Low Cost Calibration Free Pulse Oximeter

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***Abstract*— This paper deals with a pulse oximeter device, which measures pulse rate and blood oxygen levels of a person in a non-invasive way without any need of calibration. Current models involve calibration and a complex analog circuitry. The device proposed is novel not only in terms of computing the oxygen saturation levels without any calibration but also uses the digital computation power of the microcontroller leading to a simpler circuit design. Two Photo-plethysmographic (PPG) signals corresponding to Red and Infrared wavelengths are obtained from the sensor by using an Arduino microcontroller and subsequently signal is transferred to PC via serial communication where all the signal processing is carried out using MATLAB. Oxygen levels in blood are then determined using Beer Lambert Law while the Pulse rate is calculated both in time and frequency domain. Thereafter results obtained are compared with a commercial pulse oximeter. Accuracy of ±5% for oxygen saturation levels and ±7% in case of pulse rate values is achieved. This design removes the need for calibration and aids in reducing the cost of the pulse oximeter to less than $20 which can be used in the future for practical and research purposes.**

Keywords— Beer Lambert Law; Calibration free; Pulse Rate; Digital Filtering; Pulse oximetry

I. INTRODUCTION

Pulse oximetry has been in existence since the early 1930's. By using this principle, blood oxygen levels can be determined non-invasively. Continuous monitoring is required by people suffering from cardiac diseases and also by pilots, mountaineers etc. [1]. The primary function of hemoglobin is to transport oxygen from lungs to other parts of the body. Oxygen saturation is defined as the ratio of concentration of oxygenated hemoglobin to the total concentration of hemoglobin present in the blood. Oxygenated hemoglobin is the hemoglobin in blood containing oxygen while deoxygenated hemoglobin is the hemoglobin in blood without oxygen. Oxygen saturation when measured non-invasively by a finger pulse oximeter is called SpO_2. Such a device is useful to patients to monitor their oxygen levels without the need of a doctor but it cannot be substituted with a clinical evaluation [2]. The basic principle behind pulse oximetry is Photo-plethysmography (PPG). It is an optical technique that is used to measure blood volume changes in the tissue. The PPG waveforms for pulse oximetry are obtained by illuminating red and infrared light through the fingertip of a person which are sensed by a photo detector. Only a small amount of light is detected while most of the light gets scattered and reflected by the skin and bones present in the path of light. One fundamental property followed here is that oxygenated hemoglobin absorbs more infrared light while deoxygenated hemoglobin absorbs more red light. The rationale behind this property is the difference in their absorption spectrums in the wavelength range of 600-1000 nm [3]. Wavelengths in the red (R) and infrared (IR) regions around 660 and 950 nm are typically used in most pulse oximetry applications [4]. For measurement of Spo2, using the DC and AC parts of the IR and Red signals, the ratio of ratios is calculated as

$$R = \frac{(\frac{AC}{DC})_{RED}}{(\frac{AC}{DC})_{IR}} \quad (1)$$

The formula relating R to oxygen saturation measured by pulse oximetry, is then determined by proposing a mathematical relationship, given by:

$$SpO_2 = A - B * R \quad (2)$$

Where A and B are coefficients obtained by means of calibration. In the calibration based method, the ratio of ratios for a set of volunteers is determined using the built sensor and the SpO_2 levels for the same set of volunteers is simultaneously measured using another device which is already calibrated. Calibration coefficients are calculated by deriving a mathematical relationship between R and measured SpO_2 values [5]. This method is largely dependent on the set of volunteers chosen. Accurate calibration coefficients are difficult to obtain due to the variations in various attributes of a person like color of skin, age and many other factors. Almost all adaptive calibration methods designed and employed till date makes use of the calibration curves [6]. A calibration free method of measuring oxygen saturation levels is obtained by deriving a relationship between R and SpO_2 levels using Beer Lambert Law and absorption spectra of hemoglobin [7]. This relationship is used by [8] which employs lasers in place of LED's in the system. As a result, the cost of system increases by ten folds compared to a standard pulse oximeter. A calibration free oximeter is proposed by [9] but the method proposed involves both complex calculations and complicated analog circuitry. Most researchers in the past have made use of standard analog circuit design in order to measure blood oxygen levels. The standard technique used widely is to separate AC and DC values of the signal through the analog method rather than the digital method. The pulse oximeter described in [10] makes use of a low pass filter to obtain the DC component and

