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Regional Centre of Excellence in Biomedical Engineering and e-Health (CEBE)

DESIGN A NON-INVASIVE GLUCOSE MONITORING SYSTEM.

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A Dissertation Submitted to the Regional Centre of Excellence in Biomedical Engineering and e-Health (CEBE), University of Rwanda as partial fulfilment of the requirements for the Master's Degree in Biomedical Engineering.

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DECLARATION

I, Ghadi NIYOMUFASHA, declare that this dissertation entitled "**DESIGN A NON-INVASIVE GLUCOSE MONITORING SYSTEM**" is my original work based on research and prototype and has not been submitted for any other degree or professional qualification.

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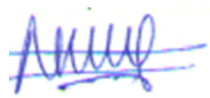

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CERTIFICATE

This is to certify that the project entitled "**DESIGN A NON-INVASIVE GLUCOSE MONITORING SYSTEM**" is a record of original work done by Ghadi NIYOMUFASHA (Reference number:220000203), a MSc. Degree student in Biomedical Engineering.

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ABSTRACT

This project outlines a non-invasive method for measuring glucose concentration in human blood using near-infrared optical technology. Traditionally, blood glucose levels have been measured through invasive techniques involving finger punctures, which are not only costly but also associated with pain, calluses, and an increased risk of spreading infectious diseases. unmanaged diabetes can lead to severe complications such as renal failure, liver failure, heart attacks, vision loss, or foot issues that may require amputation if not promptly diagnosed, monitored, and treated.

To prevent these complications, regular monitoring of blood glucose levels is essential. To address these issues, a non-invasive glucose monitoring system is needed. The development of a non-invasive blood glucose measurement system would significantly benefit diabetic patients

This study proposes a cost-effective, non-invasive glucose monitoring device using near-infrared spectroscopy techniques, where NIR light traverses through the fingertip, it engages with glucose molecules, causing some of the NIR light to be absorbed, contingent on the blood's glucose concentration. The amount of NIR light that passes through the fingertip varies according to the blood glucose concentration. This transmitted signal is processed by Microcontroller with the output displayed on an LCD screen. Additionally, the device includes a GSM module for wireless data sharing, allowing results to be easily transmitted to doctors for review.

Proteus Software is utilized to simulate testing devices and measure results. Following this, prototypes are practically implemented using various components. All test results from the main device are transmitted to a Global System for Mobile (GSM) module, which connects to the doctor’s cellphone for submission and review. The results obtained after implementation and measurement from the main device were quite satisfactory. My study demonstrates that the device achieves accuracy comparable to conventional methods while offering convenient and user-friendly operation for patients.

LIST OF ACRONYMS

WHO: World Health Organization

FBG: Fasting blood glucose

mM: millimole

mmol/L: Millimoles per liter

mg/dL: Milligrams per deciliter

LCD: Liquid Crystal Display

NIR: Near-Infrared

GSM: Global System for Mobile Communications

USFDA: American Food and Drug Administration

CGM: Continuous Glucose Monitoring

nm: nanometer

OCT: optical coherence tomography

NIRS: Near-infrared reflectance spectroscopy

LED: Light Emitting Diode

$C_6H_{12}O_6$: chemical formula for glucose

GDM: Gestational diabetes mellitus

PWM: Pulse Width Modulation

MHz: Megahertz

USB: Universal Serial Bus

ICSP: In-Circuit Serial Programming

VCC: Voltage Common Collector

GND: Ground

I2C: Inter-Integrated Circuit

SDA (Serial Data Line): Transmits data between devices.

SCL (Serial Clock Line): Carries the clock signal to synchronize data transfer.

GPRS: General Packet Radio Service

SIM: Subscriber Identity Module

PCBs: Printed circuit boards

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CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

Diabetes is a type a metabolic disease in which the blood glucose (blood sugar) level in human body increases drastically from its normal level. The increase in sugar level is either due to inadequate production of insulin in blood cells or can be because of improper response of body cells to the insulin or can be because of both the reasons. Diabetes can lead to major complications like heart failure and blindness in the human body. Hence regular monitoring of glucose level is important. The World Health Organization (WHO) estimated that the number of people with diabetes is more than 200 million. Diabetes is a state of a body where it not able to produce the quantity of insulin sufficiently required to maintain normal level of blood glucose. So, diabetic patients regulate their blood glucose levels through proper diet as well as by injecting insulin. For the effective treatment of diabetes, patients have to measure the level of blood glucose periodically. At present, diabetic persons are using invasive figure pricking instrument knows as glucose meter to know the concentration of blood glucose.

Diabetes is a metabolic disorder characterized by a significant increase in blood glucose (blood sugar) levels beyond the normal range. This increase can occur due to insufficient insulin production in the bloodstream, inadequate response of body cells to insulin, or a combination of both factors. Diabetes can lead to severe complications such as heart failure and vision impairment. Therefore, it is crucial to regularly monitor glucose levels. According to the World Health Organization (WHO), the number of individuals affected by diabetes exceeds 200 million worldwide[1].

In diabetes, the body fails to produce an adequate amount of insulin necessary to maintain normal blood glucose levels. As a result, diabetic patients regulate their blood glucose levels through careful dietary management and insulin injections. To effectively manage diabetes, patients need to monitor their blood glucose levels regularly. Currently, diabetic individuals utilize an invasive device called a glucose meter, which involves pricking the finger, to measure the concentration of blood glucose. Inadequate control and management of diabetes can result in significant health complications, including cardiovascular disorders, vascular damage, stroke, vision loss, chronic kidney failure, neurological disorders, foot amputation due to ulcers, and premature mortality[2].

Abnormal glucose levels for the long term can cause diseases like kidney problems, stokes and cardio diseases[3].Excessive levels of blood glucose, known as hyperglycemia, can contribute to various health conditions, including damage to major blood vessels in the heart, brain, and legs (macrovascular damage), as well as impairment of smaller blood vessels in the eyes, kidneys, and feet (microvascular damage). Conversely, low blood glucose levels, or hypoglycemia, can also pose a serious risk to the body, potentially leading to life-threatening harm[4]. Diabetes can be categorized into two types: type 1 and type 2. In type 1 diabetes, there is a lack of insulin secretion from the pancreas[5],[6]. Conversely, type 2 diabetes primarily arises from reduced insulin effectiveness due to insulin resistance and decreased insulin sensitivity in patients. Type 2 diabetes accounts for over 90% of individuals with diabetes, and projections from the International Diabetes Federation suggest a significant rise in the global prevalence of diabetes, leading to a continuous increase in the number of affected individuals. The World Health Organization (WHO) estimates that currently there are approximately 450 million diabetes cases worldwide, a number that could potentially reach 700 million by 2045. In the United States alone, the number of cases is expected to rise to 39.7 million by 2030 and 60.6 million by 2060[5].

In 2009, the World Health Organization (WHO) established a standard for diagnosing diabetes. According to this standard, the fasting blood glucose (FBG) level of normal individuals should fall within the range of 3.9–6.1 mmol/L, and the blood glucose level 2 hours after a meal should be 7.8 mmol/L or lower. If patients present with typical symptoms of diabetes such as excessive urination, excessive thirst, and unexplained weight loss, and their blood glucose levels are equal to or greater than 11.1 mmol/L arbitrarily, or their FBG levels are equal to or greater than 7.0 mmol/L, or their blood glucose levels 2 hours after a meal are equal to or greater than 11.1 mmol/L, a diagnosis of diabetes can be made[5].

The objective of this project is to design an innovative non-invasive glucose monitoring system that provides accurate and real-time glucose measurements for diabetic patients. This system aims to overcome the limitations of existing invasive methods while maintaining reliability and usability. By leveraging advanced technology and engineering principles, we seek to create a solution that seamlessly integrates into the daily lives of individuals with diabetes, empowering them to take proactive control of their health

1.2 Problem statement

The existing methods for monitoring glucose levels in diabetic patients rely on invasive procedures, such as blood sampling or subcutaneous sensor insertion, which can cause discomfort, inconvenience, and potential complications. There is a pressing need to develop a non-invasive glucose monitoring system that accurately and continuously measures glucose levels without the need for invasive techniques. This system should be user-friendly, reliable, and capable of providing real-time glucose readings, allowing diabetic patients to manage their condition more effectively and comfortably. By addressing this problem, the aim is to enhance the quality of life for diabetic individuals and improve their overall healthcare experience.

1.3 Research Questions (Hypotheses)

- How accurate is the non-invasive glucose monitoring system compared to traditional invasive methods?
- What is the user acceptance rate of diabetic patients using the non-invasive monitoring system?
- Does the system allow for continuous monitoring without causing disruptions to the user's routine?
- How effective is the non-invasive system in providing timely notifications and alerts for abnormal glucose levels?

1.4 Objectives

1.4.1 General Objective

To enhance the quality of life for diabetic patients by designing a noninvasive blood glucose monitoring device, that should be able to detect glucose level in blood and also determine glucose level and displaying the glucose level on the LCD screen.

1.4.2 Specific Objectives

1. Investigate the feasibility and accuracy of non-invasive glucose monitoring technologies currently available.
2. Develop a novel non-invasive glucose monitoring system that is reliable, accurate, and user-friendly.
3. Evaluate the system's performance across a range of glucose levels.

1.5 Study Scope

In the project titled "Development of a Non-Invasive Glucose Monitoring System" Near-Infrared (NIR) technology will be employed. This involves directing NIR light onto the skin, allowing the rays to penetrate the skin and interact with the tissues of the finger. The blood absorbs the light, and the transmitted signal is subsequently amplified and processed by Microcontroller with the output displayed on an LCD screen. Besides showing glucose levels, the data can be transmitted via a GSM module to the doctor for patient monitoring. Additionally, tests will be conducted on patients during the fasting period.

1.6 Significance of the Study

Significance of the Study on:

1. **National Impact:**

Healthcare Advancement: The successful development of a non-invasive glucose monitoring system contributes to the enhancement of healthcare technology in the country. It aligns with national health goals, improving the quality of life for diabetic patients and reducing the burden on healthcare infrastructure.

2. **Local Community Impact:**

Improved Healthcare Access: The non-invasive glucose monitoring system has the potential to make glucose monitoring more accessible to individuals in local communities. This can be particularly beneficial for those in remote or underserved areas who may face challenges in accessing regular healthcare services.

3. **Researchers and Scientific Community:**

Technological Advancement: The project contributes to the field of medical technology and sensor development. Researchers involved gain valuable insights into the application of Near-Infrared (NIR) technology for non-invasive glucose monitoring, potentially paving the way for advancements in related medical research.

1.7 Organization

Chapter one gives the introduction on Non-Invasive Glucose Monitoring System for Diabetic Patients and briefly explain problem statement, objectives, scope and Significance of the Study.

Chapter two discusses about critical review of the technical and academic literature on previous works on Non-Invasive Glucose Monitoring System for Diabetic Patients.

In chapter three outlines the methods and techniques employed in the research project titled "Designing a Non-Invasive Glucose Monitoring System for Diabetic Patients," and provides a brief description of the components used. The design process involves the use of Proteus software and an Arduino Uno.

