Non-Invasive Measurement of Heart Rate and Hemoglobin Concentration Level Through Fingertip

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***Abstract*—This paper proposes a low cost method for the estimation of blood parameters using photo-plethysmography (PPG) technique. Data is obtained non-invasively from the fingertip, which is processed to estimate the heart rate and the hemoglobin concentration. The signal received from fingertip is first processed via analog filters and the output is sent to a computer through a microcontroller interface to be processed using MATLAB in order to estimate the parameters. The proposed method can be used for health monitoring purposes in rural areas. Furthermore, this solution could be ported to work on a standalone device, thus eliminating the need for a computer.**

***Keywords*—Photoplethysmography(PPG), Beer Lambert law, heart rate, hemoglobin concentration, health monitoring**

I. Introduction

A lot of invasive methods of blood parameter estimation have been invented and are still in use. These approaches however tend to be wearisome and time consuming, in addition to the extra resources required for their implementation. In contrast, non-invasive methods for the same purpose are fairly new and are able to produce similar accurate results with the advantage of being relatively fast and easy to carry out. A non-invasive method allows pain free and continuous monitoring with minimum risk of infection, allowing immediate clinical follow up to the results [1]. Also most of these diagnostic procedures require little medical and technical knowledge and minimal resources, making them easy to carry out in underdeveloped areas which lack medical infrastructure.

In order to measure blood parameters non-invasively, changes in blood volume with time need to be measured using plethysmographs. Among them, absolute changes in blood volume are measured by chamber-plethysmographs. However, in cases where we require only the relative volume measurement of blood, such as pulsation rate of the heart; the information is in the timing and not in the shape or exact amplitude of the signal. In these scenarios electric impedance-plethysmography and photo-plethysmography (PPG) can be used [2].

PPG is a simple, low cost reliable optical technique that can be used to detect blood parameters by passing electromagnetic light rays through the skin. The information about blood parameters is obtained non-invasively in contrast to the painful and inconvenient invasive methods, with measurements generally made at the skin surface whereupon it is easy to record data. During the process, changes in volume caused by blood pressure pulse is detected by illuminating the skin using a light emitting diode (LED) and measuring the amount of light either transmitted or reflected through a light detector.

A PPG sensor can be used in reflection mode (at the fingertip, wherein the light gets reflected off the bone, the distal phalanges) or in transmission mode (wherein the light gets transmitted through the muscles, preferably the earlobe, the aural pinna) [2]. Reflection mode is used in this paper.

In 1991, Y. Iyriboz [3] et al. published a comprehensive study of the accuracy of pulse oximetry for the non-invasive measurement of heart rate, and concluded that the results obtained accurately estimate the heart rate at rest and during sub-maximal exercise. However, during heavy exercise when the heart rate rose above 155 bpm, this method reported an error margin of 9%.

In 1992, Joseph M. Schmitt [4] et al. proposed a non-invasive method for measuring arterial blood hematocrit, which combined with pulse oximetry, enabled the continuous monitoring of hemoglobin concentration and oxygen saturation. Similar work was also done by U. Timm et al. [5] in 2009 and R. S. Al-Baradie and A. S. C. Bose [6] in 2013, wherein both proposed methods for non-invasive continuous hemoglobin monitoring system. In 2012, M. Raikhel [7] studied the accuracy of non-invasive total blood hemoglobin measurement and reported a bias and a standard deviation of -0.5 g/dL and 1.0 g/dL respectively, when compared with invasive techniques.

The proposed device has two applications: estimation of heart rate and hemoglobin levels through PPG. Heart rate measurement is done by analyzing the frequency of AC component of voltage signal acquired by the PPG sensor. Hemoglobin level is measured by analysis of the average (DC) voltage level using the Beer-Lambert Law [8].

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II. System Description

A. Hardware Component

The hardware part consists of PPG signal acquisition circuit, as shown in Fig. 1. An infrared (IR) LED acts as the IR emitter, which illuminates the finger and the tissues underneath the epidermis. Due to changes in the blood volume in the finger, the absorption of IR radiation changes, which leads to variation in the amount of radiation getting reflected. The change is detected in the phototransistor, which varies the amount of collector current through the same. A two stage signal conditioning circuit is used for removing the noise and DC component from the received signal. DC component is not required for the measurement of heart rate; however it is needed for the measurement of hemoglobin level. It is fed into the computer for further processing after appropriate analog-to-digital (ADC) conversion through the ADC chip present on a microcontroller, Arduino Leonardo, using serial communication to send the signal to the computer.

