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Design and Development of IoT Based Optical Glucometer

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Abstract: This research presents the development of an IOT based non-invasive glucometer using optical methods for diabetes monitoring. Diabetes needs to be identified as soon as possible and its development is closely monitored. One of the measures to control this disease is the daily monitoring of blood sugar levels by using glucometer. Glucometers on the market are invasive that require blood sampling or sensors implantation. To get a blood sample, it is necessary to prick a fingertip with a needle to obtain a blood sample. This procedure is uncomfortable, and repeated punctures increase the risk of transmission of infectious diseases. Alternatively, a non-invasive method using optical technique was proposed in this paper. The prototype device is mainly consisting of an NIR LED (940nm) acting as a light transmitter delivered through a finger and reflect to photodetector (BPW34) that acting as a light receiver. The prototype was integrated with the IoT platform using Arduino Cloud for monitoring purpose. The next step involved the development of calibration model. Ten healthy individuals were recruited to take part in glucose readings measurement that conducted by National Kidney Foundation Batu Pahat. A calibration model ($y = 82.19x + 12.91$) was successfully obtained from this experiment. The accuracy of the developed device was between 93.2 and 96.9 % where the error percentage was found to be less than 7 %. In conclusion, a painless non-invasive glucometer based near-infrared LED and photodiode was successfully developed. For future development, the accuracy of the system can possibly be improved by using a longer wavelength of light emitter such as 1500 nm.

Keywords: Diabetes, glucometer, Near-Infrared (NIR), Internet of Things (IoT), non-invasive

1. Introduction

Since many years ago, diabetes mellitus or more people know it as diabetes has become a global issue. Diabetes is one of the major health issues in society and currently has the third highest incidence rate worldwide, after cancer and cardiovascular disease[1]. It is a significant public health concern due to its high prevalence and incidence and the fact that it is associated with high rates of morbidity and mortality in almost every country in the world [2]. Diabetes is a condition where the body does not produce enough insulin which causes high blood glucose levels. Uncontrolled diabetes can have negative effects and damage several organs and body tissues, including kidney failure, blindness and amputation [3].

Nowadays, one of the instruments used in the most frequent medical tests today to monitor blood sugar levels is the glucometer sensor [4]. Glucometers available on the current market are invasive that require blood sampling or sensor implantation. To get a blood sample, it is necessary to prick a fingertip with a needle to obtain a blood sample. When

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applying a drop of blood to an enzyme-coated test strip, the glucose molecules in the blood carry out a chemical reaction in the presence of the enzyme, which produces electrons. The amount of electrons generated varies in direct proportion to the amount of glucose present in the blood sample being tested [5]. The main disadvantage of the meter is discomfort at the puncture site and the risk of infection. In addition, because the test is invasive, this procedure sometimes prevents patients from participating. More than 40% of the home invasive glucometers currently available do not meet the requirements [6].

Therefore, there is a need to develop a non-invasive glucose monitoring device. There are many methods for creating a non-invasive glucose meter including optical technique ([1],[3],[7],[8],[9],[10]), microwave technique [11], and electrochemical technique [12]. One of the famous optical techniques when designing a non-invasive glucose meter is by using the near-infrared (NIR) method. The principle of absorption emission photometry serves as the basis for the developed non-invasive technique. The number of molecules present in the absorbing material determines the value of the absorbed light energy. The concentration of that material tells how intense the light energy is when it leaves the absorbing material. Based on how light is scattered and absorbed by the blood, the amount of glucose in the blood can be estimated.

Fig. 1 shows the intensity of light when pass through with different glucose level tissues. The development of a non-invasive glucometer for this study uses optical techniques. This technique is frequently used in the creation of non-invasive glucose meters due to their high accuracy [1]. This method is based on how glucose directly affects the diffusion characteristics of organs. Glucose reduces the refractive index mismatch between the scatterer and the surrounding medium, resulting in a decreased scattering coefficient and, consequently, a shorter optical path. As a result, as the glucose concentration increases, fewer photons are absorbed, and the light intensity increases [13]. The optical sensor is utilized to build up a system for NIR radiation transmission and reception, with the fingertip serving as the body site. The photodetector and transimpedance amplifier turn the transmit light into electrical signals. After that, the voltage signal is subjected to signal conditioning processing before being sent to the microcontroller. Since there is no direct electrical contact between the patient and the gadget when using this method, it is therefore safe.