Chapter four discusses the results and findings of the study and finally chapter five discusses challenges, recommendations and conclusions from Non-Invasive Glucose Monitoring System for Diabetic Patients.

CHAPTER 2. LITERATURE REVIEW

There are three main ways to measure blood glucose concentration: invasive, non-invasive, and minimally invasive (also known as interstitial)[7],[8].The invasive method involves pricking a finger with needles or syringes to draw a blood sample, which is then analyzed using a blood glucose measurement device. The partially invasive method requires inserting a sensor into the skin to measure glucose concentration. Many patients prefer the invasive method because it utilizes a cheaper device compared to the partially invasive and non-invasive approaches. However, the invasive method is not ideal for frequent or continuous blood glucose monitoring as it can cause discomfort to patients during each reading. As a result, the minimally invasive and non-invasive methods are becoming increasingly popular for continuous monitoring of blood glucose concentration. These methods offer numerous advantages, such as not requiring a blood sample for testing. An overview of techniques for measuring glucose is presented[9],[10].

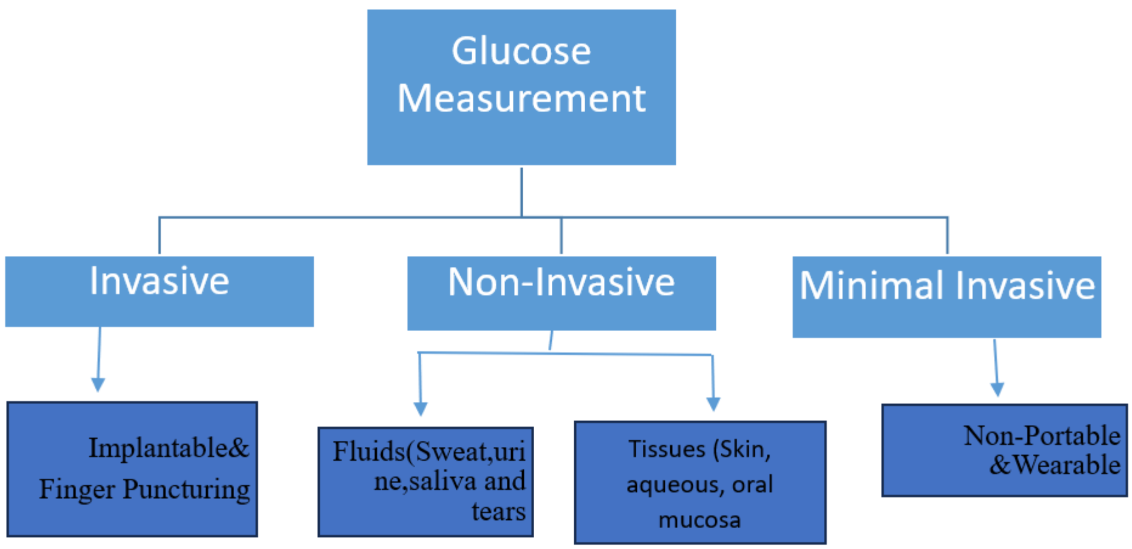

Figure 2. 1:Overview of glucose measurement techniques

The history of blood glucose monitoring systems can be traced back to their initial introduction in the 1970s[7]. Since then, these systems have undergone various developments aimed at enhancing the accuracy of readings, refining techniques and approaches, reducing device size, and incorporating advanced technology into embedded systems. Each generation of these systems will be detailed in the following section, providing an overview of the improvements made over time

First Generation (Invasive)

Anton Hubert (Tom) Clemens, the creator of the Ames Reflectance Meter, holds the patent for the first-ever blood glucose meter, which was patented in 1971[7]. This innovative glucose meter employs an enzyme test strip, onto which a drop of blood is applied and subsequently rinsed away after the reading. The meter determines the blood glucose concentration by analyzing the color it detects.

Second Generation (Invasive)

The ExacTech® strip, developed by MediSense (later acquired by Abbott Laboratories), was the pioneering blood glucose meter available for home use in 1987. This innovative technology draws upon Clark and Lyons' enzyme biosensor technology, employing an integrated electrochemical ferrocene-derivative mediator as an electron acceptor. Unlike earlier sensors that relied on oxidation, this advancement significantly enhances the device's accuracy in measuring glucose levels. Over time, the ExacTech® strip has undergone numerous improvements in terms of reading precision, size, and overall functionality.

Third Generation (minimally invasive and continuous)

The latest iteration of glucose monitoring systems, known as the third generation, places a greater emphasis on continuous monitoring. This technological advancement has been made possible through the creation of a suitable sensor that can be inserted beneath the skin and remain in place for up to a week without the need for blood draws. The pioneering company in this field is Medtronic MiniMed, which introduced the first device for continuous glucose monitoring (CGM). In June 1991, the device received approval from the American Food and Drug Administration (USFDA).

Fourth generation (Non-invasive)

The latest advancement in blood glucose monitoring devices focuses on a non-invasive approach. This method enables the measurement of blood glucose levels in the human body by simply placing sensors directly on the targeted area, eliminating the need for blood draws or the use of needles and biosensors. Research on this technology began as early as 1957 and continues to progress to this day. Although this technology has been in development for several years, it wasn't until 2014 that a limited number of devices utilizing this method were produced. Furthermore, these devices are currently only available in select countries

Blood glucose monitoring methods

Blood glucose monitoring encompasses three distinct approaches. The initial and most precise method involves invasive monitoring, relying on measurements derived from blood samples. The second approach, minimally invasive blood glucose monitoring, involves sampling interstitial fluid within the skin. The third and final method, non-invasive blood glucose monitoring, assesses blood glucose levels using body fluids other than blood, such as tears, saliva, and urine. These methods are succinctly outlined below.[8]

1.Invasive blood glucose measurement

The glucometer is a widely used invasive method for monitoring blood glucose levels, involving a skin prick on the fingertip with a lancet to obtain a blood sample. However, this process is painful, increases the risk of inflammation, and is impractical for individuals requiring frequent daily glucose checks, especially those engaged in manual activities. Additionally, the most common method for determining blood glucose levels involves collecting a blood sample by piercing the finger with a needle and syringe, followed by measuring the glucose level with a spectrophotometer. This invasive blood glucose monitoring method, which causes pain and often leaves the finger sore, is demonstrated[11].

Invasive Blood glucose testing using a glucometer

The blood glucose level is determined by obtaining a small amount of blood from a capillary in the patient's finger through a lancet prick. The blood collected on the lancet is then transferred onto a disposable test strip, which is subsequently inserted into the glucometer.

Figure 2. 2:Blood glucose testing through invasive means employing a glucometer

2.Minimally invasive blood glucose measurement

Minimally invasive blood glucose measurement involves sampling the interstitial fluid present in the skin or subcutaneous tissue to gauge blood glucose levels. This is achieved through the utilization of a subcutaneous electrochemical sensor or biosensor implanted in the abdominal region, or alternatively, by employing microdialysis technology

3.Non-invasive blood glucose measurement

Non-invasive measurement of blood glucose Various techniques are employed to enable the assessment of blood glucose levels without resorting to traditional blood extraction methods like finger pricking. Among these, absorbance techniques are particularly relevant to the subject of this thesis. Absorbance spectroscopy methods rely on the principle that different molecules in the tissue absorb distinct wavelengths of light. In this process, a beam of light with a specific wavelength is directed towards a sample, and on the opposite side of the sample, the transmitted light is measured in terms of power or intensity. This facilitates the quantification of various molecules within the sample, with the incident light wavelength tailored to target specific molecules. Two infra-red regions are considered, as outlined below.

3.1 Mid-infra-red region

Glucose exhibits higher light absorption in the region of 2500–10,000nm, with minimal interference from other blood constituents. However, the penetration depth is limited, around a few microns, and increasing the wavelength reduces penetration depth. Consequently, detection on the other side of the tissue becomes impractical, making the near-infra-red region a more suitable choice for the intended application in this design[8].

3.2 Near-infra-red region

This region is based on incident light with a wavelength between 750 and 2500nm. Within this wavelength band, light is absorbed not only by glucose molecules but also by water, proteins, cholesterol, and fat. A study compared a Near-Infrared (NIR) system with invasive measurements from finger pricks, revealing good agreement with a low percentage of difference between the two methods.

In this project, the Near-Infrared (NIR) technique is preferred because glucose molecules exhibit the highest absorption spectra in the near-infra-red region compared to other constituents such as protein, fat, and water. Noninvasive glucose monitoring technologies are employed to measure blood glucose without invasive procedures[12],[13].

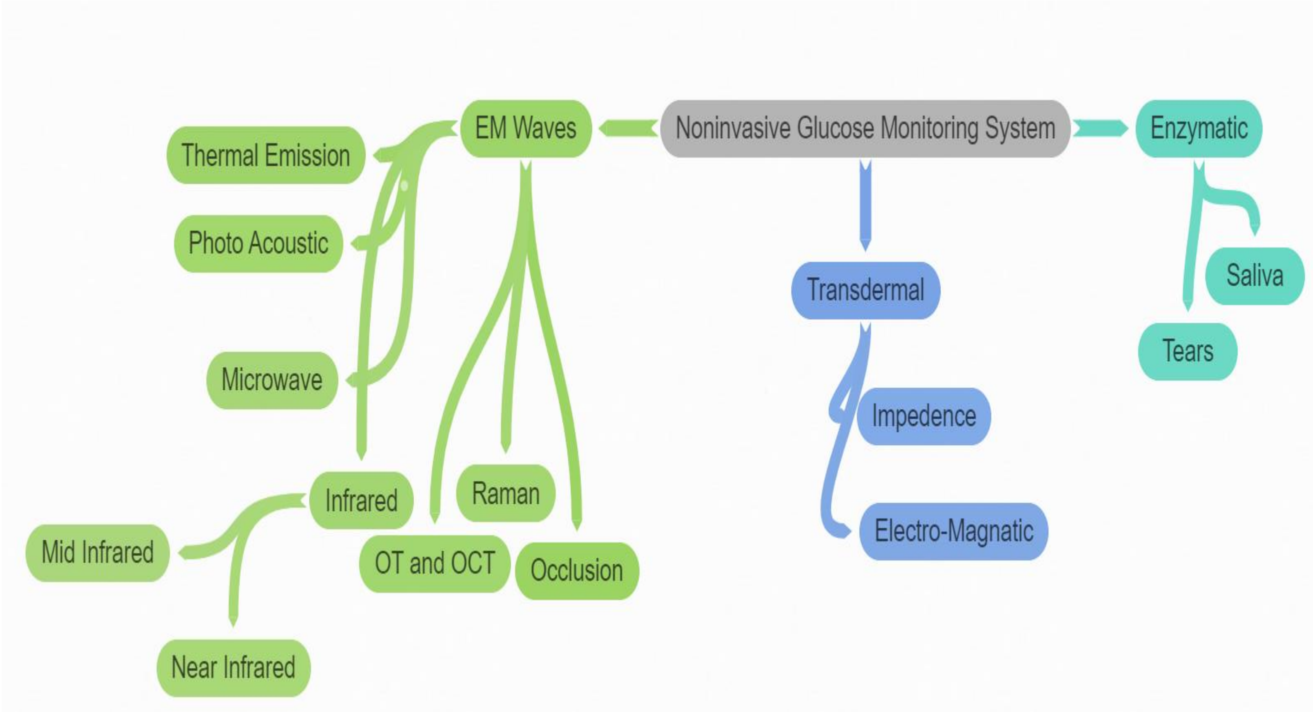

Figure 2. 3:Noninvasive glucose-monitoring technologies.

