Improving Wearable Heart Rate Detection through Integrated ECG and PPG Sensing

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Abstract

Wearable devices commonly rely on photoplethysmography (PPG) for heart rate estimation due to its low cost and ease of integration. However, PPG-based measurements are highly sensitive to motion artifacts and environmental disturbances, limiting their reliability in real-world conditions. In contrast, electrocardiography (ECG) provides a more direct and physiologically grounded measurement of cardiac activity but is less frequently integrated into consumer-grade wearables.

This work presents a hybrid wearable system that combines **external ECG sensing** using an AD8232 module with **internal PPG sensing** on the Bangle.js smartwatch. An ESP32 microcontroller acquires raw ECG signals and transmits them via Bluetooth Low Energy (BLE) to the smartwatch, where ECG waveforms are visualized in real time. Simultaneously, PPG-based heart rate values are obtained from the smartwatch's optical sensor. Both signals are relayed wirelessly to a desktop application for synchronized visualization and comparison.

Experimental results demonstrate that ECG signals remain significantly more stable than PPG signals under motion, validating the robustness of ECG-based measurements. The system highlights the potential of multi-modal sensing in wearable computing to improve physiological monitoring accuracy.

1. Introduction

Wearable health monitoring has become an integral component of modern ubiquitous computing systems. Devices such as smartwatches are widely used to monitor physiological parameters, particularly heart rate, for applications ranging from fitness tracking to preliminary health assessment. Most consumer wearables rely on **photoplethysmography (PPG)**, an optical technique that estimates blood volume changes in peripheral tissue.

Despite its popularity, PPG suffers from well-known limitations, including susceptibility to motion artifacts, sensor displacement, and ambient light interference. These factors can lead to inaccurate heart rate estimates, particularly during physical activity.

Electrocardiography (ECG) directly measures the electrical activity of the heart and is considered the clinical gold standard for cardiac monitoring. While ECG is more reliable, it is less commonly integrated into consumer wearables due to hardware complexity and electrode requirements.

This project explores the integration of ECG sensing into a wearable ecosystem by combining:

- an external ECG sensor (AD8232),
- an ESP32 microcontroller for data acquisition and BLE transmission,
- the Bangle.js smartwatch for visualization and PPG acquisition,
- and a desktop application for real-time analysis.

The objective is to compare ECG and PPG signals in real time and demonstrate the advantages of ECG-based heart rate detection within a wearable computing framework.

2. Related Background

2.1 Photoplethysmography (PPG)

PPG is an optical measurement technique that uses light-emitting diodes (LEDs) and photodiodes to detect blood volume changes in tissue. Heart rate is inferred by detecting periodic peaks corresponding to cardiac cycles. While inexpensive and compact, PPG signals are indirect and highly sensitive to motion and pressure variations.

2.2 Electrocardiography (ECG)

ECG measures the electrical depolarization and repolarization of the heart using electrodes placed on the body. ECG provides precise temporal information about cardiac events, such as the QRS complex, enabling accurate heart rate and rhythm analysis. However, ECG integration requires analog front-end circuitry and electrode placement.

3. System Architecture

The proposed system consists of four primary components:

1. **ECG Acquisition Unit**
   An AD8232 ECG sensor connected to an ESP32 microcontroller acquires raw ECG signals.
2. **Embedded Processing and BLE Transmission**
   The ESP32 samples ECG data using its 12-bit ADC and transmits raw samples via BLE notifications.
3. **Wearable Device (Bangle.js)**
   The smartwatch acts as a BLE central device, visualizing ECG waveforms while simultaneously reading PPG-based heart rate values using its internal HRM sensor.
4. **Desktop Visualization Application**
   A Python-based application receives synchronized ECG and PPG data for live plotting and analysis.

This layered architecture allows separation of concerns while enabling end-to-end physiological signal monitoring.

4. Hardware Implementation

4.1 ECG Sensor and Microcontroller

The AD8232 ECG module is used as an analog front-end for ECG acquisition. It provides amplification and filtering suitable for biopotential signals. The sensor output is connected to the ESP32's ADC input, configured for a 12-bit resolution (0–4095).

The ESP32 samples ECG signals at approximately 125 Hz, which is sufficient to capture ECG waveform morphology while respecting BLE bandwidth constraints.

4.2 Wearable Device

The Bangle.js smartwatch serves as both a visualization platform and a sensing device. Its internal PPG sensor provides real-time heart rate values, while the display renders incoming ECG waveforms.

5. Software Implementation

5.1 ESP32 Firmware

The ESP32 firmware:

- reads raw ECG samples from the ADC,
- packs samples into a compact binary format,
- transmits data using BLE notifications via a custom GATT service.

This design ensures low-latency streaming suitable for real-time visualization.

5.2 Bangle.js Application

The Bangle.js application performs the following tasks:

- scans and connects to the ESP32 via BLE,
- receives and decodes raw ECG samples,
- renders ECG waveforms on the watch display,
- reads PPG heart rate values from the internal HRM,
- relays ECG and PPG data to the desktop via Bluetooth UART.

The application emphasizes clarity and responsiveness, with visual scaling applied only for display purposes.

5.3 Desktop Visualization

A Python application using the Bleak library connects to the smartwatch and receives data in the format:

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ECG_RAW,PPG_BPM
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Baseline drift in ECG signals is removed using an exponential moving average (EMA), yielding the AC component of the ECG signal. Matplotlib is used for live plotting of both ECG and PPG signals.

6. Signal Processing

ECG signals typically contain a DC offset caused by electrode impedance and analog front-end characteristics. To isolate meaningful cardiac activity, baseline removal is applied:

$$baseline_n=(1-\alpha)\cdot baseline_{n-1}+\alpha\cdot ECG_{raw}$$
$$ECG_{AC}=ECG_{raw}-baseline$$

This approach removes slow drift while preserving rapid ECG waveform changes.

7. Experimental Results

Live experiments show that:

- ECG waveforms remain stable even during moderate motion,
- PPG heart rate values fluctuate more under the same conditions,
- ECG peaks correspond consistently to cardiac cycles,
- synchronized ECG and PPG visualization enables temporal comparison.

These results confirm that ECG-based sensing provides more robust cardiac monitoring than PPG alone.

8. Discussion

The hybrid system demonstrates the feasibility of integrating ECG sensing into consumer wearables. While PPG remains suitable for low-effort monitoring, ECG offers superior reliability, particularly in dynamic environments.

The modular design allows future expansion, such as on-device heart rate extraction from ECG or advanced filtering techniques.

9. Limitations

- Single-lead ECG limits diagnostic capability.
- Motion artifacts still affect ECG to a lesser extent.
- BLE bandwidth constrains sampling frequency.
- Electrode placement affects signal quality.

10. Future Work

Future extensions include:

- automated R-peak detection,
- pulse transit time (PTT) estimation,
- on-watch ECG-based heart rate computation,
- long-term data logging,
- integration of digital band-pass filtering.

11. Conclusion

This project demonstrates a complete wearable computing system that integrates ECG and PPG sensing for improved heart rate detection. By combining external ECG hardware with a consumer smartwatch, the system highlights the advantages of multi-modal physiological monitoring. The results support the hypothesis that ECG provides more reliable cardiac measurements than PPG, particularly in real-world usage scenarios.