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Non-Invasive Blood Glucose Monitor

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Abstract— **The growing need for affordable healthcare solutions has made it possible to create low-cost, portable, and non-invasive monitoring devices. This work introduces a non-invasive health monitoring device based on the ESP32-S3 microcontroller that can measure important vital parameters such as blood oxygen saturation (SpO_2), heart rate, and estimated blood glucose level. The system incorporates the MAX30102 SpO_2 and heart rate photoplethysmography (PPG) sensor, and a 940nm near-infrared emitter-receiver module for optical glucose measurement. The data is presented in real time on a TFT display to provide simplicity of use for both users and non-users. The system is scalable, and the ESP32 wireless capabilities are utilized for possible IoT-based remote health monitoring. With its friendly user interface and portable size, the system promises home care, rural health, and telemedicine applications and presents an appropriate preventive healthcare instrument.**

Keywords—Non-Invasive monitoring, blood glucose estimation, ESP32-S3, MAX30102, photoplethysmography, SpO_2, heart rate, near-infrared sensor, TFT display, wearable health devices, telemedicine, IoT healthcare.

I. INTRODUCTION

Since medical technologies are developing rapidly and cost-effective and preventive medical solutions are on the rise, classical diagnosis methods are being replaced or complemented by novel, non-invasive, innovative methods. Monitoring of important health parameters such as blood glucose, heart rate, and blood oxygen saturation (SpO_2) over the long term is required in diseases such as diabetes, cardiac and respiratory ailments. Classical methods of blood glucose monitoring, for example, are painful and invasive, expensive, and user-intensive for long-term monitoring.

In an attempt to break these constraints, this study aims to design an embedded system-based real-time, non-invasive health monitoring system through optical biosensing. The system is designed around the ESP32-S3 microcontroller with the use of common biosensors like the MAX30102 for SpO_2 and heart rate monitoring through photoplethysmography (PPG) and a 940nm near-infrared (NIR) sensor setup for blood glucose estimation through light absorption properties.

Portable, inexpensive, and user-friendly in design, the device displays real-time physiological information on TFT screen, allowing technical and non-technical users to monitor on a daily basis. Inclusion of in-built wireless capabilities such as Wi-Fi and Bluetooth further offers scope for IoT-based remote health monitoring, allowing integration with mobile applications and cloud platforms for convenient access and data management.

In the longer term, systems such as this research envisions are able to revolutionize how individuals manage long-term conditions with real-time, bespoke health monitoring without clinical supervision. With further advancements in wearable technology, sensor fusion, artificial intelligence, and cloud computing can enable more precise diagnosis and predictive health models. This research is an enabler to the vision and to the worldwide movement towards smarter, more inclusive, and technology-driven health solutions.

II. SYSTEM DESIGN AND METHODOLOGY

1. SYSTEM DESIGN AND SETUP

The system developed is a battery-powered, non-invasive health monitor capable of measuring blood oxygen saturation (SpO_2), heart rate, and estimated blood glucose level using optical biosensing and onboard processing. The system's center is the ESP32-S3 microcontroller, which was chosen considering its processing capability, onboard Wi-Fi/Bluetooth modules, and interfacing capability of peripherals using I^2C, SPI, and ADC channels.

Hardware Design

The hardware components are selected to be precise, power-efficient, and simple to implement:

• ESP32-S3 Microcontroller: This is the CPU, which is responsible for collecting sensor readings, signal processing, display management, and potential wireless communication.

• MAX30102 Sensor: Employed for SpO_2 and heart rate detection through photoplethysmography (PPG) using infrared and red LEDs and a photodetector. It is connected to the ESP32 using I^2C.

•940nm Infrared LED and BPV22NF Photodiode: Applied in non-invasive optical blood glucose monitoring with NIR absorption of light. Output of the photodiode is fed into ESP32's ADC to convert voltage to glucose.

• 2.4" TFT Display (ILI9341 Driver): Provides real-time visual feedback to the user. The display is interfaced with the ESP32 via SPI and is programmed to show real-time readings of SpO_2, heart rate, and glucose level.