Non-Invasive Blood Glucose Monitoring

Non-invasive blood glucose monitoring involves the measurement of blood glucose levels without causing harm to human tissues. Various methods exist for non-invasive blood glucose detection, broadly categorized into optical methods, microwave methods, and electrochemical methods. Optical methods encompass techniques such as near-infrared reflectance spectroscopy (NIRS), polarized optical rotation, Raman spectroscopy, fluorescence, and optical coherence tomography (OCT), among others[5],[6] ,[14]. Near-infrared (NIR) is a highly investigated optical method due to its excellent ability to penetrate the skin. It has been extensively utilized on different regions of the body, including the finger, palm, arm, forearm, earlobe, and cheek[2].

Non-Invasive Blood Sugar Test Kits.

The primary element of the testing kit consists of a near-infrared LED designed with the correct wavelength. This sensor, utilizing a near-infrared LED, was combined with a photodiode to analyze the light reflected from skin tissue secured to the fingertips. installation of a non-LED and a photodiode on a fingertip is illustrated[15].

GLUCOSE SENSING FOR DIABETES MONITORING

Glucose is a simple sugar, also known as a monosaccharide, and it is a primary source of energy for living organisms. It is a crucial component of carbohydrates and serves as the main fuel for various cellular processes in the human body. Glucose is a hexose sugar, meaning it contains six carbon atoms, twelve hydrogen atoms, and six oxygen atoms, with the molecular formula $C_6H_{12}O_6$.

Regular monitoring of blood sugar levels in patients provides valuable insights to doctors regarding the effectiveness of their treatment plans. Table 1&2 presents different categories of blood glucose concentrations for normal individuals, those at high risk, and individuals with diabetes[6],[8]. Throughout the day, blood glucose levels in the body fluctuate and typically increase after meals. Blood sugar fluctuations in adults, Glucose blood levels (red), insulin or sugar lowering hormone levels (blue) when consuming starch rich food (solid lines), sugar rich food (dotted lines) are illustrated[6]. Prolonged elevation of blood glucose levels can lead to glucose toxicity, resulting in cellular dysfunction and complications associated with diabetes.

Table 2. 1:Sugar level at different conditions in (mg/dL).

Condition	Fasting	Just ate	3h after eating
Normal	80-100	170-200	120-140
Pre-diabetics	101-125	190-230	140-160
Diabetic	≥126	220-300	≥200

Table 2. 2: Ranges for blood glucose concentration in (mg/dL).

Categories	Fasting blood glucose concentration
Normal	<100 mg/dL
High Risk	100 – 125 mg/dL
Diabetes	>= 126 mg/dL

Diabetes

In simple terms, diabetes is a condition where the body fails to produce sufficient insulin to regulate the absorption of carbohydrates in the body. Insulin, a hormone from the pancreas, facilitates the movement of glucose (the primary fuel for the body) from the bloodstream into cells. Insulin also converts glucose into glycogen for storage in the body. In individuals with diabetes, the inadequate production of insulin leads to unprocessed glucose circulating in the blood, causing an increase in blood glucose levels. Contributing factors to this surge include being overweight and obesity. The three main types of diabetes are Type 1 diabetes (also known as insulin-dependent diabetes mellitus), Type 2 diabetes (also known as non-insulin dependent diabetes mellitus), and gestational diabetes mellitus (GDM).[16]

Type 1 diabetes occurs when the pancreas fails to generate sufficient insulin due to the loss of beta cells, which is triggered by an autoimmune response. On the other hand, Type 2 diabetes starts with insulin resistance, where cells do not respond adequately to insulin. As the condition advances, a deficiency in insulin may also arise, typically resulting from a combination of excessive body weight and inadequate physical activity. Gestational diabetes occurs in pregnant women without a prior diabetes history, leading to elevated blood sugar levels during pregnancy.

In 2019, approximately 463 million individuals, accounting for 9.3% of the worldwide adult population aged 20-79, were believed to be experiencing diabetes. Projections indicate an anticipated rise to 578 million (10.2%) by 2030 and 700 million (10.9%) by 2045. The prevalence of diabetes among women was estimated to be 9.0% in 2019, while in men, it was slightly higher at 9.6%.[17]

Principle of Blood Glucose Measurement

When light interacts with human body tissues, it undergoes attenuation through both scattering and absorption processes within the tissues. The occurrence of light scattering in tissues is attributed to the mismatch in the refractive indices between the extracellular fluid and the cell membrane. The refractive index of the extracellular fluid varies with glucose concentration, while the index of the cellular membrane is assumed to remain relatively constant.

The Beer-Lambert Law plays a significant role in absorbance measurement, stating that the absorbance of light passing through a solution is directly proportional to the concentration of the solution and the path length traveled by the light ray. In cases of lower glucose levels, there is increased scattering, greater path length, and consequently, reduced absorption. Conversely, higher glucose concentrations in tissues result in diminished scattering, shorter optical path length, and increased absorption by the tissues.

Due to greater absorption in tissues with high glucose levels, reflected light exhibits lower intensity compared to tissues with lower glucose content. the impact of glucose molecules on the path of light is illustrated[1],[15],[18].

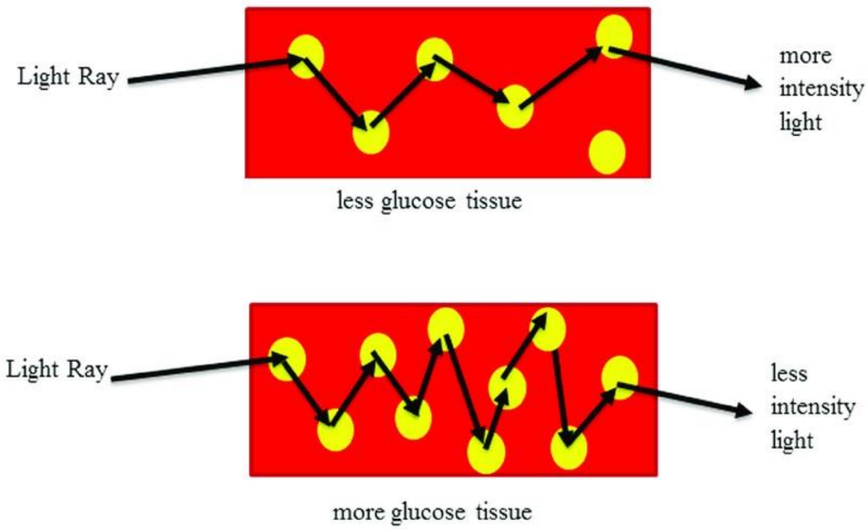

Figure 2. 4:Effect of Glucose On light Path

Working Principle of getting information of glucose.

The skin is composed of three layers: the epidermis, dermis, and hypodermis. Within these layers, blood glucose information is stored specifically in the dermis layer. By utilizing near-infrared (NIR) light with a wavelength range of 750nm to 2500nm, it becomes possible to penetrate the dermis layer and extract glucose information[3],[18]. When NIR light is directed onto the skin, it is absorbed by blood, which absorbs more light compared to the surrounding tissues. In individuals with diabetes, who have higher levels of glucose molecules, a greater amount of light is transmitted through the skin compared to non-diabetic individuals. The transmitted or reflected light is then captured by a photo detector. The key aspect in NIR technology is to use the appropriate wavelength, with the second overtone band between 780nm and 1400nm being particularly critical[19].

After the NIR sensor emits a continuous wave, it is received by a photodiode operating at a wavelength of 1550 nm. The received wave signals are then subjected to noise filtration and amplification. Subsequently, these wave signals are converted into an appropriate voltage value, which is further processed by a microcontroller. The microcontroller performs the necessary calculations to convert the voltage value into a corresponding glucose level. The obtained glucose value is displayed on an LCD monitor for the patient to see. Additionally, the microcontroller utilizes a GSM module (SIM808) to transmit this glucose value to a server. This enables observers to access and monitor the patient's glucose level using a smartphone[9].

The IR sensor detected the amount of infrared radiation absorbed by glucose molecules in the blood using a light source and a detector. As IR radiation interacted with these glucose molecules, some of the radiation was absorbed, while the rest was reflected. The detector then measured the reflected radiation, which was directly proportional to the glucose level in the blood. By scanning the skin for infrared light absorbed by glucose molecules in the blood, the IR sensor was able to measure blood glucose levels noninvasively.

Range of Wavelengths

Range of wavelengths for near-infrared (NIR)" refers to the specific band of electromagnetic wavelengths that fall within the near-infrared region of the electromagnetic spectrum. Near-infrared wavelengths typically range from around 700 nanometers to 1100 nanometers. This portion of the spectrum is characterized by light waves that have longer wavelengths than visible light but shorter than mid-infrared waves. Light with wavelengths between 700 and 1100 nm, specifically in the near-infrared (NIR) range, is well-suited for effectively penetrating deep into tissues[20].

2.3 Summary

The literature review on designing a non-invasive glucose monitoring system for diabetic patients has highlighted several crucial insights. Various innovative techniques, including Near-Infrared (NIR) technique, optical methods, impedance spectroscopy, and microwave sensing, have been explored, each with unique benefits and challenges in accuracy and practicality. Effective signal processing is essential for translating raw data into accurate glucose readings, with advanced algorithms and microprocessor technologies, The integration of user-friendly interfaces, like LCD displays, and GSM modules for data sharing, has proven vital for real-time feedback and remote monitoring. These lessons underscore the importance of a multifaceted approach in system design, combining innovative sensing, robust processing, and effective communication features. This understanding motivates me to proceed to the next chapter, Research Methodology, where we will detail my systematic approach to developing and validating an improved non-invasive glucose monitoring system and enhancing usability for diabetic patients.

CHAPTER 3. RESEARCH METHODOLOGY

Research methodology describes the methods and techniques that will be used during conducting this research project titled "Designing a non-invasive glucose monitoring system for diabetic patients". those methods and techniques used to gather the information needed either from the field (primary data) or from other sources (secondary data), data collection, data gathering procedures, interview and analysis of those data collected from different sites.

3.1 Research Process

To non-invasively measure blood sugar levels, near-infrared (NIR) rays are utilized. These rays penetrate the skin, interact with the finger's tissues, and gauge glucose concentration. Subsequently, the reflected light is transformed into an electric current, which is then converted into an electric potential. As the NIR light traverses through the fingertip, it engages with glucose molecules, causing some of the NIR light to be absorbed, contingent on the blood's glucose concentration. The amount of NIR light that passes through the fingertip varies according to the blood glucose concentration. This transmitted signal is subsequently amplified and processed by Microcontroller with the output displayed on an LCD screen. Besides showing glucose levels, the data can be transmitted via a GSM module to the doctor for patient monitoring.

