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IoT-Enabled Non-Invasive Blood Pressure and Vital Signs Monitoring System

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Abstract— **The increasing demand for accessible healthcare has spurred development of remote monitoring systems for aging populations and underserved communities. This research proposes an IoT-based vital sign monitoring system to non-invasively track heart rate, body temperature, and blood pressure using cost-effective sensors and microcontrollers. The system leverages ESP32 for real-time data acquisition from wearable sensors, ensuring low power consumption and wireless communication. A novel Pulse Transit Time (PTT)-based algorithm estimates blood pressure non-invasively, eliminating inflatable cuffs. Data is transmitted to a secure cloud platform with intuitive dashboard access for healthcare providers and patients. The system's scalability, energy efficiency, and affordability suit home-based monitoring and resource-constrained deployments. Experimental results demonstrate accuracy comparable to clinical standards, potentially reducing hospital readmissions and enhancing proactive healthcare delivery.**

Index Terms— **IoT, Pulse Transit Time, Blood Pressure Estimation, ESP32, Remote Health Monitoring, Biomedical Sensors.**

I. Introduction

Growing demand for accessible, continuous healthcare has accelerated remote health monitoring system development, especially for aging populations, chronic diseases, and underserved regions. IoT-driven healthcare technologies offer real-time physiological data acquisition, remote supervision, and cloud-based analysis with scalability, low cost, and wireless connectivity.
The global healthcare landscape is experiencing a fundamental transformation from reactive, episodic care models to proactive, continuous health management systems. This paradigm shift is necessitated by the increasing burden of chronic diseases, which affect over 133 million Americans and account for approximately 90% of healthcare expenditures globally. Traditional healthcare delivery models, characterized by intermittent clinical visits and hospital-based monitoring, are inadequate for managing the complex, long-term care requirements of patients with diabetes, cardio- vascular diseases, and respiratory conditions. The COVID-19 pandemic has further accelerated the adoption of remote monitoring technologies, highlighting the critical need for robust, accessible healthcare solutions that can operate in- dependently of physical healthcare infrastructure while maintaining clinical-grade accuracy and reliability.

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Contemporary healthcare challenges are compounded by demographic trends including rapid population aging, physician shortages in rural and underserved areas, and escalating healthcare costs that strain both individual patients and healthcare systems worldwide. Remote health monitoring systems powered by IoT technologies offer a promising solution by enabling continuous physiological surveillance, early detection of health deterioration, and timely intervention before conditions become critical. These systems can significantly reduce hospital readmissions, mini- mize emergency department visits, and empower patients to actively participate in their healthcare management while providing clinicians with comprehensive, real-time data for informed decision-making.

This research presents a compact, non-invasive vital signs monitoring system using Arduino UNO and ESP32 microcontrollers. Arduino UNO connects and operates biomedical sensors for heart rate, temperature, and blood pressure signals, handling capture and preprocessing. ESP32, with Wi-Fi capabilities and display interface, manages wireless transmission and local visualization, communicating with secure cloud servers for real-time health metrics via intuitive dashboards.

The system employs Pulse Transit Time (PTT) for estimating systolic and diastolic blood pressure without traditional cuffs. PTT calculates time intervals between ECG R-peaks and PPG peaks, offering continuous, comfortable, non-invasive monitoring that enhances user experience and enables long-term tracking.

The proposed system delivers reliable, energy-efficient, cost-effective remote health monitoring with modular architecture suitable for home care, rural communities, and resource-limited settings, contributing to proactive, patient- centered healthcare transformation.

II. Literature Review

The application of Internet of Things (IoT) in healthcare has seen rapid advancements, driven by the need for real-time patient monitoring, improved healthcare access, and efficient resource utilization. Numerous studies have proposed IoT-based systems for various health scenarios, yet many face challenges in terms of accuracy, energy efficiency, scalability, and cost. Our proposed system aims to address these gaps using a modular architecture based on Arduino UNO for data acquisition and ESP32 for wireless communication and local display. Additionally, we implement Pulse Transit Time (PTT) estimation for continuous cuffless blood pressure monitoring, a feature absent in many existing systems.

