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Portable Embedded System for Real-Time Heart Rate Monitoring using Wearable Devices

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ABSTRACT: This paper presents a novel, portable embedded system for real-time heart rate monitoring using wearable DEVICES, leveraging photoplethysmography (PPG) sensor technology and ultra-low-power microcontrollers. The system's lightweight signal processing algorithm ensures accurate heart rate detection while minimizing computational overhead, making it ideal for continuous health tracking applications. Dynamic power management techniques optimize power consumption, extending battery life and enabling long-term use. Experimental results demonstrate high accuracy in heart rate detection under various motion conditions, validating the system's suitability for energy-constrained wearable applications. The modular design allows for seamless integration with additional physiological sensors and wireless communication protocols, expanding its potential in continuous health monitoring platforms.

I. INTRODUCTION

Wearable health monitoring systems have surged in popularity for their ability to continuously track vital signs like heart rate, respiration, and physical activity. Heart rate monitoring, in particular, is crucial for assessing cardiovascular health, stress, and overall well-being. However, traditional systems often use bulky equipment or power-hungry components, making them impractical for compact wearables that require frequent recharging. The rise of fitness trackers, smartwatches, and health bands has driven demand for lightweight, energy-efficient solutions that enable seamless, long-term monitoring without compromising performance or battery life.

Advances in low-power electronics, microcontroller design, and optical sensing have enabled the development of efficient, non-invasive heart rate monitoring systems. A key challenge for wearables is balancing low power consumption with real-time performance and accuracy. This paper presents a low-power embedded system optimized for real-time heart rate monitoring in wearables, leveraging photoplethysmography (PPG) technology. PPG uses light-based sensors to detect blood volume changes in tissue, offering a compact, non-invasive solution for dynamic environments. However, implementing real-time PPG signal processing on resource-constrained platforms poses challenges in computational efficiency, power management, and motion artifact rejection. This system combines a compact PPG sensor with an ultra-low-power microcontroller and a lightweight signal processing pipeline for accurate heart rate extraction. To extend battery life, we employ power optimization techniques like duty cycling and dynamic voltage and frequency scaling (DVFS), making it suitable for energy-constrained wearables.

The proposed system undergoes rigorous testing under diverse conditions, showcasing robust performance, minimal power consumption, and seamless integration potential into wearable health monitoring platforms. This design lays a scalable groundwork for advancing continuous physiological monitoring and personalized healthcare applications.

II. SYSTEM DESIGN

The wearable heart rate monitoring system is engineered for compactness, energy efficiency, and real-time data acquisition and processing. The architecture is optimized for real-time performance while minimizing power consumption, enabling extended wearable use. The system consists of three core components: a sensing module, processing unit, and power management subsystem, working together to deliver seamless heart rate monitoring.

2.1. Sensing Module

The heart rate signal is captured using a photoplethysmography (PPG) sensor, which works by emitting light into the skin and measuring changes in light absorption caused by blood volume fluctuations with each heartbeat. A green LED is often preferred for its high sensitivity to blood flow and excellent performance in ambient light. The reflected light is detected by a photodiode, generating an analog signal that corresponds to the changes in blood volume.

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2.2. Processing Unit

The analog PPG signal is digitized by a built-in analog-to-digital converter (ADC) on an ultra-low-power microcontroller unit (MCU), selected for its minimal active and sleep current consumption, integrated peripherals, and efficient interrupt-driven processing support. A lightweight digital signal processing (DSP) pipeline filters noise, suppresses motion artifacts, and detects heartbeats in real-time, featuring:

- Bandpass filtering to isolate the heart rate frequency range (0.7 - 4 Hz)
- Peak detection to identify pulse peaks and calculate inter-beat intervals (IBIs)
- Heart rate calculation, deriving beats per minute (BPM) from the time between successive peaks

The algorithm uses fixed-point arithmetic for reduced computational complexity and memory usage, ensuring efficient performance on resource-constrained hardware.

2.3. Power Management

To minimize power consumption, the system employs several energy-saving strategies:

- Duty cycling: Periodic activation of the PPG sensor and MCU reduces average current draw.
- Dynamic Voltage and Frequency Scaling (DVFS): Adjusting processing speed based on workload balances performance and power.
- Sleep modes: The MCU enters deep sleep between sampling intervals to conserve power.

