GluQo: IoT-Based Non-invasive Blood Glucose Monitoring

M. A. Aizat Rahmat[1], E. L. M. Su[2], M. Mohd Addi[2] and C. F. Yeong[3]
[1] *Faculty of Electrical Engineering UTM, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.*
[2] *Department of Electronic and Computer Engineering, Faculty of Electrical Engineering UTM, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.*
[3] *Center of Artificial Intelligence and Robotics (CAIRO), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.*
eileensu@utm.my

***Abstract*—Diabetes is one of the deadliest diseases worldwide. To prevent further complications due to diabetes, it is vital to regularly monitor the blood glucose level. Conventional way to measure blood glucose is invasive, which involves finger puncturing. This method is painful and increases risk of infection. In this project, GluQo, a non-invasive method to monitor glucose level was proposed. Near Infrared LED was placed over the fingertip to measure blood glucose optically and the glucose concentration of the blood was calculated depending on the intensity of the received light. The signal was then filtered and amplified before being fed into the microcontroller to be displayed on an LCD display. The glucose level of a person was predicted based on the analyzed voltages received. The glucose readings were also sent to a phone via WiFi and displayed through an Android application. Validation and calibration were performed for the prototype. The percentage error of the glucose reading for the designed method was 7.20% compared to the prick method. The correlation coefficient obtained from the calibration graph of voltage versus glucose concentration was 0.9642, which indicated a strong relationship. Therefore, it can be concluded that there is a high correlation between the predicted glucose values and the voltage signals from the sensor.**

***Index Terms*—Absorption Spectroscopy; Blood Glucose; IoT; Non-invasive.**

I. INTRODUCTION

According to the International Diabetes Federation (IDF), diabetes or also known as diabetes mellitus affects around 285 million people around the world. In recent years, the number of diabetes patients has increased from 108 million in 1980 to a staggering 422 million in 2014. The number is expected to keep increasing. Diabetes is known to be the major cause of heart attacks, stroke, kidney failure, blindness and lower limb amputation. In 2030, diabetes is predicted to be the 7th leading cause of death worldwide [1]. According to [2], there has been 34576 number of deaths reported in 2015 in Malaysia and the average cost spent per diabetic patient in the same year is around RM 2500.

Diabetes mellitus is a disease where the body is unable to produce sufficient amount of insulin which is important to maintain the glucose level of the body. It may be caused by the lack of the secretion of insulin, defects in insulin action or both [3]. There are many factors that can lead to diabetes, such as inappropriate food intake, smoking, or even genetic inheritance. The main cause of diabetes is not yet to be found but mainly it is caused by genetic inheritance and a high sugar intake in a meal serving [4]. It is important to continuously monitor the level of blood glucose in order to keep it at a safe level, thus preventing the patient from danger. There are two medical conditions related to diabetes; hyperglycemia and hypoglycemia, which indicate abnormal high or low glucose level respectively.

In order to display the sugar level of the body, the glucose level of the blood needs to be measured. There are three ways or methods in measuring glucose levels in the blood; invasive, minimally-invasive, and non-invasive. The most commonly available method of measuring blood glucose accurately in the hospitals or clinics is by pricking the finger to obtain a few drops of blood before testing using test strips. This method is invasive, painful, and can cause infection to the users if the needle is contaminated or used more than once. The test strips are disposable which will add further cost. Diabetic patients need to have their blood glucose monitored frequently, a few times a day. A frequent finger puncturing will expose the patient to higher risks of infection and complications because of their slower recovery rate. Therefore, there is a need for non-invasive blood glucose measurement without having to cause any pain to the patients, to get a regular monitoring of the sugar level in the blood, to reduce the cost and most importantly, avoiding skin puncture to reduce risk of infection. Ideally, the method should be economical and more user-friendly compared to the current invasive method.

Non-invasive method is the only way to painless intermittent glucose control and it can be done by substituting blood with other fluids that may contain glucose like saliva, urine, sweat or tears [5, 6]. For continuous monitoring, it can be done by direct measurement of body tissues like the skin, cornea, oral mucosa, tongue, or tympanic membrane [7, 8]. This technique is capable of detecting weak blood signals through tissues like bone, fat, and skin while separating information on glucose from the other higher concentration substances such as proteins, urea, water, etc. There are many methods of non-invasive technique such as absorption spectroscopy, Raman spectroscopy, photoacoustic spectroscopy, fluorescence, and etc. For absorption spectroscopy, when light is focused on the biological tissues, it will reflect, scatter and transmit based on the sample structure and chemical composition. Therefore, most of the non-invasive glucose monitoring (NGM) approaches is to determine the glucose optical signature that can provide its molecular differentiation. The most commonly used techniques in NGM are the near-infrared (NIR) and mid-infrared (MIR) spectroscopy [9].

