Development of a Wireless System for Body Surface Potential Mapping

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Abstract

Cardiovascular diseases remain the leading cause of mortality worldwide, demanding innovative diagnostic tools to enhance early detection and treatment planning. Body Surface Potential Mapping (BSPM) is a noninvasive technique that enables detailed spatial analysis of cardiac electrical activity but faces barriers to clinical implementation due to equipment complexity and high cost. This study presents the development of a portable BSPM system capable of acquiring 32 channels of electrocardiographic signals using the RHD2132 microchip. The system integrates an STM32 microcontroller and ESP32 for wireless data transmission via Wi-Fi, with real-time data visualization and storage through a LabVIEW interface. Validation was conducted using a patient simulator, and the recorded signals were compared with those from a commercial ECG system, demonstrating comparable waveform fidelity. Power consumption was measured at 0.21 A, and the system was powered by a 10,000 mAh power bank, ensuring more than 40 hours of continuous operation, which reinforces its portability. These results indicate that the proposed system is a promising step toward more accessible, flexible, and integrated solutions for noninvasive cardiac mapping.

1. Introduction

According to the World Health Organization, cardiovascular diseases, including arrhythmias, account for approximately 17.9 million deaths annually, making them the leading cause of death worldwide [1]. Understanding the mechanisms that underlie conduction abnormalities is essential for accurate diagnosis and effective therapeutic strategies. Although such information is often obtained through conventional electrocardiograms (ECGs), complementary techniques like surface mapping and cardiac imaging have shown increasing potential for clinical application [2].

Body Surface Potential Mapping (BSPM) is an advanced, noninvasive technique that employs a dense array of up to 300 electrodes distributed over the torso to detect and analyze the potential differences generated by the heart's electrical activity. Despite its advantages in assessing cardiac electrical function, the implementation of BSPM in clinical practice remains limited by high system costs and reduced usability, mainly due to the size of the equipment and the abundance of electrode wires [3].

Wireless instrumentation offers a promising alternative by making these systems more practical and flexible. Eliminating the need for physical cabling simplifies setup and enables real-time remote monitoring [4].

Beyond mapping arrhythmogenic substrates, portable BSPM technologies show potential for integration with advanced imaging techniques, such as Electrocardiographic Imaging (ECGi). Combining electrophysiological and imaging data provides a more comprehensive view of cardiac function in real time, helping to identify both structural and functional abnormalities and supporting more effective treatment planning, such as cardiac ablation [2].

To address these challenges, we developed a portable acquisition platform for BSPM, integrating a 32-channel bio-potential acquisition microchip. The system supports wireless data transmission via Wi-Fi and real-time signal visualization in LabVIEW.

2. Material and Methods

The development of this work is divided into three main stages: hardware design, data visualization, and system validation.

2.1. Hardware Design

Initially, a detailed study of the technologies was conducted to specify the portable system. The study included an analysis of the RHD2000 series microchips developed by Intan Technologies for bioelectric signal acquisition. At this stage, microcontrollers from STM were also evaluated, following Intan's recommendations for integration with the microchip. For wireless data transmission, both Wi-Fi and Bluetooth were preliminarily tested. Wi-Fi was

selected for further testing due to its higher data throughput, compatibility with LabVIEW, and straightforward integration with the microcontroller.

For the proof of concept, the following components were used: the RHD2132 chip for biosignal acquisition, STM32 NUCLEO-U5A5ZJ-Q development kits for microcontroller validation, ESP32-S2-DevKit for wireless transmission validation, and a 10,000 mAh power bank as the power source.

a) RHD2132

The RHD2132 chip integrates a low-power architecture into a single silicon chip, combining a fixed 192x amplifier, adjustable analog and digital filters, a 16-bit analog-to-digital converter (ADC), and an SPI bus for communication and digital data output. The recording electrodes are directly connected to the chip. The bandwidth of the amplifiers can be dynamically programmed through internal registers. A high-speed, low-distortion analog multiplexer (MUX) allows multiple amplifiers to share the ADC on the chip, with sampling rates of up to 30 kSamples/s for each channel.