3.2 Research Design Method

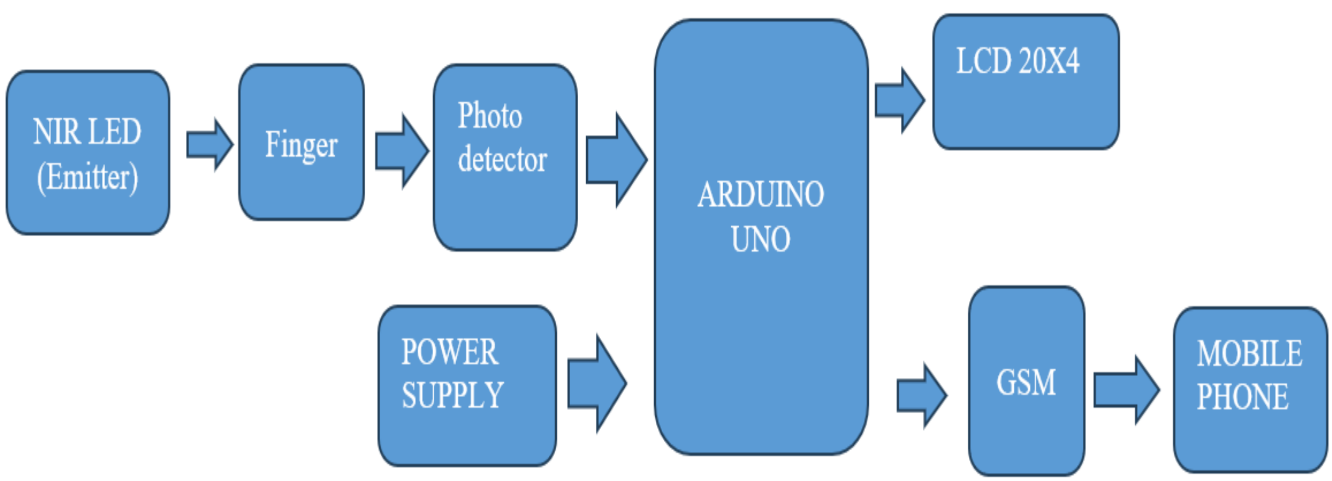

Figure 3. 1: Block diagram for measuring glucose concentration in a non-invasive manner.

3.3 The Research Plan

1. Literature Review:

- Conduct an extensive review of existing non-invasive glucose monitoring technologies, including their principles of operation, advantages, and limitations.

2. Market Analysis:

- Analyze the market for non-invasive glucose monitoring devices, including competitor products and their market share.

3. Conceptual Design:

- Develop a conceptual design for the non-invasive glucose monitoring system.
- Define the key components and technology to be employed.

4. Prototype Development:

- Build a prototype of the glucose monitoring system based on the conceptual design.

3.4 Parts Selection

After reviewing numerous scientific papers and articles that utilized various components, I selected the most suitable parts for my project based on their accuracy and cost-effectiveness. These components are:

3.4.1 Arduino Uno

The Arduino Uno is a microcontroller board built around the ATmega328P chip. It features 14 digital input/output pins, with 6 of these capable of functioning as PWM outputs, and includes 6 analog input pins. The board operates with a 16 MHz quartz crystal and is equipped with a USB port, a power jack, an ICSP header, and a reset button. By connecting all components to the Arduino Uno, it serves as the central controller for the entire device[21]

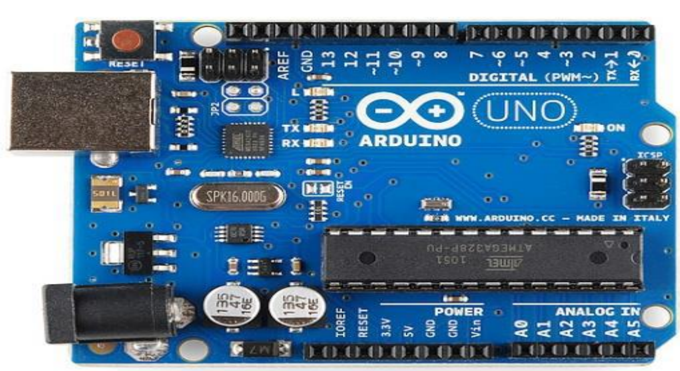

Figure 3. 2:Arduino Uno

3.4.2 Liquid Crystal Display (LCD) 20X4 With I2C

A 20x4 Liquid Crystal Display (LCD) with I_2C (Inter-Integrated Circuit) interface is a popular type of character LCD that displays information in 20 columns and 4 rows. It is often used in microcontroller projects for displaying text and numerical data due to its ease of use and low power consumption.

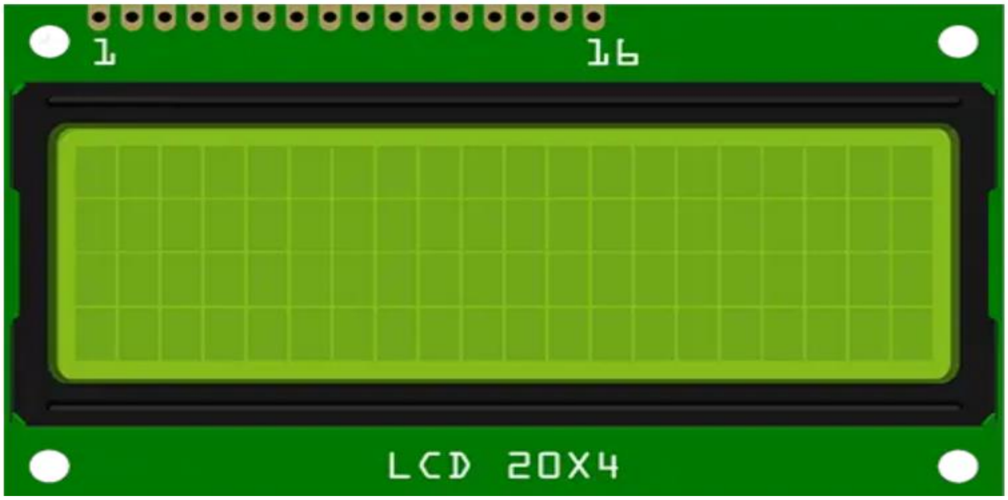

Figure 3. 3: Liquid Crystal Display (LCD) 20X4 With I2C

A 20x4 LCD display features 20 columns and 4 rows, allowing it to show up to 80 characters simultaneously. Each column can hold one character, and with four rows available, it provides a clear and organized way to present information. This type of display is particularly useful in devices requiring detailed data presentation, ensuring that ample information can be displayed at once without overcrowding the screen.

Advantages of I2C 20x4 LCD:

- **Fewer Wires**: Only requires two data lines (SDA and SCL), along with power (VCC) and ground (GND).
- **Ease of Use**: Libraries are available for popular microcontroller platforms (such as Arduino) to simplify coding.
- **Flexibility**: Multiple I2C devices can be connected on the same bus, allowing for complex projects without complicated wiring.

3.4.3 Global System for Mobile Communications (GSM)

The Global System for Mobile Communications (GSM) is a widely adopted standard for mobile networks, facilitating 2G digital cellular communications. It converts voice into digital data, transmits it via radio waves, and enables seamless global roaming through standardized protocols and international agreements[22]

GSM boasts essential features like employing a SIM card for storing user data, enabling SMS text messaging, and providing mobile data services. The SIM card, integral to GSM, stores personalized information and simplifies device switching. Moreover, GSM supports not only voice calls but also SMS and mobile internet services facilitated by technologies such as GPRS.

GPRS, or General Packet Radio Service, is a mobile data service available to users of GSM and other networks. It allows mobile phones to access internet browsing, email, and multimedia messaging by transmitting data packets over the mobile network. GPRS enhances GSM's capabilities by providing higher data transfer rates and more efficient use of network resources, enabling the use of more data-intensive applications on mobile devices.

Figure 3. 4:GSM Module.

3.4.4 Breadboard

A breadboard is a fundamental tool used in electronics prototyping and experimentation. It consists of a plastic board with numerous holes arranged in a grid pattern, with conductive metal strips running beneath the surface. The purpose of a breadboard is to allow electronic components to be easily connected together without the need for soldering.

Components such as resistors, capacitors, integrated circuits, and wires can be inserted into the holes on the breadboard, where they make electrical contact with the metal strips underneath. This enables users to quickly build and modify circuits by simply inserting and rearranging components as needed.

The primary advantage of using a breadboard is its versatility and ease of use. It allows users to test circuit designs and experiment with different configurations without committing to a permanent soldered layout. This makes it an invaluable tool for students, hobbyists, and professionals alike, facilitating rapid prototyping and troubleshooting in electronics projects.

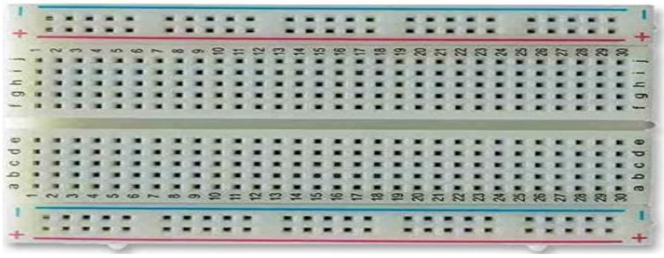

Figure 3. 5: Breadboard

3.4.5 Jumper wires

A jumper wire is a short, insulated conductor used to establish electrical connections between different points in a circuit, primarily on breadboards, printed circuit boards (PCBs), or other electronic assemblies. These wires come with pre-stripped ends or connectors, making them easy to insert into sockets, pin headers, or directly onto breadboards

Figure 3. 6**:** Jumper wires

3.4.6 infrared (IR) sensor

Infrared (IR) sensors are devices that detect infrared radiation, which is a type of electromagnetic radiation with wavelengths longer than visible light but shorter than microwaves. IR sensors can detect IR radiation emitted by objects or measure the reflection or transmission of IR light.

