Smart System for Real-time Monitoring of Vital Parameters

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Abstract

Wearable real-time systems that collect and intelligently analyze data on respiration, heart rate, oxygen saturation, blood pressure, and body temperature could assist medical personnel in selecting the most appropriate response during highly stressful situations in both military and civilian contexts, such as terrorist attacks, IED incidents, or rescue operations. These systems will issue an alert if there is a change in a person's health status to prevent overlooking critical health changes. We propose designing and developing a prototype of a patch-like device and a methodology that enables the continuous monitoring of vital parameters of personnel or victims. The system involves using Artificial Intelligence to create software capable of real-time prediction of the parameters and alerting.

Keywords

vital parameters, smart patch, artificial intelligence, medical device

1. Introduction

Wearable real-time physiological status monitors, designed as patch-like devices, have been developed to gather and analyze vital parameters including respiration rate (RR), heart rate (HR), blood oxygen saturation (SpO2), electrocardiogram (ECG), blood pressure (BP), and body temperature [1]. These devices hold promise for assisting first responders and remote personnel in both military and civilian settings, especially during urgent situations such as terrorist attacks, IED explosions, or rescue operations.

The ability to instantly analyze an individual's health status, particularly those in active roles like rescuers and emergency crews, is vital for making quick decisions and managing crises effectively [2]. In this paper we are describing the prototype of a patch-like sensor to address post-attack activities related to managing wounded victims, thus increasing their chances of survival. The sensor is intended to be placed on victims' chests after initial triage, with a focus on those labeled yellow and green according to the START (Simple Triage and Rapid Treatment) triage approach [3]. The device would issue alerts when the medical status changes from green-to-yellow (GtoY) or yellow-to-red (YtoR), thereby elevating the priority of affected victims.

Our primary research goal is to develop an integrated sensor system capable of real-time health monitoring and alerting, enhancing the efficiency and accuracy of emergency triage processes. The main contribution of this proposed solution is the integration of sensors for monitoring HR, RR, and other parameters, providing real-time monitoring of the health status of emergency crews or generating immediate alerts if the patient's health status deteriorates during the triage process. Additionally, the

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integration of Artificial Intelligence (AI) methods, represents a new generation of health monitoring solutions.

The successful development of this merged system is expected to significantly impact the readiness of squads to handle emergencies that may affect crew and victims' health status in real-time.

The paper is organized as follows. The Related Work section describes similar patch solutions. Section 3 provides an overview of the system, including the hardware part, Bluetooth low energy implementation, and the Android Software application. The conclusion is given in the last section.

2. Related Work

In exploring existing research, several studies have addressed the pressing need for continuous patient monitoring and innovative healthcare solutions. Yeri and Shubhangi [4] highlight the necessity of continuous patient monitoring in the face of increasing demands and limited medical resources. Through their IoT-based framework, which incorporates various sensors to measure vital signs, they aim to help the healthcare process, particularly in emergencies. By transmitting data to the cloud for analysis and remote viewing, their system enables healthcare providers to stay informed and intervene promptly when necessary.

In [5], the authors explore the fusion of digital data processing with established medical techniques to enhance patient care both at home and in clinical settings. They present various fall prediction and detection methods, with a particular focus on vital signs monitoring using a triple-axis accelerometer and parameters such as heart rate and temperature. The proposed system, VitaFALL, leverages the Internet of Medical Things technology for timely fall detection and notification of caregivers and doctors via GSM and GPRS modules. Despite observing some delays in detection, the system achieves promising results, with an 85% accuracy rate and high specificity and sensitivity in detecting directional falls.

Minglei et al. [6] present a real-time monitoring system designed to cater to the needs of the elderly, individuals experiencing sub-optimal health, and those suffering from insomnia. This system enables continuous monitoring of sleep quality and heart rate fluctuations, facilitating concentrated and effective management of sleep states for various demographics. Utilizing vital signs monitoring devices, including heart rate and breathing rate sensors, along with bed state detection, the system captures and transmits data to a cloud platform server via WiFi. The server then conducts screening, analysis, and calculation of vital signs data and dynamic changes, enabling individuals under monitoring to access their daily vital signs and sleep state information through a mobile terminal. Managers can also monitor user data and states in real-time, facilitating prompt detection of vital signs changes.

