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A Portable and Affordable Photoplethysmography (PPG)-Based Health Monitoring Solution for Low-Resource Settings

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Abstract: *This study presents the design and implementation of a real-time, cost-effective health monitoring system using Photoplethysmography (PPG) technology. The system aims to address the limitations of access to healthcare diagnostics in low-resource settings by providing a portable, affordable solution for continuous monitoring of vital physiological parameters. The proposed system utilizes a neonatal/adult PPG sensor equipped with red (660 nm) and infrared (940 nm) LEDs in a transmission configuration to capture pulse signals through the fingertip. The electrical output from the photodetector is processed through a transimpedance amplifier and digitized via an Arduino Uno microcontroller. Signal filtering and physiological parameter extraction—including heart rate, respiration rate, and oxygen saturation (SpO_2)—are performed using MATLAB. Wireless data transmission is enabled by an HC-05 Bluetooth module, allowing seamless remote monitoring via smartphones or computers. Comparative testing with a commercial pulse oximeter demonstrated a strong correlation in readings, validating the system's accuracy. This approach significantly enhances access to primary diagnostic tools in rural healthcare environments, potentially reducing morbidity from cardiovascular and respiratory diseases. The project also outlines opportunities for system enhancement through IoT integration and dual-stage amplification for higher signal fidelity.*

Keywords: *Photoplethysmography, Pulse Oximeter, SpO_2, Heart Rate, Respiration Rate, Arduino, Bluetooth, Low-Resource Healthcare*

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1. Introduction

Healthcare inequality remains a pressing global concern, particularly in low-resource settings (Murthy & Adhikari, 2013) where access to diagnostic tools and continuous health monitoring is limited. Cardiovascular diseases (CVDs) and other chronic illnesses are often undetected in many rural and underserved regions of the developing world owing to the inaccessibility of conventional medical equipment. The World Health Organization (WHO) reports that non-communicable diseases (Nowbar et al., 2019), including heart disease, are among the leading causes of premature death globally. For instance, in sub-Saharan Africa, these conditions are often undiagnosed until advanced stages due to infrastructural and financial constraints, resulting in high morbidity and mortality rates.

Photoplethysmography (PPG) is a non-invasive optical measurement technique that detects blood volume changes in the peripheral circulation(Taha et al., 2017). It uses the light absorption properties of oxygenated and deoxygenated haemoglobin to extract physiological parameters, such as heart rate, respiration rate, and oxygen saturation (SpO_2). Owing to its simplicity, low cost, and adaptability, PPG is particularly well-suited for integration into portable and affordable health-monitoring devices aimed at low-resource environments(Taha et al., 2017). With advancements in embedded systems, wireless communication, and digital signal processing, PPG-based systems can now be developed to function reliably outside the traditional clinical settings.

This study presents the design and implementation of a real-time portable health monitoring system utilizing PPG technology. The system features a neonatal/adult pulse oximeter probe operating in the transmission mode with red and infrared LEDs, an Arduino Uno microcontroller for signal acquisition and control, and an HC-05 Bluetooth module for wireless data transmission. The electrical signal generated by the PPG sensor was conditioned using a transimpedance amplifier and subsequently analyzed using MATLAB to extract key physiological indicators(Bansal, 2021). Heart and respiration rates were calculated using frequency-domain analysis, whereas SpO_2 was derived from the ratio of red and infrared absorption signals using an empirically calibrated formula.

Designed with affordability and ease of use, the system is particularly targeted for deployment in rural health clinics and community health programs. It addresses critical healthcare delivery challenges by offering a practical alternative to high-cost commercial devices, thereby enabling the continuous monitoring and early detection of health anomalies. By facilitating remote diagnostics and promoting preventive care, this solution aims to enhance health care outcomes in communities with limited medical resources.

Study Objectives

This study focuses on the following objectives:

1. To study effectively how to obtain physiological parameters (Heart Rate, Respiration Rate and Oxygen Saturation (SpO2)) from a real-time health monitoring system implemented using Red and Infrared Illumination.
2. To design a preamplifier circuit to amplify the signal from the sensor and convert the current into an equivalent output voltage.
3. To develop a MATLAB code for extracting physical parameters from the PPG signal.
4. To evaluate the performance of this system (real-time health monitoring system) against a commercial pulse oximeter by implementing the proposed system and testing a few subjects.