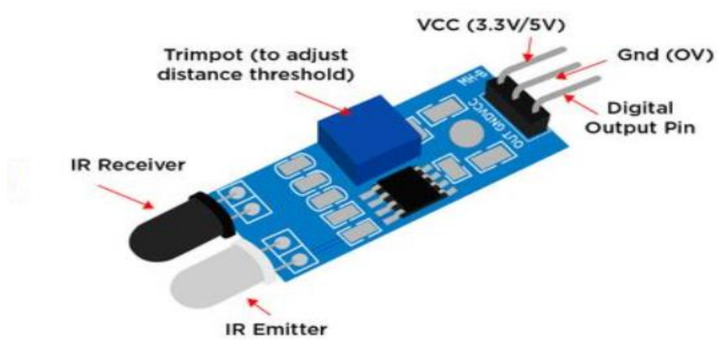

Figure 3. 7: Infrared (IR) sensor

3.5 Flowchart

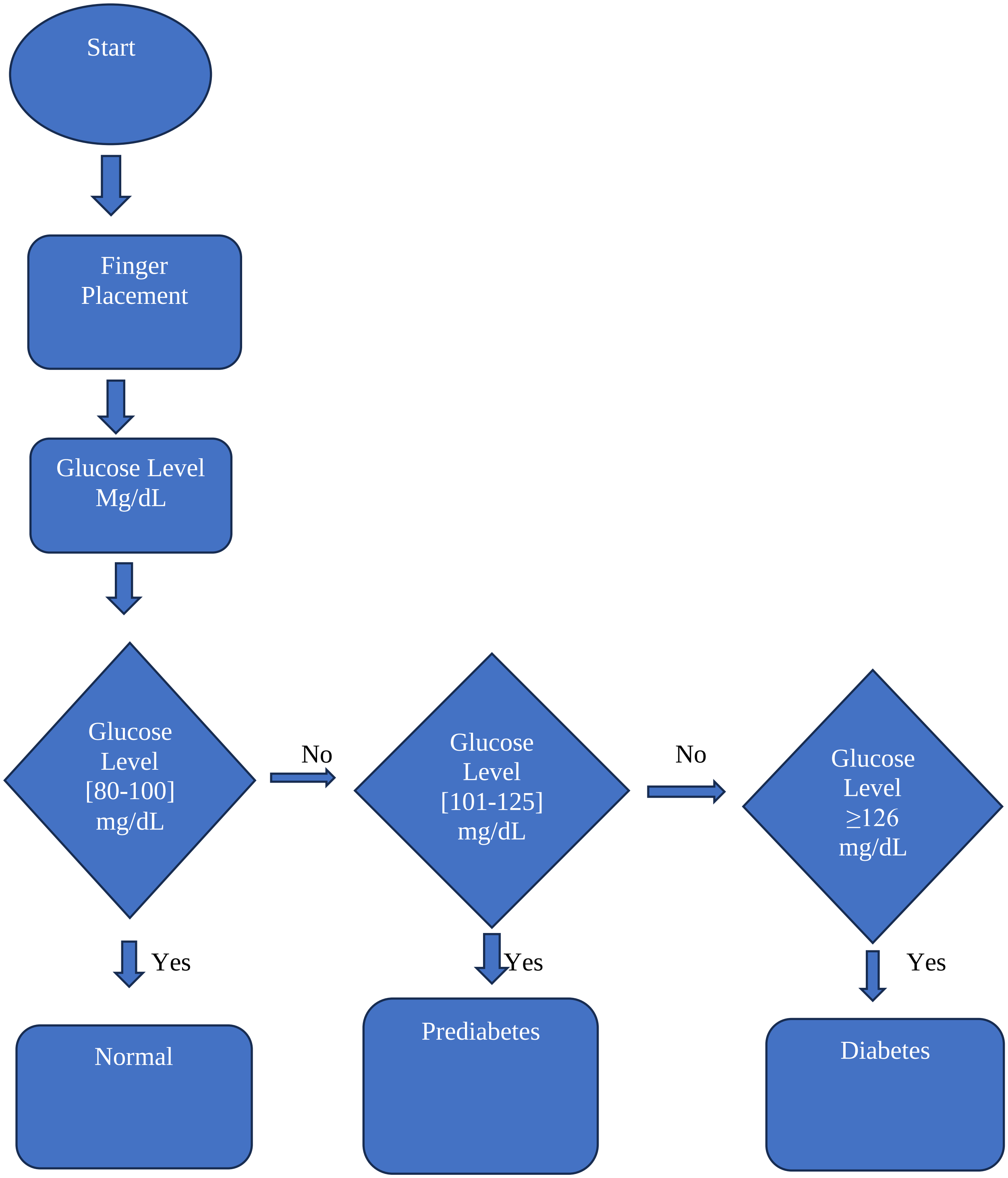

Figure 3. 8: Flow Chart Diagram Non-Invasive Glucose Monitoring System for Diabetic Patients

3.3 Summary

In the project titled "Development of a Non-Invasive Glucose Monitoring System " Near-Infrared (NIR) technology will be utilized. This method involves projecting NIR light onto the skin, enabling the rays to penetrate and interact with the tissues of the finger. The light is absorbed by the blood, and the resulting signal is then amplified and processed by a microcontroller, with the results displayed on an LCD screen. In addition to displaying glucose levels, the data can be sent to the doctor for patient monitoring via a GSM module. The design process incorporates the use of Proteus software and an Arduino Uno.

CHAPTER 4. THE PROJECT RESULTS FROM IMPLEMENTATION

4.1 Introduction

In this chapter, I am going to present the results from the implementation phase of the project titled "Designing a Non-Invasive Glucose Monitoring System This section will focus on the practical outcomes and performance of the developed system when applied in real-world conditions. It will detail how the device was constructed, the challenges encountered during implementation, and the effectiveness of the system in accurately measuring blood glucose levels non-invasively. Additionally, I will compare the device's readings with traditional glucose measurement methods to evaluate its accuracy and reliability. Through this analysis, the chapter aims to demonstrate the practicality and potential impact of our innovative glucose monitoring solution.

4.2 Implementation Result

To measure blood sugar non-invasively, NIR rays penetrate the skin and interact with the finger tissues and glucose concentration. The reflected light generates an electric current, which is then converted into an electric potential. I tested numerous sensors to read the output voltage and compared these readings with blood sugar levels determined by the conventional method. This allowed me to establish a correlation, leading to the final design of the device.

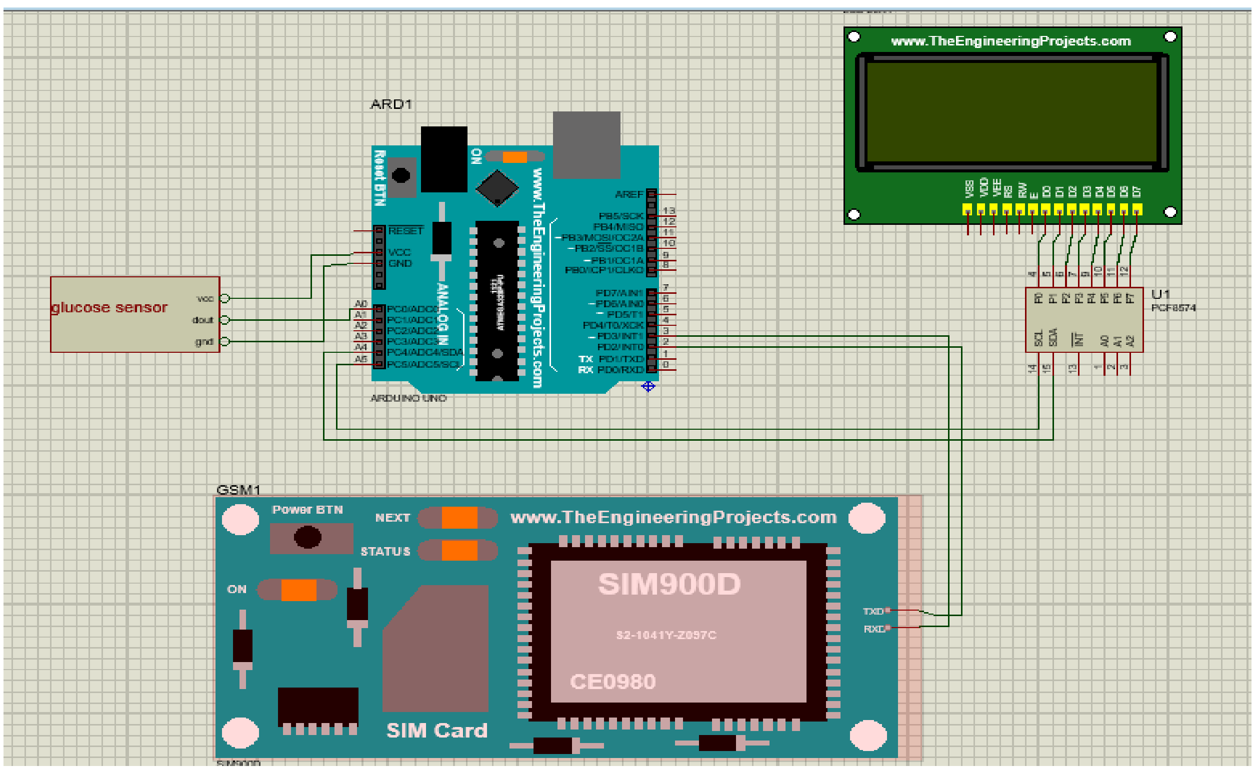

Figure 4. 1:Circuit Schematic Diagram of the NIR blood Glucose Monitoring

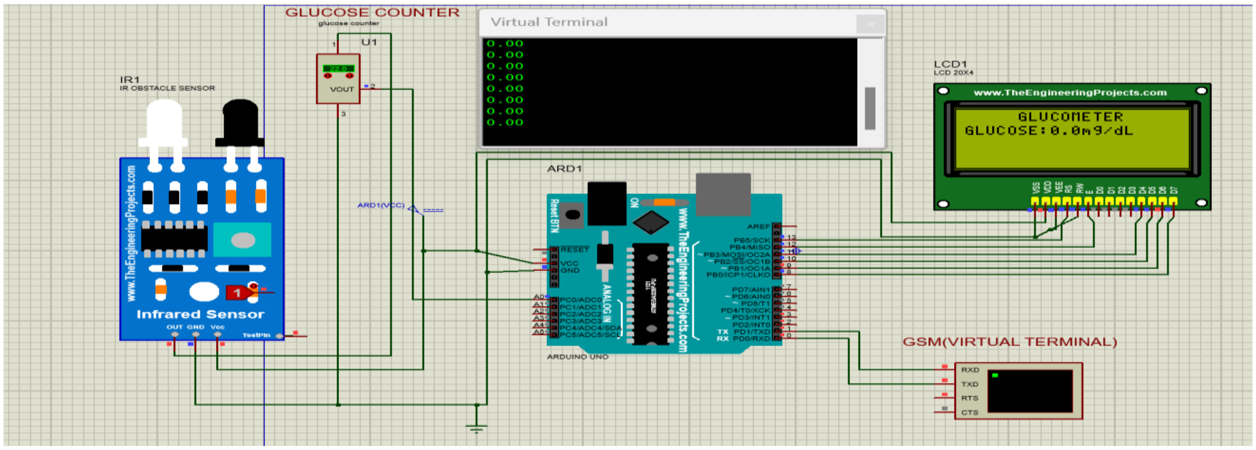

Figure 4. 2**:**Simulation circuit Diagram of the NIR blood Glucose Monitoring at initialy