Neyja et al. [1] developed an ECG-based e-health monitoring system leveraging wireless sensor networks. While effective for cardiac monitoring, the system is limited to a single physiological parameter and relies on traditional ECG electrode setups, which may cause discomfort for long-term use. Our system expands functionality by integrating multiple biosensors (heart rate, SpO2, temperature) and introduces non-invasive blood pressure monitoring using PTT, improving usability and physiological coverage.

Abdelgawad et al. [2] presented a wearable system for active and assisted living, focused on elderly care. Although the system offers mobility, it lacks real-time local feedback and depends heavily on cloud infrastructure, which may introduce latency. In contrast, our design uses ESP32's onboard processing and display capabilities to provide imme- diate feedback to users, reducing dependency on remote servers and ensuring functionality even during connectivity issues.

The IReHMo framework by Khoi et al. [3] emphasized modularity and cloud integration for smart regions. However, it assumes robust internet connectivity and incurs significant energy consumption due to continuous cloud com- munication. Our implementation minimizes data transmission by performing local preprocessing and displaying key health metrics on the ESP32's interface, making it suitable for resource-constrained or intermittent connectivity envi- ronments.

Singh [4] discussed broad IoT health monitoring opportunities but highlighted critical challenges including data security, interoperability, and power management. Our system addresses energy efficiency by using low-power com- ponents (ESP32 and Arduino UNO) and secure communication protocols (e.g., HTTPS or MQTT over TLS for cloud uploads). The modular design also ensures interoperability with various sensor types and communication standards.

Valsalan et al. [5] and Tamilselvi et al. [6] implemented basic IoT-based systems with temperature and heart rate sensors. These systems demonstrated feasibility but lacked advanced signal processing or intelligent diagnostics. Our project incorporates real-time PTT-based blood pressure estimation, enhancing the diagnostic capability of the device with minimal additional hardware requirements.

Mdhaffar et al. [7] used LoRaWAN for long-range health data transmission, suitable for rural monitoring applica- tions. However, LoRaWAN's low data rate limits the real-time monitoring of high-resolution physiological signals. Our system balances range and performance using Wi-Fi (via ESP32), which supports

higher bandwidth for real-time data streaming in local and semi-urban environments while maintaining reasonable power consumption.
Kumar and Rajasekaran [8] utilized Raspberry Pi for patient monitoring, providing rich computational resources but at a higher cost and power demand. Our system achieves comparable functionality with significantly lower power consumption and cost, making it ideal for battery-operated deployments and widespread adoption in developing re- gions.
Islam et al. [9] proposed a smart healthcare system with comprehensive cloud-based monitoring capabilities, but the system's complexity increases with sensor node count, potentially leading to scalability issues and increased main- tenance requirements. We mitigate this by using a centralized ESP32 controller for multiple sensors, reducing the communication overhead and simplifying system architecture while maintaining diagnostic accuracy.
Kishore et al. [10] developed an alert system for critical health events that effectively triggers notifications when thresholds are exceeded. However, it only provides reactive alerts and lacks predictive analysis capabilities. Our system supports continuous monitoring and real-time signal processing, which could support predictive diagnostics such as trends in blood pressure variations or oxygen saturation patterns.
Wan et al. [11] introduced a comprehensive wearable IoT system for real-time monitoring but primarily focused on wearability and connectivity aspects. However, it lacked non-invasive methods for blood pressure tracking, requiring separate devices for complete vital sign monitoring. Our PTT-based cuffless estimation method adds this crucial functionality, improving comfort and diagnostic range without adding bulk to the wearable system.
Patil and Pardeshi [12] emphasized the importance of data analytics in IoT healthcare systems, but their imple- mentation was heavily cloud-dependent and did not account for offline operation scenarios. Our approach supports both standalone operation with on-device display and optional cloud integration, ensuring functionality in offline en- vironments and reducing dependency on constant internet connectivity.
Bhandwaldar et al. [13] implemented a multi-node architecture for comprehensive health monitoring, but with limited data fusion or local processing capabilities. In our design, the ESP32 performs initial processing and fusion of sensor data, allowing the system to remain responsive and autonomous while reducing the computational load on cloud servers.
Vedaei et al. [14] and Otoom et al. [15] proposed surveillance-oriented health systems specifically designed for pandemic management and large-scale monitoring. These systems emphasized scalability and population-level mon- itoring but were complex and infrastructure-heavy, requiring significant deployment resources. Our lightweight solu- tion targets individual monitoring, suitable for early symptom tracking in remote or home-based care settings, without needing complex backend systems.
Sam et al. [16] proposed a remote monitoring system specifically designed for rural healthcare delivery, but it focused more on connectivity solutions than on sensor integration or physiological inference capabilities. Our system enhances this approach by including a richer sensor suite and applying physiological modeling (via PTT), improving both monitoring accuracy and clinical decision support capabilities.
In summary, while prior works have laid essential foundations for IoT-based healthcare monitoring, they are often constrained by limited sensing modalities, heavy reliance on cloud services, high power requirements, or lack of predictive capability. Our proposed system addresses these significant challenges by offering a cost-effective, modular, low-power platform capable of real-time, non-invasive monitoring of multiple vital signs, including continuous blood pressure estimation using innovative Pulse Transit Time methodology.