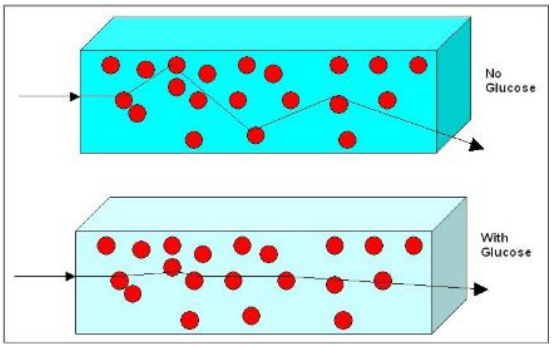


Fig. 1 - Scattering of light in tissues [13]

According to the American Diabetes Association (ADA), individuals receiving repeated insulin injections should check their blood sugar three or more times each day [14] .This procedure is uncomfortable, and repeated punctures increase the risk of transmission of infectious diseases. In addition, because it can be painful, many people avoid checking their blood sugar levels regularly. Therefore, a non-invasive device can be the best solution because it is painless for frequent checkups. Three objectives were formulated which are to develop an IOT based non-invasive glucometer using optical method, to develop a calibration model based on variation light intensity, and finally, to evaluate the functionality performance of developed system. Meanwhile, the scope of this research can be divided into 3 phases. Firstly, is related to hardware and software development. The choice of optical sensors was based on NIR led and photodiode whereas the NODEMCU was used to process the input from the photodiode. Next, a Matlab software was used to obtain the calibration equation based on the relationship between the glucose value from invasive method and the output voltage from the prototype device. Ten volunteers were recruited for the calibration model study. Meanwhile, the invasive blood glucose reading was obtained during a regular health checkup conducted by National Kidney Foundation Batu Pahat. Lastly, the evaluation of the functionality of the prototype is based on two experiments which namely as hardware testing using solution as well as error analysis and accuracy of non-invasive glucometer.

2. Methodology

This section discusses the development of the proposed non-invasive glucometer system for glucose level measuring related to hardware and software. In addition, the development of a calibration model to obtain a linear regression analysis equation is elaborated. Finally, the experiment of functionality performance is included as well in this section.

2.1 Development of Non-Invasive Glucometer Using Optical Method

Fig. 2 shows the flowchart of the project execution of optical glucometer for monitoring blood glucose level. Briefly, this project involved the development of hardware and software setup, mainly consisting of the NIR LED which acting as a light transmitter and a photodetector acting as a light receiver. For software part, the Arduino IDE and Arduino Cloud are used to perform the coding and wireless data monitoring. In calibration experiments, ten subjects were recruited for obtaining their glucose readings. Invasive glucometer (Fora 6 Plus) was used as the benchmark for the developed device. Glucose concentration levels were measured based on the intensity of reflected light at the photodiode. The results were graphed based on the variation in voltage received from the developed device and glucose concentration from the invasive device. Then, a linear regression analysis was used to determine and predict the glucose level. Lastly, the performance evaluation and analysis for prototype devices were discussed and presented.

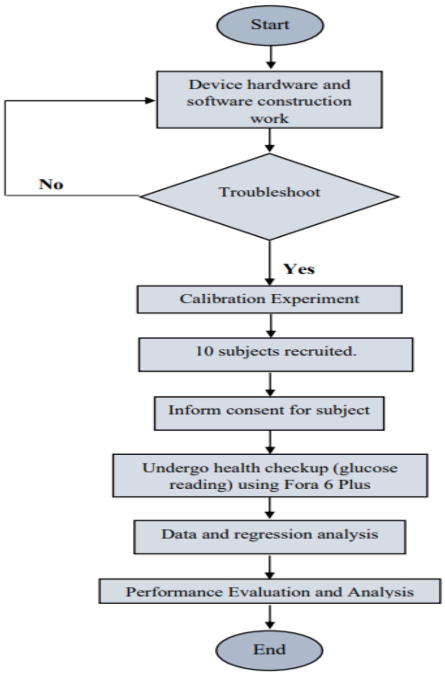


Fig. 2 - Flowchart of the proposed project

Meanwhile, Fig. 3 shows the block diagram of the hardware system. According to a research publication, glucose spectroscopy at wavelengths between 750 and 2500 nm can be used to evaluate and predict glucose content [10]. Moreover, the NIR technology is very suitable for this project since it is painless, accurate, reduces cost, and is applicable. In this study, the NIR LED emitted 940nm signal wavelength. Meanwhile, the photodiode used in this project is BPW34. It can typically work between 400 and 1100 nanometers (nm) in the visible and near-infrared range. A reflectance setup was implemented in this prototype. Therefore, the optical sensors NIR LED (TSAL6400) was placed adjacent to the photodiode (BPW34). When a finger is placed on the reflectance optical sensor, the NIR LED light will pass through finger tissues and be reflected to the photodiode. During this process, some of the light will be absorbed, scattered and the remaining light will reflect to the photodiode. Then, the quantity of light received by the photodiode was measured and analyzed. The current output of the photodiode was converted by a transimpedance amplifier to a voltage signal. For the transimpedance amplifier, the operational amplifier LM358 was used for a current converter and signal conditioning.