2. Literature Review

Photoplethysmography (PPG) is a simple, low-cost, and non-invasive optical technique used to detect blood volume changes in the microvascular bed of tissue. It has gained significant attention over the past two decades as a reliable means for monitoring vital signs, such as heart rate (HR), respiration rate (RR), and peripheral oxygen saturation (SpO_2). The technique typically employs red and infrared light-emitting diodes (LEDs) to illuminate the skin, with a photodetector capturing the variations in the transmitted or reflected light intensity due to pulsatile blood flow. As healthcare systems move toward remote and wearable technologies globally, PPG's utility of PPG in low-resource settings is increasingly being recognized (Allen, 2007).

The principle underlying PPG is the Beer-Lambert law, which describes the attenuation of light through an absorbing medium, in this case, biological tissue with varying concentrations of oxygenated (HbO_2) and deoxygenated haemoglobin (Hb). Red light (660 nm) is more readily absorbed by deoxygenated blood, whereas infrared light (approximately 940 nm) is absorbed more by oxygenated blood, enabling the estimation of arterial oxygen saturation via the ratio of these absorptions (Yellen et al., 1997). This dual-wavelength approach is fundamental in pulse oximetry, a standard PPG application.

Several studies have confirmed the effectiveness of PPG as a clinical and consumer grade tool. (Bagha & Shaw, 2011) noted that, when implemented properly, PPG can deliver reliable HR and SpO_2 measurements comparable to electrocardiography (ECG) and arterial blood gas analysis, respectively. Furthermore, the ability of PPG to track respiratory rate, derived from modulations in the amplitude or baseline of the waveform, enhances its value in comprehensive health monitoring (Almarshad et al., 2022).

Despite its advantages, PPG technology has several limitations, especially when implemented in dynamic real-world environments. The most prominent challenge is motion artifact interference, which results from voluntary or involuntary movements during the measurement. These artifacts can distort PPG signals, leading to inaccurate parameter estimation (Pollreisz & TaheriNejad, 2022),In this design 3-axis accelerometer was employed to overcome the motion artifacts challenge. Additionally, ambient light and skin pigmentation affect the signal quality. Studies by (Moço et al., 2018) demonstrated that green light exhibits a higher signal-to-noise ratio in superficial blood flow monitoring, but has a limited penetration depth, making red and infrared light more suitable for deeper vascular signals.

In terms of hardware, the integration of microcontrollers, such as the Arduino Uno, has democratized access to PPG system development. These open-source platforms enable researchers and developers to create affordable and customizable health-monitoring systems. Arduino, with its analog-to-digital conversion capabilities and support for pulse-width modulation (PWM), effectively controls the LED operation and collects photodiode signals (Abdullah, 2024). Coupling an Arduino with a Bluetooth module, such as HC-05, enables wireless data transmission, which is a critical feature for real-time monitoring and telemedicine applications in rural areas (Azmin et al., 2022).

Signal conditioning is another vital component for ensuring PPG accuracy. The photodetector's current output is typically weak and requires conversion to a usable voltage using a transimpedance amplifier (TIA). The MCP6021 operational amplifier is often selected for such applications owing to its low noise, wide bandwidth, and low power consumption, which are essential for portable medical instrumentation (Kouhalvandi et al., 2023).Filtering techniques, including band-pass filters with 0.8–5 Hz cutoff frequencies, were applied to isolate the AC component (pulsatile flow) from the DC component (non-pulsatile flow and ambient noise). Studies have shown that appropriately designed filters significantly enhance the accuracy of the HR and RR measurements derived from PPG signals (Chowdhury et al., 2016).

From a software perspective, MATLAB and similar platforms have become invaluable for PPG signal processing. These tools offer robust signal visualization, frequency analysis via a Fast Fourier Transform (FFT), and empirical modeling for SpO_2 estimation. The commonly used SpO_2 equation is as follows:

$$S_P O_2 = 110 - 25R \dots\dots\dots\dots\dots\dots\dots\dots (1)$$

is the ratio of the normalized AC to the DC signals of the red and infrared channels. While this approach provides reasonable estimates, it relies on calibration curves derived from empirical data because of the limitations of the Beer-Lambert law in accounting for light scattering in tissues (Oshina & Spigulis, 2021)

3. Methodology

This project follows a structured design and implementation process that combines hardware development, signal acquisition, and software-based signal processing to deliver a real-time PPG-based health-monitoring system.

