the PV [2].

Figure 7 shows the results of testing the PV performance directly with sunlight and the developed system. The test results show a significant difference. This is because the difference between the spectrum of the sun is much more significant than the spectrum of synthetic light such as lamps. According to Oriel's product training catalog on solar simulation, the sun's spectrum has a brightness temperature of 5600 - 6000K, much larger than the spectrum of LED lamps, which is only around 3200K. In addition, the light emitted from LED lamps is wasted in some parts due to heat conduction, heat convection, and absorption [25].

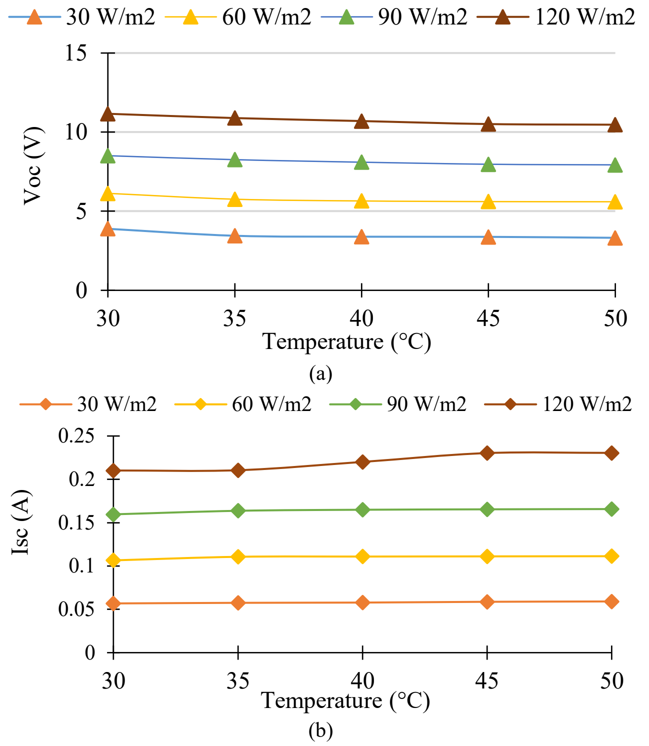
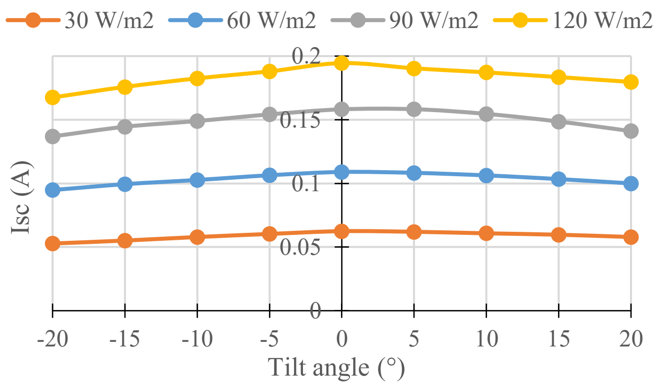


Figure 4. PV output at various irradiance and temperature conditions (a) Voc, and (b) Isc.



+ PV tilt angle is clockwise, - PV tilt angle is counterclockwise

Figure 5. PV output (Isc) at various tilt angle.

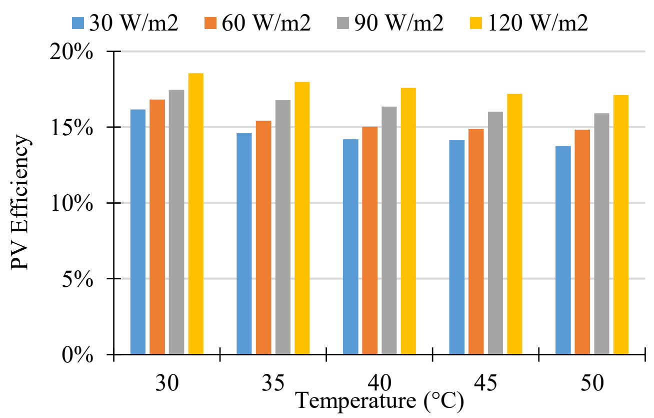
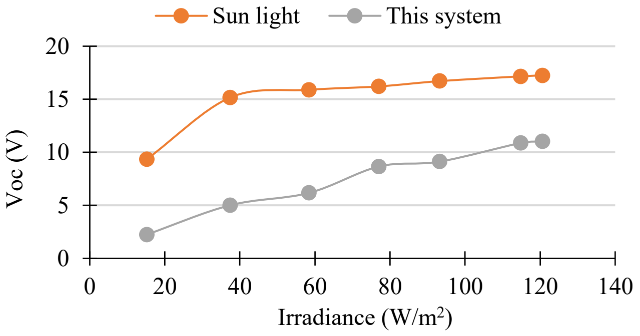
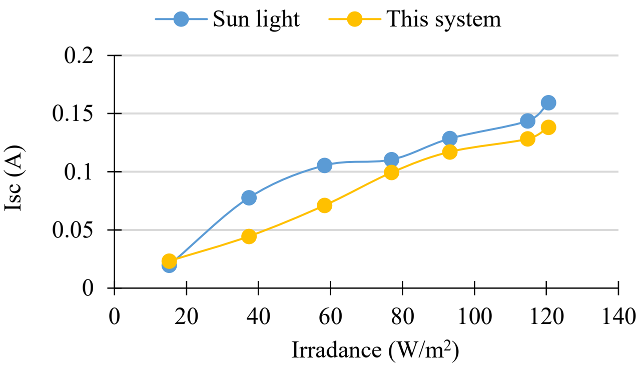


Figure 6. Efficiency of PV at various irradiance and temperature conditions.



(a)



(b)

Figure 7. Comparison of PV output measurements, (a) using the developed system and (b) using direct sunlight

IV. Conclusion

The irradiance, temperature, and tilt angle control system has been implanted on a PV performance measurement simulator that works well. Functionality testing using black box testing shows that hardware and software have worked as expected. Sensor performance has good accuracy, which is lower than 2%. PV performance measurement using this system can represent PV performance by conducting direct testing using direct sunlight. A more powerful light source than LED lights is required to improve this system's performance. Furthermore, the control can be improved by employing the PID method or comparable techniques to reduce the rising time and errors against the set point.

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