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Design and Development of a Painless, Non-Invasive Blood Sugar Monitoring System

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Abstract: Diabetes mellitus (DM) is a chronic metabolic condition that requires regular monitoring of blood sugar to be managed properly. But the usual invasive methods for testing are painful and uncomfortable, which often makes people avoid doing it regularly. To tackle this issue, we've worked on creating a painless and non-invasive glucose monitoring device using Near-Infrared (NIR) Spectroscopy along with Photoplethysmography (PPG). Our system uses two NIR light sources with wavelengths at 940 nm and 1050 nm—these were selected because glucose absorbs light well at these points. A BPV10NF photodiode is used to detect the reflected light from the fingertip, and the signal is amplified using an OPA320 Transimpedance Amplifier. An ESP32 microcontroller handles signal processing. On top of this, we've added a machine learning model to better relate optical signals to actual glucose levels for improved accuracy. The system is linked to a Firebase-powered real-time mobile and web app, where users can check their sugar levels, trends, and history. We even integrated an AI-based health assistant (Gemini) to give personalized tips and support. Lab testing showed a clear relationship between how much light is absorbed and how much glucose is in the solution, proving that non-contact glucose estimation is actually possible. The device is compact, budget-friendly, and easy to use, which could make glucose tracking less of a hassle for patients. Looking ahead, we plan to shrink the device further and improve AI prediction to make it even smarter and more adaptable.

Keywords: ESP32, machine learning, non-invasive glucose monitoring, AI health assistant, near-infrared spectroscopy, and photoplethysmography.

I. INTRODUCTION

Diabetes mellitus (DM) is a serious long-term disease and it affects millions of people all over the world. As per the International Diabetes Federation (2023), more than 540 million adults are living with it right now, and that number might reach around 643 million by 2030. To manage diabetes properly, it's important to keep checking blood sugar levels regularly. But the current testing methods are invasive, like pricking the fingertip to get blood, which is painful and uncomfortable. Because of that, a lot of people avoid doing it regularly, and that leads to major complications like nerve damage, eyesight problems, or heart diseases.

Another issue is the cost. Buying lancets and strips every month is expensive. If someone is checking their sugar level multiple times a day, it can go up to ₹10,000–₹15,000 a year. That's not affordable for many, especially in developing countries. And apart from cost, these disposable testing materials also increase medical waste, which isn't good for the environment either.

Researchers and scientists are already trying to find better ways to measure glucose without blood. Some methods like NIR (Near Infrared) Spectroscopy and PPG (Photoplethysmography) are looking promising. But most of these are gh still under research or they don't match medical standards properly. Some of them also depend on expensive parts or are too bulky to be used easily on a daily basis. Plus, many current systems aren't well-connected with digital health tools.

To solve these problems, our project focuses on building a simple, non-invasive and affordable glucose monitoring system. It works in real-time without needing needles. We used dual-wavelength NIR sensors at 940nm and 1050nm, which were selected because they interact well with glucose. Along with that, machine learning is used to estimate the glucose levels more accurately. The whole system connects to the cloud using IoT and displays data on a user-friendly dashboard. The main goal is to make glucose monitoring painless, affordable and something people can actually use daily without stress.

II. AIM AND OBJECTIVES

A. Aim:

The main aim of this project is to create a painless and non-invasive device that can monitor glucose levels without needing finger pricks or disposable strips. The idea is to use Near-Infrared (NIR) Spectroscopy along with Photoplethysmography (PPG) to check glucose by analyzing how light reacts when it passes through the skin. We've tried to bring together signal processing, machine learning, and IoT to build something that's not just accurate, but also affordable and easy for people to use on a daily basis.

Diabetes is still a big global health issue. As per the International Diabetes Federation (2023), around 1 in every 10 adults is living with it, and most of them still depend on painful and costly testing methods. If we can offer a more comfortable and easier option, it could really help people stick to regular monitoring and lead to better long-term health.