3.1 System Architecture

The system comprises the following components.

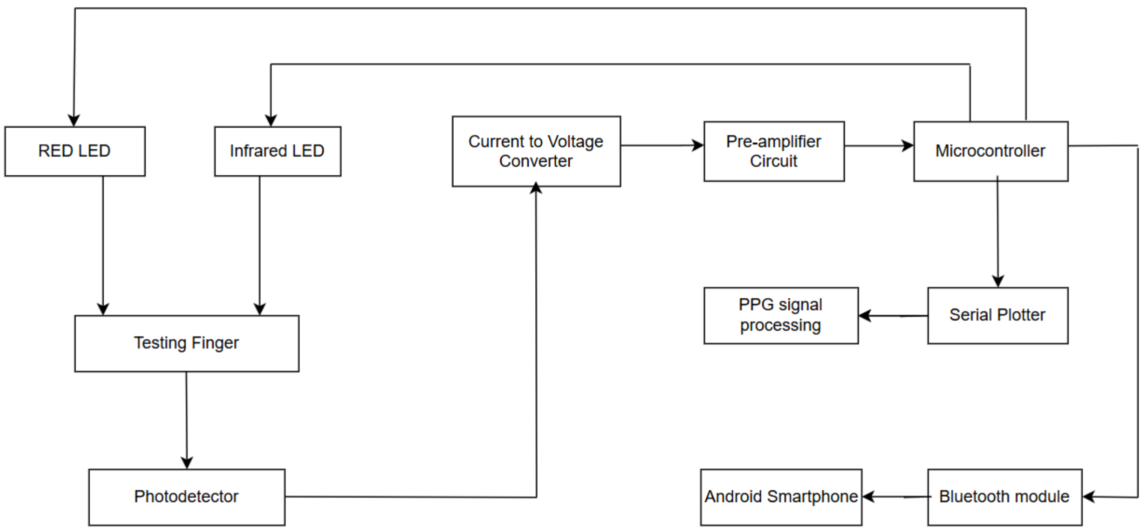

Figure 1: System Block Diagram

1. PPG Sensor Probe: A neonatal/adult sensor operating in transmission mode with red and infrared LEDs and a photodiode placed opposite each other. The probe was attached to the fingertip to ensure maximum arterial blood exposure and minimal tissue interference.

2. Microcontroller Unit: An Arduino Uno was used to control the alternating activation of LEDs via Pulse Width Modulation (PWM), acquiring analog signals from the photodiode, and transferring raw data via a serial interface.

3. Signal Conditioning Circuit: A transimpedance amplifier using the MCP6021 operational amplifier was implemented to convert the current output of the photodiode to a voltage signal. A 470kΩ feedback resistor and 470pF capacitor were chosen based on the gain and bandwidth requirements (~2 kHz cutoff frequency).

4. Bluetooth Communication Module: The HC-05 Bluetooth module is interfaced with the Arduino to facilitate the wireless transmission of the acquired data to an Android smartphone or computer terminal for further processing.

3.2 Software and Signal Processing

The signal processing was performed using MATLAB. The raw signal, transmitted via the serial port, is passed through a digital Butterworth band-pass filter (0.8–5 Hz) to isolate the AC component (pulsatile blood flow) from the DC component (static tissue and venous blood).

- Heart Rate and Respiration Rate Estimation: Fast Fourier Transform (FFT) was applied to the AC signal. The heart rate was derived from the dominant frequency component (in Hz) multiplied by 60 to convert to beats per minute (BPM). The respiration rate was similarly extracted from the slower frequency oscillations.
- SpO_2 Calculation: The ratio of AC to DC components for red and infrared signals was computed over defined sampling intervals. These ratios were used to calculate the modulation ratio (R), and an empirically derived equation was used to estimate SpO_2:

$$SpO_2 = 110 - 25R$$

$$\text{where } R = \left(\frac{AC_{red}}{DC_{red}}\right) / \left(\frac{AC_{IR}}{DC_{IR}}\right)$$

- As part of the research, an experiment was conducted in the laboratory to determine which LED to use, either the default one used in the existing pulse oximeter (red) or green LED. The obtained data were analyzed, and the signal from the red channel was better than those from the green and orange channels. Measurements were taken from the finger and compared with measurements from the palm or wrist. The differences between these channels are detailed in the graphs in Figure 2.