Near-infrared (NIR) spectroscopy is in the range of 750-2500 nm spectrum [10]. This spectroscopy allows glucose measurement in tissues in the range of 1 – 100 mm of depths, with a decrease of penetration depth for increasing of wavelength values. The light transmitted onto the body part will be partially absorbed and scattered due to the interaction with the chemical structure inside the tissue. The glucose concentration can be estimated according to the light intensity of the transmitted and reflected light itself [11].

This paper presents the GluQo system, which is a non-invasive method of blood glucose testing using the NIR method. It is convenient and not painful. Apart from the hardware, the GluQo mobile application provides accessibility for the doctors or relatives to track the glucose level of diabetic patients. The system was compared with glucose level readings from the commercial finger-prick method.

II. METHODOLOGY

A. Project Overview

The project implementation can be divided into the hardware and the software part. The hardware part will consist of the transmitter and detector circuit. The near-infrared (NIR) LED will be transmitted onto the fingertip as the measuring site and the attenuated light will be received by the detector circuit consisting of a photodiode and based on the scattering and absorption of light through the blood, the concentration of blood glucose can be calculated [12]. The transmitter LED used is LED1550E from Thorlabs that has a wavelength of 1550 nm. An Indium Gallium Arsenide (InGaAs) photodiode, FGA10 also from Thorlabs with a high response around a wavelength of 1550nm was used as the receiver. The light transmitters and receivers at 1550 nm wavelength are lower in cost as compared to other wavelengths with equal or higher response to glucose [13]. The concentration level of glucose is then displayed on the LCD display. The data can also be sent to the Internet via WiFi to be accessed by a mobile application.

Before the glucose reading can be displayed by the LCD display or/and the mobile application, the received signal must first undergo a signal conditioning stage of filtering and amplifying to filter out noise and to amplify the weak signals. The signal is then fed into the microcontroller to be converted to digital signal before carrying out regression analysis. The microcontroller used in this project is Intel Edison with the Arduino breakout board. The control algorithm was coded using C and developed in the open-source Arduino Software (IDE) Integrated Development Environment. The overall structure of the project is shown in Figure 1.

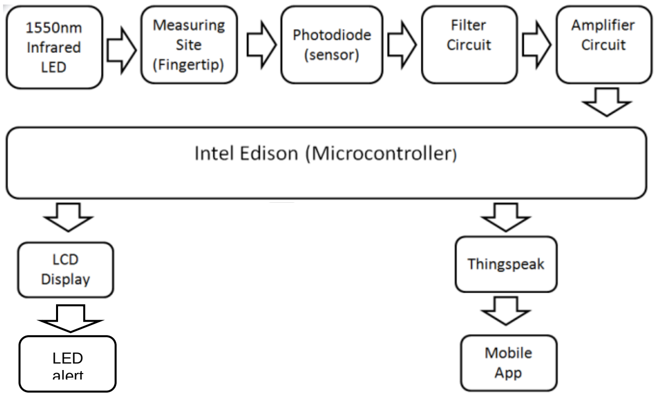

Figure 1: Overall structure of project

B. Electronic Circuit

An electronic circuit was fabricated to obtain the near infrared (NIR) spectral range for the blood glucose measurement. Different voltage values will be recorded according to the blood glucose alterations [14]. A noise filter circuit and amplifier circuit were added to ensure a better signal quality was obtained. The filter circuit was constructed based on [15] and an amplifying circuit was added to obtain a gain of 11. Operational amplifier LM 358 was selected due to its high gain and it could operate from a single power supply. The filter and amplifier circuits are shown in Figure 2.