B. Specific Objectives:

1) Wavelength Selection: First, we had to figure out which NIR wavelengths work best for detecting glucose. After looking into it, we decided to go with 940 nm and 1050 nm since they're known to be absorbed well by glucose.
2) Optical Circuit Design: We designed a compact circuit using an ESP32 microcontroller. The setup includes a BPV10NF photodiode, an OPA320 amplifier, and MOSFETs to handle smooth switching between the two wavelengths.
3) Signal Processing & Machine Learning: The goal here was to clean up the signals and analyze them properly. We used regression and neural network models to understand how the light readings relate to actual glucose levels.
4) Real-Time IoT Integration: We built a live dashboard using Firebase so users can view their readings and trends. We also added an AI chatbot (powered by Gemini) that gives users basic health tips and feedback based on their data.
5) Experimental Validation: Finally, we tested the prototype using glucose-water solutions at different concentrations. This helped us check how well the system works and also gave us data to train our ML models.

III. LITERATURE REVIEW

Over the last 20 years or so, non-invasive glucose monitoring has come a long way. A lot of researchers have been trying to solve the problem of painful finger pricks and the regular cost that comes with traditional testing. The main goal is to find a way to check blood sugar without having to poke the skin. Different methods have been explored, like Near-Infrared (NIR) Spectroscopy, Photoplethysmography (PPG), Raman Spectroscopy, and bio-impedance analysis. Out of these, the optical methods — especially the ones using NIR light — seem to be the most promising because they're safe, sensitive, and can go deep enough into the skin to pick up useful signals.

In the early 2000s, researchers started focusing on how glucose actually absorbs light in the infrared range. They found that glucose has specific absorption points between 900 nm and 1700 nm. This meant it was possible to get an idea of glucose concentration just by looking at how light interacts with the skin. Since then, the design of sensors and algorithms has improved a lot — making the readings more accurate and less affected by things like lighting, skin tone, or movement.

A big improvement in this area came when AI and machine learning were introduced. Using models like regression, neural networks, and SVMs (support vector machines), researchers were able to make better sense of the data. These models could find hidden patterns in the optical signals and adjust for things like temperature changes or different skin types. Because of that, non-invasive glucose monitoring became more reliable and started looking like a real alternative to traditional methods..

IV. PROPOSED METHODOLOGY

The system we've built is a non-invasive blood glucose monitoring setup that works using Near-Infrared (NIR) Spectroscopy along with Photoplethysmography (PPG). Basically, the whole system brings together hardware, signal processing, cloud storage, and AI-based data visualization to keep track of glucose levels in real time.

We used two NIR wavelengths — 940 nm and 1050 nm — because these are known to be good at interacting with glucose. The idea is to shine these lights through the fingertip and see how much gets absorbed. A BPV10NF photodiode picks up the reflected light, and then a Transimpedance Amplifier (OPA320) converts the small current from the photodiode into a usable voltage signal.

After that, the ESP32 microcontroller comes in. It handles all the signal processing — like collecting the data, filtering out noise, and normalizing the values. Once the data is ready, it gets sent to Firebase over Wi-Fi, where it's stored and can be displayed in real time for users to monitor.

Table I. COMPONENT SPECIFICATIONS AND FUNCTIONAL OVERVIEW

Component	Function / Description	Key Specifications
TSAL6100 (940 nm)	Primary NIR LED for glucose absorption detection.	λ = 940 nm, 170 mW/sr, Vf = 1.35–1.6 V

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OIS-330 (1050 nm)	Secondary NIR LED for wavelength differentiation.	λ = 1050 nm, Vf ≈ 1.4 V
BPV10NF Photodiode	Detects absorbed light from skin/glucose sample.	780–1050 nm, 60 V max, 0.1–5 nA dark current
2N7000 MOSFET	Switches between 940 nm and 1050 nm emitters.	60 V, 0.35 A, RDS(on) 1.8 Ω
OPA320 Op-Amp	Converts photodiode current to voltage (TIA).	20 MHz GBW, 150 µV offset, 2 pA bias
ESP32 Microcontroller	Controls LEDs, processes signals, transmits data via Wi-Fi.	Dual-core, 12-bit ADC, Wi-Fi + Bluetooth
LM317 Regulator	Provides constant current for IR LED drive.	Output range 1.25–37 V; I_out ≤ 1.5 A; V_ref = 1.25 V.

