Development of an Optical Measurement System for Plethysmographic Blood Volume Changes

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Abstract: **PPG, or photoplethysmography, is an optical measurement technique that does not need any intrusive procedures and is used to monitor changes in blood volume in peripheral tissues. The purpose of this study is to show the design and construction of a data acquisition (DAQ) system that is modular, relatively inexpensive, and capable of recording plethysmographic blood volume changes signals. The fabrication of a sensor geometry that includes both a source and a detector is carried out. A unique analogue front end is incorporated into the system. This front end features a bandpass filter that operates between 0.5 and 5 Hz. It combines a 5^{th} -order high-pass filter with a 7^{th}-order low-pass filter in order to reduce noise and motion artifacts. Following the visualization of the output signal in real time on a Digital Storage Oscilloscope (DSO), the signal is further processed in MATLAB. The findings of the experiments conducted on human volunteers demonstrated clear, periodic waveforms that provided an accurate representation of the heart cycle. The system's efficacy for fundamental biomedical research was demonstrated by the fact that the signal quality received from the system was comparable to that obtained from commercial products. The configuration is especially well-suited for use in research and educational environments, where cost and customization are of utmost importance. There is a possibility that future generations will have wireless connection, digital storage, and integration of microcontrollers. Through the provision of a platform that is easily accessible, this system bridges the gap between theoretical understanding and practical experimentation in the field of physiological signal processing.**

Index Terms: **Photoplethysmography, Data Acquisition System, Analog Filter Design, Low-Cost Medical Devices**

INTRODUCTION:

Photoplethysmography, also known as PPG, is an optical approach that is non-invasive, inexpensive, and straightforward. It is used to detect changes in the volumetric circulation of blood [1]. It was first introduced in the early 1930s, and since then, it has evolved into an essential instrument for signal gathering in numerous clinical applications and wearable health monitoring currently in use. The construction of the traditional PPG device design is very straightforward; nevertheless, there is still a lack of a standard robust design that is immune to all external circumstances. These elements include variations in skin color, the amount of pressure that is given to the sensor, and the effects of temperature that are caused by infrared and red light emitting diodes (LEDs). The technique involves the transmission or reflection of light into the tissue, and it identifies variations in the capacity of the tissue to absorb light as a result of pulsatile blood flow. The waveform that is produced as a result of these changes is rich with physiological and pathological information pertaining to

the health of the cardiovascular system. These variations are synchronized with the cardiac cycle [2]. PPG indirectly assesses cardiovascular status by evaluating scattering, absorption, reflection, transmission, and fluorescence via an optical sensor equipped with a light source.

Monitoring of PPG signals has become more essential in clinical and research contexts. The application of heart rate variability (HRV) in evaluating mental illness and identifying stress has gained momentum [3][4]. In contrast to ECG or invasive blood pressure measures, PPG is more user-friendly and necessitates minimal setup or discomfort for patients. The normal ranges of PPG waveform to emerge are 60 to 100 cycles per minute in adult subject. Numerous equipment is available in the market for measuring PPG. The fabricated apparatus introduces significant alterations relative to the existing models. This is a cost-effective method for processing the recorded signal. PPG signals typically have an amplitude that falls somewhere between 0.5 millivolts and 5 millivolts, and their frequency falls somewhere between 0.5 hertz and 5 hertz. This range of amplitude and frequency corresponds to a heart rate that can range anywhere from 30 to 300 beats per minute. The signal, on the other hand, is plagued by motion artifacts, interferences brought on by ambient light, and skin contact that is not identical throughout. Because of this, the efficiency of a PPG collection system is highly dependent on the analog signal that is received from the sensor as well as the consistency of the surrounding environment [5].

Even taking into account the widespread use of commercial pulse oximeters and smartwatches, there is still a significant lack of raw-signal acquisition devices that are both affordable and capable of being adapted to meet the specific needs of clinical research and academic investigation. All of the easily available systems are either closed-source or constrained in the signals that they are able to offer as clean, unprocessed signals that are suitable for the construction of algorithms or the analysis of physiological processes. Efforts have made to close this gap by designing a low-cost, user-built PPG acquisition system that is high-accuracy, modular, and accessible. This system will enable researchers and students to experiment, customize, and evaluate physiological waveforms using a setup that is suitable for study and research purposes.

