Development of Soft-Core system for Heart Rate and Oxygen Saturation

Caje F. Pinto, Jivan S. Parab, Gourish M. Naik

Abstract**—**This paper is about development of Non-invasive Heart rate and Oxygen saturation in Human blood using Altera NIOS II soft-core processor system. In today's world the Monitoring oxygen saturation and Heart rate is very important in hospitals to keep track of low oxygen levels in blood and Heart rate. We have designed an Embedded System On Peripheral Chip (SOPC) reconfigurable system by interfacing two wavelengths of light using two LED's (660nm/940nm) with a single photo-detector to measure the absorptions of haemoglobin species at different wavelengths. The implementation of the interface with Finger Probe and Liquid Crystal Display (LCD) was carried out using NIOS II soft-core system running on Altera NANO DE0 board having target as Cyclone IVE. This designed system is used to monitor Oxygen Saturation in Blood and Heart rate for different test subjects. The designed NIOS II processor based Non-invasive Heart rate and Oxygen saturation was verified with another Operon Pulse oximeter for 50 measurements on 10 different subjects. It was found that the readings taken were very close to the Operon Pulse oximeter.

Keywords**—**Heart Rate, NIOS II, Oxygen Saturation, photoplethysmography, soft-core, SOPC.

I. Introduction

ONE of the most important elements needed to sustain life is oxygen (O_2) because it is used by cells to turn sugars into usable energy. Oxy-haemoglobin (HbO_2) is found in a red blood cell which is bonded to O_2 that delivers 98% of oxygen to cells. The measurement and calculation of Oxy-haemoglobin (HbO_2) in arterial blood is known as oxygen saturation (SpO_2) [1],[2].

Originally, SpO_2 was measured invasively by Arterial Blood Gas (ABG) sampling. In this technique the blood sample is drawn from an artery and analyzed each time, the arterial blood gas provides only intermittent monitoring which may not be ideal for monitoring unstable patients. Since this technique is invasive, it is inconvenient, painful and can cause infections like arterial thrombosis and gangrene. The need for a non-invasive method of measuring SpO2 in real-time led to the development of a device to measure Heart rate and oxygen saturation [2].

A healthy person should have SpO_2 in between 94% to 100%. The photoplethysmography (PPG) is obtained by measuring changes in light intensity absorbed by the blood for different wavelengths. Red and infrared wavelengths are used because these can easily penetrate through tissues [3]. From PPG signal, oxygen saturation is derived from the ratio of the absorption of the two wavelengths. It is important to monitor oxygen level in blood when the patient is in the recovery room and intensive care unit to detect hypoxemia. Also it can be used to monitor oxygen level of a person while exercising and for normal outdoor activities [4].

A heart rate meter is a device that allows a person to measure and monitor their heart beat in real time. The heart rate of a healthy adult at rest is around 72 beats per minute (bpm) & Babies at around 120 bpm, while older children have heart rates at around 90 bpm. The heart rate rises gradually during exercises and returns slowly to the rest value after exercise. The rate when the pulse returns to normal is an indication of the fitness of the person. If the heart rate is lower than normal value, it is known as bradycardia, while if the heart rate is higher than normal value, it is known as tachycardia. Normally Heart rate is measured by placing the thumb over the person's arterial pulsation and counting the number pulses in a 60 second period [5]. Heart rate measurement is very important because it indicates the how good the cardiovascular system is functioning.

The important physical property is that the blood color changes depending on oxygen saturation and haemoglobin absorbs different amounts of light. Deoxy-haemoglobin absorbs more red light than oxy-haemoglobin. As oxygen saturation falls, the blood becomes darker and more red light is absorbed. At near infrared range of light, oxy-haemoglobin absorbs more infrared light than deoxy-haemoglobin [2],[4].

II. Related Work

SpO2 Sensor in a wearable Monitor was constructed using LED's/ Photodiode with signal conditioner along with Arduino Uno in [2] to measure and display Oxygen saturation on the Smart Phone using Android application. Heart Rate Counter was designed uisng PIC16F628A along with LED's/Phototransistor with signal conditioner in [5] to measure heart rate in relaxed state and stressed state. Reference [6] showed that Pulse Oximeter was done using Arduino Uno, LED's/detectors to Calculate Heart rate and Oxygen Saturation. Also pressure sensor probe was used to measure Blood Pressure. Continuous monitoring of Pulse rate and Oxygen saturation with LabVIEW was done by using LED driver circuit, Transimpedance amplifier in [7]. The

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signals from the SpO_2 sensor probe were fed to the amplifying circuit which was interfaced using the interfacing software 'LabVIEW' through Data Acquisition card (DAQ card) and the results were displayed in the LabVIEW front panel. Reference [8] showed the development of MSP based pulse oximeter with LabVIEW along with Analog Frontend (AFE4490) and Nellcor DS100A sensor probes with red LED, IR LED and a photodiode on both sides of the probe. The measurements showed good relation with standard Contec Pulse oximeter (CMS50E).

Heart Rate Monitor was designed in [9] using IR LED and Photodiode, Signal Conditioner and Arduino Uno. The Processing software displayed real time PPG waveform and heart rate.

III. Block Diagram And Implementation

Several researchers have designed Non Invasive Heart rate and Oxygen saturation meter using different controllers but in our design we have used NIOS II soft-core processor to design it. By using NIOS II, simplified designs can be updated to higher level, we can choose the components to build a soft-core processor running on FPGA and rest of the FPGA hardware can be used for accelerating the parts of the code. Also less power is consumed using NIOS II running on Cyclone IVE compared to other predefined microcontrollers.

