Jurnal Rekayasa Elektrika Vol. 21, No. 3, September 2025, page 142-151
ISSN. 1412-4785; e-ISSN. 2252-620X, Accredited by Kemendikbudristekdikti No. 105/E/KPT/2022
DOI: 10.17529/jre.v21i3.42384

Optimizing Light Detection with Photodiode Sensor Arrays Using Linear Regression

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Abstract—**Photodiode sensors are widely used in various applications such as light intensity measurement, optoelectronic devices, and automation. In improving the quality of measurement and automation systems, more sophisticated technology is needed such as photodiode sensor arrays, which allow more accurate data collection from multiple sensors simultaneously. This research aims to design a photodiode sensor array with high sensitivity. The system design consists of six photodiode sensors combined with a summing amplifier circuit and a non-inverting amplifier as a signal conditioner which is then processed by a microcontroller. After that, the linear regression function is determined through the calibration process and experiments carried out. Two linear regression functions are obtained and implemented in two operating modes: normal mode and sensitive mode. Experimental results yield two linear regression functions applied to a photodiode sensor array in normal and sensitive modes. Normal mode shows 82.50% accuracy with a 36.69% coefficient of variation, while sensitive mode boasts 94.05% accuracy and 49.81% coefficient of variation. Both modes cater to different light conditions, with sensitive mode excelling in detecting light intensity. Linear regression implementation proves precise and accurate for light detection.**

Keywords: calibration, linear regression, photodiode sensor array, signal conditioning

I. Introduction

Photodiodes play a crucial role in various applications because they can transform light into electric current, which is why they are vital parts of light detection systems. These applications include optical communication, medical diagnostics, industrial automation, and environmental monitoring. The growing need for accuracy in light detection systems has resulted in the creation of photodiode sensor arrays, providing improved sensitivity and better resolution in identifying changes in light intensity across space. Still, there are obstacles to overcome when it comes to enhancing the precision and efficiency of these sensor arrays, mainly because of the intricate and sometimes non-linear connection between light strength and the sensor's electrical response [1], [2].

Arrays of photodiode sensors are made up of numerous photodiodes organized to sense light across a spatial region, offering more detailed data compared to a solitary photodiode. They are frequently utilized in applications such as imaging, spectroscopy, and optical sensing. One major obstacle in using photodiode arrays is guaranteeing precise light detection, since external influences like noise, temperature changes, and sensor response non-linearity can affect the system's functionality [3]. Photodiodes show complex behavior that is not linear, especially when exposed to different light levels, making it difficult to accurately calibrate the sensor's output for precise measurements. In practical situations, elements such as noise and fluctuations in temperature can worsen the signal's quality even more. Hence, it is essential to utilize optimization methods that take into consideration these factors in order to improve the performance of photodiode arrays in light sensing [4].

Linear regression is a statistical technique used to analyze the connection between a dependent variable and one or multiple independent variables by creating a linear equation based on the data collected. It has been effectively used for sensor calibration and optimization, especially in systems where the input-output relationship can be considered linear [5], [6]. Using linear regression on photodiode sensor arrays allows for the development of models that relate sensor electrical output to light intensity, minimizing the impact of noise and non-linearities [7], [8]. Linear regression provides a straightforward yet powerful approach for modeling and compensating for the variations in sensor behavior, especially when the system operates under near-linear conditions. Its implementation can lead

Received 11 Feb. 2025; Revised 13 Jun. 2025; Accepted 16 Jun. 2025

to more precise light detection, making it highly suitable for applications requiring accurate measurements, such as optical communication and biomedical devices [9], [10].

The optimization of photodiode sensor arrays is critical in various advanced technological applications. For instance, in optical communication systems, accurate light detection is vital for maintaining the integrity of transmitted signals. Similarly, in medical diagnostic tools such as pulse oximeters and optical imaging systems, precise light measurement is essential for accurate diagnosis and patient care. By optimizing photodiode arrays using linear regression, the performance of these systems can be significantly enhanced, leading to more reliable and efficient light detection. This improvement is not only beneficial for current applications but also expands the potential for photodiode arrays to be integrated into emerging technologies that demand high precision [11]–[13].

The use of linear regression on photodiode sensor arrays offers a promising approach to improving the performance of light detection systems. However, a fundamental challenge of array systems is the variability in response between individual sensors, which can degrade the overall system accuracy. Addressing this challenge, this research demonstrates that the implementation of linear regression can transform a heterogeneous photodiode array into a monolithic detection system. This transformation is quantified through significant improvements in the consistency and precision of the overall system response.

II. Related Research

Bergh et al. [14] explained that typically linear regression analysis consists of two consecutive stages of statistical examination. During the initial phase, one top model is identified based on specific predictors chosen; during the subsequent phase, the coefficients from the selected model are utilized for both prediction and evaluating the significance of the predictors. Nevertheless, the neglect of model uncertainty from the initial stage in second-stage inference leads to parameter estimates that are overly confident and do not generalize well. Model smoothing is a strategy to address this weakness, where all models are kept for inference and their contributions are adjusted based on their posterior probabilities. While the idea of model smoothing is easy to understand, it is not commonly practiced in practical research, possibly because of the absence of easily available software. In order to connect theory with application, a tutorial is offered on linear regression using Bayesian model smoothing in Jeffrey's Amazing Statistics Program (JASP) software, utilizing the Bayesian adaptive sampling (BAS) package in R. Initially, a theoretical foundation is established on linear regression, Bayesian inference, and Bayesian model smoothing. Next, they apply the method to a sample data set from the World Happiness Report. In the end, they talk about the constraints of model averaging and strategies for addressing breaches of model assumptions.

