

Smart Real-Time Health Monitoring Prototype Device

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Abstract

This paper presents the design and implementation of a smart real-time health monitoring system using the ESP32 microcontroller for continuous remote monitoring of physiological parameters. The system integrates AD8232 for ECG acquisition and MAX30102 for heart rate and SpO₂ measurement. The ESP32 performs data acquisition, signal processing, and Wi-Fi communication, while digital filtering and peak detection techniques are applied to improve signal quality and extract heart rate. Sensor validation mechanisms such as lead-off and finger detection enhance measurement reliability. The processed data is transmitted to the Blynk platform for real-time visualization through a mobile interface. Experimental results demonstrate stable performance under controlled conditions, highlighting the system as a low-cost and scalable solution for IoT-based healthcare monitoring.

Keywords- ESP32, ECG, SpO₂, IoT, Health Monitoring

1. Introduction

Healthcare monitoring systems have evolved significantly with the advancement of IoT and embedded technologies. Traditional monitoring requires hospital visits, whereas modern systems enable continuous and remote tracking of vital signs.

This paper presents a low-cost ESP32-based real-time health monitoring system capable of measuring ECG, heart rate, and SpO₂. The system transmits data wirelessly to a mobile application, allowing real-time visualization and early detection of abnormalities.

The proposed system focuses on accessibility, scalability, and reliability in remote healthcare environments.

2. Related Work

Several recent studies highlight trends and challenges in wearable health monitoring systems integrating AI, multi-sensor frameworks, and ESP32-based IoT platforms:

[1] S. Gupta et al. (2025, RSIS International) discussed machine learning (ML) in wearable medical devices for anomaly detection but pointed out that many ML models rely on cloud processing, causing latency issues. Embedded ML on ESP32 reduces latency and enhances privacy, which this project emphasizes.

[2] Texas Instruments (2025) covered wireless ECG and SpO₂ monitoring using microcontroller modules. They highlighted the challenge of balancing power consumption and sensor accuracy. Our system employs ESP32 and chosen sensors to optimize these aspects effectively.

[3] T. Pardal Caixeiro (2024, ISCTE-IUL Repository) designed a wearable health remote monitoring device focusing mainly on data logging without real-time alerts. Our work builds on this by integrating on-device AI for proactive alert generation.

[4] Z. Wang et al. (2023, PMC) explored AI-based wearable sensors for real-time health monitoring,

noting that many devices lack efficient on-device AI processing and suffer from high cost. Their work stresses improving low-power AI models for affordability. In this project, ESP32 with TinyML is used for low-cost real-time anomaly detection to address this gap.

[5] Lee et al. (2022, *Frontiers in Human Neuroscience*) proposed a multi-sensor framework for remote vital sign monitoring. They reported that complex sensor integration limits ease of use and mass adoption. Our prototype simplifies sensor fusion, prioritizing comfortable continuous wear ability.

[6] Md. Rifat Rahman Akash et al. (2020, *IEEE INBUSH*) developed an IoT-based real-time health monitoring system integrating multiple sensors such as ECG, pulse oximeter, temperature, and blood pressure into a single platform. However, the system operates sensors sequentially and lacks efficient real-time parallel processing. Our system improves this by enabling continuous real-time monitoring using ESP32 with optimized sensor integration and faster data handling.

[7] J. Y. Wu et al. (2023, *Frontiers in Public Health*) proposed a wearable IoT-based health monitoring system for real-time tracking of physiological parameters with cloud connectivity and alert mechanisms. While effective, the system requires additional hardware components and infrastructure, increasing complexity and cost. Our work focuses on a compact and low-cost ESP32-based solution that reduces hardware dependency while maintaining real-time performance.

[8] A. Palamar et al. (2023, *ITTAP*) presented an IoMT-based health monitoring system using ESP32 for real-time data acquisition and cloud-based visualization. Their approach emphasizes scalability and remote access but does not fully address challenges such as data security and long-term deployment reliability. Our system enhances practicality by incorporating efficient processing and reliable communication for consistent real-time monitoring.

3. Proposed Methodology

A. System Architecture

The proposed system is designed as a multi-sensor IoT-based health monitoring device using the ESP32 microcontroller. The system integrates biomedical sensors such as the AD8232 ECG module and MAX30102 pulse oximeter sensor to measure vital parameters including electrocardiogram (ECG), heart rate, and blood oxygen saturation (SpO₂).

The ESP32 serves as the central processing unit due to its dual-core architecture, built-in Wi-Fi capability, and support for multiple communication protocols such as I2C and ADC. The sensors are interfaced with the ESP32 using appropriate communication channels, where AD8232 provides analog ECG signals and MAX30102 communicates via I2C protocol.

The acquired signals are processed in real time using embedded firmware. The processed data is then transmitted wirelessly to the Blynk cloud platform, enabling remote monitoring through a mobile application. This architecture ensures continuous monitoring, efficient data handling, and reliable communication.