In [7], the address the challenges faced by the healthcare sector in underfunded regions like Bangladesh, aiming to bridge the gap by developing an affordable and accessible real-time health monitoring system. Their solution utilizes Internet of Things (IoT) sensors connected to an Arduino microprocessor to measure vital body signs, which are then transmitted to a smartphone via Bluetooth. This data is further processed and displayed on an Android application interfaced with a web-based platform, facilitating remote communication between patients and doctors in real-time. The system underwent successful testing on multiple real-human subjects, demonstrating high accuracy in monitoring vital signs such as body temperature, heart rate, ECG, SpO2 levels, blood pressure, and glucose levels. Notably, the integration of IoT-based patient monitoring with telemedicine distinguishes this system from existing solutions, offering a comprehensive approach to remote healthcare management and potentially improving global life expectancy.

Our research uniquely focuses on developing a wearable patch-like sensor system for real-time monitoring and alerting specifically tailored to post-attack scenarios, addressing the critical needs of first responders and victims in emergencies.

3. System overview

The system comprises a patch device that gathers data directly from an individual through multiple sensors, conducting initial processing. The patch device collects ECG and PPG signals, and body temperature. The primary computations carried out by the patch include calculating heart rate (HR) and respiratory rate (RR) based on ECG signal processing and executing START triage (Fig. 2) while alerting to any state changes. The algorithm used for HR and RR estimation is the Pan-Tompkins algorithm and the details about it and the obtained results are presented in [8].

Additionally, there is a tablet that receives data from the patch. The tablet estimates oxygen saturation (SpO2) from PPG and blood pressure (BP) from ECG+PPG using trained AI models. The AI models for SpO2 estimation are elaborated in [9], while for BP in [10].

There is also a laser-induced graphene sensor (LIG) which is used also for HR and SpO2 estimation as a backup and reference [11, 12].

The simplified symbolic system design used in this project is shown in Figure 1. It represents the basic concept of acquiring samples of different signals using various sensors and transferring them to more computationally powerful devices for creating big data databases, processing the signals using neural networks or artificial intelligence and more. To make the smart patch capable of doing this, it needs the control logic which consists of low-power, inter-compatible hardware driven by well-designed firmware (software that runs directly on the hardware).