Siregar & Mujiono [15] utilized the linear regression technique in their study to create a pH meter using optical fluorescence. Living organisms rely on the important acidity level of air due to its abundance of water. Quick and precise pH measurement is crucial. However, meter readings frequently exhibit slow response. The fluorescent pH meter we have utilizes pyranine extracted from a highlighter to excite the sample with purple light and subsequently assess the intensity of green fluorescence with an AS7262 sensor. This tool accurately measures pH levels from 4 to 11 with a success rate of 98.13% and an error margin of ±0.13 in under 3 seconds. Calibration guarantees precise measurement, while linear regression analysis breaks down data to examine causal relationships. Linear regression, a statistical method utilized in manufacturing, forecasts quality and quantity outcomes by examining the relationship between causal (x) and effect (y) variables.

In the research of Nursyahid et al. [16], developed hydroponic cultivation of Nutrient Film Technique (NFT) which can be an alternative to address the increasing need for food. The availability of nutritional needs of hydroponic plants is one of the parameters that need to be considered. The NFT hydroponic nutrient control system aims to make it easier for farmers to maintain the amount of nutrients according to plant needs. This system uses a linear regression method to control the amount of nutrients. The accuracy results obtained from the control system experiment were 87.84%.

III. Research Method

A. Materials

The hardware used in this research includes 36 BPW43 photodiodes which are used to detect light, photodiode is a semiconductor device that converts light into an electrical current. It is sensitive to light and operates based on the photoelectric effect, where photons striking the surface of the photodiode generate electron-hole pairs, leading to an electric current [17]. The LM358P dual operational amplifier which is used as a voltage amplifier, the Arduino Nano microcontroller which is used to process analog data into digital and display data from light intensity measurements into the I2C LCD 20×4, one push button as a mode changer and 4 Li-Ion 18650 batteries arranged in parallel and series to produce a voltage of 8.4 Volt and a current of 3600 mAh as a source for all electronic components. The software used in this research includes EasyEDA version 6.5.46 for printed circuit board (PCB) design, Arduino integrated development environment (IDE) version 2.3.3., and Statistical Package for the Social Sciences (SPSS) version 24.

B. Photodiode Array Circuit

The objective of this research is to create a precise and effective light intensity detection system through the

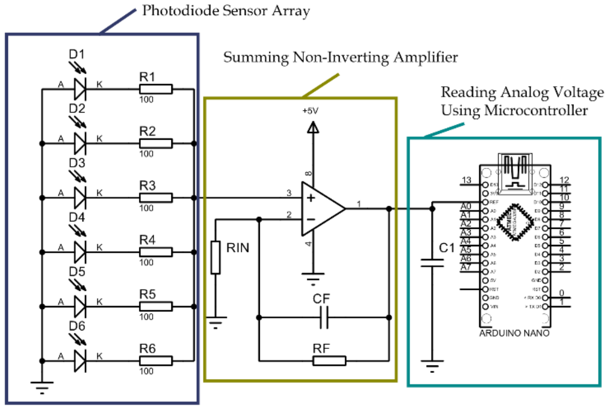


Figure 1. Photodiode sensor array circuit using summing and non-inverting amplifiers

construction of a photodiode sensor circuit. In this research, a total of 36 photodiode sensors were utilized. Each circuit for the photodiode sensor includes 6 photodiode sensors linked together in series with a resistor of 100 Ω, all of the same type and circuit configuration. The summing amplifier is made up of an amplifier, feedback resistance), input resistance , and a resistor at every photodiode input. Following the summation process, it is subsequently boosted using a non-inverting amplifier. Each output from the signal conditioning is processed using a microcontroller. The microcontroller comes with a built-in analog to digital converter (ADC) function that transforms the signal into digital format [18], [19]. This system efficiently detects light intensity when compared to a single photodiode sensor. Figure 1 shows photodiode sensor array circuit using summing and non-inverting amplifiers.

If V_{IN} is the combination of all the input signals, then this is applied at the non-inverting terminal of the op-amp. From the above circuit, we can calculate the output voltage of the non-inverting amplifier with V_{IN} as input, R_F and R_{IN} as the feedback divider resistors as follows [20]:

$$V_{OUT} = V_{IN}\left(1+\frac{R_F}{R_{IN}}\right). \quad (1)$$

Because the resistance values of $R1$, $R2$, $R3$, $R4$, $R5$, and $R6$ have the same value, the output voltage is [20]:

$$V_{OUT} = V_{IN}\left(1+\frac{R_F}{R_{IN}}\right)\left(\frac{V_1+V_2+V_3+V_4+V_5+V_6}{6}\right). \quad (2)$$

After the sensor array circuit is made, continue by designing a PCB according to the circuit scheme that has been designed. The PCB board is designed using EasyEDA software. Figure 2 shows the 3D layout of the photodiode sensor array PCB board.