• Power Supply: The microcontroller and all peripherals are powered by a 5V regulated power supply.

Software Design

The software stack is built over MicroPython, hence the system is light and easy to deploy:

• Sensor Libraries: Adafruit and SparkFun libraries are utilized to interact with the ILI9341 display screen and MAX30102 to facilitate steady data display and acquisition.

•Signal Processing: Pulse waveforms are processed internally by the MAX30102 sensor and ratio-of-ratios algorithms are utilized to compute SpO_2 and heart rate. Analog photodiode glucose sense voltage is converted linearly to the estimated blood glucose.

• User Interface (UI): A graphical UI is designed specially to display labelled regions on the TFT screen for each measurement of health. Values only update to reduce power consumption and flicker.

Fig.1. The system mounted upon the acrylic stand

Fig .2. The mounting of the sensors and the ESP32-S3

2. METHODOLOGY

Sensor Integration

- MAX30102 connected to ESP32-S3 via integrated I^2C for SpO_2 and heart rate measurement.
- 940nm IR LED and BPV22NF photodiode connected to an analog pin for glucose sensing using near-infrared light.

Signal Acquisition

- **Heart Rate & SpO_2**:
  MAX30102 detects IR and RED light absorption.
  Uses pulse detection and ratio-of-ratios method to estimate SpO_2.
- **Glucose**:
  Photodiode output read through ESP32's ADC.
  Voltage values are mapped to glucose **levels** using a calibrated linear formula

$$\text{Voltage (V)} = \frac{\text{ADC\_value} \times 3.3}{4095}$$

$$\text{Millivolts (mV)} = \text{Voltage} \times 1000$$

$$\text{Glucose (mg/dL)} = -0.03 \times \text{mV} + 221.45$$

Data Processing

- Raw ADC values are converted to voltage.
- MAX30102 outputs BPM and SpO_2 using internal processing and libraries.

Display Output

- TFT Display (ILI9341) via **SPI** shows real-time data:
  Blood Glucose (mg/dL)
  Heart Rate (BPM)
  SpO_2 (%)
- UI elements like labels and boxes are drawn using **Adafruit_ILI9341** library.

Loop Execution

- Sensors read periodically.

- Display is refreshed **only when values change** to improve performance.

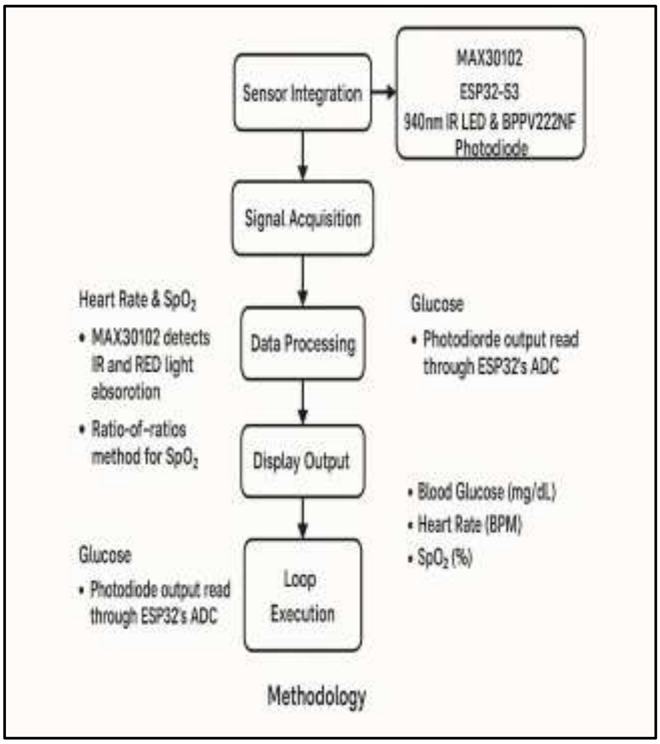

Fig.3. Flow chart of Non-Invasive Glucose Monitoring

III. IMPLEMENTATION

The implementation of the non-invasive health monitoring system is based on the integration of hardware and software components to collect, process, and display vital physiological parameters. At the core of the system is the ESP32-S3 microcontroller, which serves as the primary processing unit. It interfaces with two main sensors: the MAX30102 sensor, which is responsible for measuring blood oxygen saturation (SpO_2) and heart rate using infrared and red light through the principle of photoplethysmography, and a 940nm IR LED paired with a BPV22NF photodiode for non-invasive blood glucose estimation based on near-infrared light absorption. The output from these sensors is fed into the ESP32-S3, where raw analog signals are converted into meaningful data using built-in libraries and algorithm.

