Journal of Human Centered Technology Vol. 2: No. 1 (2023) 18 – 25

Journal of Human Centered Technology

E-ISSN: 2821-3467
https://humentech.utm.my

Blood Oxygen Saturation and Heart Rate Monitor for Home-Based Continuous Monitoring

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Received 10 October 2022; Accepted 16 November 2022; Available online 06 February 2023
https://doi.org/10.11113/humentech.v2n1.36

Abstract:
Pneumonia and COVID-19 are the most infected infectious diseases that deteriorate health of all range of people. If the early treatment is not provided, it may lead to severe heart disease and eventually to mortality. Therefore, continuous heart rate (HR), as well as blood oxygen saturation (SpO_2) monitoring can help to detect abnormalities early. As a result, this paper presents a combination of portable continuous SpO_2 and HR monitor which focuses on the improvement of internal design and graphical user interface of the mobile application. In this system, MAX30100, a photoplethysmography (PPG) sensor, was used to measure SpO_2 and HR. Then, the signal was transmitted to Arduino Nano as the master microcontroller to process all acquired data from the sensor. The device was integrated with Android-based mobile application through Bluetooth communication, for displaying the result of the measured real-time parameters continuously and for battery status indication. Quantitative measurements showed that the precision of the circuit system implemented for HR and SpO_2 were 99.16% and 99.06%, respectively. This system would improve the working efficiency and life efficiency of the healthcare provider and public.

Keywords: Pneumonia; Photoplethysmography; Pulse oximeter; Heart rate; Blood oxygen saturation

1. Introduction

According to the United Nations International Children's Emergency Fund (UNICEF), pneumonia has caused 800,000 deaths annually [1]. The most inadequate factors which cause mortality in pediatrics who are under 5 years old due to pneumonia are the lack of access to healthcare and financial status. Consequently, clinical symptoms may develop in children with severe pneumonia, such as respiratory failure and heart failure, which could damage the body system [2]. Besides, evidence shows that a decrease in blood oxygen levels is a critical indicator that a COVID-19 patient's health worsens [3]. Therefore, this deadly disease can be prevented by early abnormality detection in blood oxygen saturation (SpO_2) and heart rate (HR) through simple interventions such as pulse oximetry [4].

SpO_2 refers to the oxyhemoglobin saturation in the bloodstream, which is essential in evaluating the saturation of the hemoglobin bound to the oxygen. SpO_2 reading is considered abnormal if it is less than 90%. Meanwhile, HR is a crucial vital sign for physiological and clinical assessment. Both these parameters can be measured through the photoplethysmography (PPG) technique. PPG is based on the optical design, which utilizes the variation in light absorption of the hemoglobin during blood circulation [5, 6].

The pulse oximeter is the standard non-invasive device for measuring SpO_2 based on PPG techniques in hospitals and homes. Today's demand is for pulse oximeters based on a home environment which makes the result interpretation relatively easy and significantly reduces the patient load in the hospital during a disease pandemic. These days, healthcare professionals (HCPs) have revolutionized the use of mobile devices in numerous aspects of clinical practice. The rising accessibility leads to the rapid development of mobile devices in clinical practice and medical software application features. Mobile applications can closely monitor patients' health, collect medical data, and assist a person living independently. Therefore, this mobile application allows the user to have general surveillance of one's health without the need to go to clinics and hospitals [7]. In addition, patients and caregivers could save time and money as they can track detailed information frequently via medical applications.

Many existing projects also focus on home-based pulse oximeters. For instance, the project was done by Guerra Andrea Alejandra [8], focusing on the pulse oximeter intended for SpO_2 and HR monitoring equipped with alarms and software for the computer application, which act as diagnostic tools. Nevertheless, this project does not come with a mobile application that would be much easier for the parents, guardians, or caretakers to track the parameters. Furthermore, it shares the same drawbacks as the Mohajerani *et al*. [9] and Rahim *et al*. [10] projects, as the device itself does not provide the battery indicator through the software and only stores the database of the patients' parameters information. Another research by Khrishna and Sampath [11] proposed the implementation of the Internet of Things (IoT) in pulse oximeters primarily intended for real-time monitoring of patient's vital statistics, such as SpO_2, HR, and body temperature. However, the device has the limitation where the mobile application does not support real-time trend analysis.