In this system, the input is in the form of analog voltage obtained from the signal conditioning output, the controller processes information from the input voltage to produce an output in the form of digital voltage. In a closed loop system, the error in the form of the difference between the input signal and the feedback signal is feedback to the controller to reduce the error so that the system

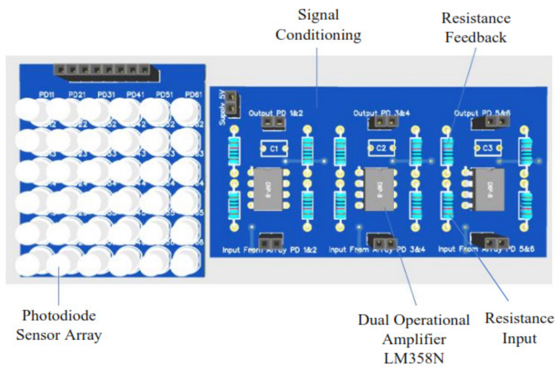


Figure 2. Photodiode sensor array circuit using summing and non-inverting amplifiers

output approaches the desired value. This process occurs continuously by the controller processing information from the sensor that produces a signal that matches the desired one. Through continuous feedback, the closed feedback system is able to maintain its output according to the system algorithm. Thus, creating a control mechanism that is responsive and stable to changes that occur in the system. The ADC process is carried out to convert the output from the signal conditioning in the form of an analog signal into a digital value [21]. The analog signal obtained from the signal conditioning is sampled using an ADC resolution of 10 bits. The ADC value reading can be shown in the following equation [22]:

$$ADC = \left(\frac{V_{IN}}{V_{ref}}\times 2^n\right)-1, \quad (3)$$

where, V_{IN} is the voltage coming from the signal conditioning output, V_{ref} is the reference voltage (5V) and n is the ADC resolution.

After the ADC value on each sensor array is obtained, it is continued by implementing a linear regression model on the system. The function of implementing linear regression on this system is to tune the sensitivity of the sensor array in detecting light intensity.

C. Calibration

In this research, calibration was conducted in order to achieve precise and accurate measurement results. Calibration was conducted by comparing the light intensity measurement values from the custom instrument with those from the factory-produced light intensity measurement instrument. The AS803 type was the lux meter used for comparison in measuring light intensity.

The calibration process on the designed instrument consists of several stages including:

1. Selecting a standard light source or photometric standard whose characteristics are known to be used as a reference during the calibration process.
2. Measuring the sensor response to light intensity without any adjustment or calibration.
3. The results of this measurement will be the basis for comparison with the calibration results later.
4. Based on the difference between the initial

measurement results and the reference standard, the instrument or sensor will be adjusted or corrected.

This process can involve changing the internal parameters of the sensor or setting certain values. After the adjustment is made, the sensor response to light intensity is re-measured using the same reference standard. The results of this measurement are expected to be more accurate and in accordance with the established standards. Next Involves re-checking to ensure that the calibration results are in accordance with the desired standards and the sensor can provide consistent and accurate responses at various levels of light intensity.

D. Determining Linear Regression Constants

The constant in the linear regression equation is the value of the dependent variable when all independent variables are zero or do not change. In this research, constant values were obtained from the results of several experiments on each photodiode sensor. In this research, 10 experiments were carried out on each photodiode sensor to obtain constant values and in the linear regression equation. The mathematical model equation of linear regression can be shown in the following equation [23]:

$$y = a + bx, \tag{4}$$

where y is response variable or dependent variable (dependent), x is predictor variable or causative variable (independent), a is constant and b is regression coefficient (the magnitude of the response generated by the predictor).

The data processing process was assisted by using SPSS software to find the coefficient and constant values so that the output value was obtained. When the sensor has a non-linear output value, the constant value and regression coefficient can be determined on each photodiode. In SPSS software, the output value on each of the 6 photodiode sensors in one array will later be processed to produce one output on each photodiode sensor array. The values of the 6 photodiode sensor arrays are processed using the C/C++ programming language with the aim of producing one photodiode sensor output with high accuracy and precision.

To determine the accuracy of the photodiode sensor array, the reading value of the photodiode sensor array is compared with the reading value of the luxmeter by calculating the absolute and percentage errors in each measurement, then finding the average percentage error. The absolute error for each measurement is calculated as follows [24]:

$$\text{AbsError} = \left|\text{Luxval} - \text{Photodiodeval}\right|, \tag{5}$$

where Luxval is luxmeter reading value and Photodiodeval is photodiode sensor array reading value. After the absolute error value is obtained, it is continued by determining the percentage error value. The percentage error for each reading is calculated as follows [24]:

$$\%\text{Error} = \frac{\text{AbsError}}{\text{Luxval}} \times 100\%. \tag{6}$$

Once the percentage error value is obtained, the Accuracy value can be determined using the formula [24]:

$$\text{Accuracy} = 100\% - \text{Average}\%\,\text{Error}, \tag{7}$$

where Average%Error is the average value of the percentage error reading.

To determine the precision of a photodiode sensor array, it is necessary to assess the consistency of its readings. Precision focuses on how close these readings are to each other, regardless of their accuracy relative to the luxmeter. A common way to assess precision is to calculate the coefficient of variation (CV), which expresses the standard deviation as a percentage of the mean of the data. The standard deviation (s) provides a measure of how much the readings vary from the mean. The formula for standard deviation is [25]:

$$s = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}\left(x_i - \overline{x}\right)^2}, \tag{8}$$

where x_i represents i-th measurement data value, m is the number of measurement sample data and $\overline{x}$ is the sample mean of the measurements.

The coefficient of variation (CV) gives a normalized measure of dispersion, which is useful for determining precision. It's calculated as [25]:

$$\text{CV} = \frac{s}{\overline{x}} \times 100\%. \tag{9}$$

The CV is a statistical measure used to assess the relative variability of data points around the mean, expressed as a percentage.