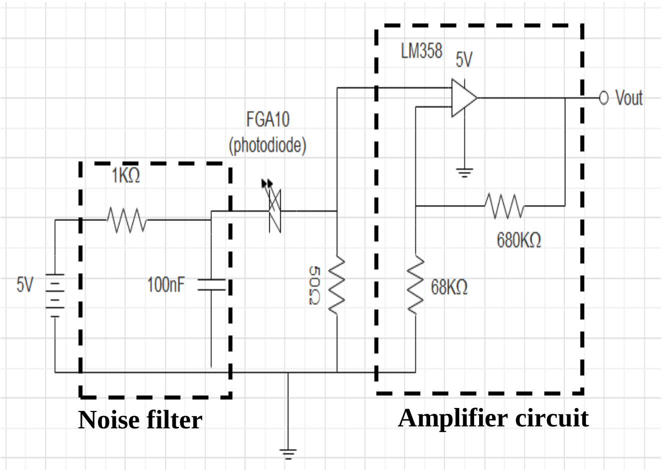

Figure 2: Filter and amplifier circuit

C. Calibration

Before displaying the blood glucose reading, the data is first processed and analyzed. Calibration was carried out to determine the relationship between the glucose concentration and the voltage obtained from the GluQo system. Several glucose concentrations ranging from (10 mg/dL – 320 mg/dL) was prepared by dissolving glucose (Glucolin) in 1 dL of distilled water [16]. The solution was then placed in a cuvette between the transmitter and receiver then the output voltage was recorded for each glucose concentration. A cuvette is basically an optically clear container that is used to hold liquid samples in a spectrophotometer.

From the results, the relationship between the glucose concentration and the voltage was determined by implementing regression analysis. From the analysis, an equation that relates between the glucose concentration and the voltage values was identified. This equation was used in the coding of the Intel Edison to predict the glucose concentration based on the voltage value obtained from the sensor. For validation purposes, the glucose concentration obtained from the designed method was also compared to the glucose concentration reading of the prick method.

D. IoT Feature

Besides displaying the glucose readings on the LCD on the GluQo device, the values were also displayed on a mobile phone via WiFi connection. An Android mobile application was developed using MIT App Inventor 2 in order to display the glucose readings. The glucose reading was sent to the cloud (Thingspeak) before it can be fetched by the mobile app. The WiFi adapter used is the one on the Intel Edison board.

III. Results And Discussion

A. Prototype Design

For this project, a prototype is successfully designed. The prototype consists of a circuit board attached with NIR LED sensor. An LCD display and 3 LEDs with different colors was integrated to indicate the glucose levels; red LED would blink when the glucose reading was high, green LED would light up when the reading was normal, and the yellow LED would blink when the glucose reading was too low. Apart from that, there was also a buzzer that would sound according to the glucose readings. A fingertip casing was added to ensure more consistent measurement from the sensor. The figure of the prototype is shown in Figure 3.

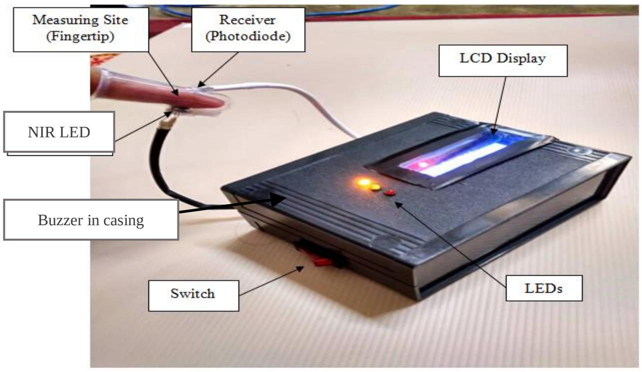

Figure 3: Project prototype

B. Android App Design

The GluQo Android app was developed to provide glucose readings on a phone. This allows a user's reading to be shared with family members or clinicians if required. The GluQo mobile application was developed using MIT App Inventor 2. The user interface for the developed app is shown Figure 4 and the glucose chart of the app is shown in Figure 5.

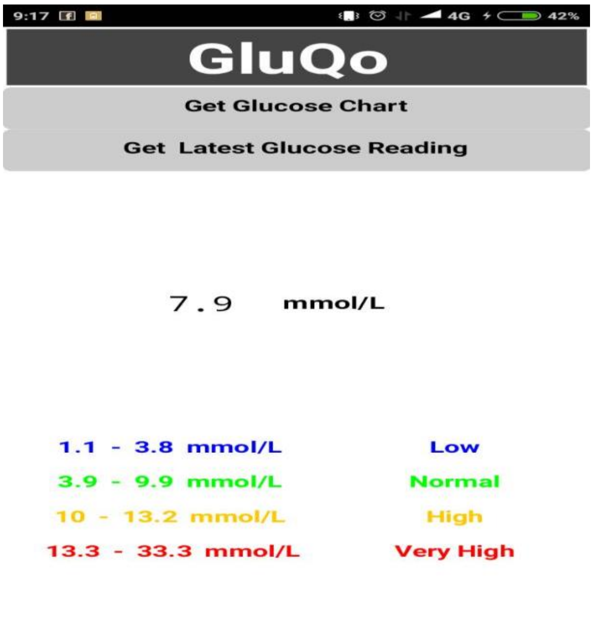

Figure 4: App graphical user interface (GUI)

