Non-Invasive Glucose Estimation Using Multi-Wavelength Optical Sensors

Organization:
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Project Overview:

The project aims to develop a simplified, cost-effective, and non-invasive prototype for blood glucose estimation. The approach uses Near-Infrared (NIR) spectroscopy principles by analyzing light absorption characteristics of glucose at specific wavelengths using IR LED, BPW34 photodiodes, LM358P op-amps, and an ESP32 microcontroller.

Abstract :

This project explores the development of a non-invasive glucose estimation system based on near-infrared (NIR) spectroscopy principles. The prototype uses IR (940 nm) LED as light sources and BPW34 photodiodes as detectors to capture reflected light intensity from human tissue. The analog signals are amplified by LM358 operational amplifiers and digitized via an ESP32 microcontroller for real-time data acquisition. Data is transmitted to Firebase and analyzed using cloud-based machine learning pipelines. While the initial implementation demonstrated basic sensing capabilities and connectivity, challenges such as low sensitivity and ambient light interference limited measurement accuracy. The results provide insights into the feasibility of low-cost optical glucose monitoring and highlight directions for further refinement, including improved hardware calibration and higher-sensitivity sensors.

1. Introduction :

Diabetes management relies heavily on frequent monitoring of blood glucose levels. Conventional methods involve invasive finger-prick sampling, which can be painful and discourages compliance. Non-invasive optical techniques offer an alternative by exploiting the absorption characteristics of glucose molecules in specific wavelength ranges. This project aims to develop a simplified, low-cost, non-invasive glucose monitoring prototype leveraging NIR spectroscopy, with an emphasis on real-time data acquisition and cloud connectivity.

2. Objectives :

To design a non-invasive glucose estimation system using IR LED.

To develop signal acquisition and amplification circuits for capturing reflected light intensity.

To integrate the sensing hardware with an ESP32 microcontroller for analog-to-digital conversion.

To implement real-time data logging and visualization using Firebase.Integrate with Firebase for real-time data storage and visualization.Use machine learning techniques (Google Colab) to predict glucose levels.

3. Literature Review :

Prior research has demonstrated that glucose exhibits absorption peaks in the near-infrared region (700–2500 nm). Systems using multi-wavelength optical sensors can detect variations in transmitted or reflected light to estimate glucose concentrations. For example, Darwich et al. (IRJET) presented an IR-based non-invasive measurement approach using specific wavelengths and regression models. Hina and Saadeh reviewed various non-invasive NIR systems, highlighting challenges such as sensor sensitivity and ambient noise. These studies underscore the need for precise calibration and optimized sensor arrangements.

4. Methodology :

4.1 System Overview

- The developed prototype consists of:
- Wavelength light source (IR LED 940nm).
- BPW34 photodiode detectors.
- LM358P operational amplifiers for signal conditioning.
- ESP32 microcontroller for data acquisition and Wi-Fi connectivity.
- Firebase Realtime Database for data storage.
- Google Colab for data analysis and machine learning prediction.

4.2 Optical Sensing Principle

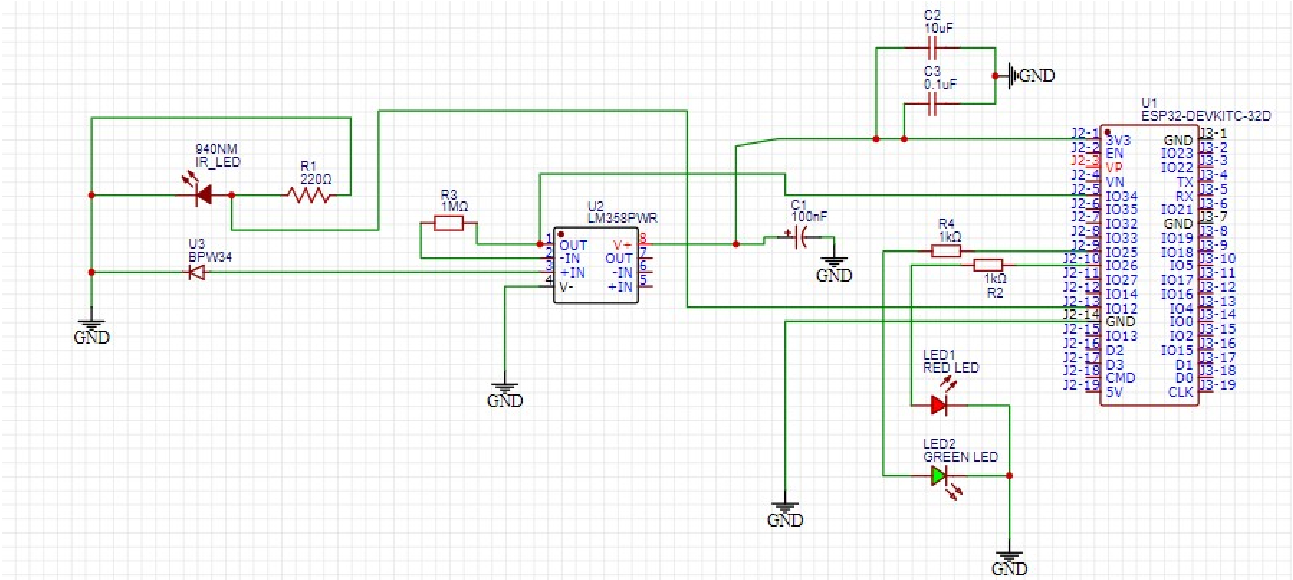
Glucose absorbs IR radiation at specific wavelengths. When the LED illuminate a fingertip, part of the light is absorbed, and part is reflected back to the photodiode. The detected voltage correlates to the absorption and, indirectly, to glucose concentration.