B. Workflow Description

The working of the system follows a structured sequence of operations. Initially, the ESP32 microcontroller powers up and initializes all connected sensors. Once initialization is complete, the system establishes a connection with a Wi-Fi network.

After successful connectivity, the ESP32 begins continuous data acquisition. ECG signals are obtained from the AD8232 sensor through analog input pins, while heart rate and SpO₂ values are collected from the MAX30102 sensor via the I2C interface.

The raw signals obtained from the sensors often contain noise and unwanted disturbances. Therefore, signal processing techniques such as filtering and smoothing are applied to improve data quality. Peak detection algorithms are used to extract heart rate values from ECG signals.

The system also performs sensor validation to ensure proper contact. For ECG, lead-off detection pins (LO+ and LO-) are used to verify electrode placement, while MAX30102 ensures finger detection.

If the sensor readings are valid, the processed data is transmitted to the Blynk cloud platform. The mobile

application displays the data in real time using graphical representations such as waveforms and gauges. If connectivity is lost, the system attempts to reconnect automatically.

C. Signal Processing

Signal processing plays a critical role in ensuring accurate physiological measurements. ECG signals are typically weak and susceptible to noise from various sources such as motion artifacts and electrical interference.

To address this, digital filtering techniques such as low-pass filtering and baseline correction are applied. These techniques remove unwanted high-frequency noise and stabilize the signal.

Heart rate is calculated using peak detection algorithms that identify R-peaks in the ECG waveform. The time interval between consecutive peaks is used to compute beats per minute (BPM).

For SpO₂, the MAX30102 sensor uses photoplethysmography (PPG) principles. The ratio of absorption of red and infrared light is used to estimate oxygen saturation levels in the blood.

These processing techniques ensure that the system provides reliable and meaningful health data.

4. Hardware And Firmware Implementation

A. ESP32 Microcontroller

The ESP32 microcontroller is selected as the core component of the system due to its powerful processing capabilities and integrated wireless communication features. It consists of a dual-core processor that allows parallel processing of sensor data and communication tasks.

The ESP32 supports multiple interfaces such as ADC, I2C, SPI, and UART, making it suitable for interfacing with a wide range of sensors. Its built-in Wi-Fi module enables seamless data transmission to cloud platforms without requiring additional hardware.

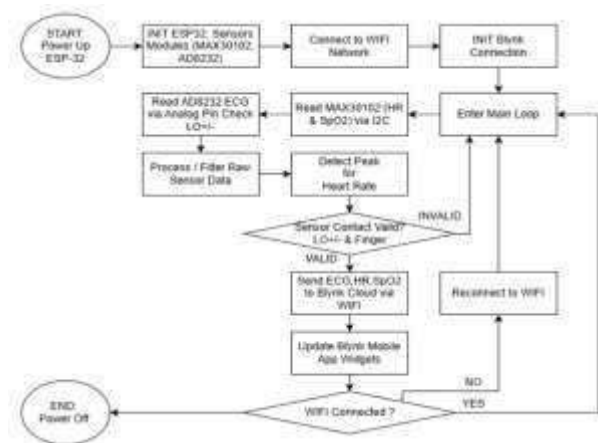


Fig. 1. System Workflow of Health Monitoring Device

B. MAX30102 Sensor

The MAX30102 is a compact and efficient pulse oximeter and heart rate sensor. It operates based on photoplethysmography (PPG), where light is emitted into the skin and the reflected light is measured to determine blood volume changes [10].

The sensor uses red and infrared LEDs to measure oxygen saturation levels. It also includes an integrated photodetector, analog signal processing, and digital conversion, making it highly suitable for wearable applications.

C. AD8232 ECG Sensor

The AD8232 is a specialized analog front-end designed for ECG signal acquisition. It amplifies weak electrical signals generated by the heart and filters out noise to produce a clean ECG waveform [9].

The sensor includes lead-off detection features that ensure proper electrode placement. The output signal is provided as an analog voltage, which is then digitized by the ESP32 for further processing.

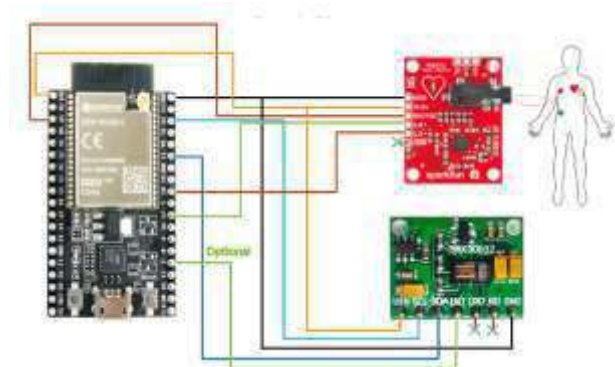


Fig. 2. Block Diagram of the Proposed System

D. Software And Firmware

The firmware for the proposed system is developed using embedded C on the ESP32 platform. The software is responsible for sensor initialization, data acquisition, signal processing, and wireless communication.