B. Software Component

The software part consists of codes running on the Arduino IDE (Integrated Development Environment) and MATLAB. This enables the setup of a serial communication link between the device and the computer. The PPG signal obtained is analyzed for the estimation of heart rate and hemoglobin level. Hemoglobin level is estimated with the help of Beer-Lambert Law, a relation between the intensity of IR radiation absorbed and concentration of hemoglobin in the blood.

III. Circuit Analysis

It is safe to assume that the heart rate lies between the extreme values of 30 bpm to 150 bpm, where 'bpm' stands for beats per minute [9]. The heart rate is obtained from this circuit by multiplying the frequency of the cleaned up PPG signal with 60, since measurement is done in beats per minute. Therefore, the only frequency components in the PPG signal obtained from the circuit, relevant to us must lie between (30/60) Hz to (150/60) Hz, i.e. 0.5 Hz to 2.5 Hz. Hence, the filter must be designed keeping these specifications in mind. A high pass filter is needed having a cut-off frequency approximately equal to 0.5 Hz coupled with a low pass filter having a cut-off frequency approximately 2.5 Hz.

Filtering at each stage is accompanied by amplification of the filtered output signal. This step is necessary to amplify the AC component of the PPG signal and block the DC component, wherein, the former contains all the information that we need and the latter is of no use to us (for heart rate estimation). Amplification is a necessary step because the AC component is too small in magnitude, compared to the DC offset which it is riding upon. Theoretically, a magnification of the order of magnitude of 10^4 is necessary to view the signal clearly.

Vishay TCRT1000 [10] was used, which is a reflective optical sensor with phototransistor output. It has a peak operating distance of 1 mm, and typical output current I_C is 0.5 mA. The emitter wavelength is 950 nm (Infrared) and it comes integrated with a daylight blocking filter.

In the two stage signal conditioning circuit, each stage consists of a low pass and a high pass filter.

The cutoff frequency of the high pass filter, $f_{c,HPF}$ comes out to be 0.72 Hz, which is close to the desired 0.5 Hz, with 4.7 μF and 47 $k\Omega$ capacitance and resistance values respectively.

The cutoff frequency of the low pass filter, $f_{c,LPF}$ comes out to be 2.34 Hz, which is close to the desired 2.5 Hz, with 0.1 μF and 680 $k\Omega$ capacitance and resistance values respectively.

The AC component of the recorded signal, which is solely needed for the heart rate estimation, is quite small in magnitude as compared to the DC offset. Therefore, along with the removal of the DC offset, it is important that the AC component be amplified. A magnification of the order of 10^4 is needed to view the signal clearly. The overall gain is the product of the gain of the two stages, each being 101, making the overall gain of the order 10^4.

Texas Instruments LM339 comparator IC has been used as a peak detector. The function of the comparator is to give a high value whenever the input signal (filtered and amplified AC signal) is above 1 V, which corresponds to a heartbeat. Therefore, the comparator circuit outputs a square wave with frequency corresponding to the pulsation of the heart.

IV. Results

The measured heart rate (in bpm) is the frequency of the comparator output times 60, since the frequency is calculated in terms of 'per second'.

Beer Lambert Law, a relation between the absorption of light and the properties of the material through which light is getting transmitted, is used to estimate hemoglobin level in this work. The law states that

$$T = \frac{I}{I_0} = 10^{-\epsilon c l}$$

where **T** is transmittance, **I** is the intensity of light transmitted through the material, $\mathbf{I_0}$ is the intensity of light incident on the material, **l** is the length through which light travels inside the material (l = 0.6 cm), **c** is the concentration and ϵ is the molar absorptivity of the material (ϵ = 602.24 $cm^{-1}M^{-1}$).

1 gm dL^{-1} = 0.1551 mM for hemoglobin solution in water [11].

In this paper, the input voltage to the sensor and output voltage from the collector of sensor phototransistor are used as parameters to the Beer Lambert Law, both measured via the microcontroller, and the mean values of the measurements over the input time are taken for calculation. The reflected light is monitored, and the input voltage (V_{in}) and the output voltage (V_{out}) are taken as substitutes for the incident and reflected intensities respectively due to their linear dependence on the same [12][13]. Thus, using the following equation, hemoglobin concentration is estimated, and the observations are tabulated in Fig. 3.