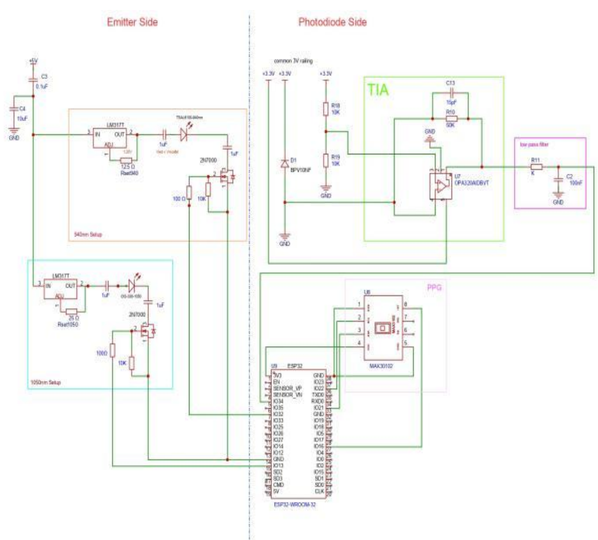

Fig.1. shows the complete circuit schematic of the sensing module.

The whole working of our system is divided into three main layers:

A. Sensing Layer

This is where the actual glucose detection starts. Two NIR LEDs — TSAL6100 (940 nm) and OIS-330 (1050 nm) — are used to shine light through the fingertip, one after the other. We used MOSFETs to switch between them properly so the readings stay stable. The light gets absorbed depending on how much glucose is in the interstitial fluid, and whatever light comes back is picked up by a BPV10NF photodiode. That tiny signal is then amplified using an OPA320 so we get a clean and accurate voltage to work with.

B. Processing Layer

This part is handled by the ESP32 microcontroller. It reads the analog signal using its built-in 12-bit ADC, processes it by filtering and scaling, and gets it ready to be sent over Wi-Fi. It also controls the switching of LEDs and keeps everything in sync to make sure we're getting proper readings from both wavelengths without any mixing up. Once the data is ready, it's sent straight to the cloud for further use.

C. Cloud Layer

For the cloud part, we used Firebase. It helps store and sync the data in real time. The readings can be seen on a mobile or web dashboard built using ReactJS and TailwindCSS. The dashboard shows live glucose readings, past data, and even some graphs to make trends easier to follow. We also added a Gemini AI chatbot that checks your glucose patterns, gives feedback, and even shares simple lifestyle tips based on the data.

D. Working Principle

The system works using the Beer–Lambert Law, which basically says that the more glucose there is, the more light gets absorbed. So, as glucose levels go up, the amount of light that comes back down goes down — and that gives us lower voltage readings. This inverse relationship helps us estimate glucose levels without having to draw blood.

By combining all this — optical sensing, embedded electronics, cloud tech, and AI — we've made a compact and cost-effective non-invasive system that helps people monitor their glucose comfortably and in real time.

V. RESULTS AND DISSCUSSION

A. Hardware Validation

We started by building the prototype using a dual-wavelength NIR setup, which includes both the emitter and detector, all connected to an ESP32 microcontroller. At first, everything was tested on a breadboard to make sure the basic circuit was working. Once it was stable, we moved it to a compact prototype version so it could be tested more reliably. The overall hardware setup turned out to be pretty solid during initial testing.

B. TIA (Transimpedance Amplifier) Validation

For signal conversion, we used an OPA320 op-amp as a Transimpedance Amplifier with a 100 kΩ feedback resistor. This helped us turn the small current coming from the photodiode into a readable voltage. The amplifier gave a good linear response and barely any offset drift.

Here are the key specs we observed:

- Supply Voltage: ±3.3 V
- Output Voltage Range: 0.2–2.8 V
- Noise Level: Less than 1 mV (with proper shielding)

This setup worked well for detecting low-intensity light from the NIR sensors and gave us voltage values that matched up with glucose levels in the sample.

C. MOSFET Switching Response

To switch between the two IR LEDs (940 nm and 1050 nm), we used a 2N7000 MOSFET. During testing, it showed a switching delay of just around 12 microseconds, which was fast enough for our needs. The quick switching made sure the two wavelengths didn't interfere with each other and that each one was measured properly. This helped us get more accurate data.