The RHD uses an SPI communication protocol. After receiving a command from the microcontroller via MOSI, the RHD chip samples the analog signal sequentially through the 32 amplifiers and performs the conversion. Once the conversion is completed, the result is transmitted back to the master device via the MISO signal, using 16-bit word data. The master device, such as a microcontroller, could process the signal then.

b) Controller

The STM32 U5 series microcontroller enables ultra-low power applications, providing a maximum CPU clock rate of 160 MHz and robust peripheral support. High-speed processing and low NSS time SPI data transmission/reception, linked to the Chip Select control signal, are key features for achieving high sampling rate communication and a high number of channels with Intan chips. The microcontroller also includes a USART interface for data transmission. Thus, the STM32U5A5ZJ chip was selected for project development.

For the proof of concept development, the C programming language and the STM32Cube development platform were used. To facilitate control of the Intan RHD2132 chip through SPI, the open C code provided by Intan was used as a reference [5].

c) Wireless data transmission

Wireless data transmission was tested using both Bluetooth and Wi-Fi.

For Bluetooth, the ESP32 module was used, which supports Bluetooth 4.0 with a maximum transmission rate of approximately 1 Mbps. The STM32 microcontroller sent data to the ESP32 via UART, configured for a baud rate of 921600. In turn, the ESP32 transmitted the data via Bluetooth at the same rate. On the receiving end, the computer used an integrated Bluetooth module to establish a wireless connection with the ESP32. Once the connection was established, the Bluetooth module on the computer generated a COM communication port, enabling serial data transfer. The software developed in LabVIEW communicated with the Bluetooth module via this virtual COM port to receive the transmitted data in real time.

For Wi-Fi, the ESP32 module was configured to transmit data packets using the UDP (User Datagram Protocol). The STM32 microcontroller also sent data to the ESP32 via UART at 921600 baud, and the ESP32 encapsulated the data into fixed-length UDP packets of 96 bytes. Each packet contained the signals from all 32 channels, with 2 bytes allocated to the signal value and 1 byte to identify the channel, resulting in 3 bytes per channel. On the receiving end, the LabVIEW GUI was configured with a UDP listener block, continuously waiting for incoming packets at a specified IP address and port. The LabVIEW includes a parsing routine to reassemble and decode the channel data from each received packet.

The UDP approach enabled faster and simpler communication, as it does not require connection handshakes or acknowledgments, reducing overhead and minimizing latency.

Both implementations (Bluetooth and Wi-Fi/UDP) were developed and tested using the Arduino IDE for ESP32 code development.

2.2. Real-Time Data Visualization

Three dedicated Graphical User Interfaces (GUIs) were implemented in LabVIEW to enable real-time visualization of the acquired signals, each one designed for a specific communication layer: Bluetooth, Wi-Fi/UDP, and a pre-existing BSPM interface.

a) Bluetooth VI

A dedicated VI was designed to handle serial data over Bluetooth using the VISA (Virtual Instrument Software Architecture) interface. The connection relied on a virtual COM port generated by the computer's Bluetooth module. This VI was responsible for parsing the received data packets, extracting channel-specific values, and updating the waveform charts in real-time. Data logging was implemented via the Write Delimited function for later analysis.

b) Wi-Fi VI

A second VI was developed to process packets transmitted over Wi-Fi using the UDP protocol, using the UDP Open/Read functions to receive packets continuously, followed by packet decoding and dynamic allocation of the samples to the corresponding waveform charts. This implementation allowed for higher scalability and efficient

packet-based transfer compared to the serial-based Bluetooth setup.

c) BSPM VI

Finally, a previously developed VI dedicated to BSPM was adapted to interface with the system. This VI included advanced modules for multi-channel visualization, filtering, and offline integration with ECGi reconstruction algorithms, capable of generating potential maps, VCG, and spatial analysis of cardiac activity. The integration with offline external modules, such as the one for ECGi reconstruction, is also possible. This module uses standardized three-dimensional geometries of the heart and torso to compute cardiac potentials from acquired BSPM signals, generating ECG maps, VCG, and other relevant information for analysis.