Therefore, this study aims to modify an in-house wireless pulse oximeter focusing on SpO_2 and HR monitoring and enhancing the mobile application for real-time continuous monitoring purposes with a user-friendly graphical user interface (GUI).

2. Methodology

Home-based SpO_2 and HR monitoring is a standalone device where the system is associated with the mobile application. MAX30100 photoplethysmography (PPG) sensor is used in this project to monitor SpO_2 and HR as measured parameters. The measured parameters are acquired from the transmission of two light emitting diodes (LEDs) which are RED and infrared LED (IR LED). Arduino Nano is used as a microprocessor to process the SpO_2 and HR measurements. The in-house pulse oximeter was improved by being replaced with an Arduino Nano microprocessor due to its compact size compared to the existing ESP32 microprocessor. The measured results will be sent to the mobile application via the HC-05 Bluetooth module for real-time continuous monitoring display. In addition, the mobile application also helps to check the battery status of the device. Figure 1 shows the overall system architecture of the reproduced home-based pulse oximeter.

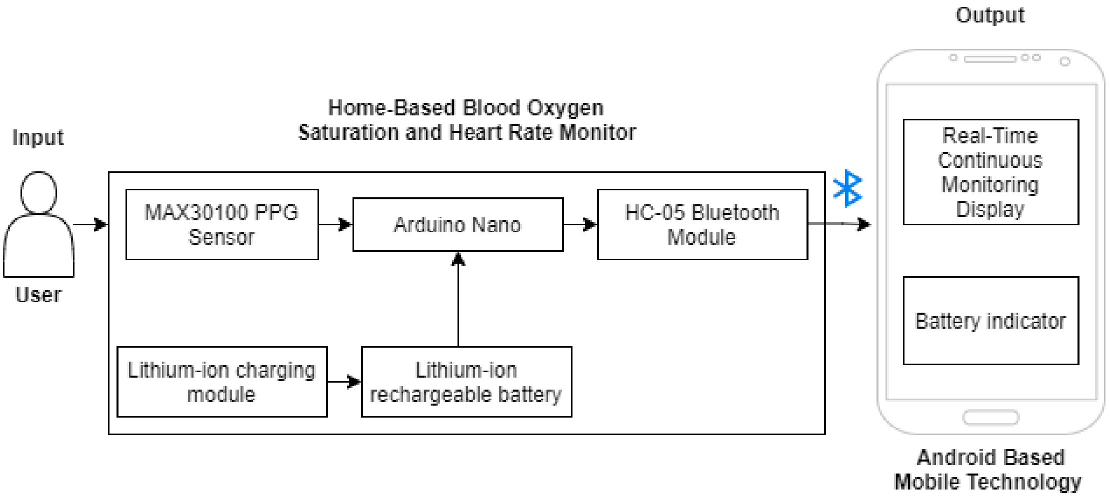


Figure 1. System architecture

Before starting the measurement, user must activate the Bluetooth connection in the mobile application to be connected to the device. Then, the user must place the sensor on the finger to start the SpO_2 and HR measurement. The result will be directly displayed in the mobile application. If the abnormality is detected, an alert message will be displayed together with the abnormal results to warn the user about the abnormalities. The system workflow is demonstrated in Figure 2.