5. Hardware Design :

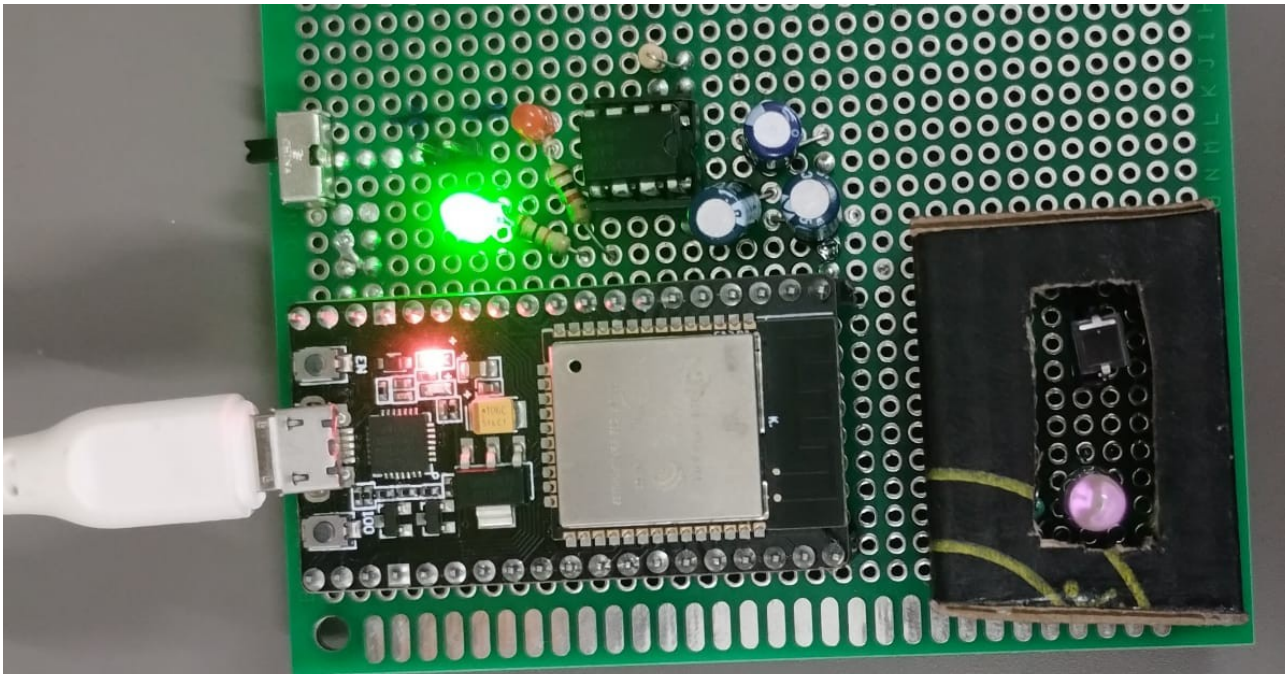
5.1 Components:

Component	Specification
IR LED	940nm wavelength
Red and Green Leds	Green LED blinks for normal glucose levels and Red LED blinks for high glucose levels
Photodiode	BPW34
Operational Amplifier	LM358P
Microcontroller	ESP32 Dev Board
Capacitors	100nF and 10 µF for filtering
Resistors	220 Ω current limiting, 1MΩ feedback resistors
Power Supply	3.3V regulated

5.2 Circuit Design:



5.3 The Hardware setup:



LED Circuit:

GPIO pin → 220 Ω resistor → LED → GND

Photodiode Amplification:
Photodiode anode connected to LM358P input.
Feedback resistor (1 MΩ) added for voltage gain.
Parallel capacitors filter high-frequency noise.