Next, the output was passed to the analog input of the microcontroller unit for analysis of the variation of the input signal voltage. The Node MCU ESP8266 converted the analog input to digital. The collected analytical findings were shown on the OLED display and were sent to the smartphone via the IoT platform (Arduino Cloud) informing the person about their diabetes level.

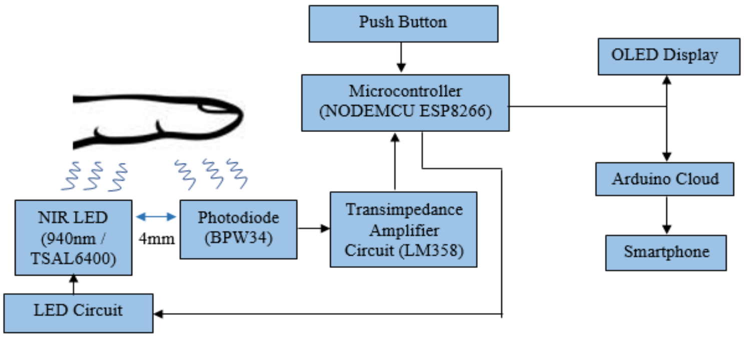


Fig. 3 - Block diagram of the proposed hardware system

Fig. 4 shows the transimpedance amplifier circuit and led circuit simulated in Multisim Live software. Varying currents at BPW34 were experimented to see the voltage difference at transimpedance amplifier output. The function of the transimpedance amplifier is to convert the small current of the sensor or photodetector into a useful voltage signal that can be further processed by other electronic parts. Operational amplifiers and feedback resistors are often combined in certain ways to form these devices. The feedback resistor (R_f) and feedback capacitor (C_f) are required to maintain the stability of the circuit. Firstly, to design transimpedance amplifier circuit, a suitable operational amplifier must be selected based on the input photodiode current. For this project, the operational amplifier use is LM358. The LM358 is a dual operational amplifier integrated circuit (IC) that has two Op-Amps driven by a single power source. It consists of two separate compensating operational amplifiers with high gain frequency and low power. The value of R_f and C_f were determined using this formula:

$$Rf = \frac{Vout(MAX) - Vout(MIN)}{In(MAX)} \quad (1)$$

$$(C_f + C_i) = \sqrt{\frac{C_t}{2\pi R_f f_{GBW}}} \quad (2)$$

where, R_f = feedback resistor, $V_{out(MAX)}$ = voltage output maximum= 3.3 V, $V_{out(MIN)}$ = voltage output minimum= 0 V, I_n = input current = 50 µA, C_f = feedback capacitor, C_i = Input capacitor, C_t = total capacitance of photodiode and op-amp =71.6pF, and f_{GBW} = gain-bandwidth product of the op-amp =700kHz.

A feedback resistor can balance the desired gain with system stability and noise considerations [15]. Equation 1 until 2 were taken from Bhaskar Mishra, Dr. Kanika Sharma, Pawan Choudhary [15].