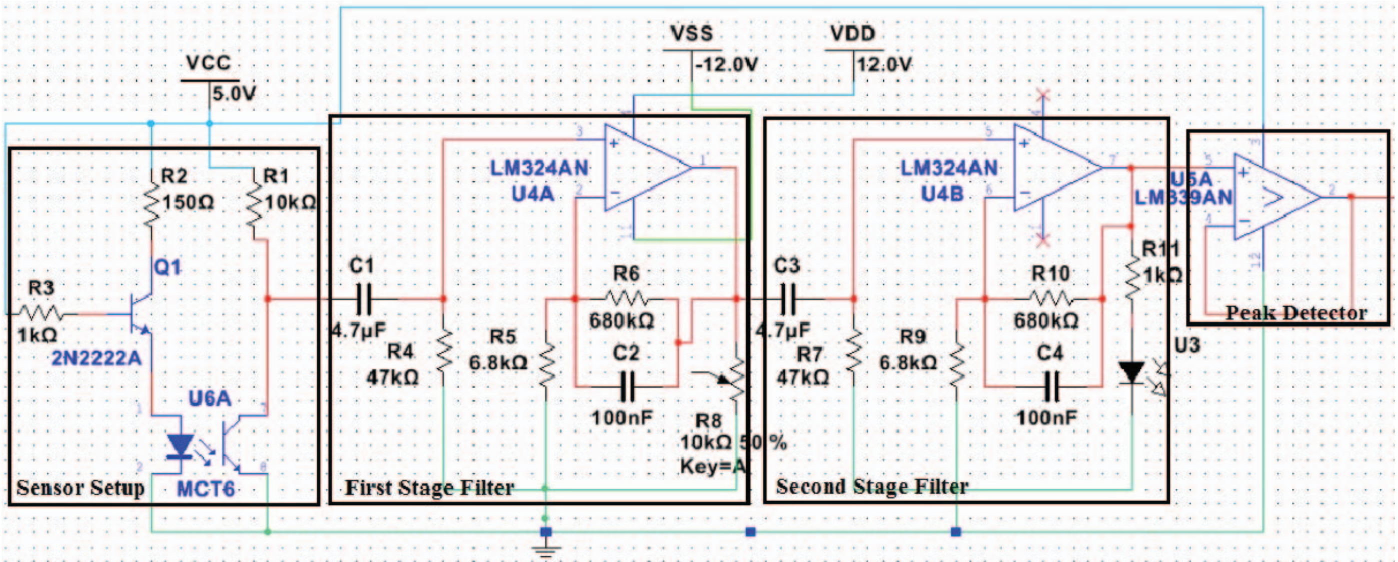

Fig. 1: Overall circuit layout in NI Multisim

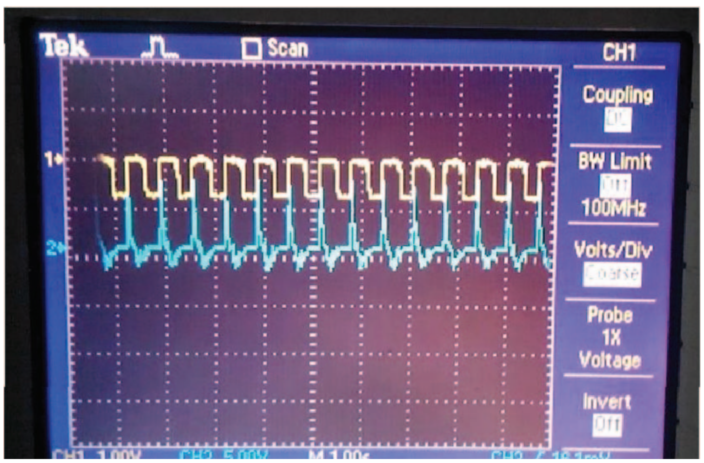

Fig. 2: Output of the second signal conditioning stage (blue, below) and comparator (yellow, above)

Sl. No.	Observed Values		
	Actual Heart Rate (bpm)	Observed Heart Rate (bpm)	Observed Hemoglobin Concentration (gm/dL)
Subject 1	78	75	12.8
Subject 2	73	75	12.1
Subject 3	92	90	13.7
Subject 4	81	83	12.5

Fig. 3: Observation Table

$$\frac{V_{in} - V_{out}}{V_{in}} = 10^{-\epsilon cl}$$

V. Conclusion

In this paper, heart rate and hemoglobin levels of human blood have been estimated non-invasively with a good level of accuracy. The technique is a low cost and convenient way to estimate blood parameters, and also promises similar accuracy in the determination of other essential medical parameters like respiration rate, blood pressure, glucose level in blood, partial pressure of oxygen in blood etc. The easy realization of concept and added benefits of low cost components can help in increasing the availability of cheap healthcare in remote areas.

Future augmentation to the work can also be in the direction of making the process increasingly portable and comfortable. This can be done by using the means of wireless connection for sending the data to the computer in place of a physical wired connection. The data would then have to be sampled by a microcontroller and sent to the computer after the sampling has been performed. A better implementation of the entire setup would be to make it portable and a standalone unit by removing the computer and performing the entire processing on the microcontroller. Portability makes it easy to use in the remote areas as well.

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