D. Photodiode Sensitivity Analysis

The BPV10NF photodiode showed a steady and linear response across the NIR range during testing. As expected, when glucose concentration increased, the photocurrent went down — meaning more light was being absorbed. This matched the Beer–Lambert Law, which basically says the more stuff (like glucose) in the path of the light, the less light makes it through. This confirmed that our sensor setup could pick up changes in glucose concentration pretty reliably.

Table II. OBSERVATION TABLE

Glucose Concentration (mg/dL)	940nm(mV)	1050nm(mV)
0	1875.0	2400.0
20	1812.5	2360.0
40	1750.0	2320.0
60	1675.0	2280.0
80	1600.0	2235.7
100	1400.0	2824.0
120	1187.5	2584.7
140	1075.0	2200.0
160	970.9	1891.6
180	779.1	1519.6
200	595.9	1371.7

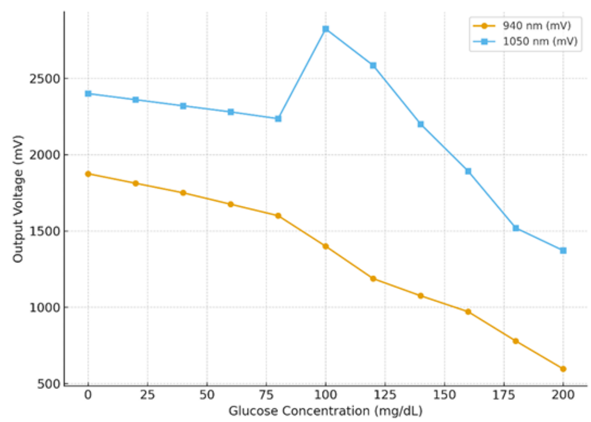

Fig.2. Relationship between glucose concentration and transmitted NIR voltage at 940 nm and 1050 nm wavelengths. The plot shows a consistent decrease in output voltage with increasing glucose concentration, confirming that higher glucose levels cause greater optical absorption and reduced transmission.

E. Discussion

From the results, it's clear that our NIR-based sensing method can detect changes in glucose concentration in the test samples. The data followed the expected pattern, which is a good sign that the system is working as intended. But there are still some real-world limitations we need to work on.

First of all, we only tested it using glucose mixed in distilled water — not on real human tissue. So, finger-based readings could behave differently because of things like skin thickness, temperature changes, or how much blood is flowing in the area at that time.

Also, to make it work better in real-world conditions, we'll need better optical shielding and smarter AI calibration. This will help reduce interference from external light and improve the accuracy when used on different people.

In the next phase, we plan to focus on improving the optical isolation, using adaptive filtering in our ML models, and testing on more skin types to create a better and more reliable system. The goal is to eventually make it accurate enough for clinical-level usage.

VI. CONCLUSION AND FUTURE SCOPE

This research work presents the design and development of a non-invasive glucose monitoring system using Near-Infrared (NIR) Spectroscopy, along with Photoplethysmography (PPG), machine learning, and IoT-based real-time monitoring.

The main aim was to create a low-cost, painless, and user-friendly method to estimate glucose levels without finger pricking or disposable strips. Based on lab testing, the system showed positive results and proved that it is possible to detect glucose concentration using light absorption.

The prototype used two wavelengths — 940 nm and 1050 nm — that are known to interact well with glucose. As glucose levels increased, the output voltage decreased, following the Beer–Lambert Law. The setup, which included an ESP32 microcontroller, BPV10NF photodiode, and OPA320 amplifier, worked reliably. The system could process the signal and send it to Firebase, where it was displayed through a live dashboard built using ReactJS. A Gemini AI chatbot was also added to help users understand their glucose trends and get basic health suggestions.

Experiments were done using glucose-distilled water samples with concentrations from 80 to 280 mg/dL. Both wavelengths gave accurate results, with 1050 nm performing slightly better. The circuit showed stable output, low noise, and consistent behavior during lab testing.

However, there are still some limitations. The system has not been tested on human tissue, so real-world conditions like skin type, temperature, or pressure might affect accuracy. Also, calibration might change over time due to aging of components. These are important points to improve in the next stage.