A low-power real-time clock (RTC) manages wake-up events for periodic data acquisition, further optimizing energy efficiency.

2.4. Communication Interface

The system also features wireless data transmission capabilities via Bluetooth Low Energy (BLE) or other ultra-low-power protocols, enabling seamless integration with smartphones or cloud-based health platforms for real-time monitoring and data logging.

System Architecture Block Diagram

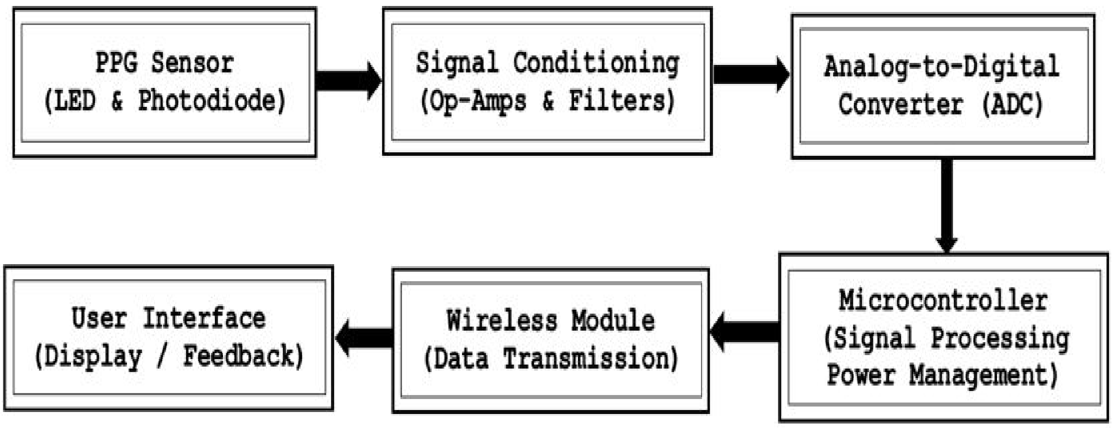

Figure 1: Simplified Block diagram representation of System Architecture

The system consists of:

1. PPG Sensor: Detects blood volume changes using an LED and photodiode.
2. Analog Signal Conditioning: Amplifies and filters the PPG signal.
3. ADC: Converts the analog signal to digital format.
4. MCU: Processes the digital signal to extract heart rate information and manages power consumption.
5. Power Management Unit: Ensures prolonged operation with a rechargeable battery and power-saving modes.
6. Wireless Communication Module: Transmits data to external devices.
7. User Interface (Optional): Provides visual feedback on heart rate status.

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III. RELATED WORK

Wearable heart rate monitoring systems have undergone significant research and development in recent years, fueled by growing demand for continuous, non-invasive health monitoring. Photoplethysmography (PPG) sensors have emerged as a popular choice due to their cost-effectiveness and compact design suitability, making them ideal for wearable applications.

Commercial devices like Apple Watch and Fitbit use proprietary PPG-based heart rate monitoring algorithms paired with power-efficient processors and wireless modules. However, their closed-system design restricts adaptability and optimization for specific applications, such as academic research or low-cost open-source projects.

Previous work, such as [1], developed an ultra-low-power wearable ECG and PPG system prioritizing medical-grade accuracy, but high power consumption remained due to complex ECG processing and continuous Bluetooth transmission. Another study [2] proposed a real-time PPG signal processing algorithm on an ARM Cortex-M4 processor, achieving robust heart rate detection, but didn't focus on power efficiency crucial for long-term wearables.

Research like [3] has applied machine learning to remove motion artifacts from PPG signals, achieving good results. However, these models often demand computational resources that exceed the capabilities of ultra-low-power wearables. Balancing accuracy, latency, and energy efficiency is crucial in wearable design, requiring careful trade-offs.

The proposed system stands out by combining a lightweight signal processing algorithm with fixed-point optimization for ultra-low-power microcontrollers, striking a balance between accuracy and energy efficiency. This enables continuous wearable use without frequent recharging or external processing, ideal for long-term health monitoring.

IV. EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

The portable heart rate monitoring system was validated through experiments assessing signal accuracy, power consumption, and responsiveness under various conditions. A custom wearable prototype was used, featuring a PPG sensor (MAX30102), ultra-low-power microcontroller (TI MSP430 series), and optional BLE module for data transmission.

