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Vital Signs Monitoring

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Abstract

The aim of this project is to design, implement and evaluate a vital signs monitoring system. The proposed solution is a Bluetooth Low Energy Mesh connected system that consists of three types of nodes: battery powered wearable monitoring devices collecting photoplethysmographic (PPG) data, transmitting heart rate (HR) and peripheral oxygen saturation (SpO_2) information; relay nodes retransmitting the data; provisioning nodes configuring the mesh network, and end nodes publishing the collected data via an MQTT protocol. The battery powered nodes and relay nodes are implemented on nRF52 series modules by Nordic Semiconductor, while the end nodes utilize ESP32 modules made by Espressif. Analysis of the collected PPG data is achieved by forward-backward filtering using a fourth-order Chebyshev II bandpass filter, followed by smoothing using the moving average algorithm, and extraction of vital signs indicators using a custom implementation of a peak detection algorithm with a single data pass-through. With its minimal requirements on both energy supply and supporting infrastructure, the system presents a convenient solution that could be especially compelling to medical institutions with limited funding. Moreover, the non-stationary nature of the proposed non-invasive continuous monitoring makes the product suitable for use in other facilities such as nursing homes.

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1. Introduction

The idea for this project originated from a common inconvenience in nursing homes, where caretakers periodically examine the vital signs of their elderly patients throughout the day. However, the resulting system has a much broader scope of applicability and is a viable solution in both clinical and domestic environments.

At the very core of the proposed system are wearable devices that use a sequence of algorithms to extract vital signs indicators from the collected PPG wrist measurements. Hence, the proposed design should provide a continuous collection of real-time data further transmitted into the system network, ensuring stable and reliable coverage across the facility area, which makes it a convenient aid for health care.

Although there are existing systems for continuous centralized monitoring of patients based on electrocardiography or plethysmography on the market already (e.g., [1]), they serve a different purpose – monitoring of patients in a critical state. In addition, devices of such systems are mostly stationary and require installation of supporting infrastructure for data transmission, significantly increasing the system cost. In contrast, our solution offers an easily-implementable wireless transmission of health status assessment, sending alerts at a moment's notice with a potential future improvement of giving patient's location.

The selection of Bluetooth Low Energy (BLE) Mesh was considered carefully. It proved to be outstandingly energetically efficient while providing a remarkable coverage range even in indoor settings, where walls often pose a challenge for connectivity. Furthermore, the advanced security measures and encryption at every layer of the BLE Mesh protocol stack ensure no risks to the potentially sensitive medical data transmitted.

2. PPG Data Acquisition and Analysis

Biometric data acquisition and robust analysis represent the core part of the system. The literature contains several digital filter implementations, smoothing approaches (e.g., high-pass filter [2]), and peak detection algorithms (e.g., AMPD, HeartPy [3]), the biggest challenge, however, was selecting those that are memory efficient and produce quality results with minimal requirements on iterations in the collected biometric data.

2.1 Filtration and Smoothing

Open-source PPG filtration libraries commonly utilize a Butterworth low-pass filter. Unfortunately, the PPG method is highly susceptible to disruptions by signal noise of various frequencies, including that generated by any motion of the subject wearing the device, which introduces pollution in the detected waveform. Thus, selecting a quality filter with appropriate parameters presented a fundamental step in enhancing the robustness and performance of the PPG signal processing.

The monitoring devices perform filtration using a fourth-order Chebyshev II filter on account of a comparative study assessing PPG filter results on a large PPG dataset, which found that it makes systolic and diastolic waves more salient, allowing for real-time and low-computation signal processing in wearable health devices [4].

To further enhance signal quality, detrending and smoothing of the signal by applying the moving average algorithm (by convolution with a kernel of ones) proved beneficial, as it improved the recognizability of the modulated cardiac cycle in the waveform.

2.2 Peak Detection and Oxygen Saturation Approximation

Robust and reliable detection of peaks in a PPG waveform is an elaborate task as well as a subject of many studies and complex algorithms these studies propose. Even though there are sources evaluating the functionality of these algorithms [3] proposing the best ones available (MSPTD, AMPD, qppg), their implementation in this project was not feasible due to the pre-set requirements on constrained memory and performance. A modified implementation of peakdet [5] algorithm was thus selected and used with a delta parameter corresponding to the value standard deviation of the detrended signal.

3. BLE Mesh Communication

BLE Mesh protocol stack resembles the TCP/IP protocol stack, sharing some basic principles, such as layered architecture, encapsulation, mechanisms for reliable communication, and addressing.

After provisioning, a process in which the wearable device becomes a mesh node and a network member, the device can read the information encrypted up to the network layer using a network key. Even though the device can relay the message, it cannot read its application data. For the message content decryption, an application key is then required.

Models in a BLE Mesh network serve as an abstraction that standardizes how we describe a device and how we can interact with it. Despite the BLE specification providing the so-called foundation models for generic functionalities (e.g., Generic On/Off, Generic Level), there was a need for a custom sensor type introduction into the Zephyr RTOS to achieve more effective transmission and thus also better energy economy.

Sending and receiving messages within the system conform to the publish/subscribe and client/server communication models. This project implements a solution in which all the monitoring devices contain a custom Sensor Server Model publishing the collected HR and SpO_2 information in unsolicited messages. These messages get relayed to an end node with both BLE Mesh and Wi-Fi connectivity. In contrast to the monitoring devices, the end nodes contain a subscribed Sensor Client Model (bound to the same appKey for application data decryption).

Zephyr RTOS provides high-level API functions for the BLE Mesh protocol stack and, combined with the nRF software development kit, proved to be an excellent choice for embedded IoT projects focused on BLE Mesh.

4. Conclusions

Taking into account the constraints of embedded solutions in general and the challenging nature of wireless communication in indoor setting in particular, the prototype performs surprisingly well in tasks that were the main objective of the thesis, including data acquisition, filtration, smoothing, extraction of HR and SpO_2 indicators, reliable transmission of data towards the end node, and its publication via an MQTT protocol.

Lastly, since the presented device is only a prototype in the form of a development kit board, the next logical step is migrating the solution to a custom-printed circuit board to minimize the device size, taking the project even closer to becoming a commercial-grade product.

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