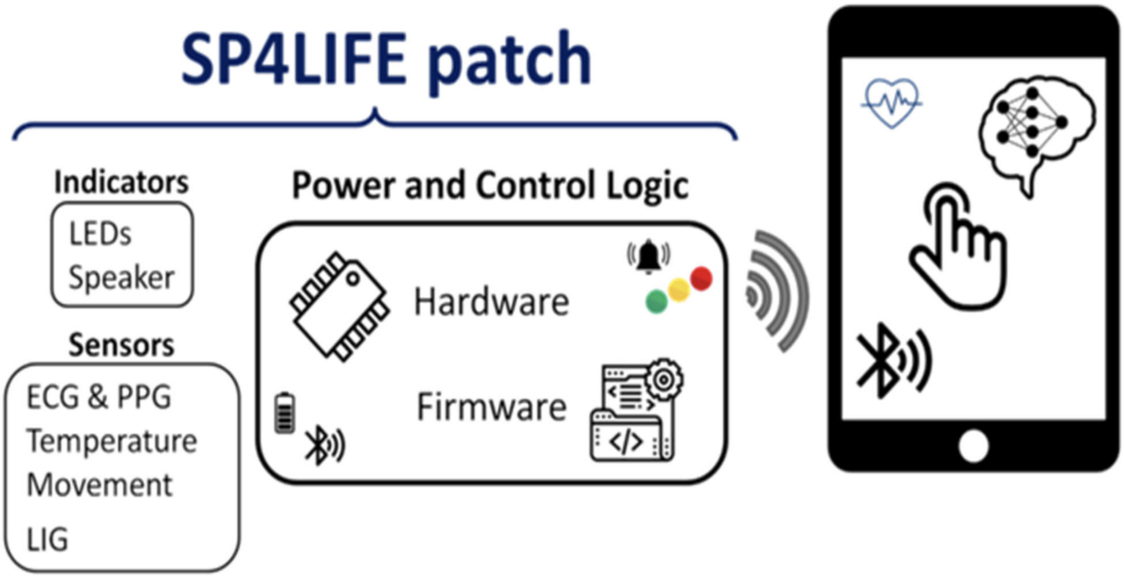


Figure 1: Smart patch with monitoring tablet - system block diagram.

The patch assesses whether an individual's vital signs (HR and RR) deviate from the anticipated values, referencing the guidelines and values outlined in the triage process depicted in Figure 2. In the event of a patient transitioning from a green to yellow or yellow to red status, the alarm is triggered, accompanied by sound and the blinking of a light diode.

The functions of the smart patch and their communication with the monitoring tablet were first checked in laboratory conditions and the obtained values (Heart rate, Respiratory rate, Temperature, Blood pressure, Oxygen saturation) were compared with data from reference devices. Based on the tests, also the algorithms for BP and SpO2 estimation were improved.

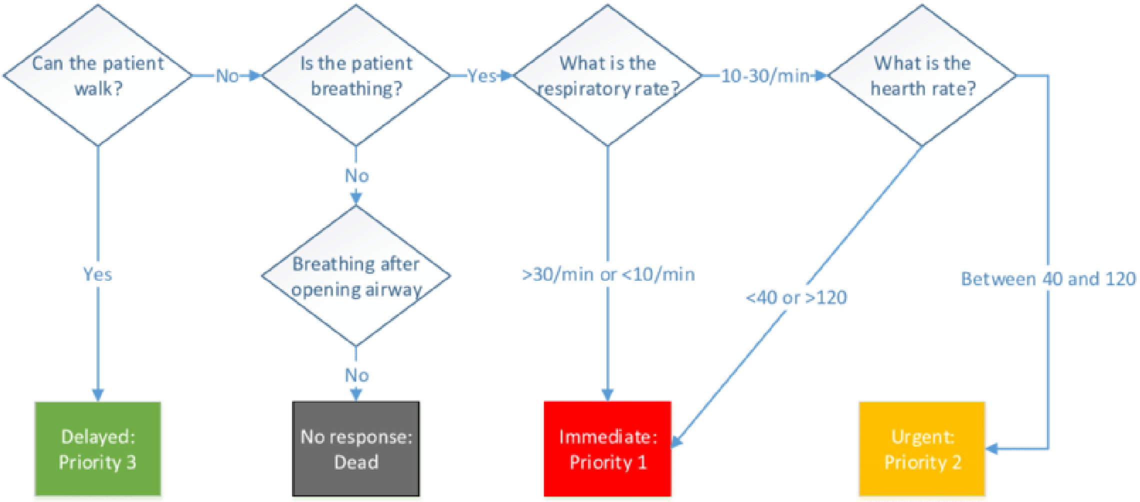


Figure 2: START triage decision tree

3.1. The Smart Patch Hardware

The SmartPatch utilizes the MAX32630 ultra-low-power microcontroller, equipped with 2MB flash memory and 512kB RAM. Its single Arm Cortex M4 core, featuring an FPU, operates at 96MHz. Facilitating communication with the tablet, the PAN1780AT Bluetooth module is employed, supporting the LR (long range) mode of BT v5.0 LE standard. This module is connected to the microcontroller through an asynchronous serial interface (UART) with flow control and is managed through AT commands. It includes MAX86150 ECG&PPG sensor, laser-induced graphene sensor (LIG), STS35-DIS temperature sensor, inertial measurement unit – BMI323, power management unit MAX77650, piezo speaker driver PAM8904, and 4 high-intensity LEDs. The basic hardware block diagram, which also mimics the firmware structure, is shown in Figure 3.