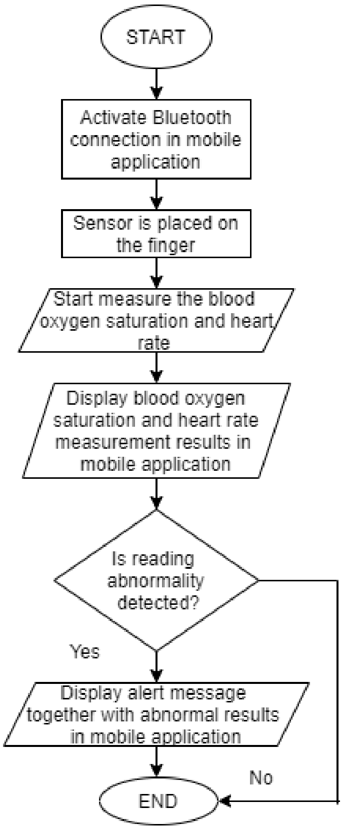
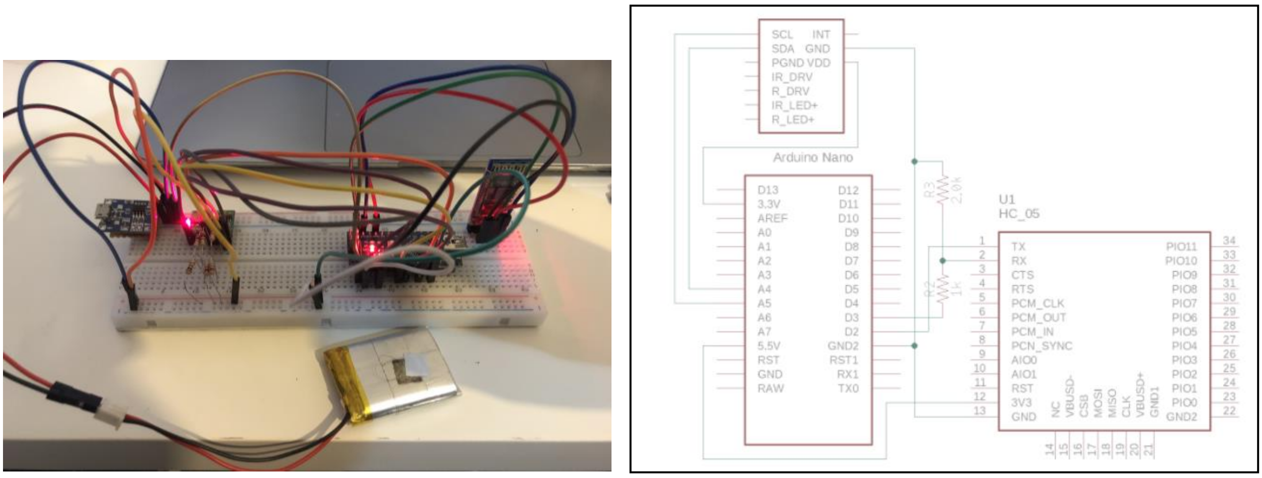


Figure 2. System workflow

2.1 Hardware circuit design and assembly

Figure 3 (a) shows the complete circuit on the protoboard, which integrates with the MAX30100 PPG sensor, Arduino Nano, HC-05 Bluetooth module, Lithium-ion battery, and Lithium-ion charging module that have been proposed for SpO_2 and HR monitoring. Figure 3 (b) shows the schematic diagram of the components involved in this project.



(a) (b)

Figure 3. (a) Complete circuit on breadboard and (b) circuit schematic diagram

2.2 Bluetooth acquisition

Bluetooth connection initiates the activation of the Bluetooth module in connecting the Bluetooth of the device and smartphone. Once the Bluetooth module is activated, the Bluetooth signal will be transmitted, which is then discovered by the device and smartphone. The smartphone will be paired to the device once the Bluetooth of both devices is detected. However, if both devices are not paired, the activation process of Bluetooth is repeated in the device and smartphone. Once both devices are paired, the output measurement is transmitted to the smartphone and displayed in the mobile application. The output shows real-time data, which is responsible for monitoring. Reactivation of the Bluetooth module is needed if there is no data display in the mobile application. Figure 4 shows the low-level technical flowchart of Bluetooth connection acquisition.