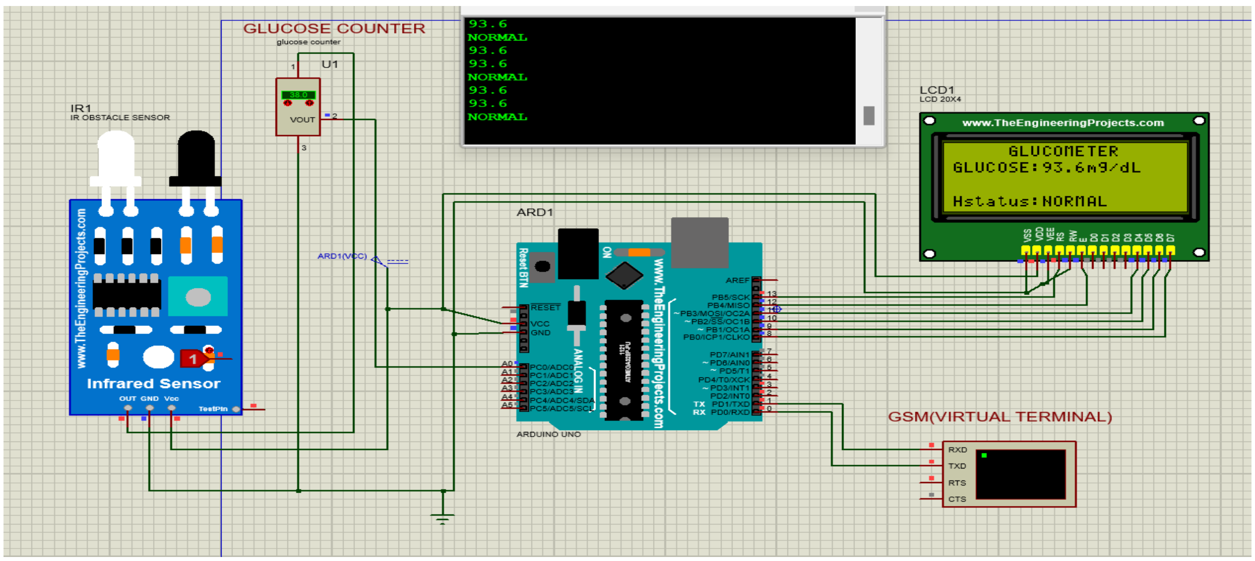

*Figure 4. 3***:** Simulation circuit Diagram of the NIR blood Glucose Monitoring at Normal Status

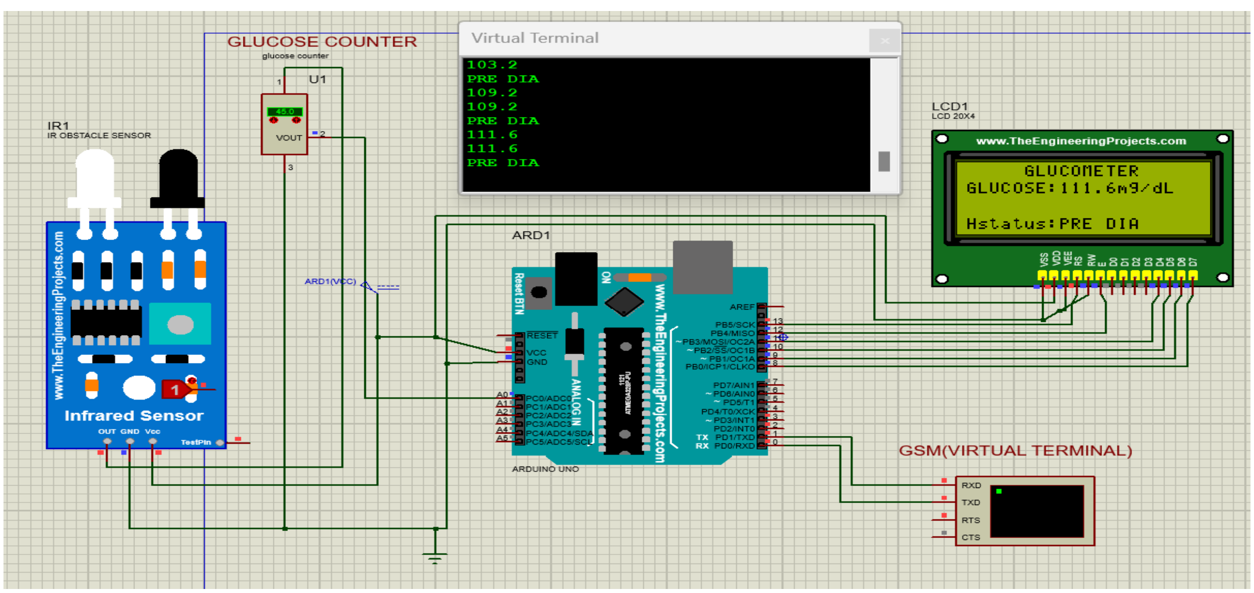

Figure 4. 4**:** Simulation circuit Diagram of the NIR blood Glucose Monitoring at Pre-Diabetic Status.

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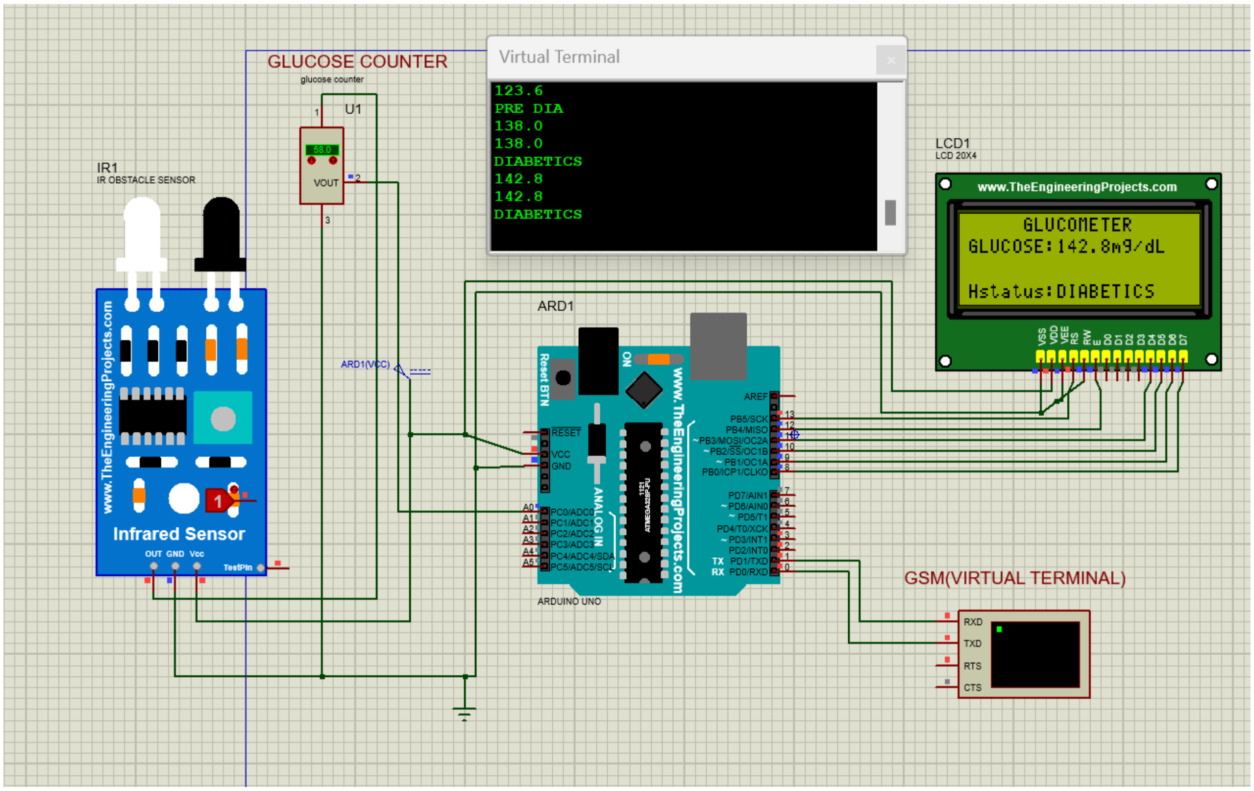

Figure 4. 5: Simulation circuit Diagram of the NIR blood Glucose Monitoring at Diabetic Status.

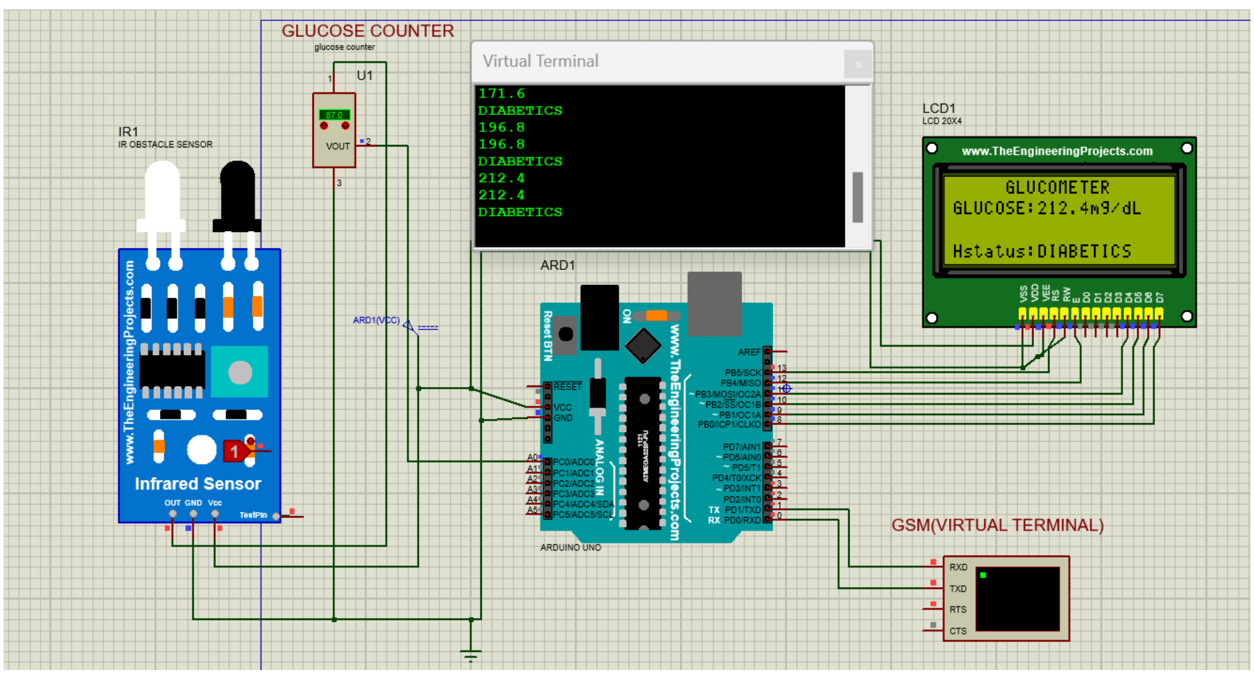

Figure 4. 6: Simulation circuit Diagram of the NIR blood Glucose Monitoring at Diabetic Status with high level of Glucose.

4.2.1 Discussion/ Working principle

The sensor is placed on the fingertip to measure the blood glucose concentration.
This involves directing NIR light onto the skin, allowing the rays to penetrate the skin and interact with the tissues of the finger. The blood absorbs the light, and the transmitted signal is subsequently amplified and processed by Microcontroller with the output displayed on an LCD screen. Besides showing glucose levels, the data can be transmitted via a GSM module to the doctor for patient monitoring.