IV. Results and Discussion

A. Photodiode Sensor Array

At this stage, the photodiode sensor system comprises 6 arrays, with each array containing 6 individual photodiode sensors, resulting in a total of 36 photodiodes. Within each array circuit, a summing amplifier is implemented, utilizing a 1 kΩ input resistor (R_{IN}). Following the summing amplifier, a non-inverting signal conditioning amplifier is employed for each array to enhance the output signal, thereby improving the sensitivity and accuracy of the light intensity measurements. The configuration of the photodiode sensor array is illustrated in Figure 3.

As shown in the photodiode sensor array figure, a signal conditioning circuit featuring a summing amplifier is first used to aggregate the inputs from each photodiode sensor. This summed signal is then further amplified using a non-inverting amplifier, thereby enhancing the array's sensitivity to light intensity variations. The gain of the non-inverting amplifier is determined by the ratio of the feedback resistance (R_F) to the input resistance (R_{IN}), with the signal conditioning stage powered by a 5 VDC supply.

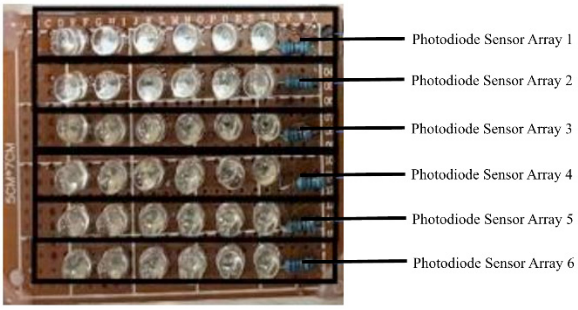


Figure 3. Photodiode sensor array

Thus, based on (1) and (2), the amplification of the signal conditioning circuit in the photodiode sensor circuit is shown in the following equation:

$$\text{Gain} = \left(\frac{10\text{k}\Omega}{1\text{k}\Omega}\right) + 1 = 11. \quad (10)$$

Based on the equation above, the output voltage of the entire photodiode array that has been summed is amplified by 11 times.

B. Calibration Process

During the calibration process, each photodiode sensor array's light intensity is measured using a 10-bit ADC scale, while a digital lux meter AS803 is employed concurrently for reference measurements. The ADC readings from each photodiode sensor array are interfaced with the analog input pins of a microcontroller, specifically an Arduino Nano, which handles the data processing. Arrays 1 through 6 are connected to the microcontroller's analog pins A0 through A5, respectively. The resulting measurements are displayed on a 20×4 LCD module.

The calibration enclosure is constructed from acrylic with dimensions of 215 mm × 215 mm × 220 mm and is lined internally with black manila cardboard to minimize light reflection and ensure optimal sensor and lux meter readings. The light source utilized for calibration is a 12V DC bulb, with adjustable intensity controlled by a voltage divider circuit that increments the voltage in 1 V steps across a 1–12 VDC range. During calibration, both the photodiode sensor array and the lux meter are positioned directly beneath the light source, ensuring perpendicular

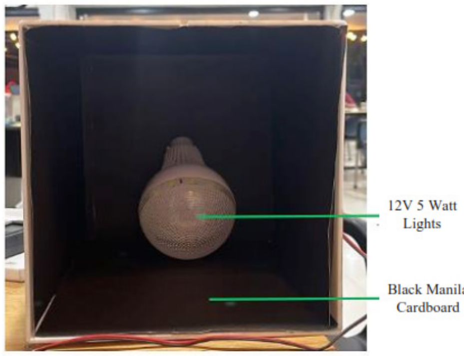


Figure 4. Calibration container

(90°) illumination. The calibration is performed in two modes: normal and sensitive. Figure 4 depicts the calibration enclosure, while Figure 5 illustrates the voltage divider circuit.

For calibration in normal mode, the photodiode sensor array is positioned within the calibration enclosure, with the light source placed 100 mm directly above the array at a 90° angle. The calibration results, derived according to (3), are obtained by recording the voltage response of each photodiode sensor array. These results are presented in Figure 6.

The PD1 through PD6 refer to photodiode sensor arrays 1 to 6, respectively. According to the normal mode calibration results presented in the figure, each array effectively measures light intensity on a 10-bit ADC scale. The figure illustrates the response of all six arrays (PD1 to PD6), with voltage represented on the X-axis and the corresponding 10-bit ADC output on the Y-axis. Generally, all six photodiode arrays exhibit a similar trend, their ADC values remain near the maximum (approximately 1000) when the applied voltage is between 0 and 8V, indicating minimal variation in sensor output at low to moderate light intensities. Beyond 9 volts, a pronounced drop in ADC values is observed across all arrays, particularly in the 11 to 12V range, signifying increased sensitivity to higher light intensities. Variations among the arrays are also evident for instance, PD3 demonstrates a notably sharper decline, suggesting greater sensitivity to intense illumination, whereas PD4 and PD5 display a more