For user interaction and real-time feedback, a 2.4-inch TFT display (ILI9341) is connected via the SPI protocol to the ESP32. The display presents real-time values of blood glucose, heart rate, and SpO_2 using a custom user interface designed with graphical elements. The software implementation is done using MicroPython in the Thonny IDE, utilizing essential libraries for sensor communication (I^2C, ADC) and display control. To ensure efficiency, the display updates only when there is a change in the sensor readings.

During development, the system underwent calibration, particularly for glucose measurements, by comparing non-invasive photodiode-based readings with standard invasive blood glucose meter results. Multiple tests were conducted to ensure accuracy and reliability, taking into account variables like ambient lighting and hand movement. The final output of the system is a compact, low-power, and user-friendly device capable of monitoring vital signs in real-time, with applications in home care, rural healthcare, and telemedicine.

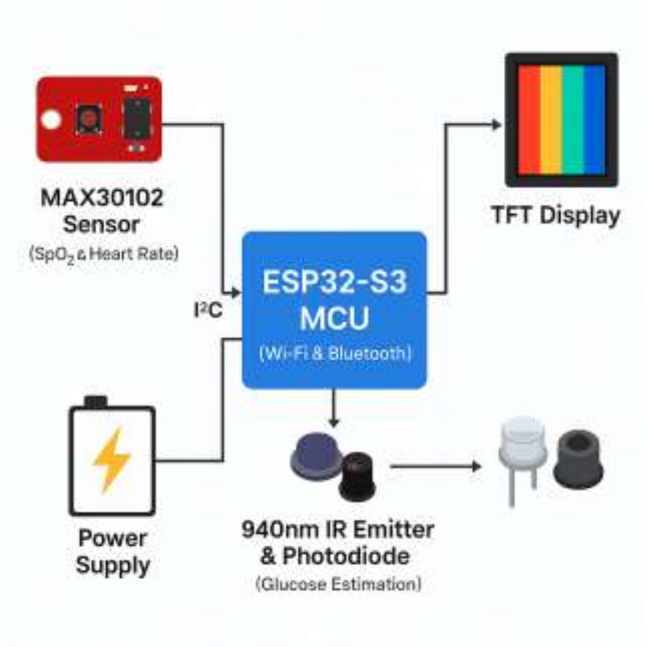

Fig .4. Block Diagram of Non-Invasive Blood Glucose Monitor

Fig.5.Software implementation

IV. RESULTS AND DISCUSSION

The non-invasive health monitoring system was successfully developed and tested using the ESP32-S3 microcontroller, Pulse Oximeter sensor, IR LED, and photodiode. The system was able to measure three primary health indicators: heart rate, blood oxygen saturation (SpO_2), and estimated blood glucose level. During testing, heart rate readings from the Pulse Oximeter sensor closely

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matched those from commercial pulse oximeters, showing deviations within ±5 BPM. Similarly, SpO_2 measurements showed a high degree of accuracy, maintaining readings within ±2% of standard pulse oximeter devices under normal ambient conditions.

For glucose sensing, the photodiode-based analog voltage readings were calibrated using reference values from a commercial invasive glucometer. The resulting glucose values demonstrated a reasonable correlation with invasive methods when the finger was kept steady under the NIR sensor. However, environmental lighting and finger movement slightly affected the photodiode readings, highlighting the importance of consistent sensor positioning and shielding from ambient light. The use of a linear mapping formula provided a basic estimation of glucose concentration, suitable for trend monitoring rather than diagnostic use.