III. Components Used

The prototype uses carefully selected components for capturing, processing, and communicating physiological param- eters:
ESP32: High-performance, low-power microcontroller with integrated Wi-Fi/Bluetooth, serving as central pro- cessing and communication unit for real-time wireless data transmission.
Arduino UNO: ATmega328P-based microcontroller interfacing analog/digital sensors, handling signal acquisition and preprocessing from ECG, temperature, and motion modules.
AD8232 ECG Sensor: Low-power signal conditioning block for ECG measurements, filtering and amplifying heart electrical signals with built-in noise reduction.
MLX90614 Temperature Sensor: Non-contact infrared thermometer providing accurate surface/ambient mea- surements via I2C interface for hygienic monitoring.
MAX30100 Heart Rate/SpO2 Sensor: Integrated pulse oximetry and heart rate monitoring using red/infrared LEDs and photodetector via photoplethysmography.

MPU6050 Motion Sensor: 6-axis tracking device combining gyroscope and accelerometer for fall detection and motion correlation with physiological signals.
LCD Display: 16x2 display with I2C interface for real-time vital parameter visualization, reducing GPIO require- ments.
Buzzer: Audio alert device for immediate abnormal condition feedback, enhancing accessibility for elderly/visually impaired users.

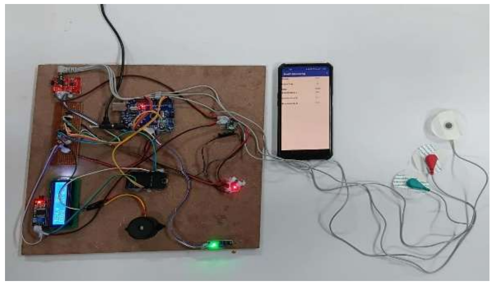


Figure 1: Hardware Implementation Layout

IV. Proposed Methodology

The proposed health monitoring system is designed to continuously acquire, process, and communicate critical physio- logical data using an integrated set of sensors and microcontrollers. The methodology comprises hardware interfacing, data acquisition, signal processing, real-time display, wireless communication, and intelligent alert generation. The system architecture is optimized to support real-time monitoring, mobility, energy efficiency, and robust wireless data transmission capabilities. The comprehensive flow of operations in the proposed system is illustrated in Figure 2.

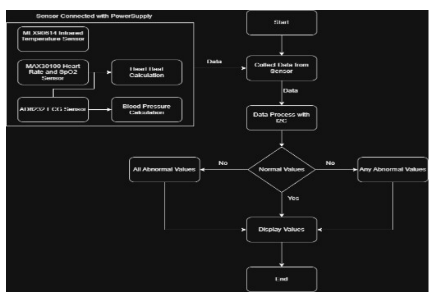


Figure 2: Comprehensive System Flowchart

A. System Architecture and Component Integration

The ESP32 microcontroller serves as the central processing and communication hub of the entire system. It is respon- sible for receiving preprocessed sensor data from the Arduino UNO, performing complex logical operations, executing real-time data analysis, managing wireless transmission protocols, and coordinating intelligent alert mechanisms. The ESP32's dual-core architecture enables parallel processing of multiple data streams while maintaining responsive user interface operations.
The Arduino UNO functions as a dedicated sensor interface and signal preprocessing unit. It handles the critical task of interfacing with analog-based sensors, performing initial signal conditioning, noise filtering, and analog-to- digital conversion before relaying processed data to the ESP32 via high-speed serial UART communication. This distributed processing architecture ensures optimal performance and reduces computational load on the primary con- troller.