4.3 EXPERIMENTAL RESULTS

4.3.1 Before measurement

Before measurement, the data from the serial plotter program used to visualize data from the Arduino are zero, as shown in Figure 4.7, due to the absence of any readings or measurements. In Figure 4.8, the graph line is constant and horizontal, while the LCD display in Figure 4.9 shows "GLUCOSE: 0.0 mg/dL," indicating that the program is designed to display glucose readings but currently shows none because no measurement has been taken. Without a finger connected as the measurement point, the program cannot obtain or display any readings. In short, everything is functioning as expected before a measurement is taken. Once the glucose meter is connected and a measurement is made, the program should display the glucose reading on both the graph and the LCD screen.

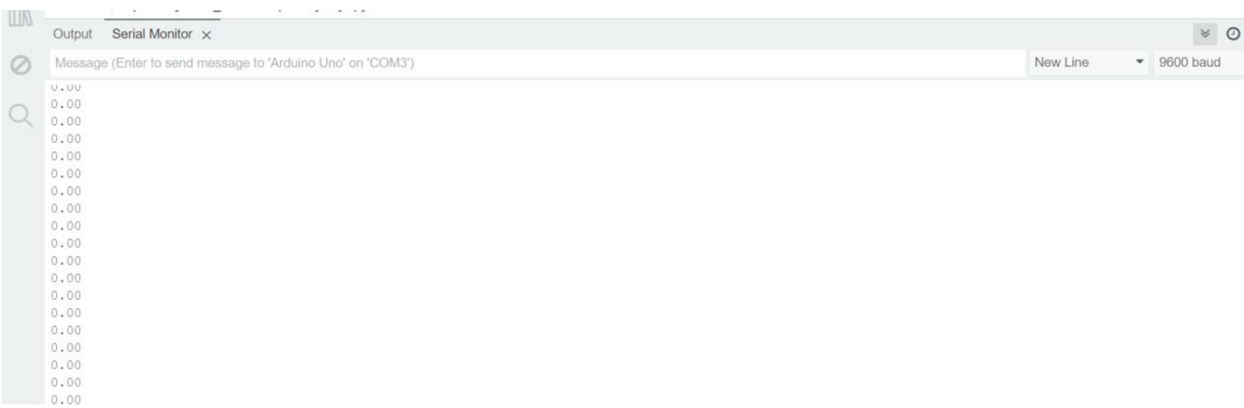

Figure 4. 7: Data from the serial plotter program Before measurement

Serial plotter at zero: The horizontal line at zero on the graph indicates the program is waiting for input. This is expected before a measurement is taken by the glucose meter.

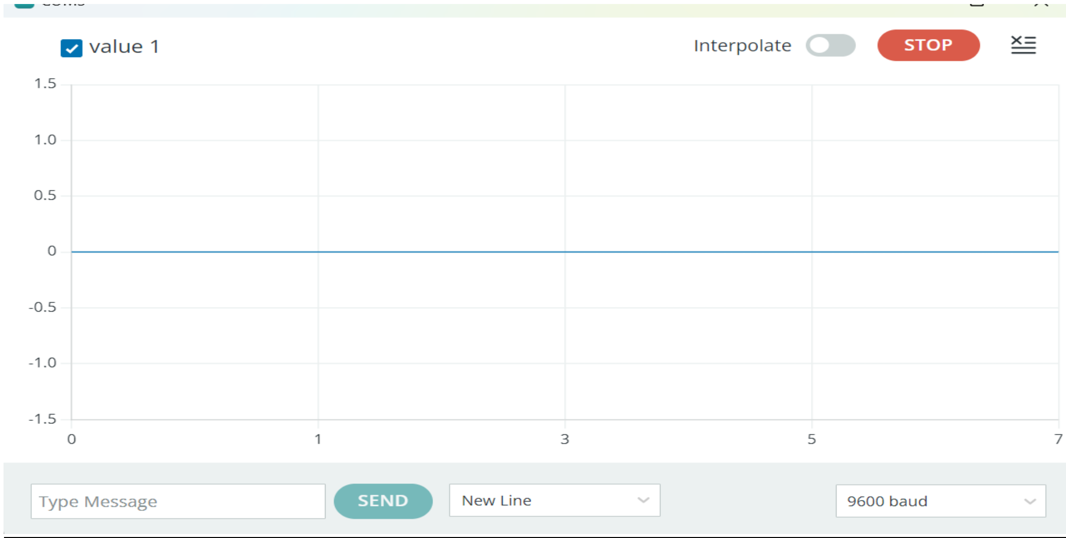

Figure 4. 8: The horizontal line at zero on the graph for Serial plotter at zero

LCD display showing zero: The "GLUCOSE:0.0mg/dL" on the LCD screen matches the zero reading on the graph. This confirms that the program is correctly communicating with the LCD and is ready to display upcoming readings.

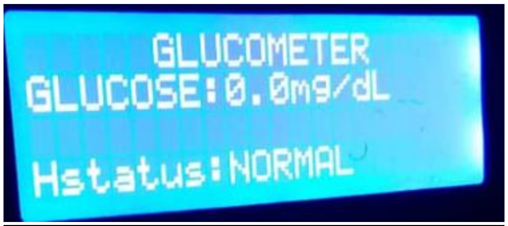

Figure 4. 9:shows "GLUCOSE: 0.0 mg/dL, Before measurement

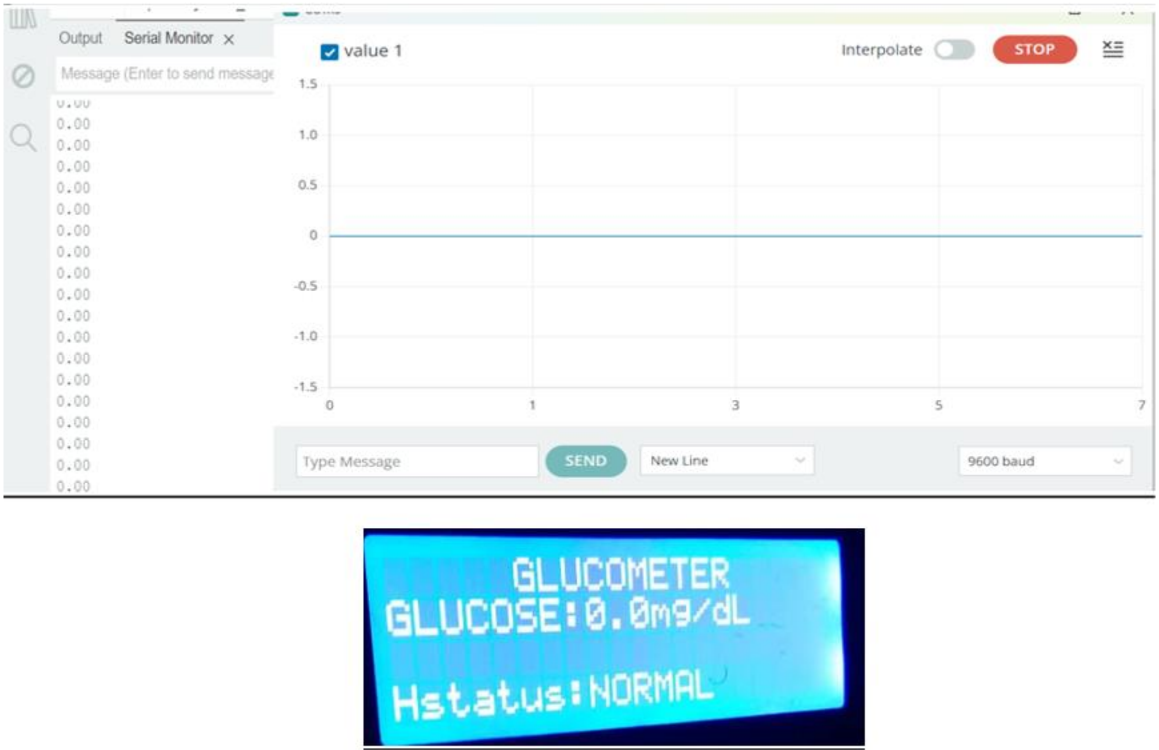

Figure 4. 10**:** Serial Plotter Graph and LCD display Before Measurement

4.3.2: During glucose measurement

During measurement, the data from the serial plotter program used to visualize data from the Arduino vary up to 91 mg/dL, as shown in Figure 4.11. Figure 4.12 depicts the blood sugar readings over time on a graph, while the LCD display in Figure 4.13 shows "GLUCOSE: 91.0 mg/dL" with a health status of "NORMAL." According to the American Diabetes Association, a reading of 91.0 mg/dL is considered within the normal range. Variations in sensor readings over time occur due to the analog nature of the data measurement.

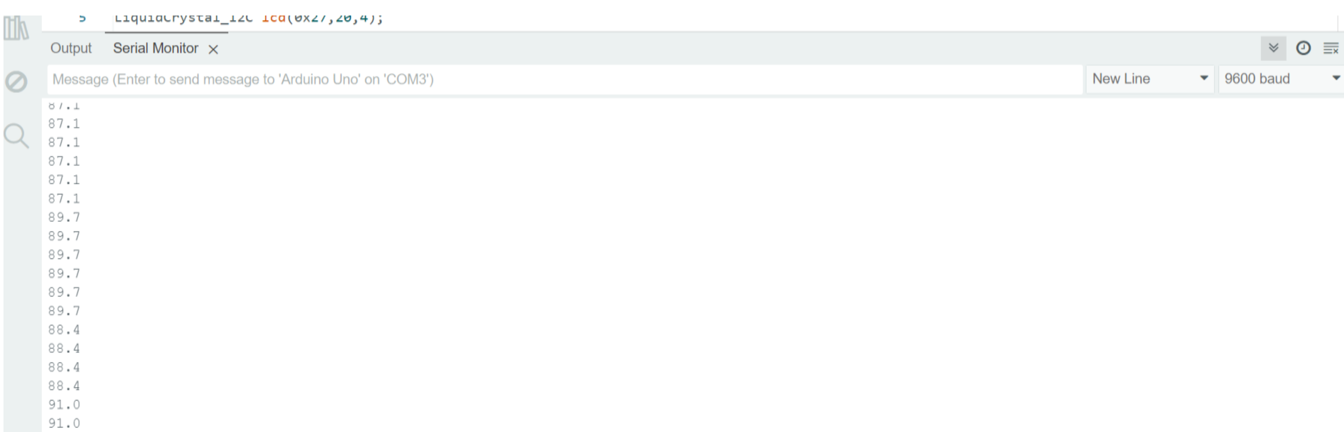

Figure 4. 11: Data from the serial plotter vary up to 91 mg/dL

Figure 4. 12:Graph depicts the blood sugar readings over time.

Figure 4. 13:shows "GLUCOSE: 89.6.0 mg/dL" with a health status of "NORMAL."

Figure 4. 14: SMS Message on Mobile Phone sent through GSM Module.

4.4 Results from Invasive device

These are the results I got out of my device and I compered them with those I extracted from the invasive method and I found the difference between them.

The proposed model is evaluated by measuring and comparing the glucose levels of 5 individuals using both the traditional invasive method and the new model. The findings are presented in Table 4.1.