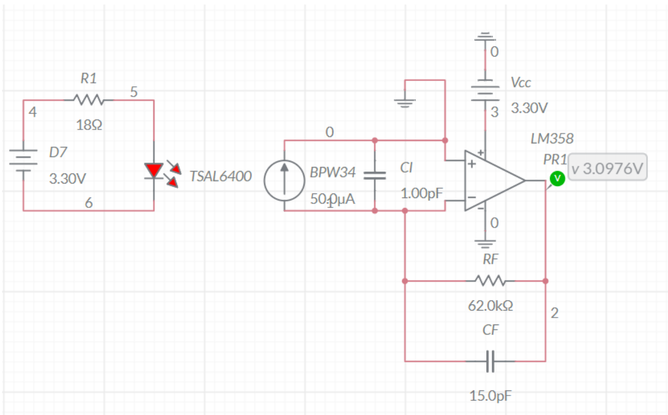


Fig. 4 - Transimpedance amplifier and LED circuit

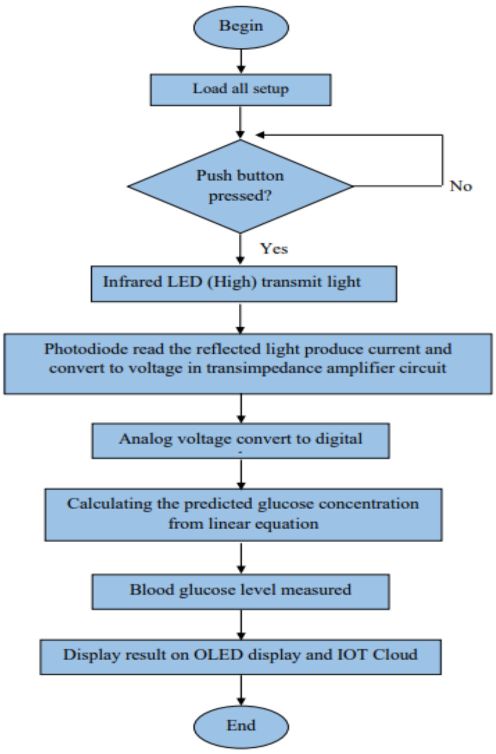


Fig. 5 - Flowchart of the Arduino IDE program for the non-invasive IOT glucometer

Lastly, for software part, the Arduino IDE and Arduino Cloud were used to perform the coding and data monitoring. Fig. 5 shows the overall flowchart of the Arduino IDE program for the non-invasive IOT glucometer. Referring to Fig. 5, when a push button is pressed, the optical sensors will transmit and receive the light. The reflected light produces a current that flows to transimpedance amplifier circuit. Then, the microcontroller will perform an ADC and calculate the predicted glucose concentration based on the resulted linear equation. The results then will be transferred wirelessly to IOT cloud and displayed on the OLED.

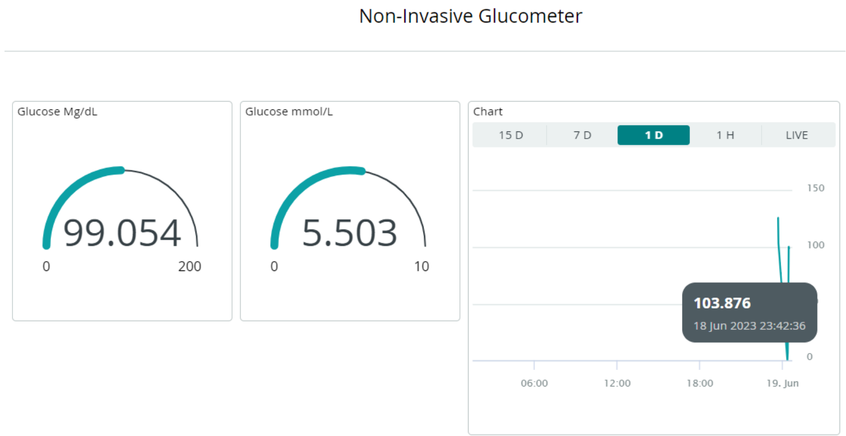
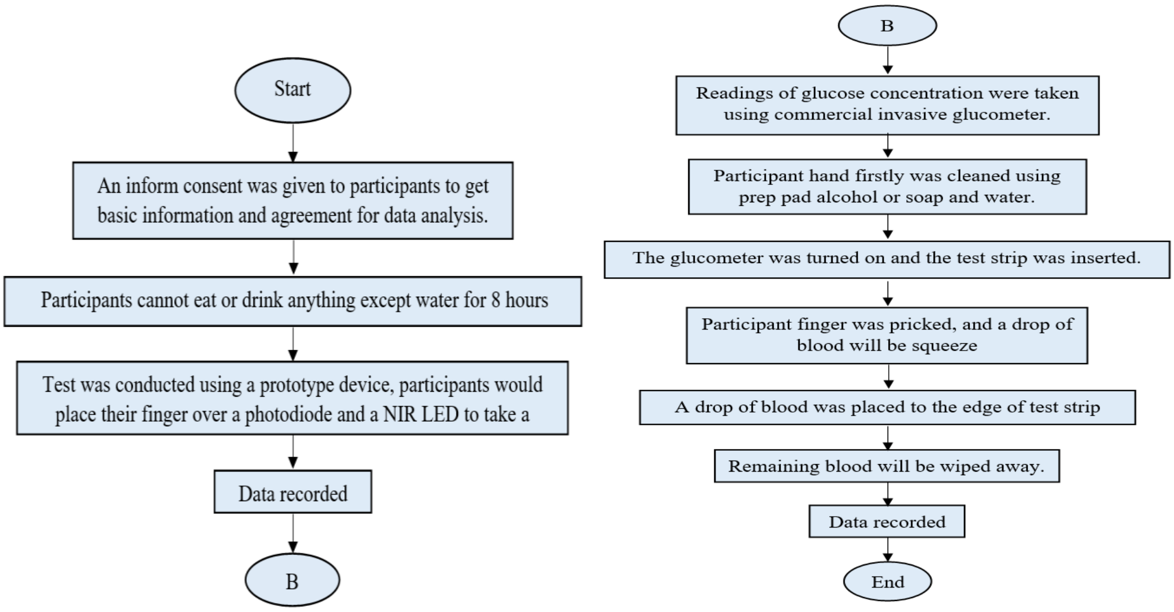