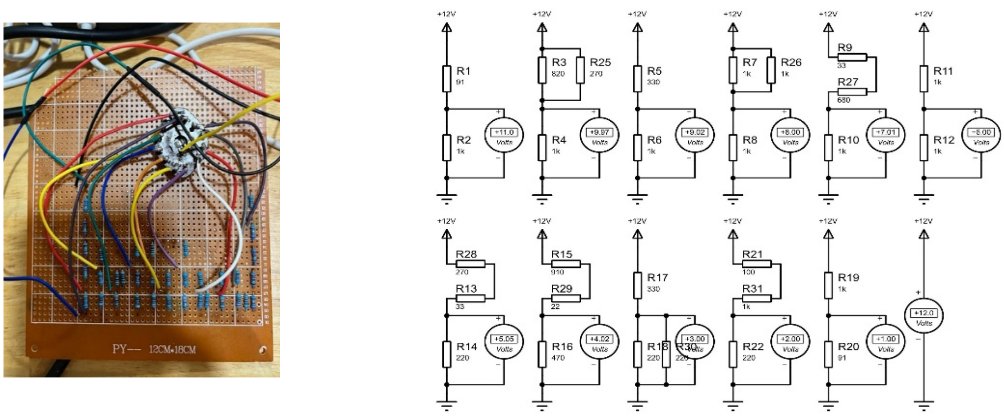


Figure 5. The voltage divider circuit

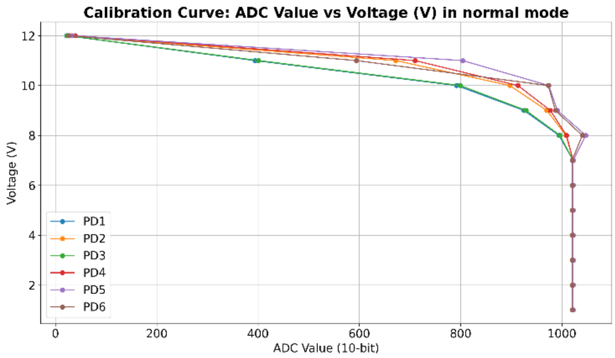


Figure 6. Photodiode array value curve in 10-bit ADC scale against voltage in normal mode calibration

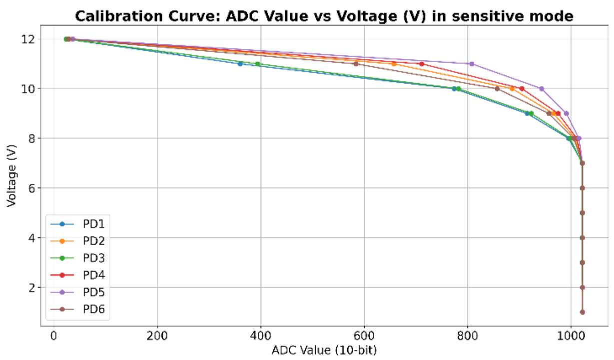


Figure 7. Photodiode array value curve in 10-bit ADC scale against voltage in sensitive mode calibration

gradual decrease, indicative of a steadier or less sensitive response to increasing light intensity.

For calibration in sensitive mode, the photodiode sensor array is positioned within the calibration enclosure, with the light source situated 50 mm directly above the array at a 90° angle. The calibration results, calculated using (3), are obtained by measuring the voltage response of each photodiode sensor array. These results are presented in Figure 7.

Figure 7 presents the response curves of the six photodiode arrays (PD1 to PD6) to varying light intensities, with voltage (V) plotted along the horizontal axis and 10-bit ADC values on the vertical axis. Overall, the arrays exhibit similar trends, at low voltages (0 to 8V), the ADC values remain high and relatively constant, but they decline sharply as the voltage increases from approximately 9 to 12V. This indicates that the photodiode response is stable at lower light intensities, while a marked decrease in ADC value at higher voltages reflects increased sensitivity to intense illumination. Each photodiode array demonstrates distinct response characteristics, for instance, PD1 and PD2 display the steepest declines in ADC value, suggesting greater sensitivity to changes in light intensity, whereas PD4 and PD6 exhibit more gradual decreases, indicating a slower or more consistent response to higher light levels.

C. Linear Regression Function Based on Calibration

After the calibration stage is carried out, the calibration data is then processed using SPSS software to obtain the

Table 1. Constant values *a* and *b* on each photodiode array in normal mode

Sensor Array	Constant	
	a	*b*
PD1	1146.344	-1.079
PD2	1179.826	-1.079
PD3	1149.501	-1.078
PD4	1183.496	-1.006
PD5	1147.305	-0.932
PD6	1182.988	-1.049

Table 2. Constant values *a* and *b* on each photodiode array in normal mode

Sensor Array	Constant	
	a	*b*
PD1	8034.38	-8.84
PD2	10074.14	-10.59
PD3	8279.29	-9.08
PD4	10391.16	-10.79
PD5	10755.96	-10.90
PD6	9637.05	-10.27

constant values *a* and *b* in the linear regression function. In the linear regression function, the results of the constants *a* and *b* are obtained in the normal mode and sensitive mode measurements. Table 1 shows the constant values *a* and *b* on each photodiode array in normal mode and Table 2 shows the constant values *a* and *b* on each photodiode array in sensitive mode.

After the constants *a* and *b* on each photodiode array are obtained in normal mode and sensitive mode measurements, then continue by determining the value of the linear regression function that will be applied to the system. The value of the linear regression function applied to the system is done by taking the average value of all photodiode sensor array values in normal mode and sensitive mode measurements.

Based on Table 1, the linear regression constant values *a* and *b* are averaged and then implemented into the microcontroller. Based on (4), the following equation is a linear regression function in normal mode applied to the microcontroller:

$$y = 1164.91 + (-1.052)x. \tag{11}$$

Based on Table 2, the linear regression constant values *a* and *b* are averaged and then implemented into the microcontroller. Based on (4), the following equation is a linear regression function in sensitive mode applied to the microcontroller:

$$y = 9528.66 + (-10.08)x, \tag{12}$$

where y is the light intensity in lux units, x is the average reading value of the ADC in 10-bit scale.