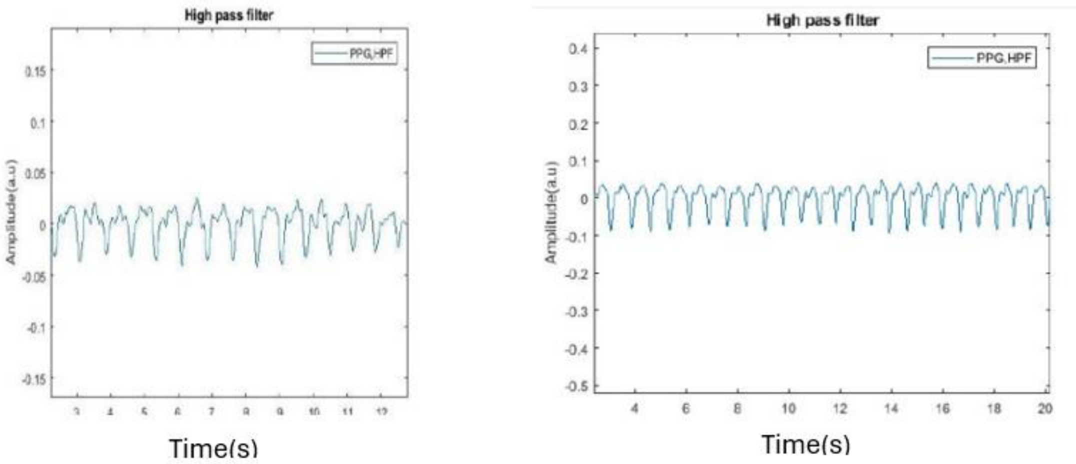

Figure 2: PPG signal using Green and RED LEDs

It can be observed from the graphs that the signal obtained from the green channels is not clear and small in magnitude; hence, a good amplifier must be used for better results, although the signal from the red channel also needs to be amplified, but not compared to the green channel, as the red channel single-stage amplification is sufficient to provide a clear measurement. It is important to note here that depending on the skin, measurement also varies; for researcher's black skin gives good measurement with red rather than green wavelength, which was the main reason for choosing red as one source of illumination in this project.

3.3 Experimental Testing

The experimental testing phase was designed to validate the performance, accuracy, and usability of the developed PPG-based health monitoring system. The primary goal was to evaluate the system's ability to accurately measure the heart rate (HR), respiration rate (RR), and peripheral oxygen saturation (SpO_2) in comp son with a commercial grade pulse oximeter.

3.3.1 Experiment Setup and Participants

The experiment for this design was conducted at Arusha Technical Biomedical Laboratory. The system was tested on a cohort of 12 adult participants. Test subjects were selected to reflect the typical user population expected in rural or low-resource environments. All participants were seated in a relaxed, resting state during measurements to minimize motion artifacts and external disturbances. Ethical approval for testing was obtained under institutional project guidelines, and informed consent was obtained from each subject. The PPG sensor was clipped onto the participant's index finger with a photodiode and dual LEDs (red and infrared) arranged in a transmission configuration, as shown in figure 3. The Arduino Uno microcontroller was connected to the sensor and powered via a USB, controlled LED modulation, and data acquisition. The signal output was read from analog pin A0 and transmitted through both USB and Bluetooth interfaces. A laptop running MATLAB software received serial data for real-time processing and visualization.

Figure 3: Fore finger connected and Sensor Probe D connector

3.3.2 Measurement Procedure

Each participant underwent two sequential measurement procedures.

1. PPG-Based System Recording: The developed system collected data for approximately 60 seconds per participant. The raw signal was filtered using a Butterworth bandpass filter (0.8–5 Hz), and the AC and DC components for both the red and infrared channels were isolated. The heart rate was computed by identifying the dominant peak in the frequency spectrum of the AC signal and converting it from Hz to BPM. The respiration rate was similarly determined from low-frequency fluctuations.
2. Commercial Pulse Oximeter Reading: Immediately after each session with the proposed system, the same participants were assessed using a medically certified commercial pulse oximeter. The device measured and displayed the SpO_2 and pulse rate, serving as the benchmark for comparative analysis.