3. System Validation

The system validation was performed using a patient simulator (HS14, R&D Mediq) configured to generate standard waveforms, including ECG, sine, triangular, and square waves. The purpose of this validation step was to evaluate the accuracy and fidelity of the system in capturing and transmitting bioelectrical signals, ensuring that the data acquisition and wireless transmission worked as intended.

For the signal acquisition performance, the waveforms generated by the patient simulator were compared with those obtained from a commercial electrocardiograph, the ECG PC from TEB. Both systems were set up under identical conditions, allowing for a direct comparison of signal fidelity, waveform morphology, amplitude, and stability. To minimize noise and external interference, shielded cables were employed in the electrode connections.

The integrity of the signal during wireless transmission was tested for both Bluetooth and Wi-Fi. Possible distortions, data loss, and signal degradation were assessed in both communication modes. The latency between signal generation and display on the graphical user interface (GUI) was measured using timestamps, enabling evaluation of the real-time performance of the system under different transmission protocols. For the Wi-Fi implementation, additional tests were conducted to evaluate throughput and packet integrity when transmitting 96-byte UDP packets corresponding to the 32 acquisition channels, ensuring reliable multichannel data transfer.

3.1. Results and Discussion

For the tests, the bandwidth of the amplifiers was configured between 0.1 and 110 Hz through the registers of the acquisition chip. Additionally, the chip's internal digital signal processing (DSP) module was used to implement a single-pole high-pass filter with a cutoff of 0.1 Hz in each channel, effectively removing residual DC offsets. The system was evaluated with sampling rates of 500 Hz and 1 kHz per channel.

The proposed portable BSPM system was assembled and validated using a 10 000 mAh power bank as the power source. The power bank supplied 5 V to the STM32 NUCLEO-U5A5ZJ-Q development kit, which in turn powered the ESP32-S2-DevKit with 5 V and the RHD2132 acquisition board with 3.3 V. Current consumption was measured with a USB ammeter connected to the power bank, showing an average draw of 0.21 A during operation. This measurement confirmed the feasibility of battery-powered operation and allowed the estimation of the system's autonomy of 30 hours, considering typical DC–DC conversion efficiency (75–85%).

Tests were conducted using standard waveforms generated by the patient simulator (HS14, R&D Mediq), including ECG, sinusoidal, and triangular signals. Shielded electrodes were connected to the simulator's terminals, with common reference and ground connections. The setup is presented in Figure 1. The results demonstrated that the portable system was able to capture and reproduce the signals adequately, with morphology consistent with the reference equipment (ECG PC, TEB LTDA). As expected, the commercial device exhibited slightly superior noise performance, but this can be mitigated in the proposed system through the implementation of more robust digital filtering strategies.

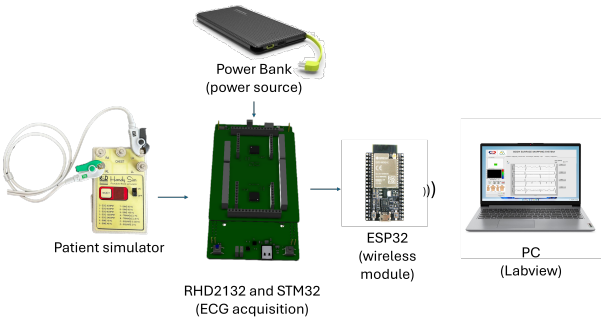

Figure 1. View of the developed acquisition board integrated with the STM32 development kit, the ESP32 kit, power bank and patient simulator. This setup was used for system validation and signal acquisition tests.