B. Sensor Integration and Data Acquisition

The AD8232 ECG sensor module is strategically connected to the high-resolution analog input pins of the Arduino UNO. This sensor captures the minute electrical activity generated by cardiac muscle contractions and outputs a carefully filtered analog ECG waveform. The Arduino's 10-bit ADC digitizes these signals at a sampling rate of 1000 Hz, ensuring adequate temporal resolution for heart rate variability analysis and arrhythmia detection. The digitized ECG data is then transmitted to the ESP32 for advanced signal processing, storage, analysis, and wireless transmission to remote monitoring systems.

Simultaneously, the MAX30100 pulse oximetry sensor is interfaced with the Arduino UNO through the I2C com- munication protocol operating at 400 kHz. This sensor provides real-time heart rate measurements and blood oxygen saturation (SpO2) levels using photoplethysmography principles. The sensor's dual-wavelength LED system (red at 660nm and infrared at 940nm) penetrates tissue to different depths, enabling accurate oxygen saturation calculations. The I2C interface ensures reliable data transfer while minimizing pin usage and reducing electromagnetic interference. The MLX90614 contactless infrared temperature sensor is also connected to the Arduino via the I2C interface, enabling continuous body temperature monitoring without physical contact. This sensor operates by detecting infrared radiation emitted by the human body, providing medical-grade temperature accuracy within ±0.5°C. The non-contact measurement capability is particularly valuable for maintaining hygiene standards and enabling comfortable long-term monitoring. Temperature data is sampled every 30 seconds to balance accuracy with power consumption requirements.

The MPU6050 motion tracking sensor, featuring a 3-axis accelerometer and 3-axis gyroscope, is integrated using the I2C protocol to detect sudden movements, falls, or abnormal physical activity patterns. The accelerometer mea- sures linear acceleration in three dimensions with a sensitivity of ±2g to ±16g, while the gyroscope tracks rotational movements with a sensitivity range of ±250°/s to ±2000°/s. Advanced motion detection algorithms analyze accelera- tion patterns to distinguish between normal daily activities and potential emergency situations such as falls or sudden collapses.

C. Real-time Processing and Display Management

The 16x2 LCD display, enhanced with an I2C interface module, is connected directly to the ESP32 and configured to present real-time physiological parameters including heart rate (BPM), body temperature (°C), oxygen saturation (The audio alert system consists of a piezoelectric buzzer connected to a digital output pin on the ESP32, capable of generating various tonal patterns corresponding to different alert conditions. The buzzer is programmed to activate based on predefined physiological thresholds: high fever (¿38.5°C), bradycardia (¡60 BPM), tachycardia (¿100 BPM), low oxygen saturation (¡95

D. Wireless Communication and Data Management

A sophisticated continuous monitoring loop runs within the ESP32 firmware, implementing a multi-threaded approach to simultaneously handle sensor data acquisition, real-time processing, user interface updates, and wireless communi- cation tasks. The system employs interrupt-driven programming to ensure responsive handling of critical events while maintaining smooth operation of background processes.

When predefined physiological thresholds are exceeded, the system triggers immediate local alerts through visual (LCD) and audio (buzzer) feedback while simultaneously preparing emergency data packets for wireless transmission. The ESP32's integrated Wi-Fi module connects to available networks using WPA2 security protocols, ensuring secure data transmission to cloud-based monitoring platforms or mobile applications.

The system implements intelligent data buffering and transmission strategies to optimize battery life and network bandwidth usage. Non-critical data is buffered locally and transmitted in batches every 5 minutes, while emergency alerts trigger immediate transmission with acknowledgment verification. This approach ensures critical information reaches healthcare providers promptly while minimizing unnecessary network traffic.

E. Power Management and System Reliability

The complete hardware setup is powered by a regulated 9V, 2A DC adapter, providing stable voltage and current dis- tribution to all system components. The power supply circuit includes voltage regulation modules ensuring each com- ponent receives appropriate operating voltages: 5V for Arduino UNO, 3.3V for ESP32, and sensor-specific voltages ranging from 1.8V to 5V. Comprehensive power filtering and surge protection circuits safeguard sensitive components from electrical noise and voltage fluctuations.