3.3.3 Data Collection and Analysis

Data were tabulated for each participant to capture three primary parameters: heart rate, respiration rate, and SpO_2. The results from the proposed system were compared to those from a commercial pulse oximeter using correlation analysis and Bland-Altman plots to assess agreement. The heart rate readings from the proposed system ranged from 68 to 97 BPM, aligned with standard adult resting ranges, and closely matched those from the commercial device, which ranged from 69 to 97 BPM. The respiration rates derived from the PPG signal ranged from 15 to 20 breaths per minute, all within the normal adult resting range (12–20 bpm).

SpO_2 values calculated by the system ranged from 98% to 99.1%, compared to 97% to 99% from the commercial pulse oximeter. A strong positive correlation coefficient was observed between the two datasets. Bland-Altman analysis showed that most data points clustered within the ±2% limits of agreement, with a small mean bias of 1.5%, suggesting acceptable agreement for non-clinical use. The data collected from the participants are presented in Table 1. These points demonstrate strong alignment with the ideal correlation line (Figure 4), which is consistent with the calculated correlation coefficient of 0.898.

Table 1: Measured Vital Signs from 12 Adult Participants

Subject	Heart Rate (PPG) [BPM]	Respiration Rate (PPG) [Breaths/min]	SpO_2 (PPG) [%]	Heart Rate (Commercial) [BPM]	SpO_2 (Commercial) [%]
1	84	15	98.2	85	99
2	82	18	98.71	87	99
3	97	20	98.23	89	98
4	85	15	98.46	87	99
5	68	17	98.47	89	99
6	89	20	98.06	97	99
7	87	20	98.33	87	99
8	90	18	98.67	89	98
9	87	18	99.19	95	99
10	69	17	98.12	89	97
11	87	18	98.42	69	99
12	89	20	98.03	87	98

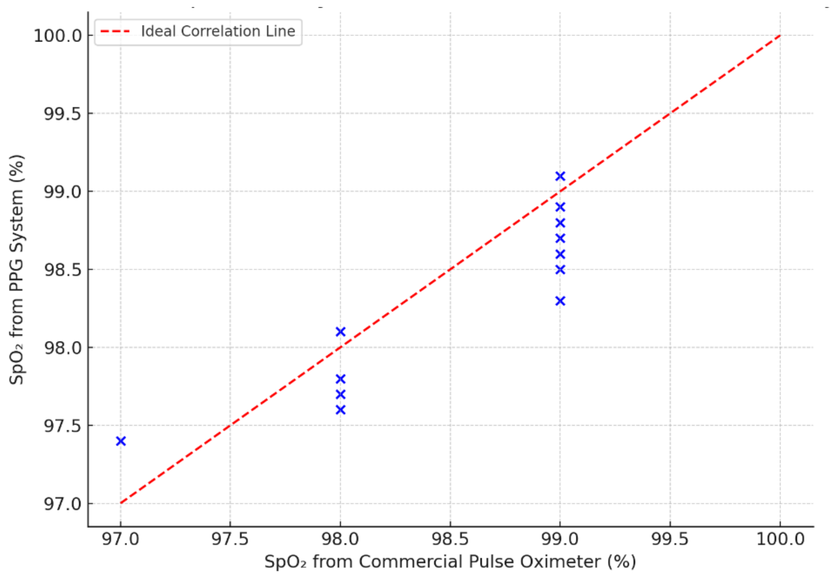

Figure 4: Correlation Between SpO_2 (PPG System) and Commercial Pulse Oximeter

4. Results and Discussion

4.1 LED Results

As shown in Figure 3, the Arduino board was connected to the PC via a USB and powered by a PC. The board has two pins for power of either 3.3V or 5V. The amplifier circuit is powered through 3.3V pin as its operating voltage ranges from 1.8V-5.5V. After connecting the USB, the built-in diode of the board should be blown, indicating that it is ready. Using a serial port, the code is uploaded to the board, and the Red LED of the sensor blinks, showing that the sensor is powered and there is current flowing through. The sensor was attached to the fore finger, ready for measurement. On the computer screen, using serial monitor readings, the light transmitted through the finger to the photodiode changes with the blood flow, so the readings also vary.