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a band pass filter to obtain the AC signal. As this process has to be carried for two signals such as RED and IR simultaneously, the circuit must consist of two sets of filters and amplifiers in addition to a multiplexer circuit. Similarly, in [11] a calibration free pulse oximeter is proposed with separate analog filters and amplifiers for Red and IR PPG signals. This kind of circuit designing increases the complexity of the circuit which not only increases the cost of the system but also more number of components would mean more interference resulting in more noise in the system. By means of digital filtering, these limitations could be overcome easily. The results obtained by following the digital processing approach are comparable to the results obtained using the standard analog circuitry used in [11]. The calibration free pulse oximeter based on Beer Lambert Law is proposed in this research paper. Using this model, calibration curves are not required for SpO_2 calculations. Also in the proposed circuit design the chief aim is to use lesser number of components and make use of the microcontroller and PC to perform most of the functions. In order to achieve this, a simple circuit is designed to ensure that fine quality signals in the range of 0-5 Hz are obtained for RED and IR regions.

i. Calibration free Pulse oximeter

According to Beer Lambert Law, the amount of absorbance when light is passed through a substance is directly proportional to the thickness and concentration of that substance and is given by:

$$A = \ln\frac{I_o}{I_t} = \varepsilon * C * L \quad (3)$$

Where A is the absorbance, ε is the extinction coefficient corresponding to a particular wavelength, C is the concentration of substance present in the path and L is the path length travelled by light. I_o, I_t corresponds to the incident light and transmitted light respectively. If n substances are present in the path of light, then absorbance can be expressed as

$$A=\sum_{i=0}^{n} \varepsilon * C * L \quad (4)$$

The absorbance corresponding to Red and IR wavelengths are measured and are expressed as

$$A_{RED} = (\varepsilon_{hbored} * C_{hbo} + \varepsilon_{hbred} * C_{hb}) * L \quad (5)$$

$$A_{IR} = (\varepsilon_{hboIR} * C_{hbo} + \varepsilon_{hbIR} * C_{hb}) * L \quad (6)$$

C_{hbo} & C_{hb} are the concentrations of oxygenated and deoxygenated hemoglobin in blood. $\varepsilon_{hbored}, \varepsilon_{hbred}$ are the extinction coefficients of hemoglobin at Red wavelength while $\varepsilon_{hboir}, \varepsilon_{hbir}$ are the extinction coefficients of hemoglobin at Infrared wavelength. Ratio R is expressed as the ratio of absorbance measured at wavelengths of Red and IR given by

$$R=\frac{A_{RED}}{A_{IR}} \quad (7)$$

Substituting equation (5) and (6) in the above equation gives

$$R=\frac{(\varepsilon_{hbored}*C_{hbo}+\varepsilon_{hbred}*C_{hb})*L}{(\varepsilon_{hboIR}*C_{hbo}+\varepsilon_{hbIR}*C_{hb})*L} \quad (8)$$

Calculating concentration of deoxygenated hemoglobin in blood (C_{hb}) from the above equation gives:

$$C_{hb} = \left(\frac{R*\varepsilon_{hboIR}-\varepsilon_{hbored}}{\varepsilon_{hbred}-R*\varepsilon_{hbIR}}\right) * C_{hbo} \quad (9)$$

Spo2 is defined as the ratio of concentration of oxygenated hemoglobin to the total hemoglobin concentration present in blood.

$$\%\text{Spo2} = \frac{C_{hbo}}{C_{hbo}+C_{hb}} * 100 \quad (10)$$

Substituting equation (9) in the above equation gives the relationship between the ratio R and SpO_2 as

$$\%SpO_2 = \frac{\varepsilon_{hbred}-R*\varepsilon_{hbIR}}{(\varepsilon_{hbred}-\varepsilon_{hbored})+R*(\varepsilon_{hboIR}-\varepsilon_{hbIR})} * 100 \quad (11)$$

The value of ratio R can be determined using the AC Component of the PPG signal as

$$R = \frac{\log10(AC_{\lambda 1})}{\log10(AC_{\lambda 2})} \quad (12)$$

Where ⋋ 1 and ⋋ 2 corresponds to RED and IR wavelength respectively.
Hence using the measured ratio R and known values of extinction coefficients, SpO_2 levels can be determined without the need of calibration curves.

ii. Role of Extinction Coefficients

For calculation of SpO_2 values, the extinction coefficients of oxygenated and deoxygenated hemoglobin corresponding to Red and IR signals need to be known. The absorption spectrum of hemoglobin has been examined by various researchers in the past and values of extinction coefficients are presented by [12, 13, 14]. The difference among the extinction coefficients is not very large but the values of hemoglobin concentration can get affected by a maximum of 20% [15]. This error is dependent on the wavelengths used in the sensor and in the design proposed, the wavelengths are selected in order to have the minimal possible error.