6. Firmware Development :

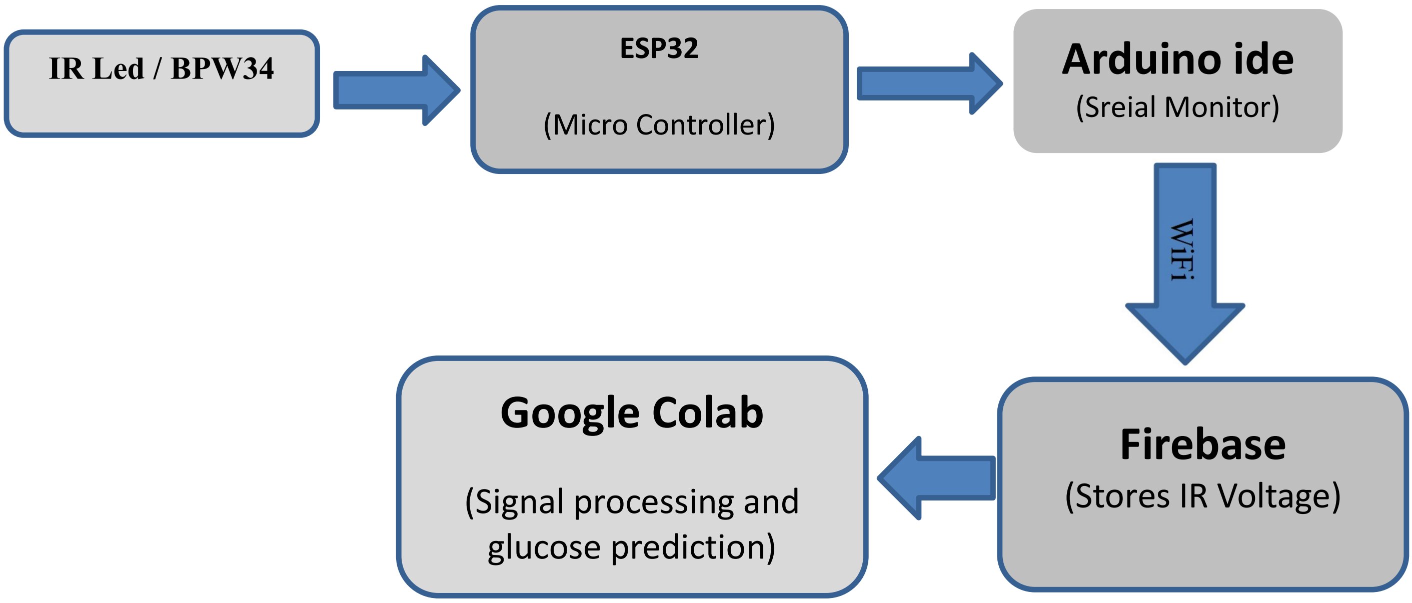
Arduino IDE used for firmware.
LEDs blink alternately with delays to separate readings.
ESP32 ADC reads amplified signals from the photodiode.
Serial Monitor displays voltage readings.
FirebaseESP32 library used to push data to Firebase.
Machine learning techiques (Google Colab) to predict glucose levels.

Conditional statements trigger LED alerts:

Green LED: Normal glucose range (0.25–1.80 V)
Red LED: High glucose (>1.80 V)

7. Data Flow and System Architecture :

Block Diagram:



7. Observations and Challenges :

7.1 Signal Stability

Minimal variation observed between finger placement and removal.
Ambient light interference contributed significant noise.