The readings obtained and lines of code are added to help the serial data from Arduino be sent to MATLAB through the specified USB port so that the data can then be analyzed and processed using MATLAB code. Raw data were plotted by reading the data from the serial port. Then, by further processing and passing the signal through filters with both high- and low-pass filters, PPG signals from both LEDs were obtained as shown in the attached graphs (figure 5).

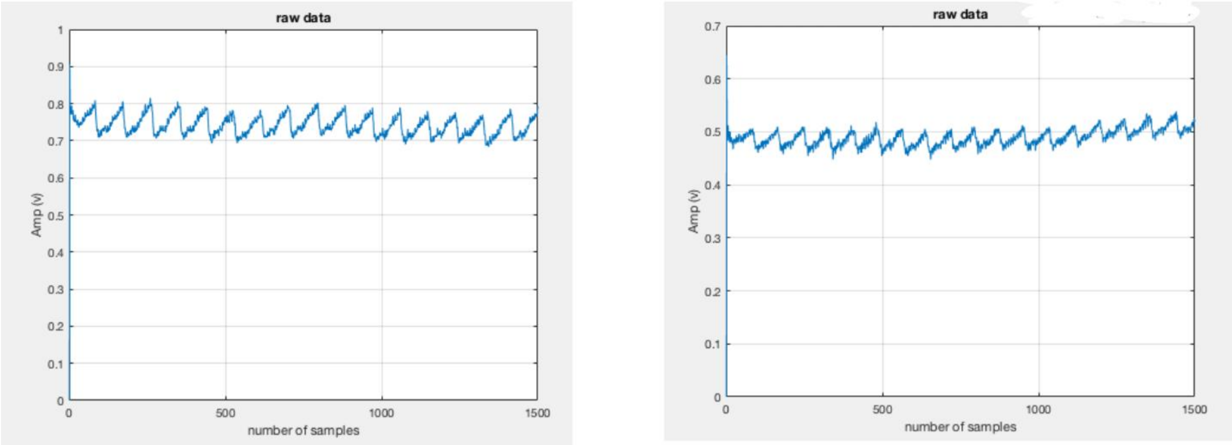

Figure 5: Raw data obtained from Red and Infrared LED

The raw data obtained contains primary unwanted noise due to the sensor, and a filter must be employed to obtain a clear signal. A bandpass filter(butter-worth) is used, whereby the low-pass filter removes all high noise due to electromagnetic interference, and the high-pass filter removes all DC values remaining with only AC. The signal comprised only a DC signal (figure 6) and an AC signal (figure 7). The main purpose of these signals is to extract physiological parameters that can be used for the health assessment of human beings. The obtained signals were then used for this task, whereby the heart rate was calculated as the frequency of the dominant peak in Hz multiplied by 60 to convert it to beats per minute (BPM). The calculation was performed after performing a Fast Fourier Transform on the dynamic pulse waveform. Similarly, Respiration rate is calculated by acquiring FFT of the AC signal and multiply answer by 60 to get beats per minutes

In this study, red and infrared illumination sources were used for signals of two different wavelength measurements obtained from the DC and AC components, which represent the absorption light (Dasgupta et al., 2003). The DC components were extracted from the raw data, and the AC components were determined from the positions of the peaks and troughs. The AC and DC values obtained using both LED are presented in figures 8.