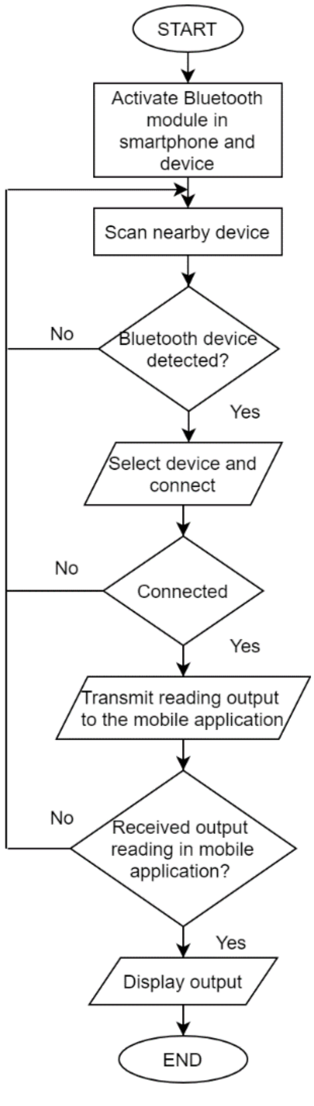


Figure 4. Low-level technical flowchart of battery status acquisition

2.3 Battery status acquisition

Measurement of the battery level begins with an analog input of the battery, which receives by the microprocessor. The analog reading is then converted into a digital value, representing the battery's voltage level. The battery output is then measured in percentage (%), displayed in the mobile application via Bluetooth. Figure 5 shows a low-level technical flowchart of battery status acquisition.

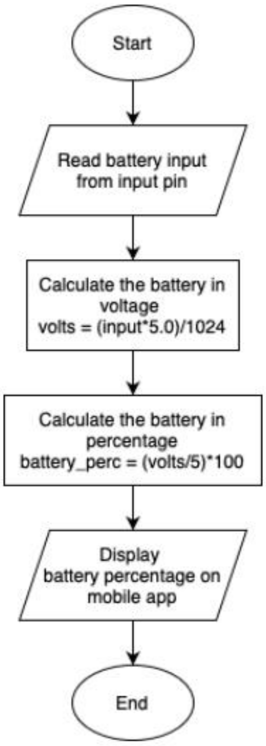


Figure 5. Low-level technical flowchart of battery status acquisition

2.4 Android mobile application

The mobile application is developed using Android Studio, a platform for creating suitable quality mobile applications supported by Android devices. Throughout the development process, Java is used to code the user interface and the main activity, which controls all the functions in the mobile application. This mobile application runs on Android version 9 with Application Programming Interface (API) level 28. In this project, the Android mobile application's primary function is checking the battery status and analyzing the real-time monitoring.

2.4.1 Battery status indication

This sub-section explains the battery indicator of the device, where the user can track the battery level of the device. The charging status and the battery percentage are displayed on the mobile application. The image of the battery status will vary accordingly depending on the available battery percentage. For example, if the battery percentage exceeds 90%, the battery image will display a 'bat100' image. However, if it is less than 30%, the battery image will show a 'bat20' image. In addition, the battery status will show as "Charging" when the device is on charging and "Discharging" when the battery is not charging. Figure 6 shows the sample output of battery charging and discharging.

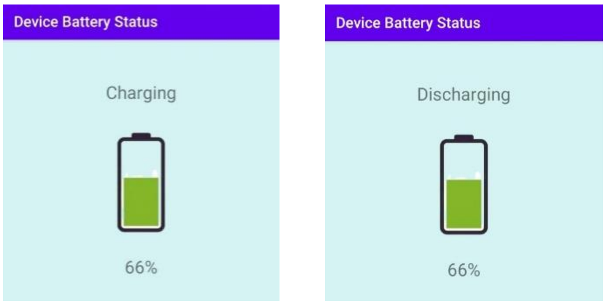
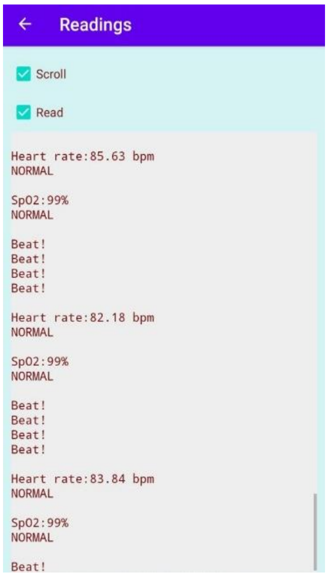