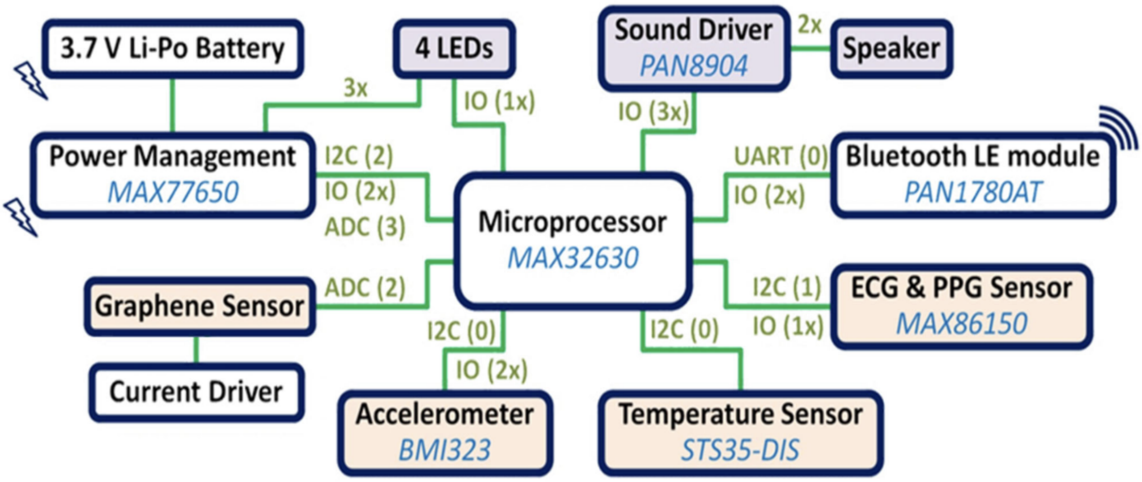


Figure 3: Smart patch hardware block diagram.

Figure 4 illustrates the assembly of components on the Smart Patch. To construct an individual patch, the control board must be flexibly linked with two holder boards. The battery and beeper will be positioned above the control board and enclosed within a sealed, biocompatible, flexible packaging. The complete patch will be fastened together using two snaps along with an adhesive strip containing two ECG electrodes, an adhered LIG sensor, and an aperture for PPG and temperature sensors.