Fig. 6 - Developed user interface for IOT platform using Arduino Cloud software for non-invasive glucometer

Fig. 6 shows the developed user interface for IOT platform using Arduino Cloud software for non-invasive glucometer. Based on Fig. 6, two parameters can be seen on the user interface which are glucose values in mg/dL and mmol/L. In addition, this user interface also provides the time chart showing the time when the blood glucose reading is taken, make it easier for the end-users to monitor their blood sugar.

2.2 Calibration Experiment

For an analytical result, the MATLAB software was employed to provide the linear regression equation for prediction of glucose level non-invasively. The prediction of the glucose concentration is calculated by using a linear regression analysis. This is because, theoretically, the voltage reading, and the blood glucose level is in a linear relationship. An experiment was set up to find the relationship between the variation of the received voltage and the glucose concentration. Ten male healthy individuals without diabetes history were recruited to take their glucose readings during regular health checkups conducted by National Kidney Foundation Batu Pahat to develop a calibration model. An inform consent was created in Google Form and all participants were willing to take part in this study. All subjects underwent a fasting blood glucose test. The fasting glucose tests were conducted in the morning so that participants did not need to fast during the day. Fasting before a blood glucose test is important as it will give more accurate results. The process involved in the calibration study is described in Fig. 7.



(a) (b)

Fig. 7 - Process involve in calibration study using (a) developed device and; (b) commercial invasive device (Fora 6 Plus)

To develop the calibration equation, the voltage reading acquired in the process as described in Fig. 7(a) was be recorded for all ten participants. After that, the ten participants were then undergoing the health checkup supervised by the health practitioner of the National Kidney Foundation. The invasive blood glucose concentration (in mg/dL) was recorded for each participant. Since, the relationship of the voltage of light intensity is in linear relationship with invasive blood glucose concentration, a linear graph was constructed in MATLAB. Then, a linear regression analysis was applied to obtain the mathematical relation between voltage, x and invasive blood glucose concentration, y.

2.3 Evaluation On Functionality Performance

This section discusses the evaluation of the prototype functionality based on two experiments which are non-invasive sensor performance evaluation and the accuracy of non-invasive glucometer.

2.3.1 Hardware Testing Using Solution

The sensor performance was evaluated using several solutions as shown in Table 1. This is to test whether the NIR LED and photodiode can transmit and read different voltage values under specific conditions. The experiment was conducted at night to prevent ambient light. Meanwhile, the experiment setup is shown in Fig. 8**.**

Table 1 - Description of the components

No.	Solution Under Test (SUT)
1.	Direct measurement
2.	Water
3.	Distilled Water
4.	Milk
5.	Black Ink
6.	Random Glucose Solution

