Wearable Clothing-Embedded Physiological Monitoring System

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Problem Definition & Background

The demand for continuous health monitoring is growing rapidly as patients and healthcare systems shift toward preventive care. Current consumer devices can only track a limited number of vital signs, while clinical systems are expensive and impractical for everyday use. Therefore, there is a clear need for a low-cost, non-invasive, and wearable system capable of continuous physiological monitoring in real-world settings [1].

The objective of this project is to design and validate a low-cost, wearable system for continuous multimodal physiological monitoring that is non-invasive, comfortable, and suitable for real-time use.

Design Requirements

- **Technical Functionality:** Continuously acquire Electrocardiogram (ECG), Heart Rate, Blood Oxygen Saturation, Respiration Rate, Body Temperature, and Pulse Wave Velocity (PWV) derived from Pulse Transit Time (PTT)
- **Usability & Ergonomics:** Non-invasive, lightweight, and comfortable for extended wear, with sensor placement designed to minimize motion artifacts and user comfort
- **Communication:** Wireless data transmission to external devices for real-time visualization and analysis
- **Power & Efficiency:** Sustain a minimum battery life of 8 hours to enable practical continuous use
- **Manufacturability**: Use of commercially available, off-the-shelf components and modular design to enable ease of fabrication, assembly, and scalability
- **Economic Constraints:** Low-cost and scalable, with a total system cost under $400 to ensure accessibility for the general public
- **Safety & Standards Compliance:** Adhere to IEEE and ISO biomedical device standards for biocompatibility, electrical safety, and wireless communication to ensure safe and reliable operation
- **Ethical & Privacy Considerations:** Secure handling of user data through protected wireless communication, responsible interpretation of health information, and maintaining accessibility and affordability

Design Alternatives & Iteration

- **Blood Pressure vs PWV & ECG:** A cuffless blood pressure estimation model was considered but was discarded due to its requirement for constant calibration. A PWV & ECG approach was chosen for its predictive nature for cardiovascular health and its potential for future expansion into a cuffless blood pressure estimation model
- **Respiration Belt vs Strain Gauge:** Respiratory Inductance Plethysmography belt was initially chosen for the system as it was the gold standard for non-invasive respiration estimation. However, due to high cost, the strain gauge replaced the previous component as a novel approach for the respiration rate estimation
- **Wi-Fi vs Bluetooth Low Energy (BLE):** Wi-Fi was initially considered as the communication protocol between data acquisition system and user device due to its high-speed data transfer capabilities. However, after consideration of power efficiency and usability constraints, BLE was chosen instead

Design Approach & Implementation

1. Hardware System

Hardware Components

- **Arduino Nano ESP32:** Data acquisition and communication hub
- **AD8232 ECG sensor:** Captures ECG signal for Cardiac Electrical Activity monitoring and PTT
- **MAX30102 pulse oximeter:** Captures Photoplethysmogram signal (PPG) to measure Heart Rate, Blood Oxygen Saturation, and PTT
- **Strain gauge:** Tracks abdominal expansion for respiratory rate estimation
- **MCP9808:** Measures body temperature