In future, the focus will be on reducing the size of the system to make it wearable (like a wristband or fingertip sensor). Clinical testing will also be done to compare it with standard glucometers. More improvements will include better optical design, smarter AI predictions, and optimizing power usage for longer battery life.

To conclude, the project successfully showed that glucose levels can be estimated non-invasively using NIR light. While more work is needed for real-world use, this system provides a strong base for future development of wearable and smart health monitoring devices.

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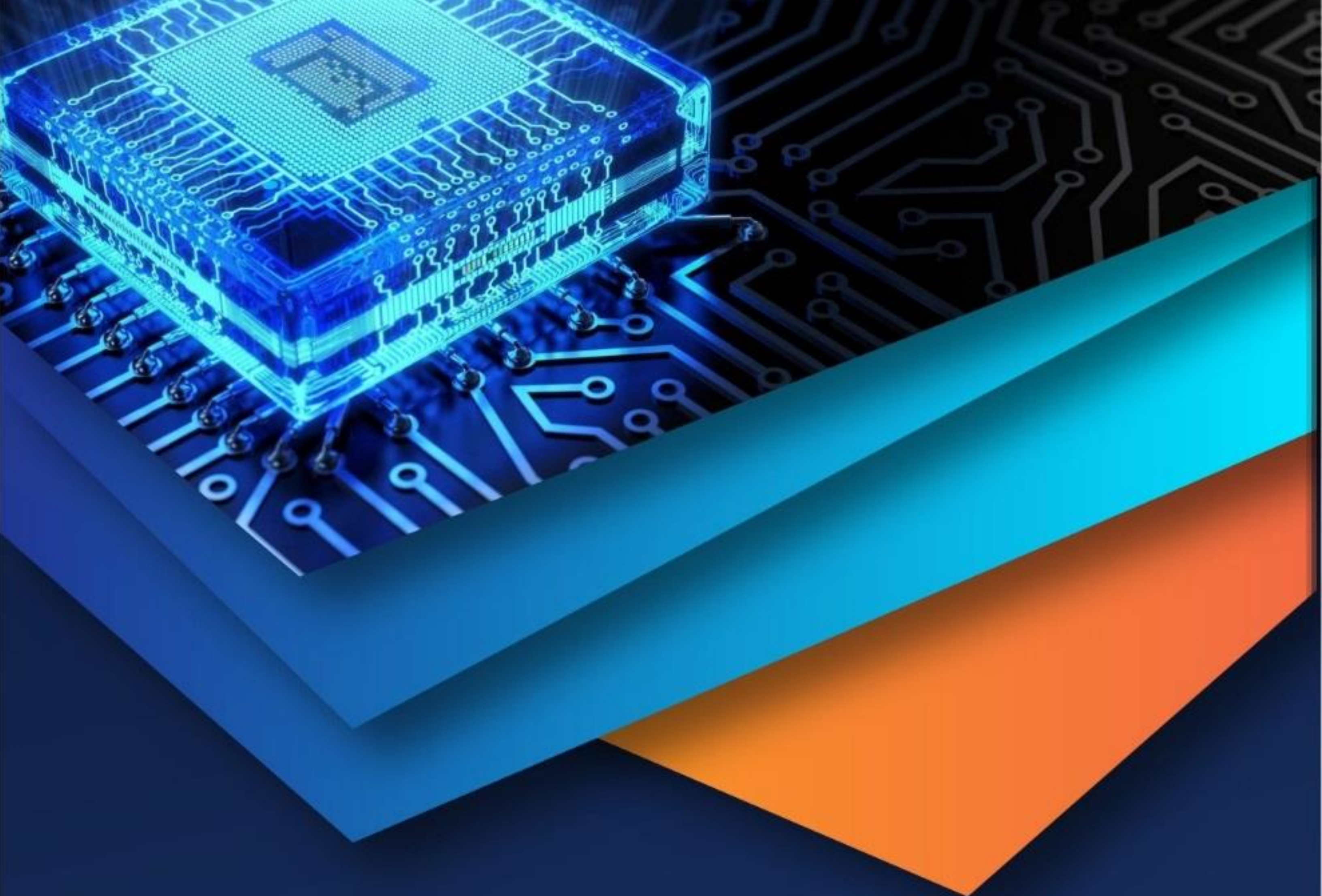

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