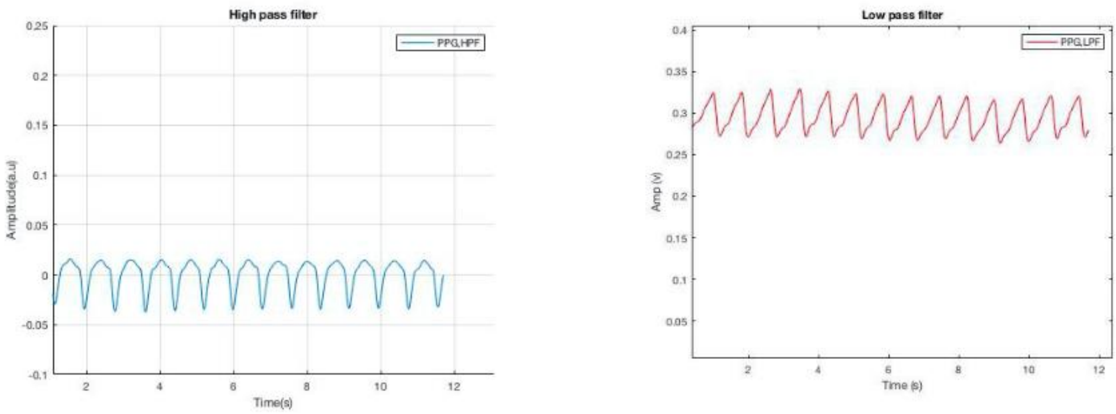

Figure 6: Red LED DC and AC Components

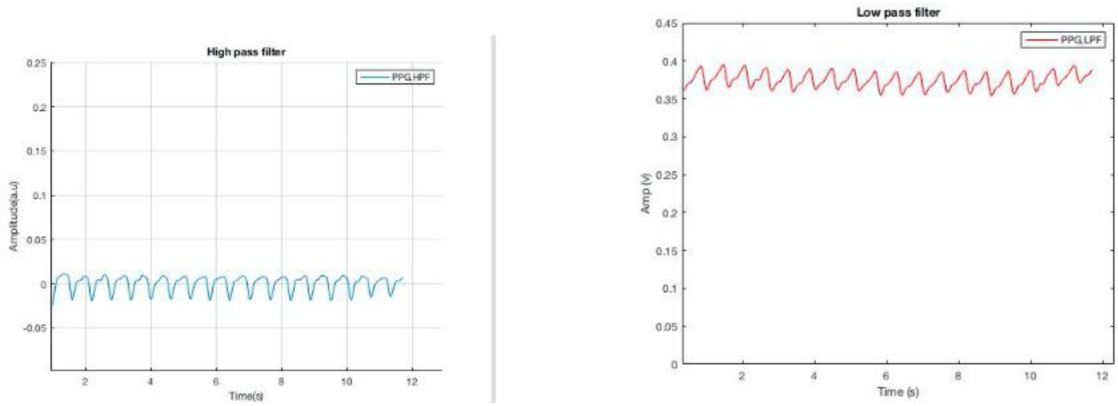

Figure 7:Infrared DC and AC Components

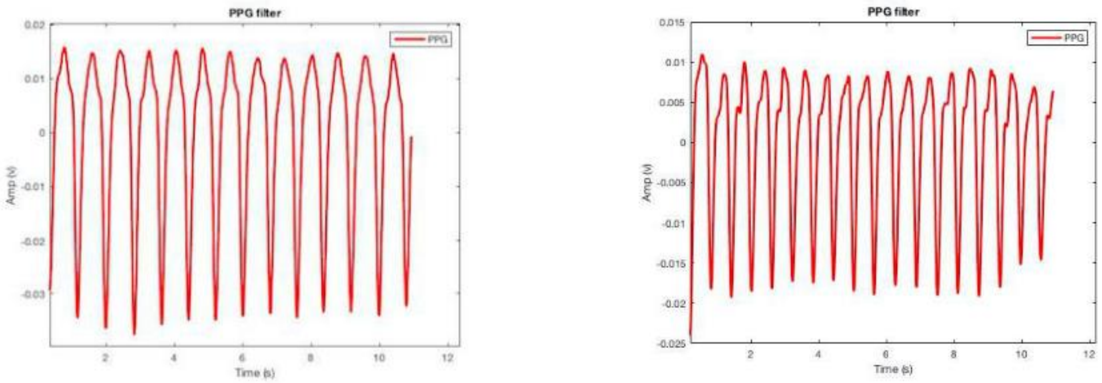

Figure 8: Red and Infrared LED Photoplethysmography signal

4.2 Oxygen saturation (SPO2) Results

By using two illumination sources of light, that is, two wavelengths, measurements were taken as the calculation of S_PO_2 with two wavelengths, and the RMS of the AC signal was calculated as the ratio of this RMS to the mean of the DC signal for the first wavelength (RED LED), which gives the value of R_1, Then Normalized ratio(R) was obtained as the ratio of these two ratios from each wavelength signal from both LEDs, as shown in figure 9.