Wireless transmission was identified as a critical aspect of system performance. In the case of Bluetooth, the system operated stably but was limited to a maximum sampling frequency of 500 Hz across 32 channels. Additionally, the Bluetooth link introduced a measurable delay of approximately 8 seconds between signal generation and visualization. This latency is explained by the serial-to-Bluetooth retransmission in the ESP32 and the data pars-

ing routines in LabVIEW. Although this delay may be acceptable for quasi-real-time monitoring, it restricts applicability in scenarios requiring strict real-time feedback.

In contrast, the Wi-Fi implementation provided significantly better performance. Two transmission strategies were tested: (i) sequential sending of each channel individually (3 bytes per transmission), which introduced a delay of approximately 2 seconds; and (ii) grouping data into UDP packets of 96 bytes (32 channels × 2 bytes + 1 byte channel identifier), which eliminated the delay entirely. With this second approach, as shown in Figure 2, visualization occurred with no perceptible latency, even at higher data rates. Moreover, Wi-Fi transmission allowed stable operation at both 500 Hz and 1 kHz, demonstrating its superior suitability for high-density BSPM acquisitions.

The LabVIEW interface for BSPM was implemented exclusively using Wi-Fi, taking advantage of the higher throughput and reduced latency, as shown in Figure 2. This configuration enabled the simultaneous visualization of all 32 channels without delay, confirming the robustness of the Wi-Fi approach for large-scale, multichannel bioelectrical mapping.

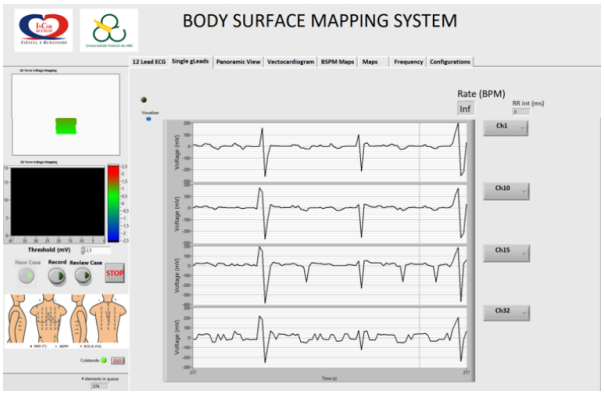

Figure 2. LabVIEW VI previously developed for BSPM data analysis, adapted to visualize the signals acquired via WiFi by the proposed wireless system.

WiFi was considered the best communication solution for this specific application. It supports higher sampling rates with reduced latency and better scalability compared to Bluethooth.

A total of 32 channels were tested, but the architecture supports expansion to 64 channels through the parallel use of two RHD2132 chips. In this case, the CS, SCLK, and MOSI lines are shared, while the MISO line is kept separate for each chip. The system's integration with ECGi represents a significant advantage, enabling the reconstruction of cardiac images from BSPM data, with potential applications in clinical mapping of arrhythmogenic substrates and improved treatment planning.

4. Conclusion

A portable BSPM system was successfully developed and validated, capable of simultaneously acquiring 32 channels with real-time visualization through the LabVIEW interface. The integration of Wi-Fi wireless transmission was demonstrated, ensuring stable data transfer and enabling greater portability and flexibility compared to wired configurations. Tests using a patient simulator confirmed the accuracy of signal acquisition, while the use of shielded cables minimized interference, improving signal integrity.

This system represents a promising tool for non-invasive cardiac disease diagnosis, combining multi-channel acquisition, wireless communication, and a customizable interface. Future work will focus on expanding the system to 64 channels, optimizing wireless transmission to reduce latency, and further integrating with ECGi (Electrocardiographic Imaging) for cardiac image reconstruction. Finally, tests in human subjects will be performed to validate the clinical applicability and robustness of the system in real-world scenarios.

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