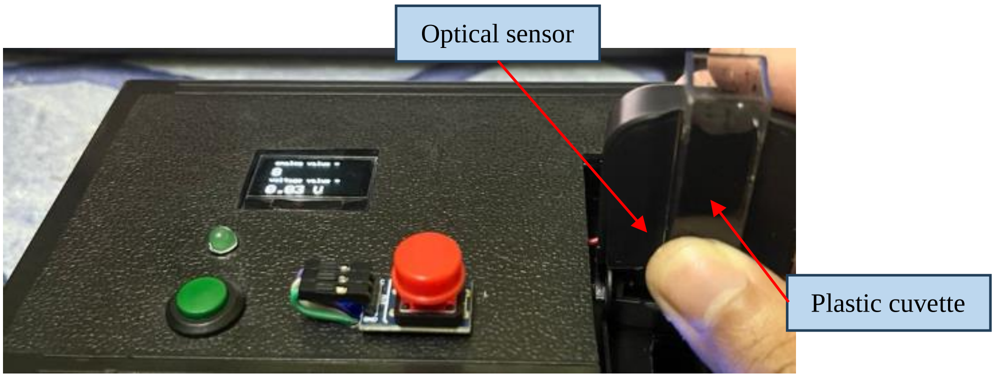


Fig. 8 - Cuvette filled with black ink for solution testing

2.3.2 Error Analysis and Accuracy of Non-Invasive Glucometer

Five out of ten recruited subjects were again agreed to be as the subjects for the evaluation of prototype's accuracy. A similar procedure as discussed in Fig. 7 was implemented. Equation 3 is used to calculate the percentage difference for each reading after the measurement process is complete. Meanwhile, Equation 4 shows the formula of accuracy.

$$Percentage\ Error(\%) = \left|\frac{Non\text{-}Invasive\ reading - Invasive\ reading}{Invasive\ reading}\right| \times 100 \quad (3)$$

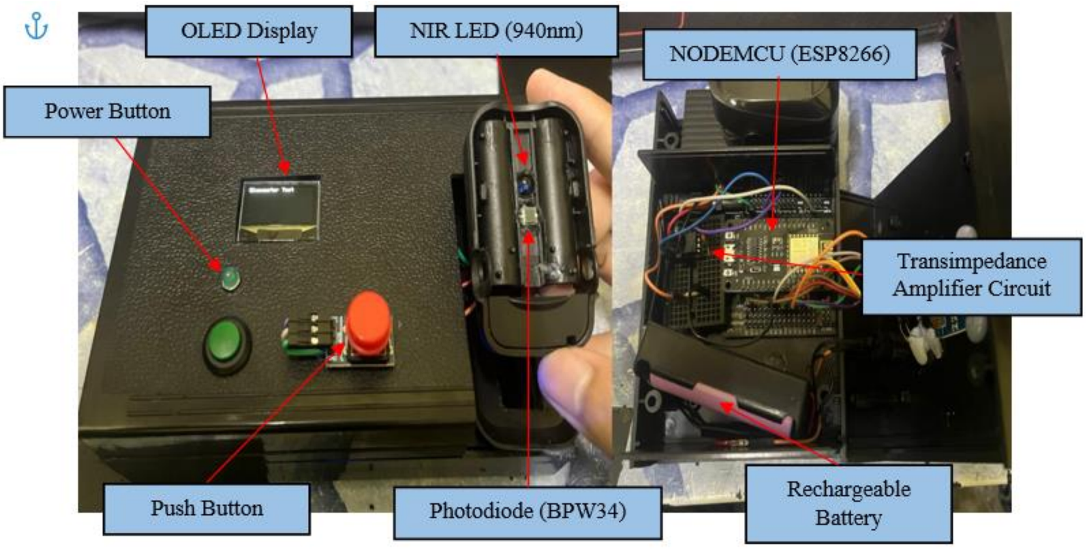
$$Accuracy\ (\%) = 100 - Percentage\ Error(\%) \quad (4)$$

3. Results and Discussion

This section consists of the result of the development of a non-invasive glucometer, the prototype of the developed system, calibration experiments, and a prototype of functionality performance.

3.1 Prototype of Non-Invasive Glucometer

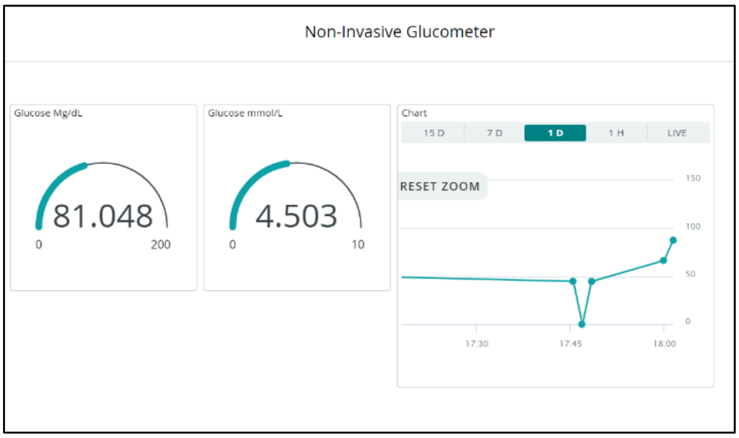
Fig. 9(a) shows the hardware set-up of the prototype device with all pertinent components were labelled accordingly. The casing of the prototype was made of plastic. Meanwhile, Fig. 9(b) shows the glucose value on the OLED display from the prototype device. It shows two units for blood sugar values which are in mg/dL and mmol/L. The conversion of mg/dL to mmol/L can be done by dividing the resulting concentrations in mg/dL over 18.0182. On the other hand, Fig. 10(a), and 10(b) show the user interface for the IOT platform using Arduino Cloud software and smartphone application, respectively.