Table 3. Test results in normal mode

Light source	Distance (m)	Room Dimension	Photodiode sensor array (lux)	Luxmeter (lux)
10W LED	2	6m×5m×3m	250.43	162
5W LED	3	4m×3m×3m	205.32	160
35W LED	0.3	4m×3m×3m	1156.76	5624
5W LED	0.2	Outdoor conditions	129.79	158
5W LED	2	1.5m×1.5m×3m	177	98
12W LED	2	3.5m×2.5m×3m	156.02	91

D. Photodiode Sensor Array Testing

After the linear regression function value is obtained on each photodiode sensor array in normal mode and sensitive mode calibration, the photodiode sensor array is tested under several conditions. Testing was conducted with different light sources and different distances in each mode, both in normal mode and sensitive mode. Table 3 shows the test results in normal mode and Table 4 shows the test results in sensitive mode.

As shown in Table 3, all photodiode sensor arrays are capable of measuring light intensity in accordance with luxmeter readings under normal mode conditions. In experiments conducted within a 6 m × 5 m × 3 m room using a 10W LED light source, the PD3 array produced readings most closely matching the luxmeter values. For experiments in a 4 m × 3 m × 3 m room with a 5W LED source, the PD1 array showed the closest agreement. When using a 35W LED motorcycle headlamp at a distance of 30 cm, none of the sensor arrays yielded values closely matching the luxmeter measurement. For a 5W LED tumbler lamp positioned 20 cm away, the PD4 array provided the closest match. Similarly, in a 1.5 m × 1.5 m × 3 m room with a 5W LED source, the PD3 array aligned best with the luxmeter, while in a 3.5 m × 2.5 m × 3 m room with a 12W LED source, the PD1 array showed the closest correspondence. As presented in Table 4, under sensitive mode conditions, the photodiode sensor array was able to measure light intensity values in agreement with the luxmeter only during the experiment involving a 35W LED motorcycle light positioned 20 cm away, with

Table 4. Test results in sensitive mode

Light source	Distance (m)	Room Dimension	Photodiode sensor array (lux)	Luxmeter (lux)
10W LED	2	6m×5m×3m	0	174
5W LED	3	4m×3m×3m	0	161
35W LED	0.3	4m×3m×3m	9436.06	7651
5W LED	0.2	Outdoor conditions	0	157
5W LED	2	1.5m×1.5m×3m	0	101
12W LED	2	3.5m×2.5m×3m	0	91

(a) (b)

Figure 8. Testing the photodiode sensor array with 10W LED at a distance of 2 m in (a) normal mode and (b) sensitive mode

(a) (b)

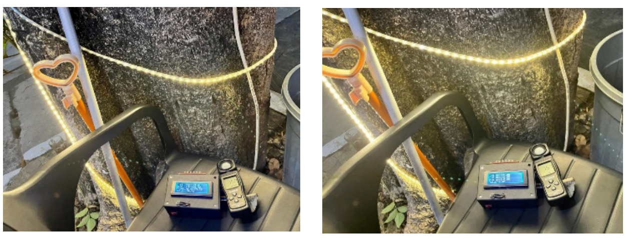
Figure 9. Testing the photodiode sensor array in 4 m × 3 m × 3 m room with: (a) normal mode and (b) sensitive mode

the PD1 array providing the closest match to the luxmeter reading.

Figure 8 present the results of tests conducted in both normal and sensitive modes under various conditions. In the initial test, performed in a 6 m × 5 m × 3 m room, the luxmeter and photodiode sensor array were placed side by side beneath a 10W LED light source at a distance of 2 m. Figure 8 (a) shows the test in normal mode, while Figure 8 (b) depicts the corresponding test in sensitive mode.

The photodiode sensor array was tested by positioning it parallel to a 35W LED motorcycle lamp, with the luxmeter placed adjacent to the array at a distance of 30 cm from the light source. Figure 9 (a) displays the results obtained in normal mode, while Figure 9 (b) shows the outcomes under sensitive mode conditions. The photodiode sensor array was evaluated under illumination from a 5W tumbler lamp, with both the array and the luxmeter positioned parallel to the light source at a distance of 20 cm. Figure 10 (a) shows the test results in normal mode, while Figure 10 (b) shows the results in sensitive mode.

Testing of the photodiode sensor array was carried out in both normal and sensitive modes using a cellphone flash as the light source, with the luxmeter positioned adjacent to the sensor array. Measurements were taken at varying distances of 6 cm, 12 cm, 18 cm, 24 cm, and 30 cm from the light source. Figure 11 illustrates a comparative curve of light intensity measurements (in lux) obtained from the



(a) (b)

Figure 10. (a) normal mode and (b) Testing the photodiode sensor array in normal mode with 5W LED at a distance of 20 cm

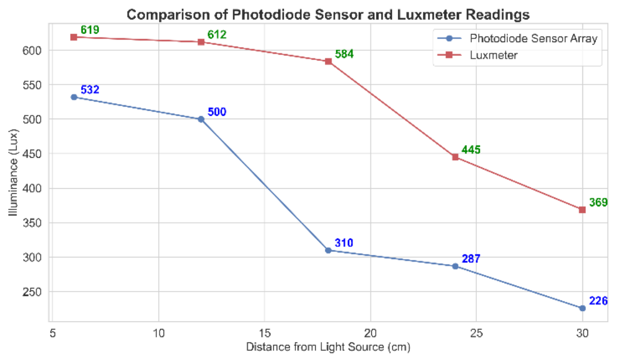


Figure 11. Curve of the light intensity value vs luxmeter against changes in distance in the normal mode

photodiode sensor array and a standard luxmeter in normal mode, across varying distances from the light source.