iii. Pulse rate detection

Pulse rate can be determined instantaneously or using the FFT of the complete signal. Instantaneous heart rate is the beat by beat heart rate which can be calculated using the time interval between two peaks in the signal. This time is measured in seconds and dividing it by 60 gives the instantaneous heart rate of a person.
Using the frequency spectrum of the signal, pulse rate can be determined. The fundamental pulse frequency of an adult is 1.17 Hz, which corresponds to 70 beats per minute [16]. The frequency range of a pulse signal is between 0.5 Hz and 2.5 Hz accordingly [17]. The PPG signal corresponding to IR LED is used to calculate the pulse rate. Only one fundamental frequency is detected in the range of 0.5-2.5 Hz which is interpreted as the pulse rate using the following relation.
Pulse Rate = (Fundamental Frequency of the user/Standard fundamental frequency (1.17 Hz)) *70

II. Product Design

The overall system design consists of the following main components

- Sensor module
- Signal Pre-processing using analog filters and amplifiers
- Signal acquisition and A/D conversion using microcontroller
- Digital filtering via MATLAB
- Calculation of SpO_2 levels from AC values of signal
- Calculation of pulse rate

i. Sensor and Signal Pre-Processing

Light is passed through the fingertip of a person using Red (630nm) and IR (940nm) LED's, which is sensed by a photodiode [400-1000nm]. LED's are switched with an interval of T1 ms for a duration of T seconds in order to obtain two PPG signals. The switching between LED's with their intensity control is done using Arduino Uno microcontroller. Pulse width modulation is employed to control the intensity of LED's. The output of the photodiode is in the form of current which is converted into voltage using a transimpedance amplifier. This amplifier is also designed as a low pass filter allowing frequencies below 15Hz to pass while rejecting all other frequencies. The desired pulse signal is in the range of 0-5Hz and in order to acquire a signal in this range, a 2nd order Butterworth Low pass filter is designed with a damping ratio greater than or equal to 1. The signal obtained after the above filtering stages is low in amplitude and is amplified using a non-inverting amplifier with a gain greater than 100. Two amplified signals corresponding to RED and IR wavelengths of duration T seconds are acquired by the microcontroller, which converts the analog signals into digital form. The A/D converter in Arduino Uno is 10 bit and hence can interpret analog values in the range of 0-1023 into digital form. Signals are sampled at a rate of 100Hz.

The two PPG signals are then transferred to PC via serial communication where further processing is done in MATLAB. Processing IDE software is used to display the signal in real time on PC.

ii. Digital filtering

Signal acquired via serial communication contains lots of noise even after passing through analog filters as seen in fig.1. Major sources of noise are the motion artifacts and power line interference that leads to inaccurate results. Baseline drift is another type of noise found in PPG signals which can be removed during circuit designing. Several external factors including the environment conditions under which the test is being conducted and the temperature of subject's skin also affect the quality of PPG signal.

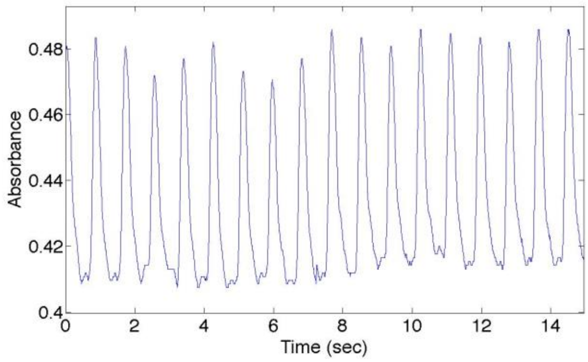

Figure 2: IR PPG signal

Ambient light and the electromagnetic signals interfere with the signal affecting the different features of the PPG signal [18]. Such type of noise has a frequency value of 50Hz. A notch filter is employed to remove the unwanted 50 Hz frequency from the signal. A 100 taps FIR filter is designed as a notch filter.