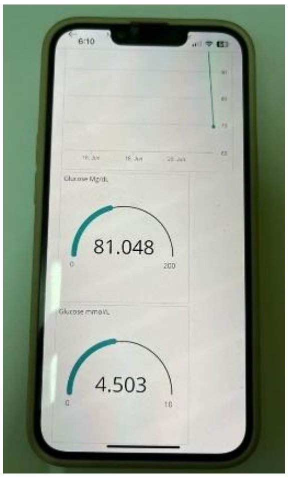


(a)

(b)

Fig. 9 - (a) Hardware set-up of the prototype device and; (b) glucose readings on OLED





(a) (b)

Fig. 10 - (a) User interface for IOT platform using Arduino Cloud software and; (b) user interface for IOT platform using Arduino Cloud application in smartphone

3.2 Calibration Method

Table 2 - Summarizes the blood glucose level and voltage output measured using Fora 6 Plus and prototype device

Participant	Prototype Device (V)					Average (V)	Commercial Glucometer (mg/dL)
A	0.95	0.94	0.96	0.94	0.95	0.948	88.2
B	1.06	1.07	1.07	1.07	1.07	1.068	102.6
C	0.68	0.69	0.70	0.71	0.66	0.688	68.4
D	1.12	1.11	1.12	1.12	1.13	1.12	108
E	0.96	0.91	0.92	0.93	0.91	0.926	84.6
F	1.12	1.09	1.09	1.01	0.99	1.06	99
G	0.80	0.81	0.80	0.82	0.80	0.806	81
H	1.03	1.02	1.02	1.02	1.03	1.024	95.4
I	0.78	0.77	0.78	0.79	0.77	0.848	79.2
J	0.78	0.80	0.82	0.81	0.82	0.834	82.8

The prediction of the glucose concentration is calculated by using the linear regression analysis based on the relationship between the voltage reading and the blood glucose level. Regression analysis was used to calculate the association between voltage and glucose levels from the data. The results were taken and plotted to investigate their mathematical relationships. Table 2 summarizes the blood glucose level and voltage output measured using Fora 6 Plus and the prototype device. An average voltage reading was calculated from five repetitive measurements using the prototype device. Fig. 11 shows the relationship between voltage output and blood glucose level as determined with the Fora 6 Plus glucose monitor and a prototype device of a non-invasive glucometer. From Fig. 11, the linear regression equation is obtained shown in Equation 5 which provides the mathematical relationship between glucose concentration and voltage output.

$$y = 82.19x + 12.91 \tag{5}$$

where x is the voltage output in Volts and y denotes the level of blood glucose concentration in mg/dL. The final hardware prototype for a non-invasive blood glucose monitor was developed using this equation. The Arduino Uno program uses it as a mathematical process to predict blood glucose levels. From the linear regression model in Fig.11, the value that shows R-squared is greater between the range of 0 to 1 which is 0.9574 which indicates that the regression model can predict the data well.

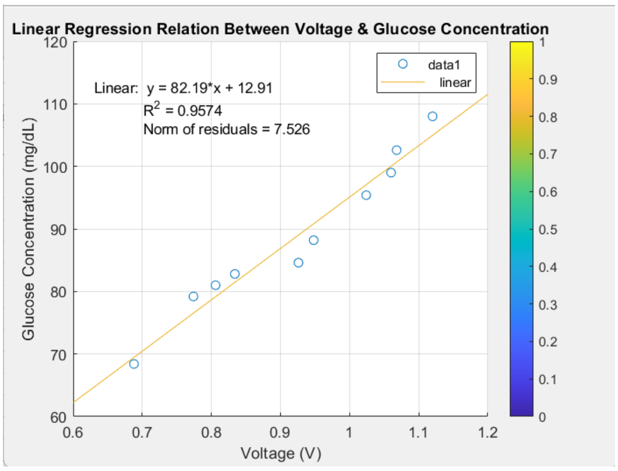


Fig. 11 - The relationship between voltage output and blood glucose level

Table 3 - Simulated glucose concentration (mg/dL) in blood for a diabetic patient with corresponding voltage measured by the op-amp LM358 using obtained calibration model