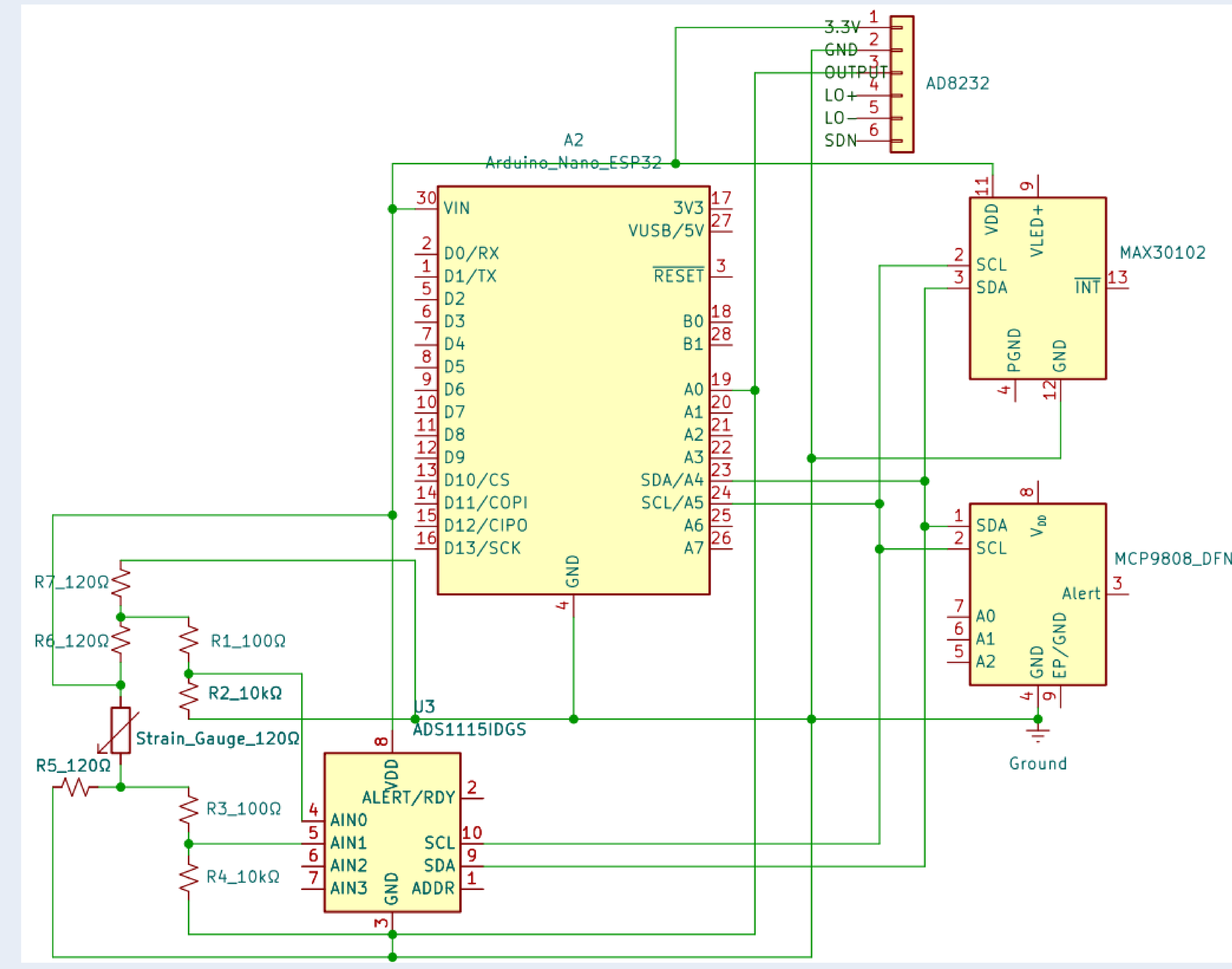


Figure 1. System Hardware Schematic

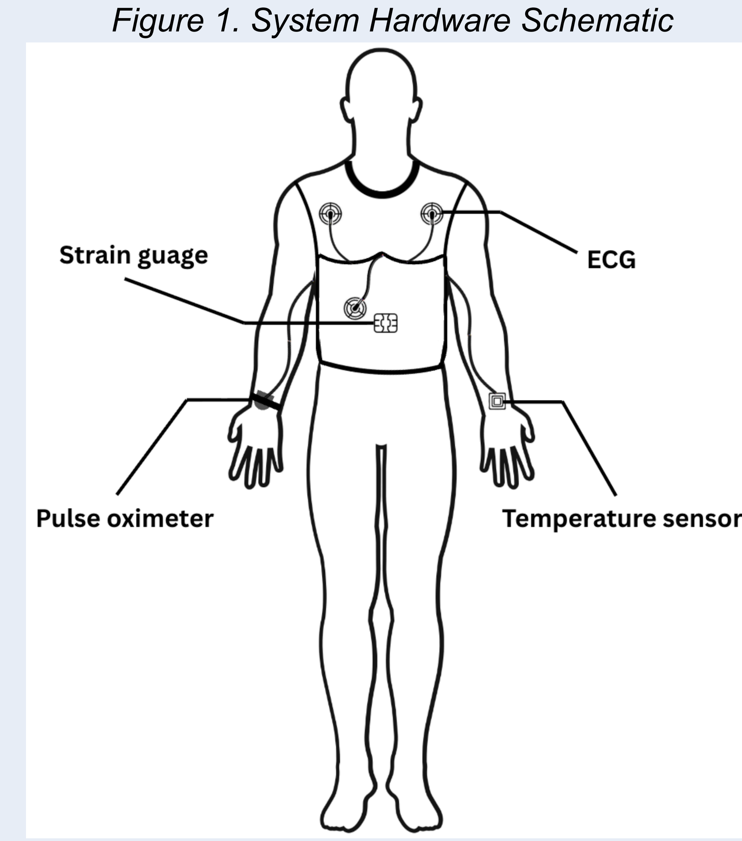


Figure 2. Schematic of sensor placement

2. Software System

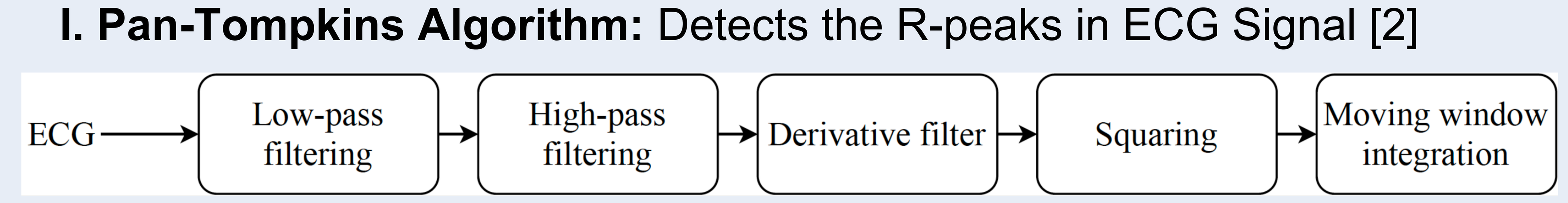
Software Overview

- **Arduino IDE:** Control data acquisition and manage real-time data transmission
- **Python:** Process raw data and display vital signs estimation

Data Acquisition & Signal Processing

- **Pre-processing:** Sample at 400 Hz using a bandpass filter between 0.5 and 150 Hz
- **Vital Signs Estimation:**

I. Pan-Tompkins Algorithm: Detects the R-peaks in ECG Signal [2]



II. Sum Slope Function: Detect Peaks in PPG and Respiration Signals [3]

$$SSF_i = \sum_{k=i-w}^{i} \Delta u_k \quad where \quad \Delta u_k = \begin{cases} \Delta y_k, & \text{if } \Delta y_k > 0. \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