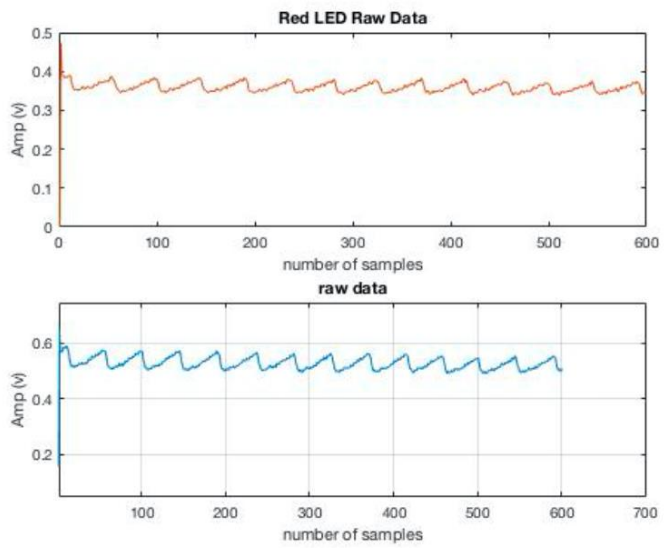

Figure 9:Raw PPG signal as obtained from both LEDs

5. Conclusion and Recommendations

5.1 Conclusion

The designed system demonstrated that physiological parameters can be effectively analyzed using Photoplethysmography (PPG) signals. The system was specifically designed with two wavelengths that are two sources of illumination: Red and Infrared LEDs. From the PPG signal obtained using each wavelength, the heart rate and respiration rate were obtained separately, and using both wavelengths, oxygen saturation was obtained as SpO2 calculation requires two wavelengths to be calculated. The main aim of this project was to extract physiological parameters from PPG signals so that health conditions can be monitored easily using the state of these parameters. This project provides detailed information, the working principle of PPG, and the importance of using PPG in monitoring our health.

After designing the system, measurements were taken using the forefinger, and the signal processing was performed using MATLAB to analyze the obtained signal to obtain the expected output. The signal heart rate obtained was within the range of 60–97 BPM, and the respiration rate was 15-20 which is the required range. Using both wavelengths, SpO2 was extracted, which was ranging to from 96-100% and which is the range required for normal healthy persons.

Another feature of using Bluetooth was implemented, which allows raw data to be communicated at a certain distance, ideally 2m, this was successfully implemented, and raw data can be sent to a smartphone with an Android application through Bluetooth. The designed system can be used to provide adequate cardiovascular health care, especially in developing countries, by modifying and taking measurements under the supervision of an accurate result will be obtained. Hence, this device can be used in low-income and developing countries or families to obtain better and cheaper cardiovascular health care for better health assessment.

5.2 Recommendation

Real time health monitoring system designed was able to achieve the required scope as explained in conclusion part, but more improvement has to be done to have better precise, reliable and robust system. Things which are recommended to be done in the future so as to overcome shortcomings of this entire system are as below:

1. Improved Signal Conditioning: The signal from the amplifier can be improved by implementing a two-stage amplification system instead of the single-stage used in this project. Additionally, incorporating a sample-and-hold circuit immediately after amplification can ensure that only the relevant portions of the signal are sampled and analyzed, thereby minimizing noise interference.
2. Power Flexibility: To increase accessibility in rural or off-grid settings, the system should be adapted for use with renewable energy sources such as solar or battery power.
3. IoT Functionality: The system can be extended to include Internet of Things (IoT) capabilities. This would allow patient data to be stored and accessed remotely, facilitating broader use in telemedicine applications and continuous long-term monitoring regardless of geographic location.
4. Integration of Artificial Intelligence (AI): To further enhance system accuracy and functionality, AI can be integrated for real-time motion artifact detection and removal. Machine learning models can be trained on labelled PPG data to distinguish between genuine physiological signals and motion-induced noise, thus improving parameter estimation accuracy. AI can also support personalized analysis, anomaly detection, and even generate alerts for early intervention. In low-resource settings, AI-powered mobile applications can serve as intelligent assistants to healthcare workers, offering instant diagnostic insights and reducing clinical workload.

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