The objective of this study is to design and develop a robust and cost friendly data acquisition system as well as plethysographic sensor to measure underlying blood volume changes. The sensor design is the most important component of our technology. It is an optical sensor – a paired geometry of source and detector that is accurate and offers reliable detection of arterial pulse signals while simultaneously reducing excess noise. The design is based on the idea of red & infrared light absorptions, and it has great tissue penetration and a high signal-to-noise ratio. Due to the fact that the sensor is compatible with bespoke analog circuitry and possesses clinical-grade precision, it is an ideal research subject for this particular investigation.

PROPOSED METHODOLOGY

The proposed sensor design for measurement of plethysmographic blood volume changes works on the principle of Beer-Lambert's Law of spectroscopic principle which states that:

$$A = \varepsilon * C * L$$

Where, A = absorbance, ε = molar absorptivity, C= concentration, L = optical path length

In blood two major absorbers exists i.e. deoxygenated hemoglobin (Hb) and oxygenated hemoglobin (HbO_2). In the red region of the spectra (fig. 1), Hb absorbs considerably at 660 nm, whereas Hbo2 absorbs the least amount. At higher absorption levels, this indicates that more deoxygenated blood was provided, which resulted in a lower perceived light intensity. In the infrared region, that is at 940nm HbO_2 absorbs more amount of light than Hb hence higher absorption for more oxygenated blood resulted in lower detected light. This way the differential absorption from both the sources are captured at detector which is placed opposite side from the source. Ambient light cancellation is incorporated during fabrication of the system to avoid false positive readings. The chosen near-infrared wavelength LEDs has an output radiant intensity not more than 3 mW, which is below the IEC (International Electrotechnical Commission) 60825-1 suggested limit, assuming an area of >2 mm^2.

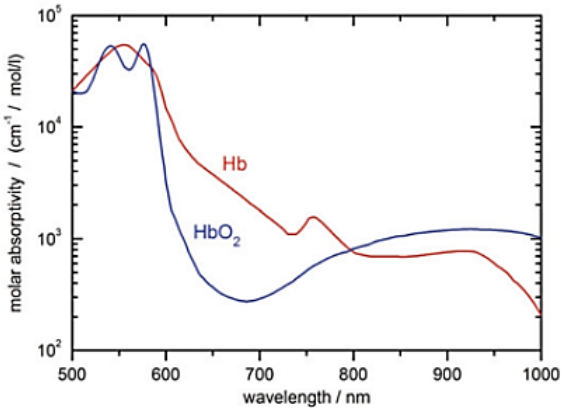


Figure 1: Molar absorptivity spectra of hemoglobin (Hb) and oxyhemoglobin (HbO_2) as a function of wavelength

Following section contains details of the architecture, sensor and design of our custom DAQ.

System architecture:

The architecture of the system is essentially composed of three primary functional stages: signal acquisition, signal conditioning (which includes filtering and amplification), and signal output and display. An illustration of the architecture is presented in the form of a block diagram in fig. 2. It was decided to build and construct a photoplethysmographic (PPG) sensor for the purpose of acquiring signals regarding changes in blood volume. The participant's index finger served as the location for the sensor, which was designed to detect differences in blood volume inside peripheral tissue structures. The sensor was provided with an excitation voltage of 9V via regulator circuit, and an analog signal was obtained as responses from both the light sources. These signals were given as input to the signal conditioning circuit firstly into the instrumentation amplifier. Further, to remove noise signal the inclusion of 5^{th} order high-pass and 7^{th} order low pass filter was achieved by design a custom build Data Acquisition (DAQ) .

Signal Conditioning Stage: Custom Built DAQ

In this system, the filtering unit serves as the central point. It is made up of a higher order low pass and high pass filter, which eliminates the PPG signals that are collected from the sensor and minimizes the noise component of the signal. Together both of this circuits have a band-pass frequency range of 0.5 to 5 Hz.

High pass Filter (5^{th} order): The first stage is an active high pass filter which has a cut-off frequency of 0.5 Hz. The cutoff frequency is calculated as: fc (HPF1) = 1/(2.л.R.C1) Hz

Low pass Filter (7^{th} order): Next stage is an active low-pass filter set at cut-off frequency of 5 Hz value. The cut-off frequency of this filter is given by the relation: fc (LPF1) = 1/(2.л.R.C2) Hz.