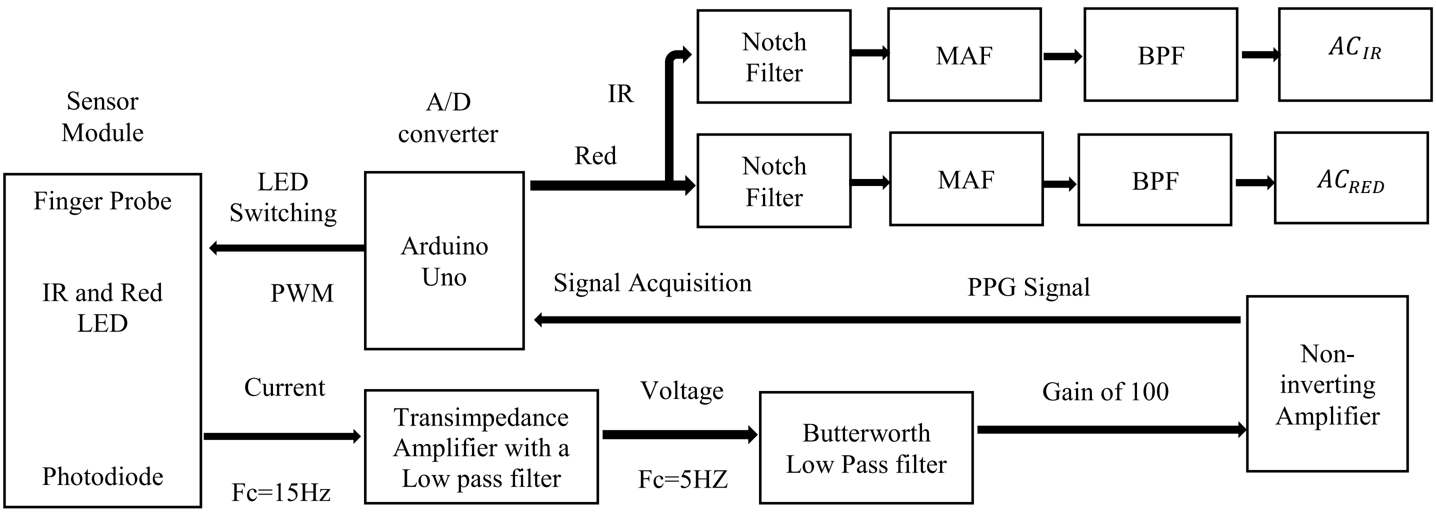

Figure 1: System Overview

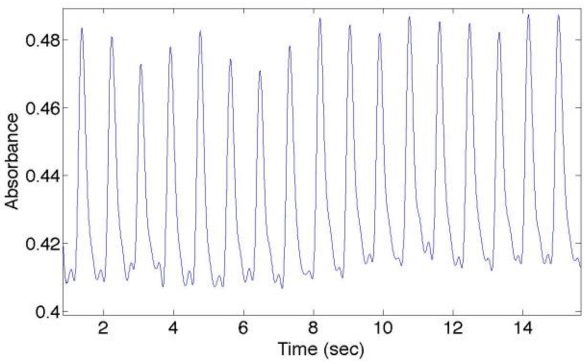

Figure 3: 50 Hz Notch Filter Output

Another source of noise is the motion artifacts, which results in a lot of jitters in the signal. These artifacts arise mainly due to movement of finger or due to poor contact between finger and the sensor which results in the values of SpO_2 levels and pulse rate of a person [19] getting significantly affected. These jitters are removed from the signal using a moving averaging filter. A moving averaging filter filter's out the small fluctuations in the signal by taking average of the S samples in the data and outputs a smoothed data as seen in fig.4.

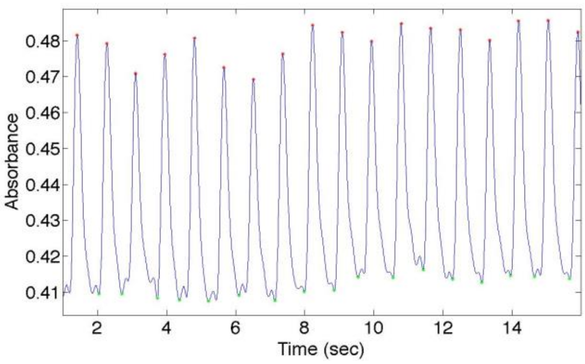

Figure 4: Moving averaging Filter (MAF) Output

In order to obtain the PPG signal in the pulse frequency range, a 100 taps FIR band pass filter is designed which allows passing of frequencies between the ranges of 0.5-2.5 HZ while rejecting all other frequencies. FIR filter is preferred over IIR filter due to its performance characteristics [20].