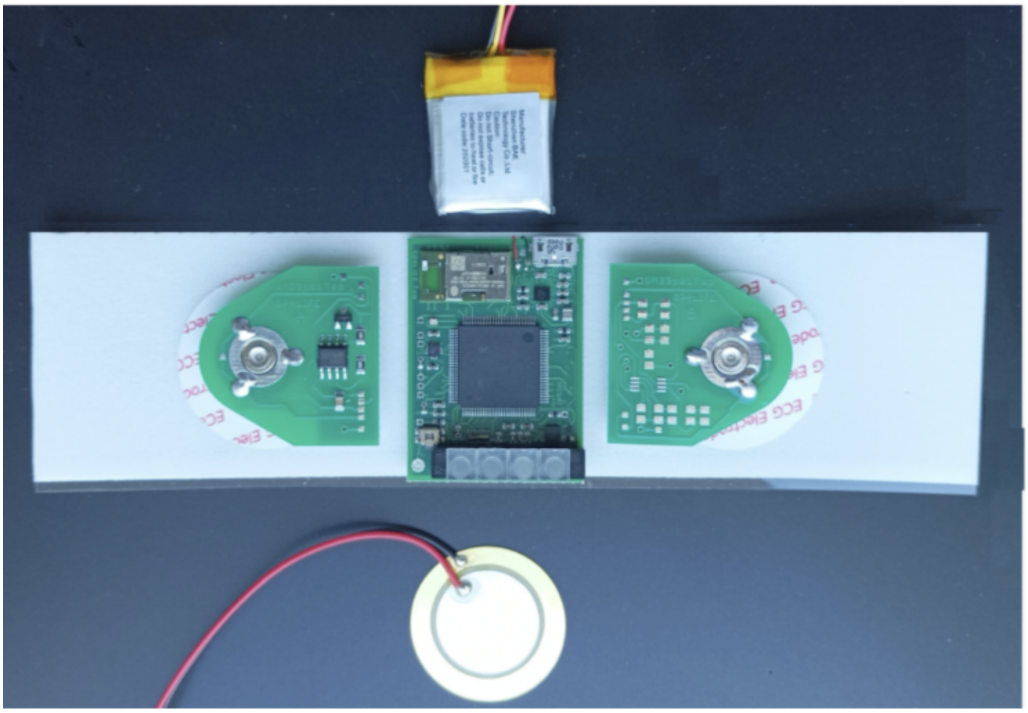


Figure 4: Smart Patch prototype configuration (without packing): set of boards with electronics, beeper, battery, adhesive strip with ECG electrodes – top view.

For the sensor prototype of the smart patch, it was necessary to adapt existing firmware driver APIs accessible online or to create new APIs if they were not available:

- API driver for temperature sensor STS35-DIS enables composing and sending configuration bytes by calling representatively named functions. It also performs conversion from raw data to temperature in °C;
- API driver for Inertial Measurement Unit BMI323 was developed. It is a reduced and completely new API for configuring and data acquisition because the driver directly available from the manufacturer did not fit our application, because incorporating all features of the device made the driver slow;
- Simple API driver for piezo buzzer driver PAM8904 was created to simplify code writing;
- API driver for selected Power Management Unit MAX77650 was developed for comfort programming of the IC. API is logically structured into separated blocks with various functions corresponding to the IC's internal hardware (Global Resources, Charger, LDO, Buck-Boost Converter, and Current Sinks).

3.2. Bluetooth Low Energy connection

The system uses Bluetooth Low Energy for sending data to the tablet. To better understand the complexity of Bluetooth low-energy communication, we will briefly explain the most important parts. There are three communication methods, Advertising, Discovery, and Connection [13].

Advertising is the public transfer of short data and server device information. Discovery is scanning by client device which results in a list of nearby advertising server devices. Connection is a private 1-to-1 data exchange (with a selectable security level).

In these communication methods, there are different BLE roles, Server and Client. The server device (a smart patch in our case) can communicate using advertising (transmitting device information) and connection. In connection, it can receive data from the client and notify (send data to) the client. The client device (Android tablet in our case) can communicate using discovery (looking for advertising devices) and connection. In connection, it can write data to the server and receive notifications from the server if the client subscribes to them. The notifications are triggered by the value of the characteristic in the server device. Subscribing to notifications is done by the client by writing to the corresponding descriptor in the server device. The actual data transfer in connection happens in the value of the characteristics. The BLE server device structure is quite complicated regarding extensive and constantly updated Bluetooth Core Specifications. To keep this explanation short and to better understand these previously mentioned terms, refer to the simple structure shown in Figure 5.

The advertising data are public, thus anyone can receive them. However, the recipient still has to know how to decode the bytes carrying the data. We transfer just the basic short data (ID, RR, HR …) in the advertising, but still to increase privacy, we use a Coded PHY (Coded Physical Layer) transfer layer because devices are not usually discovered on this PHY. This PHY also brings another advantage of longer communication distances. After connection, the transfer of all available data on the smart patch starts only if the correct key or password request is sent from the client (tablet) to the server (patch).

The advertised data by the patch at this point are patch ID, status bit field representing the state of the patch sensors and algorithms, heart rate, respiratory rate, body surface temperature, patch battery voltage, and version of the patch firmware.