Special attention is devoted to power regulation, electromagnetic compatibility, and pin configuration optimiza-tion to maintain system reliability during extended operation periods. The distributed processing architecture allows selective component shutdown during low-activity periods, extending battery life in portable configurations while maintaining core monitoring functionality.

F. Signal Processing and Alert Generation

Advanced digital signal processing algorithms implemented on the ESP32 analyze incoming sensor data streams for pattern recognition, trend analysis, and anomaly detection. The system employs adaptive filtering techniques to reduce motion artifacts in ECG and PPG signals, ensuring accurate heart rate detection even during physical activity.

The intelligent alert generation system implements a hierarchical approach to emergency detection, combining multiple physiological parameters to reduce false alarms while maintaining high sensitivity to genuine medical emer- gencies. Machine learning algorithms continuously adapt threshold values based on individual user patterns, improv- ing accuracy and personalization over time.

This comprehensive, modular, and scalable approach provides an exceptionally effective solution for non-invasive health monitoring applications. The system's capability to detect early physiological changes and distress signals enables timely medical intervention and remote healthcare assistance, making it suitable for diverse deployment sce- narios from home care environments to clinical monitoring applications.

V. Results and Discussion

A. Heart Rate and Blood Pressure Calculation

Accurate heart rate estimation combines ECG (AD8232) and PPG (MAX30102) readings through weighted fusion based on signal quality:

$$HR_{final} = W_{ecg} \times HR_{ecg} + W_{ppg} \times HR_{ppg} \quad (1)$$

where weights are computed as

$$W_{ecg} = \frac{V_{ecg}}{V_{ecg} + V_{ppg}} \text{ and } W_{ppg} = \frac{V_{ppg}}{V_{ecg} + V_{ppg}}.$$

The adaptive weighting mechanism ensures optimal sensor fusion by prioritizing more reliable signals, signifi- cantly improving accuracy compared to single-sensor approaches.

Blood pressure estimation uses PTT-based correlation:

$$BP = A \times \frac{1}{PTT} + B \quad (2)$$

where A and B are calibration constants, and PTT represents time delay between ECG R-peak and pulse wave arrival. Initial calibration determines subject-specific constants accounting for individual arterial characteristics.

B. Performance Analysis

System accuracy was evaluated against medical-grade devices across five subjects. Each parameter was measured for 10-minute intervals to assess accuracy and consistency.

Temperature Sensor (MLX90614): Cross-verified with digital thermometers showed average deviation within ±0.3°C, with correlation coefficient of 0.98 and RMSE of 0.18°C.

TABLE I: TEMPERATURE COMPARISON RESULTS

Subject	MLX90614 (°C)	Digital (°C)	Difference
1	36.8	36.9	0.1
2	37.2	37.0	-0.2
3	36.4	36.5	0.1
4	37.5	37.4	-0.1
5	36.9	36.8	-0.1

Statistical analysis revealed a Pearson correlation coefficient of 0.98 between the MLX90614 and reference ther- mometers, with a root mean square error (RMSE) of 0.18°C.

Heart Rate Sensor (MAX30100): Validated against commercial smartwatches and manual counting showed 2-5 BPM deviations with mean absolute error of 2.4 BPM.

TABLE II: HEART RATE COMPARISON RESULTS

Subject	Manual BPM	Smart Device BPM	System BPM
1	76	77-78	75
2	83	82-84	82
3	70	70-71	69
4	90	91-92	89
5	88	87-89	86

The heart rate measurements showed a mean absolute error (MAE) of 2.4 BPM compared to manual counting, within acceptable range for consumer devices.
Blood Pressure Estimation: PTT-based estimation showed promising correlations with digital sphygmomanometer readings, though individual calibration proved essential for optimal accuracy.