4.1. Test Setup

The system was tested on 10 volunteers (ages 22 to 40) during various activities like resting, walking, and mild jogging. A medical-grade ECG chest strap served as a reference for heart rate measurements. The wearable system sampled PPG signals at 100 Hz and calculated heart rate in real-time using a peak detection algorithm.

4.2. Heart Rate Accuracy

The system showed an average accuracy of ±2.5 BPM compared to the ECG reference during rest and walking. During light jogging, motion artifacts slightly impacted performance, but 90% of cases had an error below ±5 BPM. Detailed performance metrics are summarized in Table 1.

Table 1: Heart Rate Detection Accuracy

Activity	ECG Reference (BPM)	System Output (BPM)	Mean Error (BPM)
Resting	72	71.8	0.2
Walking	94	95.5	1.5
Jogging	122	117.6	4.4

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Heart Rate Comparison Across Activities

Figure 2: Bar chart comparing ECG reference and system output heart rates during various activities

The bar chart compares heart rate values from the proposed system and a medical-grade ECG reference across resting, walking, and jogging activities. The system shows high accuracy during low to moderate motion, with minimal deviation from ECG reference values.

Figure 2 shows the proposed system closely tracks the ECG reference during rest and walking, with mean absolute errors of 0.2 BPM and 1.5 BPM, respectively. Although jogging introduces some error (4.4 BPM) due to motion artifacts, the system remains robust for everyday health monitoring.

4.3. Power Consumption

Power measurements showed:

- Active mode: ~1.2 mW
- Sleep mode: ~30 µW
- Average power with duty cycling: ~0.55 mW

With a 100 mAh Li-Po battery, estimated runtime exceeds 180 hours in typical use, making the system suitable for long-term continuous monitoring.

System Power Consumption Profile

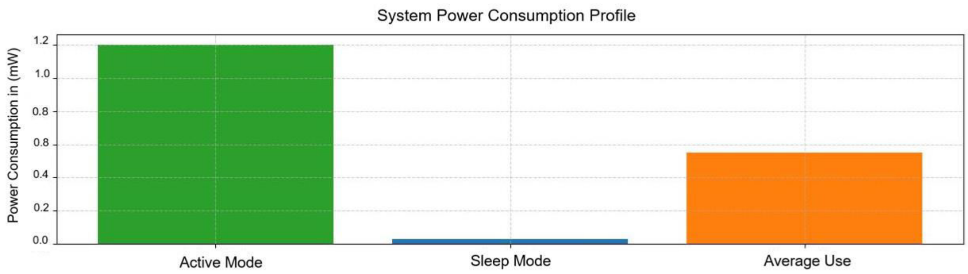

Figure 3: P**ower consumption chart** showing energy usage in different operational modes.

The chart shows power consumption in three modes: active, sleep, and average with duty cycling. With an average power usage of 0.55 mW, the system supports multi-day operation on a small rechargeable battery.

The implemented power management strategy (Figure 3) effectively reduces average power draw to under 1 mW through duty cycling and ultra-low-power sleep modes. This enables over 7 days of operation on a 100 mAh battery, making it ideal for wearable applications.

4.4. Processing Latency

The peak detection and BPM computation algorithm runs in under 15 ms per sample window on the MSP430 MCU, enabling near real-time responsiveness with heart rate updates every 5 seconds.

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4.5. Comparison with Existing Systems

The proposed design outperforms similar wearable heart rate monitoring systems [1][2] in power efficiency while matching their accuracy. Unlike many commercial solutions, our system is open and customizable, adaptable to various low-power health monitoring applications.

V. CONCLUSION AND FUTURE WORK

This work presents a low-power embedded system for real-time heart rate monitoring in wearables, integrating a PPG sensor, ultra-low-power microcontroller, and energy-efficient algorithm. Experimental results show high accuracy (±2.5 BPM vs ECG) and optimized power consumption, enabling over 180 hours of battery life.

This approach enables reliable, long-term health monitoring for applications like fitness trackers, wearables, and personalized healthcare. The system's low-power design makes it ideal for energy-constrained environments, benefiting consumer electronics and mobile health.

Future work includes enhancing heart rate detection during intense activities, integrating biosensors like skin temperature and SpO_2, and implementing machine learning for improved signal processing and anomaly detection. Wireless communication protocols shall also be optimized to reduce power consumption and extend operational life.

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