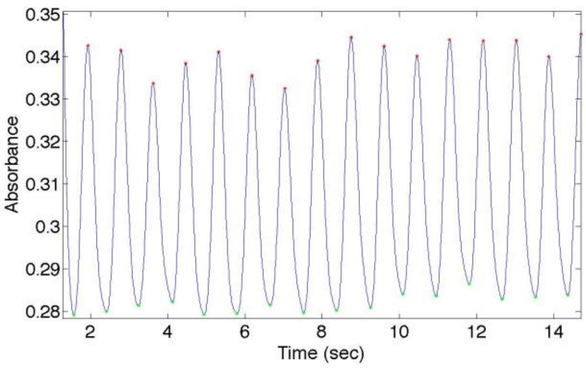

Figure 5: Band Pass Filter (BPF) Output

Fundamental pulse frequency is determined by converting the time domain signal into frequency domain using Fast Fourier Transform of the PPG signal. A single peak is detected in the range of 0.5-2.5 Hz as seen in Fig.6 which corresponds to the frequency of the pulse signal. This frequency is used to determine the pulse rate of a person. For calculating SpO_2 values, AC values of the PPG signals needs to be determined. AC value of the signal corresponds to the amount of absorbance of the signal by the fingertip of a person. Peak to peak values of both the RED and IR signals are measured and the ratio R is determined.

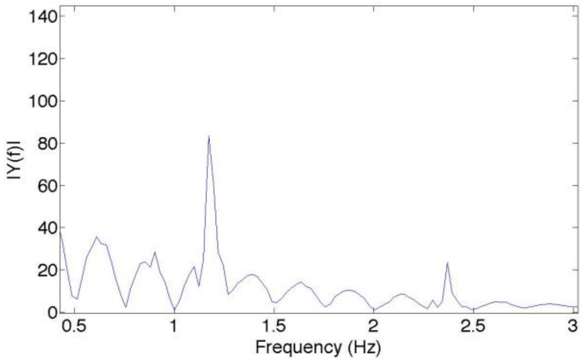

Figure 6: FFT of BPF signal

III. RESULTS

Using the Arduino Uno microcontroller, Red and IR PPG signals from 15 volunteers are recorded and for each person pulse rate and SpO_2 levels are calculated. While taking measurements, a commercial pulse oximeter is also used in order to validate the data. The commercial device is placed on the left index finger while the sensor built is placed on the right index finger of the person. Extinction coefficients presented by [14] were not considered as data corresponding to 630nm was not examined by the researcher. System accuracy is determined by the following equation

$$S.A = 100 * \left(1 - \frac{(Actual\ Value - Measured\ Value)}{Actual\ Value}\right) \tag{13}$$

The SpO_2 values for five volunteers are presented here

Table 1: SpO_2 Values

Person	**SpO_2 Values**		
	%Spo2 using S.Prahl[13]	***%Spo2 using Zijlstra[12]***	***%Spo2 using commercial oximeter***
Male 1	101.8	98.5	96
Male 2	100.8	97.4	97
Male 3	100.8	97.3	97
Female1	99	95.4	98
Female2	99.7	96.1	96

By observing the resulting SpO_2 values, it can be inferred that by using the extinction coefficients mentioned in [12] by Zijlstra, SpO_2 levels obtained have lesser difference with the commercial oximeter values with a mean of 96.5, standard deviation of 1.17 and system accuracy of ±5%. Extinction coefficients given by [13] are not able to give accurate values of SpO_2 in most of the cases. It is also noted that a commercial pulse oximeter is not able to detect the fingertip if nail polish is applied by the person while the sensor proposed in this paper is able to measure SpO_2 and pulse rate values under such conditions. Similarly pulse rate values have been reported in the following table:

Table 2: Pulse Rate values

Person	***Pulse Rate Values***		
	Instant Pulse Rate	***Pulse Rate using FFT***	***Pulse Rate from commercial Oximeter***
Male 1	71	71	67
Male 2	70	69	71
Male 3	56	55	52
Female1	73	74	73
Female2	71	70	69

The pulse rate obtained from the two proposed methods have a maximum difference of 2% between them giving a system accuracy of ±7% with pulse rate computed in frequency domain giving more stable and accurate values with a mean of 73 and a standard deviation of 9%.

IV. CONCLUSION

Presently, SpO_2 levels are determined using the calibration method by computing the calibration coefficients. Calibration coefficients vary from person to person which leads to inaccuracies. A calibration free method has been proposed here using the beer lambert law and photoplethysomography. The ratio R is determined by measuring the AC values of red and IR PPG signals using digital filtering. Using R and known extinction coefficients, SpO_2 levels of a person are measured. Extinction coefficients mentioned by Zijlstra gives more accurate values of oxygen levels in blood. The SpO_2 sensor designed is low in cost involving a simple circuit model and also nullifies the effect of nail polish on the sensor. Arduino Uno microcontroller used here cannot perform complex digital computations and this limitation can be overcome in the future by using ARM microcontroller as it has enough computational power to make the system a real time embedded system.

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