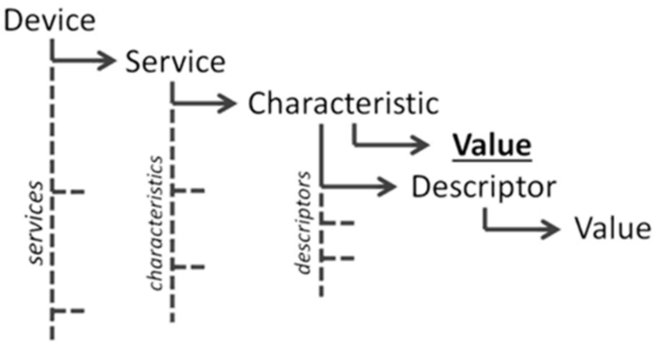


Figure 5: Bluetooth Low Energy Server device structure.

3.3. Software Application

The Android application is developed in Android Studio IDE [14] using Kotlin language [15]. The GUI uses Jetpack Compose [16]. The Bluetooth Low Energy interface is from Standard Android Libraries to have access to the newest implemented features. For compatibility with Python modules for the SpO2 and blood pressure estimation, ChaquoPY [17] is used. It is necessary for the simplified development of artificial intelligence predictive neural network models in Python.

First, a short brief of the main application capabilities:

- one Android device can show multiple advertising patches;
- one Android device can connect to multiple patches;
- any Android device can connect to any patch;
- data can be stored in a file for later examination;
- values on the screen are updated each second;
- battery and Bluetooth signal quality information;
- measured signals (ECG, PPG) can be displayed in a selectable timebase;
- AI predictive models are computed in parallel threads;
- received measured data are converted and processed in parallel threads.

The most complex part of the application is the Bluetooth Low Energy backend. In discovery mode, it scans for advertising devices. When the BLE server device is found, it checks if it has the correct device name prefix if its extended advertising includes the correct service data structure, and if the value of this structure has a minimal required length. If all these conditions are satisfied, the BLE device is recognized and it is added on the screen or if it is already there, values sent by it are updated. In connection mode, the low-level hardware connection establishment happens "in the background".

Then, there are actions that the code must perform using the GATT (Generic Attribute Profile) interface. If a connection is established, the application discovers services in the BLE server. If there is the correct service in the "on discover services" callback, it discovers characteristics. If there are correct characteristics in service, it reads and updates the value of the CCCD descriptor (Client Characteristic Configuration Descriptor) of one of the characteristics. If the descriptor is successfully written in the "on descriptor write" callback, it writes a password request to the other characteristics, indicating the subscription for notifications. Then, the data will be received from the patch in the "on characteristic changed" callback.