The TFT display effectively presented real-time values of heart rate, SpO_2, and glucose concentration with a clean user interface. The system also implemented a change-detection logic, where the display only updated when new readings differed from previous ones, enhancing responsiveness and reducing unnecessary refreshes. Overall, the results indicate that the developed system is capable of providing non-invasive monitoring of vital parameters, with sufficient accuracy for home or personal health tracking. Further improvements in signal filtering and machine learning-based calibration could enhance glucose estimation accuracy for clinical applications.

Fig.6. Functional Setup of Smart Aquaponics System with Microcontroller-

Based Automation and Sensor Integration and monitoring

Fig.7. Comparison between our Non-Invasive Blood Glucose monitor and Invasive Blood Glucose Monitor

Invasive Glucose Monitor and Pulse Oximeter value			Non-Invasive Glucose Monitor and Pulse Oximeter value		
GLU	BPM	SPO2	GLU	BPM	SPO2
174 mg/dl	102	88.30%	168 mg/dl	105	85.3%
107 mg/dl	111	92.40%	115 mg/dl	102	92.5%
105 mg/dl	98	92.20%	111 mg/dl	92	93.3%
103 mg/dl	92	95.40%	107 mg/dl	94	95.4%
146 mg/dl	105	93.50%	140 mg/dl	112	92.4%
181 mg/dl	99	98.70%	173 mg/dl	105	96.5%
167 mg/dl	105	89.30%	174 mg/dl	114	85.8%
108 mg/dl	115	93.45%	118 mg/dl	112	91.7%
127 mg/dl	124	87.50%	120 mg/dl	113	85.8%
143 mg/dl	103	97.40%	147 mg/dl	94	95.2%

Fig.8. Invasive Glucose Monitor and Pulse Oximeter value v/s Non-Invasive Glucose Monitor and Pulse Oximeter value.

V. CONCLUSION

In this project, a portable non-invasive health monitoring system was successfully designed and implemented using the ESP32-S3 microcontroller. The system integrated multiple sensors, including the Pulse Oximeter for heart rate and SpO_2 measurement, and a IR LED with a photodiode for estimating blood glucose levels. The results obtained demonstrated that the system can effectively measure and display vital health parameters in real-time using a TFT screen. The accuracy of heart rate and SpO_2 readings was comparable to commercial devices, while the glucose readings—though not as precise as invasive methods—showed consistent trends that can support preliminary screening and wellness monitoring.

The device is low-cost, compact, and suitable for use in home-care settings, especially for individuals requiring regular monitoring of blood-related health metrics. Its non-invasive nature improves user comfort and compliance. Although the current implementation provides basic glucose estimation using a linear mapping technique, further improvements involving signal filtering and machine learning algorithms could significantly enhance its clinical relevance. Overall, the project demonstrates the feasibility and potential of wearable, non-invasive health monitoring systems in promoting preventive healthcare and remote patient management.

VI. Future Scope

The non-invasive health monitoring system developed in this project lays the groundwork for several future enhancements and applications. One of the most promising directions is the integration of advanced signal processing and machine learning algorithms to improve the accuracy of blood glucose estimation, enabling more reliable trend detection and possibly clinical-grade measurements. In addition, incorporating temperature and blood pressure sensors would further expand the system's capabilities, making it a more comprehensive health monitoring device.

From a connectivity standpoint, enabling Wi-Fi or Bluetooth features of the ESP32-S3 would allow real-time data transmission to cloud platforms or mobile applications. This would facilitate remote monitoring by healthcare providers and family members, especially useful in telemedicine and elderly care. Furthermore, developing a compact and wearable form factor—such as a wristband or patch—would increase user convenience and encourage continuous usage. Battery optimization, waterproofing, and integration with health tracking platforms like Google Fit or Apple Health are also viable improvements.

Lastly, clinical validation through trials and collaboration with medical institutions would be essential for moving toward FDA or similar regulatory certifications. This could eventually make the device suitable for widespread use in both preventive and diagnostic healthcare settings.

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