Glucose concentration (mg/dL)	Transimpedance voltage output (V)
177.3	2.00
200	2.27
243	2.80
259.5	3.00
284.1	3.30
380	4.47

Meanwhile, Table 3 shows the performance of the calibration model when simulated using the glucose concentration of a diabetic patient. This calibration model and the developed device can only measure a maximum between 243 mg/dL and 259.5 mg/dL at 2.8 V and 3.0 V, respectively assuming the maximum op-amp voltage can only output up to 3 V.

3.3 Functionality Performance

This section discusses the result of the prototype functionality based on two experiments which are non-invasive sensor performance evaluation and accuracy of a non-invasive glucometer.

3.3.1 Hardware Testing Using a Solution

Several tests were carried out to test the NIR LED and photodiode capability to transmit and read different voltage values under specific conditions. Table 4 shows a summary of the voltage results of solution testing. The intensity of the voltage varies according to the solution being tested. From the experimental results, the voltage values from the milk have high reflection because the milk does not absorb the light from the LED. While the voltage value obtained from black ink shows a greater difference because the black color absorbs all the light that shines on it. The voltage result water and distilled water shows a 0.13 V difference. It is presumed that water contains contaminants and minerals that affect the transmission of light. Finally, distilled water and glucose solution measurements show slight changes because glucose solution contains glucose that affects the resulting light at the detector.

Table 4 - Summary of the voltage readings from solution testing

No	Solution Under Test (SUT)	Voltage (V)
1	Direct measurement	0.06
2	Black ink	0.03
3	Milk	2.05
4	Water	0.48
5	Distilled water	0.35
6	Glucose solution	0.45

3.3.2 Error Analysis and Accuracy of Non-Invasive Glucometer

Five random subjects from the previous ten participants then underwent another experiment to calculate the error analysis and the accuracy of the prototype device. According to the findings in Table 5, the percentage error in glucose measurement between invasive and non-invasive is found to be less than 7 %. Meanwhile, the accuracy of the developed device was between 93.2 % and 96.9 %. The findings can be varying depending on the conditions for example, subjects factors often alter glucose measurements due to physical characteristics, such as skin color, skin hydration, and blood biochemistry that possibly prevent the glucose from absorbing at 940 nm [16]. Besides that, the infrared signal may be scattered into the environment, which reduces the ability of the photodiode to detect the effect, as the last element of the environment.

Table 5 - Comparison of glucose concentration using invasive and non-invasive glucometer

No	Subject	Glucose Concentration		Percentage Error (%)	Accuracy (%)
		Invasive Glucometer (mg/dL)	Non-invasive Glucometer (mg/dL)		
1	A	93.6	99.05	5.8	94.2
2	B	77.4	81.00	4.7	95.4
3	C	86.4	83.68	3.1	96.9
4	D	84.6	90.00	6.4	93.6
5	E	70.8	75.60	6.8	93.2

4. Conclusion

In conclusion, a simple, portable, and non-invasive blood glucose monitor using an optical approach was successfully developed in this study. glucose meter system uses near-infrared spectroscopy and non-invasive blood glucose monitoring devices that are painless and reduce cost. The smartphone receives data from the glucose meter via Wi-Fi, which is then displayed on a user-friendly application like IOT Cloud. Patients can receive remote assistance without having to visit the hospital, saving time and money. To maintain normal glucose levels and promote a healthy lifestyle, this tool is useful for everyone, not just those with diabetes.

A calibration model ($y = 82.19x + 12.91$) was successfully obtained to determine the glucose-voltage relationship. The designed device has shown accuracy ranging from 93.2% to 96.9%. This figure cannot be used as a yardstick for the project's performance because it was evaluated on only ten people and excluded diabetes patients. However, it is enough to show that this system has great potential to be commercialized in the future provided that greater samples that include healthy and diabetes subjects can be acquired.

One of the limitations of this device is the maximum glucose reading that it can measure non-invasively is only between 243 and 259.5 mg/dL or equivalent to 13.5 mmol/L and 14.4 mmol/L, respectively assuming the maximum op-amp voltage can only output up to 3 V based on the resulted calculations using calibration equation. For future study, the accuracy of the developed system can be improved if the emitter with a longer wavelength for instance at 1500 nm and a matching photodetector with high sensitivity at the chosen longer wavelength are applied.

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