3.3.1. Application beta testing

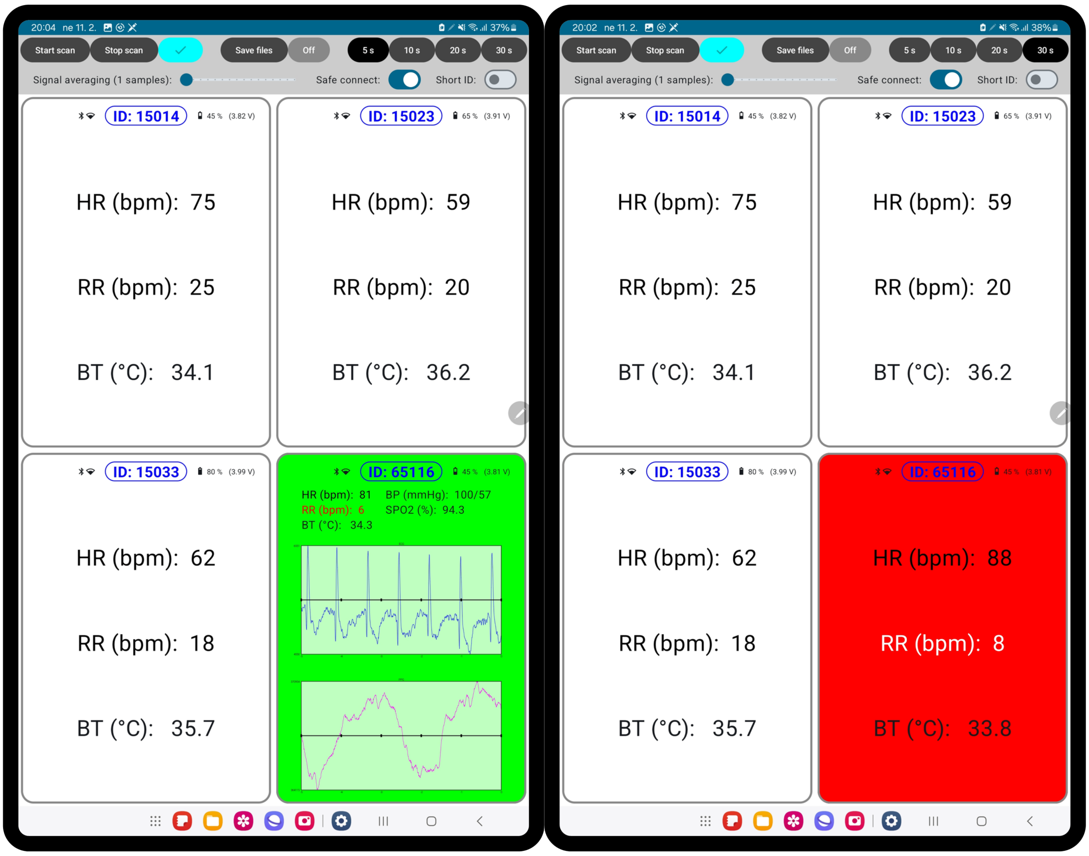
The application uses Bluetooth LE Long Range Coded Physical Layer for both discovery and connection mode. When the application starts, it checks if it has all the necessary permissions. If they are not allowed, the application asks the user for their approval. If the Bluetooth feature of the device is disabled, the application prompts the user to allow it to turn the Bluetooth on.

The application can run with both, the portrait and landscape orientation of the screen. The user interface has control buttons at the top of the screen. There are buttons for controlling the Bluetooth LE discovery (Start scan – Stop scan). If there are more available smart patches, they will appear on the screen. Then there is a button to enable or disable storing of received raw data after connection.

In the top right part of the screen, there are buttons for selecting the plot time base of displayed ECG and PPG signals on connected patch panels. Most to the right there are two switches: the first one changes the behavior of the patch panels. When the switch is checked, only the ID field in the patch panels acts as a button to change the state of the connection (connect to the smart patch or disconnect from the patch). When the switch is unchecked, the whole patch panel is clickable. Thus, clicking anywhere inside the patch panel will cause the connection change. In some cases, the medical personnel do not have enough time to hit precisely one button, so they can touch the patch panel anywhere. On the other hand, when the user wants to point out some features of the displayed signals or values, he might accidentally touch the screen and cause unwanted patch disconnection. This is the reason for this control element, so the users can adapt the control behavior based on the situation. The second switch turns on/off the display of a short patch ID on the top of the patch panel.

3.3.2. Patch panels

When the smart patch is discovered, its panel displays just the values that are computed or measured on the patch. Currently, these are the heart rate (HR), respiratory rate (RR), and body surface temperature (BT). The blood pressure (BP) and SpO2 are computed in the Android device (tablet) using artificial intelligence predictive neural network models, so they are displayed only after the Android device connects to the patch (and reads the raw data from the patch). It is the same with plots of ECG and PPG signals: they are displayed only during connection because the signal data are streamed in real-time only when the patch is connected. The smart patch panel background is white when it is discovered, not connected, and the HR and RR are in the "yellow" patient limits of the START triage procedure. The vital signs are black in default. When HR and/or RR are/is out of bounds of these limits, the panel background turns red to indicate that the patient needs medical attention. The out-of-bounds vital sign value will change its color to white (on a red panel background). When the patch is connected, its panel background changes to green to indicate the active connection. During connection, the out-of-bounds values will be red (on the green tab background). Some screenshots from the application documenting the above-mentioned features and functions are in Figures 6 and 7.