Figure 6. Battery charging and discharging

2.4.2 Real-time monitoring display

The output of SpO_2 and HR will be continuously displayed together with the warning message if abnormalities are detected. The user must ensure the device and smartphone are connected through Bluetooth for continuous reading display. The analysis page where the measured reading is displayed is shown in Figure 7.



```
Heart rate:85.63 bpm
NORMAL

Sp02:99%
NORMAL

Beat!
Beat!
Beat!
Beat!

Heart rate:82.18 bpm
NORMAL

Sp02:99%
NORMAL

Beat!
Beat!
Beat!
Beat!

Heart rate:83.84 bpm
NORMAL

Sp02:99%
NORMAL

Beat!
```

Figure 7. Real-time monitoring analysis

3. Result and Discussion

The reproduced prototype of this project includes a MAX30100 PPG sensor, Bluetooth module, and microcontroller and is supported by a mobile application for real-time monitoring. The user will need to place the finger on the sensor, and the output of HR and SpO_2 is continuously displayed on the mobile application through the Bluetooth connection, as shown in Figure 8.

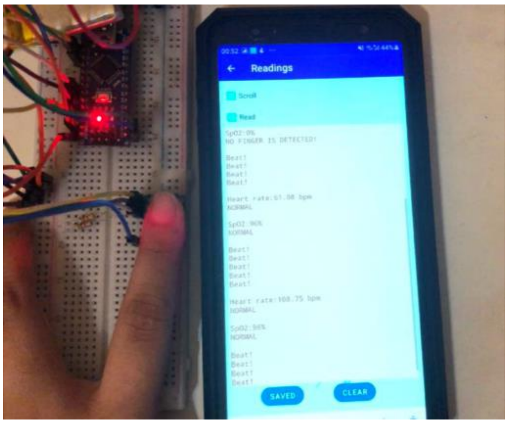


Figure 8. Reproduced in-house prototype on protoboard circuit and sample output in mobile apps

The SpO_2 and HR measurement accuracy test is conducted to analyze the device's performance. A total of 30 readings of SpO_2 and HR are collected using both the Oxitech pulse oximeter and the proposed device from a healthy adult female subject. The readings obtained from the Oxitech pulse oximeter are compared with those obtained from the proposed system. The accuracy of the proposed system is then calculated using the following mathematical expression (1). Finally, based on the overall readings, the average accuracy of the measured parameters is tabulated in Table 1.

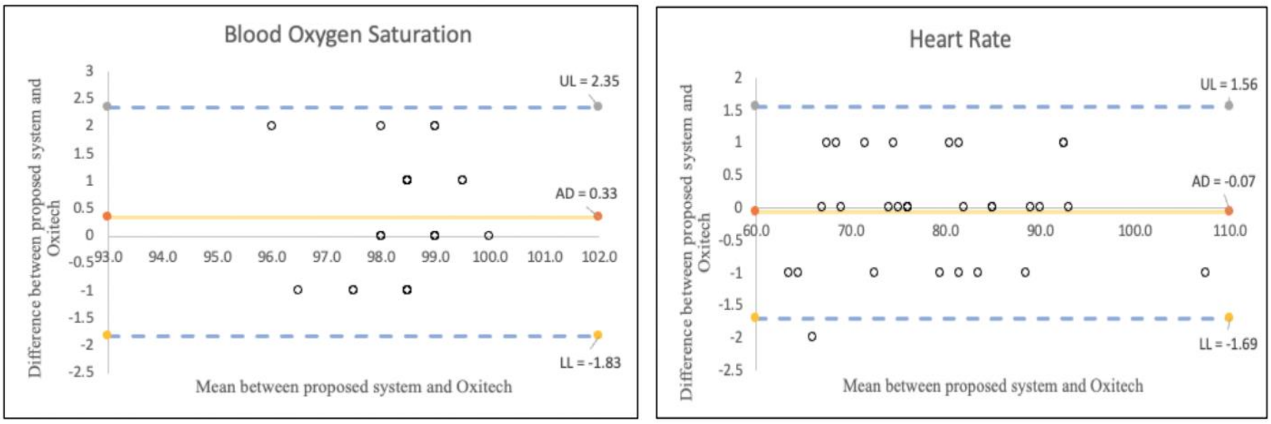
$$\text{Accuracy} = \frac{|(\text{theoretical value} - \text{experimental value})|}{\text{theoretical value}} \times 100\% \qquad (1)$$