Given that the frequency range of PPG signals typically lies between 0.5 Hz to 5 Hz, signal conditioning is essential for accurate analysis. In order to obtain the signal, DIN male-female connector was used. This ensured a noise free signal acquisition with better placement to the signal conditioning circuit. The acquired signal was amplified and passed through a custom designed band-pass filter to attenuate high-frequency noise and low-frequency drift as shown in fig. 3.

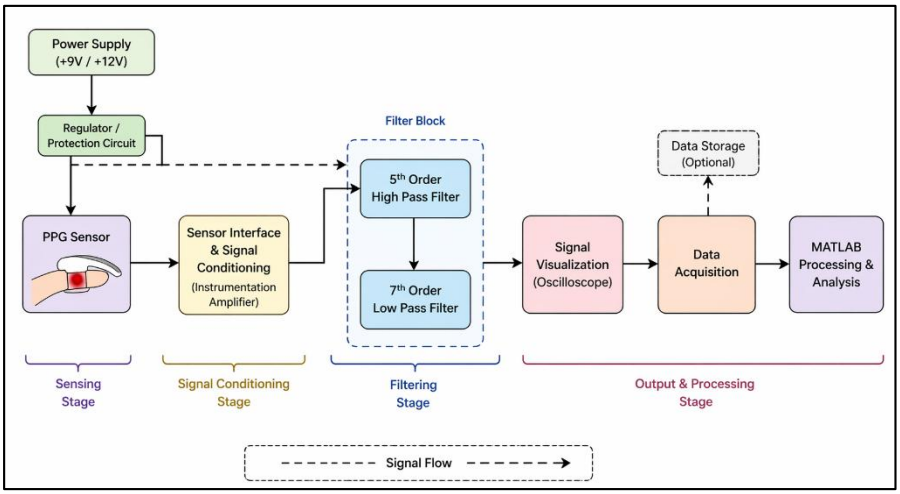


Figure 2: Block diagram of the system architecture

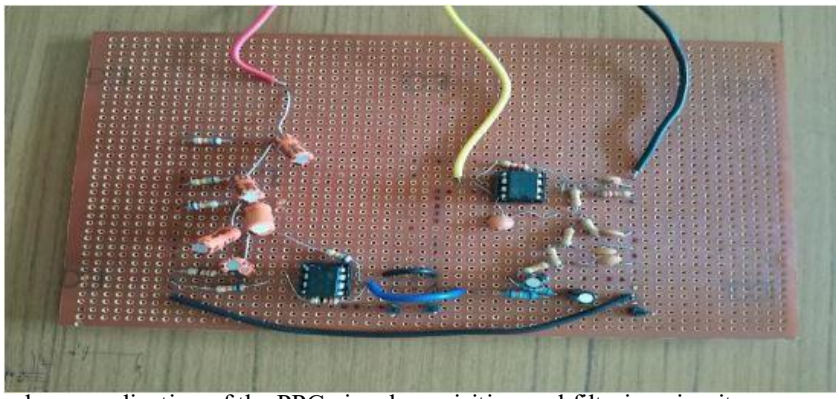


Figure 3. Hardware realization of the PPG signal acquisition and filtering circuit on general-purpose board

RESULTS AND DISCUSSION

A digital storage oscilloscope (DSO) was utilized in order to visualize the filtered analog output. The frequency of the signal as well as the peak-to-peak amplitude were observed. The waveforms of the additional calculations of SpO_2, heart rate, and blood volume changes were recorded and validated against a commercial pulse oximeter device. Through the facilitation of the Universal storage bus (USB) port of the DSO, this output might then be collected and utilized for additional digital analytic needs. Figure 4 shows the waveform of plethysmographic blood volume changes when sensor was wrapped around index finger of 20-year-old male subject ensuring consistent sensor contact and minimizing motion artifacts. All recordings were conducted under controlled ambient lighting, temperature and pressure conditions with subjects in a seated and relaxed posture to ensure data consistency.