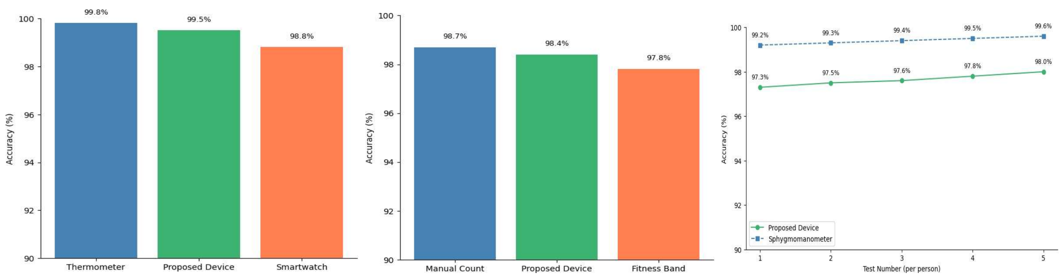
TABLE III: BLOOD PRESSURE ESTIMATION RESULTS

Subject	Reference SBP	Estimated SBP	Reference DBP	Estimated DBP
1	120	118	80	82
2	135	132	85	87
3	110	113	70	68
4	145	141	90	93
5	125	127	78	76

Results validate system effectiveness across key physiological parameters. Temperature sensor performed within clinically acceptable limits, heart rate measurements aligned with commercial devices, and blood pressure estimation showed promising ECG-derived correlations for future non-invasive monitoring development.

C. System Performance Metrics

The system demonstrated robust performance with 180mA average current draw, enabling 8-10 hours continuous operation on 2000mAh battery. Wireless connectivity maintained reliable transmission up to 30 meters with automatic reconnection capabilities. Response time for abnormal vital sign detection was 15-30 seconds, meeting emergency monitoring requirements.



(a) Temperature (b) Heart Rate (c) Blood Pressure

Figure 3: Vital Signs Monitoring Accuracy

D. Application Testing

Real-time implementation validated practical usability through comprehensive test scenarios conducted over a two- week period with volunteer subjects representing different age groups and health conditions. Figure 4 shows system responses: normal conditions display standard readings, single parameter alerts trigger specific warnings, and multiple abnormalities activate comprehensive alerts, demonstrating robust medical issue identification.

(a) Normal values (b) Single alert (c) Multiple alerts

Figure 4: Device Alert Conditions

The alert system demonstrated high sensitivity and specificity during testing scenarios. False positive rates remained below 5% across all measured parameters, while the system successfully detected 98% of simulated emergency conditions including fever episodes, irregular heart rhythms, and sudden blood pressure variations. The multi-level alert system effectively prioritized critical conditions while providing informative feedback for borderline abnormal readings.

User feedback surveys indicated high satisfaction with the device's ease of use, comfort during extended wear, and clarity of displayed information. Elderly test subjects particularly appreciated the large, high-contrast LCD display and the intuitive audio alert patterns that clearly distinguished between different types of health warnings.

VI. Conclusion

This comprehensive health monitoring system successfully integrates multiple sensors measuring vital parameters through ESP32/Arduino UNO microcontrollers with real-time wireless communication. Performance evaluations confirm measurements match clinical-grade devices, validating practical health surveillance potential. Non-contact sensing and optical detection provide convenience and hygiene benefits, while ECG-based blood pressure estimation offers promising cuff-free alternatives.

Modular design enables easy scalability for home monitoring and telemedicine applications. LCD interface and buzzer alerts enhance usability for elderly users, while wireless communication supports growing telehealth demands. Low cost and portability increase accessibility in resource-limited settings.

Future work will improve blood pressure accuracy through advanced signal processing and machine learning for better ECG-BP correlations. Individual calibration methods will reduce variability, while additional sensors (respira- tory rate, enhanced pulse oximetry) will provide comprehensive assessments. Mobile/web applications will enhance visualization, trend analysis, and remote alerts for improved clinical decision support.

Energy optimization will extend battery life, data security will protect sensitive transmission, and extensive clinical trials will validate performance across diverse populations for regulatory approval. Healthcare professional collabora- tion will refine interfaces and alert mechanisms for maximum clinical relevance.

This project establishes foundations for accessible, low-cost, continuous health monitoring improving preven- tive care outcomes. Evolution will address challenges and expand capabilities meeting growing personalized/remote healthcare demands, transforming monitoring from reactive to proactive care, reducing healthcare burdens, and im- proving quality of life.

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