Both measurement devices demonstrate a declining trend in lux values as the distance increases, consistent with the physical principle that light intensity diminishes with greater separation from the source. While the photodiode sensor array generally registers lower readings than the luxmeter, the overall pattern of decrease remains proportional and consistent. Notably, a pronounced reduction in intensity is observed between 12 and 18 cm, highlighting the sensor's sensitivity to distance changes within this range. These results indicate that the photodiode sensor array, in normal mode, provides a linear response to variations in distance, although its absolute values are lower than those of the luxmeter. The consistent trend in its measurements suggests reliable performance for detecting changes in light intensity with distance. Consequently, the photodiode sensor array can serve as a viable alternative for light intensity measurement, provided that appropriate calibration against the standard luxmeter is performed to enhance accuracy.

Figure 12 presents the response curves of the photodiode sensor array and the standard luxmeter in sensitive mode, measured at various distances from the light source. Both devices exhibit a closely aligned, consistently decreasing trend in lux values as distance increases, demonstrating a high degree of agreement between the sensor array and the reference instrument. Across all measurement points from 6 cm to 30 cm, the photodiode array's lux readings are nearly parallel to those of the luxmeter, indicating enhanced accuracy and sensitivity in this operating mode. Compared to normal mode, the sensitive mode yields a sharper and more precise response to changes in distance, highlighting the sensor's improved performance in detecting variations in light intensity.

A comparison of test results in normal and sensitive modes reveals marked differences in both response rate and measurement accuracy. While normal mode allows the photodiode sensor array to register the general downward trend of light intensity with increasing distance, the sensor's values tend to be lower and less accurate relative to the standard luxmeter, reflecting reduced sensitivity in this mode. In contrast, sensitive mode produces lux readings that closely match the luxmeter across all tested distances, with a consistent and linear decline in intensity. This demonstrates that sensitive mode substantially enhances the detection capabilities and measurement accuracy of the sensor, particularly at higher lux levels. In summary, the sensitive mode offers superior accuracy, sensitivity, and consistency, making it better suited for applications requiring precise and responsive light intensity monitoring, such as advanced light monitoring systems or automation based on light levels. In comparison, normal mode is adequate for indicating general trends but lacks the precision necessary for high-accuracy requirements.

Figure 13 illustrates the absolute error defined as the absolute difference between the readings from the photodiode sensor array and the luxmeter in both normal and sensitive modes across various distances from the light source. The results indicate that normal mode generally yields substantially higher error values compared to sensitive mode at nearly all tested distances. The largest error in normal mode is observed at 18 cm, exceeding 250 lux, highlighting the limitations of the sensor's accuracy at intermediate distances in this mode. In contrast, sensitive mode demonstrates markedly improved performance, with consistently lower error values and greater measurement stability, even approaching zero at a distance of 24 cm. This clear distinction underscores the significant enhancement in measurement accuracy provided by sensitive mode. Additionally, while the error pattern in normal mode is irregular, sensitive mode maintains a more stable trend.

Figure 14 depicts the percentage error between the

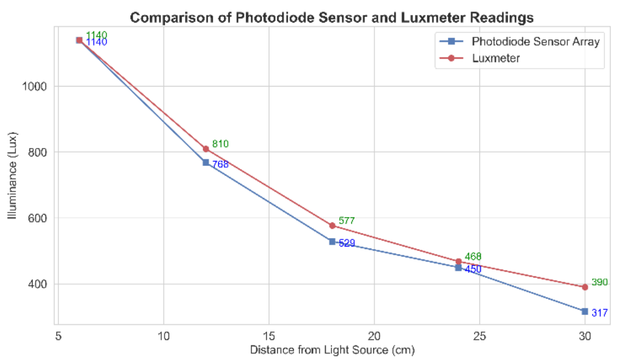


Figure 12. Testing curve of the light intensity value vs luxmeter against changes in distance in the sensitive mode

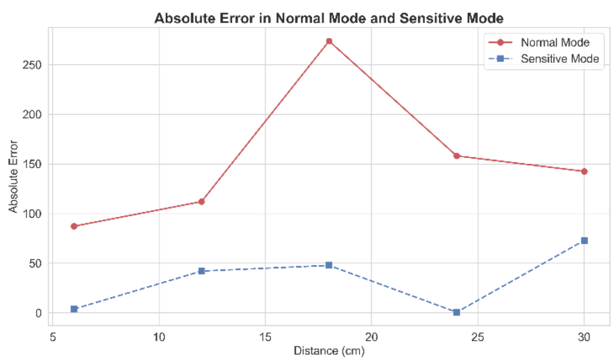


Figure 13. Absolute error value in normal mode and sensitive mode for each reading in each experiment

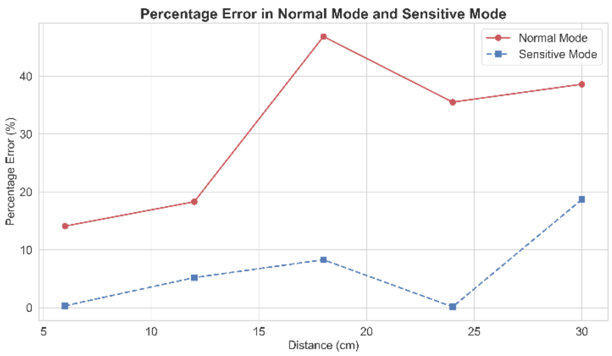
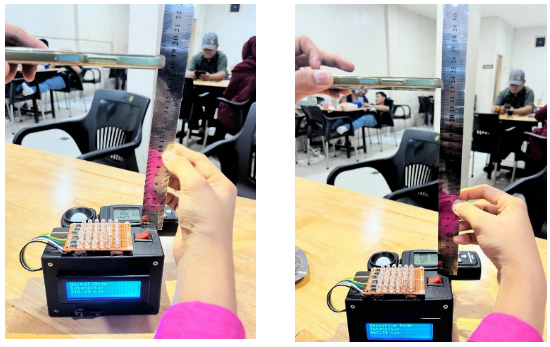