ID: 15014 45 % (3.82 V)
HR (bpm): 75
RR (bpm): 25
BT (°C): 34.1

ID: 15023 65 % (3.91 V)
HR (bpm): 59
RR (bpm): 20
BT (°C): 36.2

ID: 15033 80 % (3.99 V)
HR (bpm): 62
RR (bpm): 18
BT (°C): 35.7

ID: 65116 45 % (3.81 V)
HR (bpm): 81 BP (mmHg): 100/57
RR (bpm): 6 SPO2 (%): 94.3
BT (°C): 34.3

ID: 65116 45 % (3.81 V)
HR (bpm): 88
RR (bpm): 8
BT (°C): 33.8

Figure 6: Android application GUI.

ID: 65116 40 % (3.8 V)
HR (bpm): 85 BP (mmHg): 105/63
RR (bpm): 24 SPO2 (%): 95.0
BT (°C): 34.4

Figure 7: Detailed screen for one patient.

The development of mathematical models for health status was integrated into the smart patch processor using the C programming language, specifically through the START procedure. This integration facilitates the generation of alerts when the health status transitions from the Yellow label to the Red label is identified.

Additionally, the most effective artificial intelligence (AI) models were selected and incorporated into the Android application. This enables the AI predictive neural network (NN) models for blood pressure (BP) and SpO2 estimation to undergo computation in parallel threads. This parallel processing capability enhances real-time processing power, enabling the extraction of desired features in real-time. The most important task of the Smart patch is to perform part of the triage procedure continuously in real-time. If the respiratory rate is in bounds from 10 to 30 breaths per minute (including) and the heat rate is in bounds from 40 to 120 beats per minute including, in other words: $RR \in <10; 30> \wedge HR \in <40; 120>$, the patient status is Yellow. If this condition is not satisfied, hence HR or RR is out of these bounds, the patient status is red. In the tablet application, there is a programmable hysteresis to prevent the possible rounding error to cause false fast switching between states. The hysteresis of one count (±1) has been used. If there is a change in patient triage status, the appropriate LED is lighted up (red or yellow) and the other one is turned off (yellow or red) and the corresponding sequence of tones starts to play for the required amount of time.

4. Conclusion

In this paper, we have presented a comprehensive approach to the development of a Smart System for Real-time Monitoring of Vital Parameters. Our research addresses the critical need for continuous monitoring of vital signs in both military and civilian contexts, particularly during high-stress situations such as terrorist attacks, IED incidents, or rescue operations.

We proposed the design and development of a prototype patch-like device capable of gathering and analyzing vital parameters including respiration rate, heart rate, blood oxygen saturation, blood pressure, and body temperature in real-time. Through the integration of Artificial Intelligence (AI) models, our system enables the prediction of blood pressure and oxygen saturation and issues alerts in the event of any health status changes, thus assisting medical personnel in making timely decisions.

The system incorporates advanced features such as Bluetooth Low Energy connectivity, real-time data processing, and graphical user interfaces for visualization of vital signs. Furthermore, we have demonstrated the efficacy of our system through laboratory testing and validation, comparing the measured data with reference devices and refining algorithms for improved accuracy.

Our research lays the groundwork for further innovation in this field, with ongoing efforts focused on refining the hardware, optimizing software algorithms, and conducting real-world trials to validate the effectiveness of our system in diverse operational environments.

However, our study has several limitations. The prototype has been primarily tested in controlled laboratory environments, and its performance in real-world scenarios remains to be thoroughly evaluated. Additionally, the system's reliance on Bluetooth connectivity may pose challenges in areas with significant interference or limited connectivity. The AI models require further optimization and extensive training with larger datasets to enhance their predictive accuracy and reliability.

Future research will focus on refining the hardware, optimizing software algorithms, and conducting real-world trials to validate the system's effectiveness in diverse operational environments. This will include integrating additional sensors, developing more sophisticated AI algorithms, and implementing robust security measures to ensure data privacy and integrity.

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