III. PWV Estimation: Compute via PTT [4]

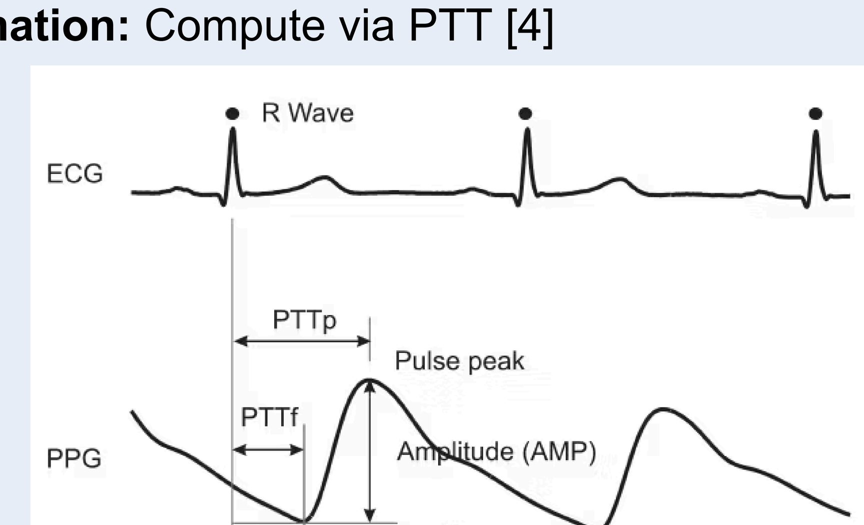


Figure 3. PTT estimation diagram

Serial Communication Protocol

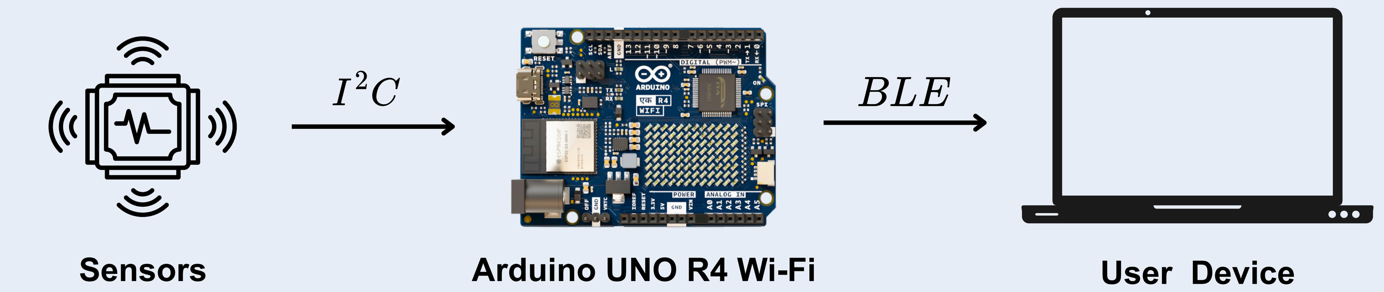


Figure 4. Serial Communication framework

3. User Interface

Software Functions

- **Log in page:** Users log in to access their personal physiological data
- **Home page:** Connect the users to the monitoring hardware
- **General:** Display the comprehensive vital signs estimation
- **Physiological plots:** Display ECG, respiratory, PPG, and PWV signals

Figure 5. User interface (general)