Figure 5: App glucose chart

C. Calibration Results

From the calibration experiment done in the earlier section, the relationship between the glucose concentration and the voltage from the proposed method can be obtained. By using the voltage values as the X-axis, the glucose concentration (Y-axis) can be predicted. Table 1 shows the dataset obtained for the glucose concentrations ranging from (10 mg/dL – 380 mg/dL) with their respective voltage values.

By using Microsoft Excel, a regression analysis is carried out to determine the relationship between the glucose concentration and the voltage values. The result of regression analysis is shown as in Figure 6.

Based on the regression analysis of the above relationship, the amount of glucose concentration can be predicted based on the voltage values obtained from the receptor as mentioned in Equation (1). This equation will be used to obtain the glucose reading in real time based on the voltage signal from the sensor.

$$y = 1398.7x - 2361.2 \quad (1)$$

Table 1
Dataset of Glucose Concentrations with the Voltage Values

Glucose Value (mg/dL)	Voltage Value (v)
10	1.66
20	1.72
40	1.73
60	1.74
80	1.775
100	1.775
120	1.78
140	1.79
160	1.81
180	1.805
200	1.81
220	1.815
240	1.855
260	1.87
280	1.9
300	1.905
320	1.915
340	1.925
360	1.95
380	1.955

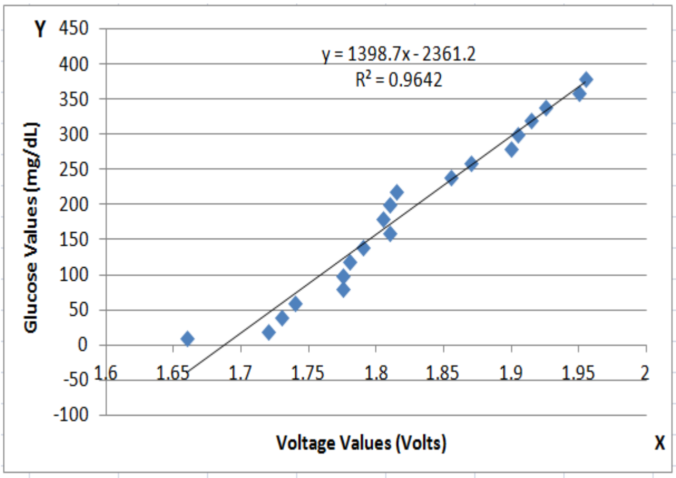

Figure 6: Regression analysis of glucose values with voltage values

D. Percentage Error

To validate the value of glucose concentration obtained, the reading of the glucose value of the designed method is compared with the reading from the prick method. By using the Equation (2), the percentage error can be calculated.

$$\text{Percentage error} = [(\text{Measured value} - \text{Actual value}) / \text{Actual value}] * 100\% \quad (2)$$

Table 2 compares the glucose readings by using the designed method and the glucose reading by using the prick method. From the table, the percentage error for the glucose reading taken by using the proposed method compared to the prick method is not more than 11.11%. On average, the percentage error is 7.20% based on 7 tests.

Table 2
Calculate for the percentage error

No.	Glucose Reading using Designed Method (mg/dL)	Glucose Reading using Prick Method (mg/dL)	Percentage Error (%)
1	79	87	9.20
2	77	81	4.94
3	92	86	6.98
4	90	85	5.88
5	81	75	8.00
6	88	92	4.35
7	80	72	11.11
Mean	83.86	82.57	7.20

E. Linearity

For the linearity, it can be obtained from Figure 6. As shown in the figure, the correlation coefficient between the glucose reading and voltage value is 0.9642 (square of R). This means that the value is closely approaching 1 which indicates a good relationship between both of the glucose and voltage values. It also indicates a strong linear relationship between them.