At system startup, the ESP32 initializes all peripherals including ADC for ECG acquisition and I2C communication for MAX30102. The firmware continuously reads sensor data in a loop and processes it in real time.

To improve signal quality, filtering algorithms such as moving average and low-pass filters are implemented. These techniques reduce noise and improve accuracy of physiological readings.

The firmware also includes error handling mechanisms. If sensor readings are invalid or if connectivity is lost, the system attempts recovery by reinitializing sensors and reconnecting to Wi-Fi.

Additionally, the system supports real-time data transmission using the Blynk cloud platform. The processed data is sent to the cloud and visualized through a mobile application.

The modular design of the firmware allows easy expansion of the system by integrating additional sensors or features in future.

5. Results and Discussion

The developed system was evaluated under controlled conditions to analyze its performance in monitoring physiological parameters such as heart rate and SpO₂. The observations presented are intended to demonstrate system functionality and comparative behavior with standard reference devices, and are not meant to represent clinically certified measurements.

A. Heart Rate Analysis

The comparison of heart rate readings between the prototype and reference device is presented in Table I, demonstrating the system performance under controlled conditions.

TABLE I
HEART RATE COMPARISON RESULTS

S.No	Age	Clinical (bpm)	Prototype (bpm)	Diff.	Accuracy
1	23	72	74	2	97.29%
2	24	74	77	3	96.10%
3	29	65	66	1	98.48%
4	31	78	76	2	97.43%
5	37	70	76	6	92.11%
6	42	82	84	2	97.61%
7	48	76	79	3	96.20%
8	52	69	73	4	94.52%
9	57	88	91	3	96.70%
10	59	74	78	4	94.87%

The comparison indicates that the prototype produces heart rate readings that are reasonably close to those obtained from a standard reference device. Minor variations are observed due to sensor limitations, environmental factors, and the absence of medical-grade calibration.

Overall, the system demonstrates consistent performance in capturing heart rate trends, making it suitable for real-time monitoring and educational applications.

B. SpO₂ Analysis

The comparison of SpO₂ readings is shown in Table II.

The SpO₂ readings obtained from the prototype show close agreement with those from the reference device under controlled testing conditions. The observed differences are minimal and fall within acceptable limits for non-clinical usage.

TABLE II
SpO₂ COMPARISON RESULTS

S.No	Age	Clinical (%)	Prototype (%)	Diff.	Accuracy
1	23	99	98	1	98.98%
2	24	98	98	0	100%
3	29	98	96	2	97.95%
4	31	97	95	2	97.93%
5	37	96	97	1	98.96%
6	42	97	98	1	98.97%
7	48	96	96	0	100%
8	52	97	96	1	98.96%
9	57	96	95	1	98.95%
10	59	95	95	0	100%

These results indicate that the system is capable of providing stable and reliable oxygen saturation measurements for demonstration and monitoring purposes.

C. System Output Visualization

The processed physiological data is transmitted wirelessly to the Blynk cloud platform and visualized through a mobile application interface. The application provides real-time graphical representation of ECG signals, heart rate, and SpO₂ values, enabling continuous monitoring and user-friendly interaction.



Fig. 3. Real-Time Data Visualization on Blynk Mobile Application

D. Performance Evaluation

The system demonstrated stable performance with minimal delay in data transmission. The Wi-Fi connectivity remained consistent during operation, and automatic reconnection ensured uninterrupted data flow. The integration of multiple sensors with ESP32 proved effective for real-time data acquisition and transmission.

E. Discussion

The proposed system demonstrates the practical implementation of IoT-based healthcare monitoring using embedded systems. By integrating multiple sensors, the system is capable of measuring important physiological parameters in real time.

One of the major strengths of the system is its ability to provide continuous monitoring without requiring hospital visits. This makes it particularly useful for elderly patients and individuals with chronic conditions.

However, certain limitations exist. The accuracy of the system can be affected by motion artifacts and improper sensor placement. ECG signals are highly sensitive to noise, which may require advanced filtering techniques for improvement.

Power consumption is another important consideration for wearable devices. Although ESP32 provides efficient performance, further optimization is required for long-term battery operation.

Despite these challenges, the system provides a strong foundation for future improvements. Integration of machine learning algorithms can enable early detection of abnormalities and predictive healthcare monitoring.

Overall, the system successfully demonstrates a cost-effective and scalable solution for modern healthcare applications.

6. Future Work

Future enhancements include integration of AI-based anomaly detection, battery-powered wearable design, and addition of more physiological sensors.

7. Conclusion

This paper presented an ESP32-based health monitoring system capable of real-time tracking of ECG, heart rate, and SpO₂. The system demonstrates reliable performance, efficient wireless communication, and effective data visualization through a mobile application.

Although the system is not intended for clinical use, it provides a strong foundation for low-cost, scalable, and accessible healthcare monitoring solutions. The proposed design highlights the potential of IoT-based systems in enabling continuous health tracking and improving remote healthcare accessibility.

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