Design Evaluation and the Iterative Process

System Validation

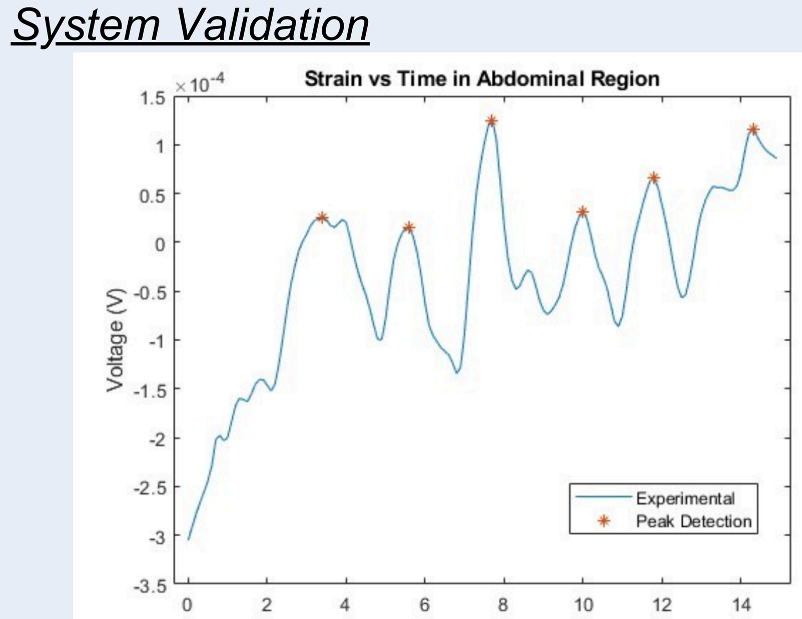


Figure 6. Strain gauge voltage versus time curve

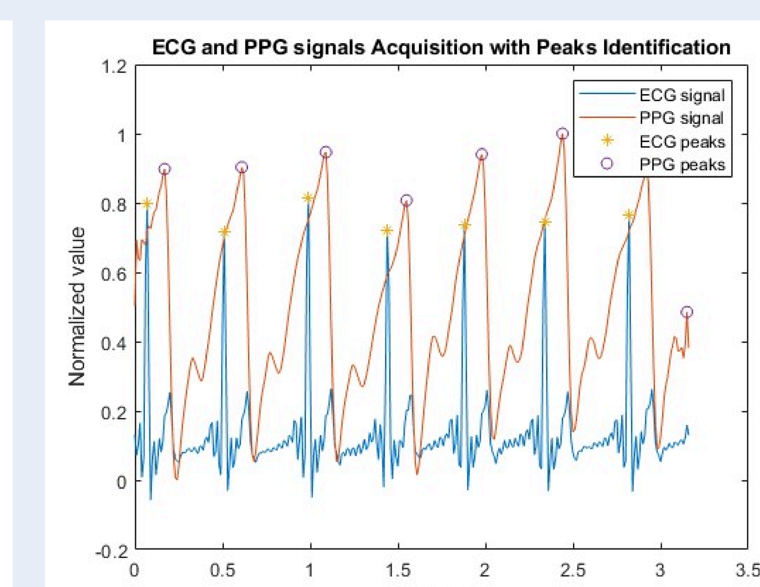


Figure 7. ECG + PPG peak identification

Iterative Process

- **Dual vs single strain gauge**: Initially, a dual strain gauge setup was considered for detailed respiratory data. However, since the system measures respiration rate, not volume, a single strain gauge provides sufficient signal for peak detection while reducing complexity and power consumption
- **Arduino Uno R4 Wifi vs Arduino Nano ESP32:** Initially prototyped with the Arduino Uno R4, later replaced by the ESP32 for its superior BLE performance

Discussion, Conclusions, and Recommendations

The system successfully demonstrated real-time acquisition and processing of multimodal physiological signals in a wearable, clothing-integrated platform. Results confirm that a low-cost, non-invasive system can reliably estimate key vital signs, validating the feasibility of continuous wearable health monitoring. Future work should focus on improving signal robustness, expanding validation, and enabling fully continuous cuffless blood pressure estimation.

References

[1] S. Patel et al., "A review of wearable sensors and systems with application in rehabilitation," J. NeuroEng. Rehabil., vol. 9, p. 21, 2012.
[2] J. Pan and W. J. Tompkins, "A Real-Time QRS Detection Algorithm," IEEE Trans. Biomed. Eng., vol. BME-32, no. 3, pp. 230–236, Mar. 1985.
[3] D.-G. Jang et al., "A Real-Time Pulse Peak Detection Algorithm for the Photoplethysmogram," Int. J. Electron. Electr. Eng., vol. 2, no. 1, pp. 45–49, 2014.
[4] N. Pilz et al., "Pulse Wave Velocity: Methodology, Clinical Applications, and Interplay with Heart Rate Variability," Rev. Cardiovasc. Med., vol. 25, no. 7, p. 266, Jul. 2024.