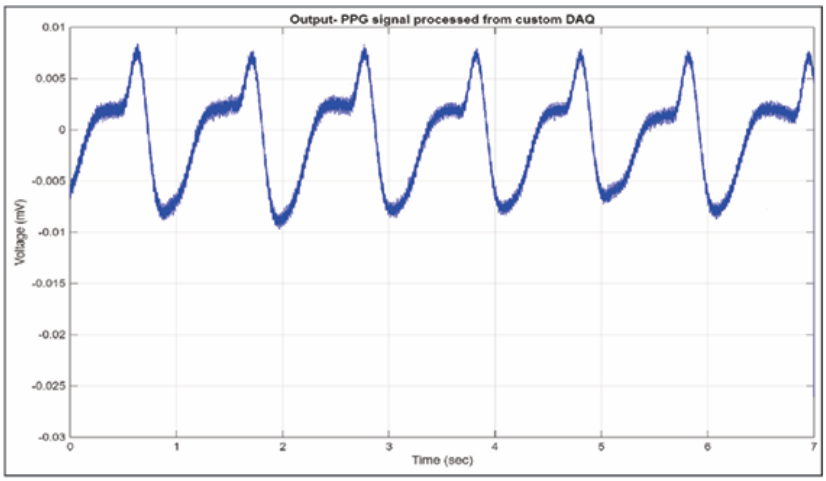


Figure 4. Plethysmographic waveform obtained from our developed custom built DAQ

The design was validated by recording the SpO_2 from the observation taken and manually calculating SpO_2 from the DSO. Parallelly commercial device for the measurement of SpO_2 was also taken to check the accuracy of developed system. Table 1 shows the number of participants in the study and results.

No. of Participants (n)	Developed DAQ system		Commercially available device	
	SpO_2(%)	Heart Rate (beats per minute)	SpO_2(%)	Heart Rate (beats per minute)
Male (12)	95±2	80±5	97±2	70±6
Female (8)	98±3	82±7	99±1	78±8

Table 1. Experimental results of developed sensor system on healthy adults (n=20)

The performance of the developed data acquisition system for plethysmographic blood volume changes and SpO_2 was evaluated against a commercially available oximeter across a cohort of 20 participants (12 males

and 8 females). The mean SpO_2 values obtained using the proposed system were 95 ± 2% for male subjects and 98 ± 3% for female subjects, compared to 97 ± 2% and 99 ± 1%, respectively, measured by the reference device. The observed deviation between the two systems remained within ±2–3%, indicating acceptable agreement.

Similarly, heart rate measurements demonstrated comparable trends, with the developed system reporting mean values of 80 ± 5 bpm (males) and 82 ± 7 bpm (females), while the commercial device recorded 70 ± 6 bpm and 78 ± 8 bpm, respectively. Although a slight overestimation in heart rate was observed in the proposed system, the values remained within clinically acceptable limits. Overall, the results indicate that the developed SpO_2 monitoring system exhibits good agreement with the commercial reference device, demonstrating its potential for reliable estimation of arterial oxygen saturation and pulse rate in practical applications.

A paired t-test was performed to compare the measurements obtained from the developed SpO_2 system and the commercially available device. No statistically significant difference was observed in SpO_2 measurements for both male ($p > 0.05$) and female ($p > 0.05$) groups, indicating good agreement between the two systems. Similarly, heart rate measurements did not show a statistically significant difference ($p > 0.05$) across both groups, despite a slight variation in mean values. These findings suggest that the developed system provides measurements comparable to the reference device within an acceptable confidence level. All statistical analyses were performed at a 95% confidence interval using a significance threshold of $p < 0.05$

CONCLUSION

A novel data acquisition system for noninvasive measurements of plethysmographic blood volume changes, oxygen saturation (SpO_2) and heart rate using optical sensing mechanism were successfully developed and evaluated in a cost-effective manner. The proposed system demonstrated good agreement with a commercially available oximeter, with mean deviations within ±2–3% for SpO_2 measurements across both male and female participants. Heart rate measurements also showed comparable trends, with minor variations remaining within clinically acceptable limits. Statistical analysis further confirmed that the differences between the two systems were not significant ($p > 0.05$), indicating the reliability of the developed device.

The results validate the feasibility of the proposed system for real-time monitoring of blood volume changes and heart rate using optical sensing principles. Owing to its simple design, low-cost implementation, and satisfactory performance, the developed system has potential for portable and resource-limited healthcare applications.

FUTURE SCOPE

Future work will focus on enhancing signal robustness, expanding validation across larger and more diverse populations, and integrating advanced signal processing techniques for improved accuracy under motion and low-perfusion conditions.

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