IV. Conclusion

In this project, we have designed and implemented a blood glucose meter that is working non-invasively without the need to draw blood sample from any part of the body to measure the glucose level. It is convenient for the users to get their glucose reading without having to puncture their skin, encounter any pain and also reduce the risk of getting infection. In addition to that, some IoT features are added to the prototype, such as the accessibility for the family and doctors to monitor the glucose reading of the patient. Data from the glucose meter is sent via WiFi to their smart phone and displayed on a user-friendly Android app. It can help the doctors monitor the patients remotely without the need for the patient to come to the hospital, saving time and cost.

Based on the results obtained from the designed project and analysis on the validation, the percentage error of the glucose reading for the designed method is 7.20% compared to the prick method. According to the “Clark Error Grid”, which is used to evaluate the clinical accuracy of a glucose sensor, the glucose reading can be considered as clinically accurate if the percentage difference is within 20%. The correlation coefficient obtained is 0.9642 and is close to 1. Therefore, it can be concluded that there is a high correlation between the predicted glucose values and the voltage signals from the sensor.

Acknowledgment

This work is supported by Universiti Teknologi Malaysia Research University Grants Q.J130000.2523.12H34, 12J78 and CREST grant R.J130000.7323.4B244.

REFERENCES

[1] World Health Organization, "Global Report on Diabetes," [Online]. Available: http://www.who.int/mediacentre/factsheets/fs312/en/. 2016.

[2] International Diabetes Federation. [Online]. Available: http://www.idf.org/membership/wp/malaysia. 2015.

[3] K. Alberi and P. Zimmet, "Definition, diagnosis and classification of diabetes mellitus and its complications, part 1: diagnosis and classification of diabetes mellitus, provisional report," *Diabet Med*., vol. 15, pp. 539-553, 1998.

[4] V. A. Saptari, "A Spectroscopic System for Near Infrared Glucose Measurement", *PhD Thesis,* Massachusetts Institute of Technology, Cambridge, 2004.

[5] V. Srinivasan, V. K. Pamula, M. G. Pollack and R. B. Fair, "Clinical diagnostics on human whole blood, plasma, serum, urine, saliva, sweat, and tears on a digital microfluidic platform," in *Proceedings of MicroTAS*, USA, 2003, pp. 1287-1290.

[6] H. D. Park, K. J. Lee, H. R. Yoon and H. H. Nam, "Design of a portable urine glucose monitoring system for health care," *Comput Biol Med,* vol. 35, pp. 75-86, 2005.

[7] J. S. Baba, B. D. Cameron and G. L. Cote.. "Effect of temperature, pH, and corneal birefringence on polametric glucose monitoring in the eye," *J Biomed Opt*, vol. 7, no. 3, pp. 321-329, 2002.

[8] M. Rohrscheib, R. Robinson and R. P. Eaton, "Non-invasive glucose sensors and improved informatics- the future of diabetes management," *Diabetes, Obesity and Metabolism*, vol. 5, pp. 280-284, 2003.

[9] S. K. Vashist, "Non-invasive glucose monitoring technology in diabetes management: A review," *Analytica Chimica Acta*, vol. 750, pp. 16-27, 2012.

[10] S. F. Malin, T. L. Ruchti, T. B. Blank, S. N. Thennadil and S. L. Monfre, "Non-invasive prediction of glucose by near-infrared diffuse reflectance spectroscopy," *Clin. Chem*, vol. 45, no. 9, pp. 1651-1658, 1999.

[11] A. Tura, A. Maran and G. Pacini, "Non-invasive glucose monitoring: Assessment of technologies and devices according to quantitative criteria," *Diabetes Research and Clinical Practice,* vol. 77, pp. 16-40, 2007.

[12] K. Lawand, M. Parihar and S. N. Patil, "Design and development of infrared LED based non invasive blood glucometer," in *2015 Annual IEEE India Conference (INDICON),* New Delhi, 2015, pp. 1-6.

[13] M. Ahmad, A. Kamboh and A. Khan, "Non-invasive blood glucose monitoring using near-infrared spectroscopy," *EDN Network*, 2013.

[14] K. A. U. Menon, D. Hemachandran and A. T. Kunnath, "Voltage intensity based non-invasive blood glucose monitoring," in *2013 Fourth International Conference on Computing, Communications and Networking Technologies (ICCCNT),* India, 2013, pp. 1-5.

[15] Thorlabs FGA10 - InGaAs Photodiode specification sheet, 2234-S01, Rev 1, February 27, 2017.

[16] R. A. Buda and M. M. Addi, "A portable non-invasive blood glucose monitoring device," in *2014 IEEE Conference on Biomedical Engineering and Sciences (IECBES)*, Malaysia, 2014, pp. 964-969.