Table 1. The average accuracy of SpO_2 and HR measurement

Measured Parameters	**Average Accuracy (%)**
Heart rate (HR)	99.16
Blood oxygen saturation (SpO_2)	99.06

HR and SpO_2 differ by ±0.84% and ±0.91%, respectively. The accuracy percentages are highly encouraging to prove that the SpO_2 and HR monitoring for the proposed system is acceptable.

The accuracy results were further analysed using Bland-Altman statistical analysis. The test was carried out to determine whether the suggested device and the benchmark systems differed or were comparable. Figures 9 (a) and 9 (b) demonstrate the Bland-Altman plot illustrating the commonalities between the proposed system and the Oxitech pulse oximeter for SpO_2 and HR, respectively. Table 2 shows the Bland-Altman results for the SpO_2 and HR measurements.



(a) (b)

Figure 9. Bland-Altman plot for: (a) SpO_2 and (b) HR

Table 2. Bland-Altman results for SpO_2 and HR measurement

Measured Parameters	**SpO_2**	**HR**
Average difference	0.33	-0.07
Upper limit	2.35	1.56
Lower limit	-1.83	-1.69
Boundaries of agreement (%)	96.7	96.7

The error in the SpO_2 measurement between the proposed device and the Oxitech pulse oximeter was within the limits of agreement (96.7%), with the upper and lower limits of 2.35 and -1.83, respectively. The average difference between these two devices is 0.33. Meanwhile, the error of HR measurement between the proposed device and Oxitech pulse oximeter was within the limits of agreement of 96.7% with the upper and lower limits of 1.56 and -1.69, respectively. The average difference in HR measurement between these two devices is -0.07. Few HR and SpO_2 values that fell beyond the agreement lines are presented in Figures 9 (a) and 9 (b). According to previous studies of Bashar Fakri *et al.* [12] and Yang *et al.* [13], limits of agreement were indicated only if the data were within 95%. Hence, the proposed study is comparable to previous studies. To conclude, based on the following results, the Bland-Altman study shows that the proposed system and benchmark systems agree very well.

Battery performance is tested by comparing the battery percentage, which is available through the serial monitor of the Arduino IDE. The battery shown from the serial monitor is almost similar to the battery status in the mobile application. When the battery in the device was charging, the battery indicator in the mobile app showed the 'charging' status. Once the charger is removed from the battery, the battery status shows 'discharging,' indicating that the battery was not in charge mode. The Bluetooth performance is evaluated by assessing the Bluetooth range accessible for connection. Along with multiple tests, the maximum capacity was determined to be 9.7 m, a typical range offered by most Bluetooth devices.

4. Conclusion

Home-based SpO_2 and HR monitoring allow early detection of potential diseases. Furthermore, implementing the Android mobile application for real-time measurement analysis offers an alternative for users to keep track of their health at home while keeping up with their daily routines.

This monitoring system positively impacts the public community in this busy working era. Early detection allows for immediate treatment and reduces the mortality rate in youngsters. This is because the young generation will be our future generation who will play an essential role in the country's growth as they are the most critical asset of future development. Therefore, good care is needed to produce an excellent future generation. In short, this product would improve the healthcare provider and public's working and life efficiency.

Acknowledgment

The Ministry of Higher Education partly supports this work under the Prototype Research Grant Scheme (PRGS/1/2019/TK04/UTM/02/12).

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