Figure 14. Percentage error value in normal mode and sensitive mode for each reading in each experiment



(a) (b)

Figure 15. The light intensity measurement of the photodiode sensor array vs luxmeter in: (a) normal mode and (b) sensitive mode

photodiode sensor array readings and the luxmeter measurements in both normal and sensitive modes across varying distances from the light source. Overall, the normal mode exhibits a significantly higher percentage error at all tested distances, reaching a maximum of approximately 46% at 18 cm, and remaining elevated between 35% and 39% even as the distance increases. In contrast, the sensitive mode consistently demonstrates much lower percentage errors, with a peak of around 18% at 30 cm and values approaching zero at 6 cm and 24 cm. These results indicate that sensitive mode delivers more stable and reliable measurement accuracy, while normal mode is characterized by greater fluctuations and increased error, particularly at medium to longer distances. This suggests that normal mode is less effective in adapting to changes in light intensity as the distance from the light source increases.

According to the data presented in the Tables 2 and 3, the average percentage error of the sensor readings calculated by using (6) is 17.50% in normal mode and 5.95% in sensitive mode. Consequently, the accuracy of the photodiode sensor array can be determined using (7), as outlined below:

- Normal mode:

$$\text{Accuracy}_{\text{normal\_mode}} = 100\% - 17.50\% = 82.50\%.$$

- Sensitive mode:

$$\text{Accuracy}_{\text{sensitive\_mode}} = 100\% - 5.95\% = 94.05\%.$$

The photodiode sensor array demonstrates an overall accuracy of approximately 82.50% in normal mode and 94.05% in sensitive mode when compared to the reference luxmeter. Following the determination of the photodiode sensor array's accuracy in both normal and sensitive modes, the next step is to assess its precision. Precision is evaluated by calculating the standard deviation of the sensor readings, as described by (8). The standard deviation values for the photodiode sensor array in normal and sensitive modes are calculated as follows:

- Normal mode:

$$s_{\text{normal\_mode}} = \sqrt{\frac{74141.80}{4}} = 136.16.$$

- Sensitive mode:

$$s_{\text{sensitive\_mode}} = \sqrt{\frac{411861.83}{4}} = 320.96.$$

Based on the preceding equation, the overall standard deviation (s) of the sensor readings is 136.16% in normal mode and 320.96% in sensitive mode. The CV, which offers a normalized measure of dispersion, is useful for evaluating the precision of the sensor array. Accordingly, the coefficient of variation for the photodiode sensor array can be calculated using (9) as follows:

- Normal mode:

$$\text{CV}_{\text{normal\_mode}} = \frac{136.16}{371.05} \times 100\% = 36.69\%.$$

- Sensitive mode:

$$\text{CV}_{\text{sensitive\_mode}} = \frac{320.96}{644.14} \times 100\% = 49.81\%.$$

The photodiode sensor array exhibits a coefficient of variation of 36.69% in normal mode and 49.81% in sensitive mode, suggesting a moderate degree of dispersion in the measurement data relative to the mean. A lower CV value would correspond to greater precision. Therefore, the precision of this photodiode sensor array can be considered moderate, with potential for further improvement if higher precision is required. Figure 15 (a) shows the comparison of light intensity measurements between the photodiode sensor array and the luxmeter in normal mode, while Figure 15 (b) shows the same comparison for sensitive mode.

In photodiode sensor-based measurement systems, precision is a key parameter that reflects the stability and consistency of data relative to the mean measurement value. The CV, calculated as the ratio of the standard deviation to the mean and expressed as a percentage, serves as an indicator of this precision. According to the measurement results, the CV is 36.69% in normal mode and 49.81% in sensitive mode. The lower CV observed in normal mode suggests that the data are more tightly clustered around the mean, resulting in greater consistency and stability. In contrast, the higher CV in sensitive mode indicates increased variability, which may be associated with heightened responsiveness to changes in light intensity but comes at the expense of precision. Therefore, it can be concluded that normal mode offers a higher level of precision, making it preferable for applications where stable and reproducible measurements are required.

V. Conclusion

The photodiode sensor array has been made with the appropriate method and the photodiode sensor array has been able to measure the light intensity value in lux units. Based on the experimental results, two linear regression functions have been obtained which are implemented on the photodiode sensor array which are in two modes, namely in normal mode and in sensitive mode where average reading value of the photodiode sensor array in a 10-bit ADC scale. In normal mode, this photodiode sensor array has a fairly poor level of accuracy with an average accuracy value in normal mode of 82.50% with a CV value of the photodiode sensor array of 36.69% and in sensitive mode the photodiode sensor array has a very good level of accuracy with an average accuracy value in sensitive mode of 94.05% with a CV value of the photodiode sensor array of 49.81%. Of the two modes, normal mode is used in low light conditions and sensitive mode is used in maximum light conditions. The sensitivity of the photodiode sensor array is very good in detecting light intensity, especially in sensitive mode. In the photodiode sensor array, the implementation with the linear regression function method can be used as a precise and accurate method in light detection.

Acknowledgments

This research is supported by the Faculty of Engineering, Universitas Muhammadiyah Sumatera Utara.

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