7.2 Sensitivity

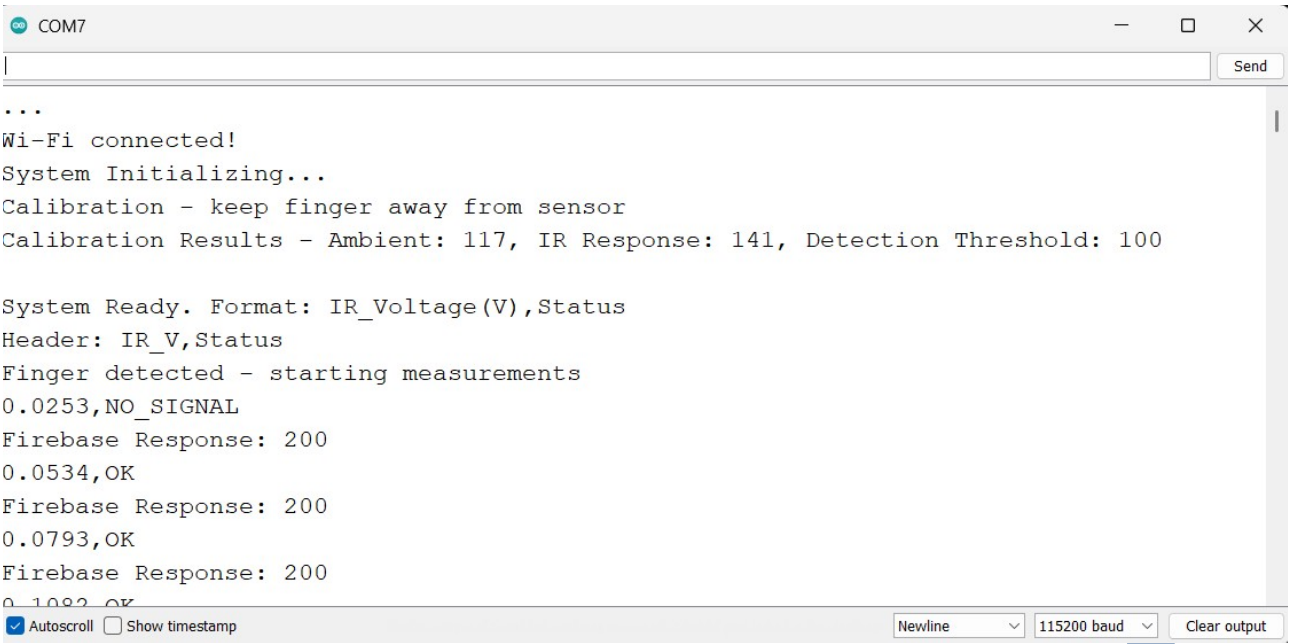
BPW34 photodiode and LM358P op-amp combination showed low sensitivity to glucose-induced absorption changes.
Component limitations hindered the detection of meaningful signal differences between IR wavelength.

7.3 Connectivity

Firebase integration encountered initialization errors, resolved by updating library versions.
Wi-Fi transmission tested successfully after debugging.
Google Colab connected to firebase to monitor real time measurements.

8. Results :

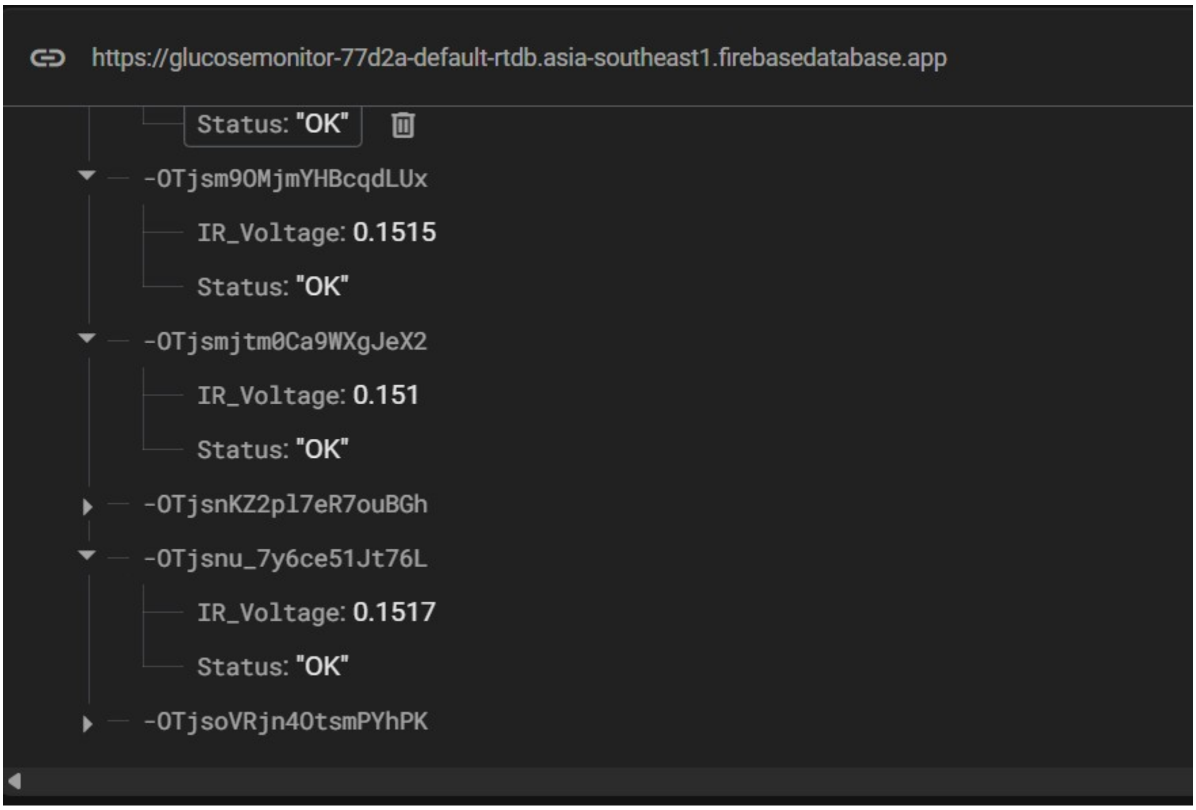
Arduino ide:



IR Sensor Initialization and Calibration Summary:

The system initializes and performs calibration to establish a baseline IR level without any object (ambient: 117). When a finger is placed, the IR response rises to 141. A detection threshold of 100 is set to reliably distinguish between ambient noise and actual finger presence. During operation, any IR reading above this threshold indicates that a finger is detected for measurement.

Firebase:



Google Colab :

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••• IR: 0.1392 → Glucose: 67.38 mg/dL

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    IR: 0.1383 → Glucose: 67.37 mg/dL

    IR: 0.1310 → Glucose: 67.22 mg/dL

    IR: 0.1354 → Glucose: 67.31 mg/dL

    IR: 0.1310 → Glucose: 67.22 mg/dL

    IR: 0.1357 → Glucose: 67.31 mg/dL

    IR: 0.1404 → Glucose: 67.41 mg/dL
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Real-time voltage readings acquired and displayed via Serial Monitor.
Firebase data logging functional.
Visual indicators for normal and high glucose simulated.
Observed limitations in measurement accuracy due to hardware constraints and environmental factors.

8. Discussion :

This prototype validates the feasibility of using affordable components to build a basic optical glucose monitoring system. However, the current setup does not yield clinically reliable results, primarily due to:

- Low photodiode sensitivity.
- Limited wavelength penetration depth.

Transitioning to specialized NIR sources (e.g., 1450 nm) and using transmission-mode sensing can enhance accuracy. Additionally, applying regression models to calibrated datasets can improve prediction capability.

Capture reflected light intensity and process it using microcontrollers and cloud services:

Optical Sensing:
- Using of multi-wavelength light sources to illuminate the skin.
- Detect the intensity of reflected light using light sensor.

Glucose Absorption Characteristics:
- Glucose absorbs light at specific wavelengths.
- By analyzing the light attenuation patterns, we can estimate glucose concentration.

Signal Processing:
Raw sensor data is filtered and normalized to reduce noise and standardize values. A calibrated regression or ML model then maps this processed data to estimate glucose levels.

9. Conclusion :

A functional non-invasive glucose estimation system was successfully designed, assembled, and tested. While the system achieved basic signal acquisition, cloud connectivity, and data visualization, limitations in sensitivity and signal stability affected measurement accuracy. These results highlight both the potential and the challenges of low-cost optical glucose sensing. Overall, the work establishes a strong foundation for further development toward a more accurate, reliable, and user-friendly device.

Future work should focus on:

- Upgrading to higher-sensitivity photodiodes.
- Incorporating additional NIR wavelengths.

Future efforts will focus on improving sensor precision and reducing ambient interference. Key priorities include upgrading to higher-sensitivity NIR components, enhancing circuit shielding, refining machine learning calibration models, and testing with reference glucose samples. Additionally, the system will be miniaturized and enclosed for better stability, with the long-term goal of integrating it into a wearable, real-time monitoring solution.

References :

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