Comparative Reliability Tests: Invasive vs. Non-invasive Methods

A reliability test was performed on five (5) subjects, utilizing both the invasive finger-prick method (Accu-Chek) and a non-invasive portable device. Blood glucose measurements from both methods are compared in Table 4.1, with the percentage differences between each measurement calculated using Equation 4.1.

$$\% \text{ Error} = \frac{GLUCOSE\ (invasive) - GLUCOSE\,(non-invasive)}{GLUCOSE\,(invasive)}\ x100 \qquad \text{Eq 4.1}$$

Where

"Glucose $_{\text{invasive}}$" refers to the glucose reading obtained using the invasive method (Accu-Chek), while "Glucose $_{\text{non-invasive}}$" refers to the glucose reading obtained using the non-invasive method.

Table 4. 1: Glucose levels of patients using both invasive and non-invasive methods.

N^0	Invasive Glucose Values (mg/dl)	Non-Invasive Glucose Values (mg/dl)	Difference	% of Error
1	88	89.6	1.6	1.8
2	90	92.4	2.4	2.6
3	86	84	2	2.3
4	81	82.8	1.8	2.22
5	93	87.6	5.4	5.8

Results from the reliability test demonstrated a strong agreement in glucose measurements between the invasive method (Accu-Chek) and the non-invasive method. This is evidenced by the low percentage difference (1%-6%) observed when comparing the glucose measurements for the same subjects.

After designing the device, I needed to verify its accuracy. To do this, I measured the glucose levels of patients using both invasive and non-invasive methods. I tested more than five patients' glucose levels before meals using both methods. The figures below show the results of these glucose measurements before meals, comparing invasive and non-invasive methods.

Figure 4. 15: Glucose levels of patients using invasive 88 mg/dl and non-invasive 89.6 mg/dl.

Figure 4. 16: Glucose levels of patients using invasive 90 mg/dl and non-invasive 92.4 mg/dl.

Figure 4. 17: Glucose levels of patients using invasive 86 mg/dl and non-invasive 84 mg/dl.

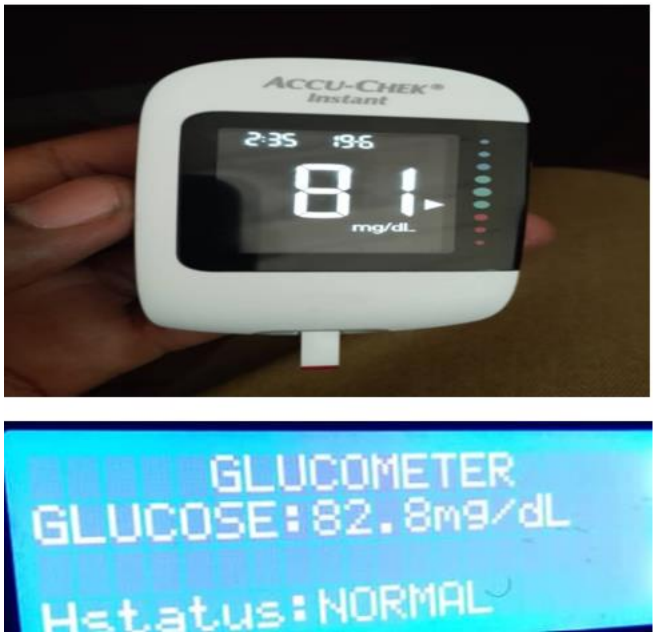

Figure 4. 18: Glucose levels of patients using invasive 81 mg/dl and non-invasive 82.8 mg/dl.

Figure 4. 19: The device's final appearance.

CHAPTER 5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This method eliminates the risk of infection from finger pricking and is more comfortable and cost-effective compared to invasive techniques. It offers a straightforward way to monitor blood glucose levels for diabetic patients at home, without requiring a specialist. Current invasive methods are painful and impractical for continuous blood glucose monitoring. With this non-invasive technique, continuous monitoring can be achieved simply by placing the sensor on the fingertip.

My design includes a data sharing feature that enables transmission of patient glucose levels and location to doctors for further investigation. The accuracy of my design is comparable to existing invasive methods currently available.

5.2 Recommendations

For future work, it is recommended to incorporate a battery into the design to allow for blood glucose monitoring while traveling or when external power sources are unavailable. Integrating patient location tracking into the system will facilitate quick assistance during emergencies. To ensure accurate results and prevent hand shaking, especially in unstable patient conditions, a tight band around the hand should be used to stabilize blood flow. The device should be designed to categorize and clearly indicate in SMS messages whether the patient's glucose level is fasting, post-meal, or at specific times after meals. Additionally, these messages should indicate the patient's status as normal, pre-diabetic, or diabetic based on the measured glucose levels. incorporate the measurement of blood pressure, by integrating a device that displays both systolic and diastolic values on an LCD screen. This will provide a comprehensive overview of blood pressure readings, improving accuracy and user convenience. Lastly, the device should store results for future reference, enabling the analysis of blood glucose variations and the adjustment of medication dosages.

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APPENDICES

Appendix 1: The Utilized Codes

```
#include<SoftwareSerial.h>
#include<Wire.h>
#include<LiquidCrystal.h>
//Create software serial object to communicate with A6
LiquidCrystal lcd(13,12,11,10,9,8);//RS=13,E=12,D5=10,D6=9,D7=8,Then connect
VEE&VSS&RW TOTHE GROUND
SoftwareSerial mySerial(3, 2); //A6 Tx & Rx is connected to Arduino #3 & #2
int sensor=A0;
float glucose=0;
float data;
void setup()
{
 pinMode(sensor,INPUT);//n serial communication with Arduino and Arduino IDE
(Serial Monitor)
  Serial.begin(9600);
                           // initialize the lcd
  lcd.begin(20,4);

  lcd.setCursor(3,0);
  lcd.print("glucometer ");
  lcd.setCursor(2,1);
  lcd.print("system based ");
   lcd.setCursor(0,2);
  lcd.print("system based");
   lcd.setCursor(2,3);
  lcd.print("on gsm");
  //Begin serial communication with Arduino and A6
  mySerial.begin(9600);

  Serial.println("Initializing...");
    mySerial.println("AT ");
  delay(2000);
lcd.clear();
 lcd.setCursor(0,0);
 lcd.print("GLUCOSE:0");
}

void loop()
{
glucose=analogRead(sensor);



 delay(500);
 if((glucose)*1.2<=80){
  glucose=0;
```

```
 lcd.setCursor(0,0);
lcd.print("     GLUCOMETER");
 lcd.setCursor(0,1);
 lcd.print("GLUCOSE:");
lcd.print((glucose*1.2),1);
lcd.print("mg/dL   ");
lcd.setCursor(0,2);
//lcd.print("BP:");
//lcd.print(glucose,1);
 Serial.println(glucose);
delay(500);

}
else{
  lcd.setCursor(0,0);
lcd.print("     GLUCOMETER");
lcd.setCursor(0,1);
 lcd.print("GLUCOSE:");
lcd.print((glucose*1.2),1);
 lcd.print("mg/dL   ");
lcd.setCursor(0,2);
//lcd.print("BP:");
//lcd.print(glucose,1);
 Serial.println((glucose*1.2),1);
 delay(500);

if((glucose*1.2)>=80&&(glucose*1.2)<=100){
 lcd.setCursor(0,0);
lcd.print("     GLUCOMETER");
lcd.setCursor(0,1);
 lcd.print("GLUCOSE:");
lcd.print((glucose*1.2),1);
 lcd.print("mg/dL   ");
lcd.setCursor(0,2);
//lcd.print("BP:");
//lcd.print(glucose,1);
lcd.setCursor(0,3);
lcd.print("Hstatus:NORMAL  ");
 Serial.println((glucose*1.2),1);
   Serial.println("NORMAL  ");
sms();
delay(500);

}
if((glucose*1.2)>=101&&(glucose*1.2)<=125){
 lcd.setCursor(0,0);
lcd.print("     GLUCOMETER");
```

```
 lcd.setCursor(0,1);
  lcd.print("GLUCOSE:");
 lcd.print((glucose*1.2),1);
  lcd.print("mg/dL   ");
 lcd.setCursor(0,2);
 //lcd.print("BP:");
 //lcd.print(glucose,1);
 lcd.setCursor(0,3);
 lcd.print("Hstatus:PRE DIA   ");
  Serial.println((glucose*1.2),1);
  Serial.println("PRE DIA  ");
  sms1();
 delay(500);
 }
 if((glucose*1.2)>=126){
  lcd.setCursor(0,0);
 lcd.print("     GLUCOMETER");
 lcd.setCursor(0,1);
  lcd.print("GLUCOSE:");
 lcd.print((glucose*1.2),1);
  lcd.print("mg/dL   ");
 lcd.setCursor(0,2);
 //lcd.print("BP:");
 //lcd.print(glucose,1);
 lcd.setCursor(0,3);
 lcd.print("Hstatus:DIABETICS    ");
  Serial.println((glucose*1.2),1);
  Serial.println("DIABETICS   ");
  sms2();
 delay(500);
 }

 }

}
void sms(){
   mySerial.println("AT"); //Once the handshake test is successful, it will back
to OK
  updateSerial();

  mySerial.println("AT+CMGF=1"); // Configuring TEXT mode
  updateSerial();
  mySerial.println("AT+CMGS=\"+250782773188\"");//change ZZ with country code and
xxxxxxxxxxx with phone number to sms
  updateSerial();
   mySerial.print("GADI DATA ");
  mySerial.print("glucosevalue:"); //text content
  mySerial.print((glucose*1.2)); //text content
```

```
  mySerial.println("Normal "); //text content
  updateSerial();
  mySerial.write(26);
}

void sms1(){
   mySerial.println("AT"); //Once the handshake test is successful, it will back
to OK
  updateSerial();

  mySerial.println("AT+CMGF=1"); // Configuring TEXT mode
  updateSerial();
  mySerial.println("AT+CMGS=\"+250782773188\"");//change ZZ with country code and
xxxxxxxxxxx with phone number to sms
  updateSerial();
   mySerial.print("GADI DATA ");
  mySerial.print("glucosevalue:"); //text content
  mySerial.print((glucose*1.2)); //text content
  mySerial.println("PRE DIA  "); //text content
  updateSerial();
  mySerial.write(26);
}
void sms2(){
   mySerial.println("AT"); //Once the handshake test is successful, it will back
to OK
  updateSerial();

  mySerial.println("AT+CMGF=1"); // Configuring TEXT mode
  updateSerial();
  mySerial.println("AT+CMGS=\"+250782773188\"");//change ZZ with country code and
xxxxxxxxxxx with phone number to sms
  updateSerial();
  mySerial.print("GADI DATA "); //text content
  mySerial.print("glucosevalue:"); //text content
  mySerial.print((glucose*1.2)); //text content
  mySerial.println("DIAbetic  "); //text content
  updateSerial();
  mySerial.write(26);
}

void updateSerial()
{
  delay(500);
  while (Serial.available())
  {
    mySerial.write(Serial.read());//Forward what Serial received to Software
Serial Port
  }
```

```
  while(mySerial.available())
  {
    Serial.write(mySerial.read());//Forward what Software Serial received to
Serial Port
  }
}
```