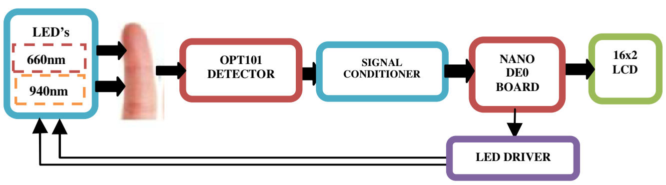


Fig.1 Block diagram of the Model.

Fig. 1 shows the design for the Non Invasive Heart rate and Oxygen saturation meter. The section consists of NANO DE0 Board, Finger Probe with two wavelengths of LEDS, a single photo detector, Signal Conditioning Block and Liquid Crystal Display (LCD).

The LED sources are 660nm and 940nm. These two LED sources are controlled by NANO DE0. It sends two square waves to turn on and off the two LEDs in such a way that both LED's are not on at the same time. To control the light intensity, a resistor is added with each LED. Behind the finger, a photo detector is used to convert the light signal into electrical signal. The electrical signal amplitude is extremely low. Thus, an amplifier is added directly after the photo detector. To make the signal detectable an IC OPT101 is used as transimpedance amplifier which can be used not only to amplify but also to convert the current into voltage. Variation in light intensity is due to changes in perfusion in the blood volume. The most recognizable waveform is the photoplethysmograph signal which is synchronized to each heartbeat of the person. The signal from OPT101 contains lots of other undesired frequency components. Thus, an active band-pass filter is needed to remove the undesired signal, leaving the frequency which is desired. The filter's pass band should be in range of 0.07 Hz to 3.38Hz.

The next block is the NANO DE0 FPGA Board. The analog output from the band pass filter is given to the NANO DE0 FPGA Board. It has a 12-bit ADC which is used to convert analog data to digital data. The switching of the 660nm and 940nm is controlled by NIOS II soft core processor running on FPGA. It stores the output when either of the LED is switched ON. This data can be calculated to find the concentration of oxy-haemoglobin and de-oxyhaemoglobin and hence calculate oxygen saturation and Heart rate which is displayed on the LCD.

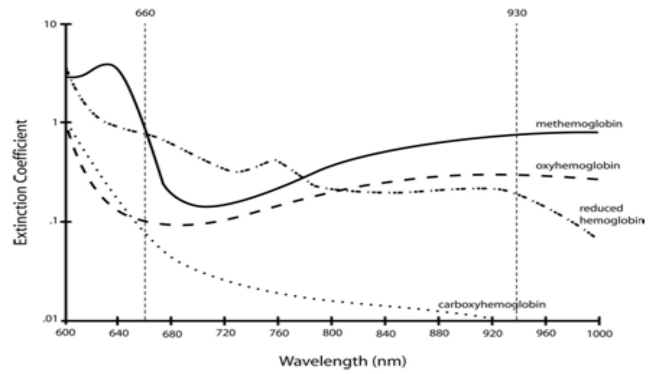


Fig.2 Light absorbance (Extinction coefficient) *vs* wavelength [10]

Fig. 2 shows absorbtion extinction coefficient for different haemoglobin species. Here we are interested in Oxy-haemoglobin and deoxy-Haemoglobin for our calculations to find Oxygen Saturation.

A. Principle of Beer-Lambert Law

The Beer-Lambert Law describes the attenuation of incident light (I_0) crossing a material with absorbing properties when an incident beam (I_0) enters the sample, the intensity of transmitted light (I) decreases exponentially as shown in (1) [4].

$$I = I_0 . e^{-\varepsilon(\lambda).C.L} \qquad (1)$$

where I is intensity of transmission light;
I_0 is intensity of incident light;
C is concentration of absorbent, mol (mol);
L is optical path length in the cm.
ε is absorptivity (extinction coefficient) of the substance at a specific wavelength, mol-1 cm-1 (1/mol centimeters) [2].
Absorbance can be calculated using the following equation.

$$A = -\ln\frac{I}{I_0} = \varepsilon.(\lambda).C.L \qquad (2)$$

where A is absorbance and λ is wavelength in (2).
Hence we use different wavelengths to get different equations with different unknowns, which are the concentrations of haemoglobin like oxyhaemoglobin, and deoxyhaemoglobin. We can solve these equations to get the concentration ofthese components. Equation 3 shows that Absorbance is an additive function Absorbance of a mixture is a sum of the absorbances of the components.

$$A = \varepsilon_X[X]L + \varepsilon_Y[Y]L \qquad (3)$$

where [X] and [Y] are unknowns concentrations.
To determine the unknown concentrations of N substances in mixture, absorbance's of this is measured at N wavelengths having N number of equations.

A. Analysis of Two-Component Mixture (Deoxy-hemoglobin and Oxy-hemoglobin)

For two unknown components, we require two wavelengths. The wavelength is chosen to maximize the differential molar absorptivity.
Absorption of the mixture at wavelength at λ_1:

$$A_1 = \varepsilon_1^{Hb}[Hb]L + \varepsilon_1^{HbO_2}[HbO_2]L \tag{4}$$

Absorption of the mixture at wavelength at λ_2:

$$A_2 = \varepsilon_2^{Hb}[Hb]L + \varepsilon_2^{HbO_2}[HbO_2]L \tag{5}$$

To solve this system of equation with regards to [Hb] and $[HbO_2]$ we must:

1. Measure the molar absorptivities of deoxy- hemoglobin and oxyhemoglobin at two wavelengths: $€_1^{Hb}$, $€_1^{Hb02}$,$€_2^{Hb}$,$€_2^{Hb02}$
2. Measure absorbance, A_1 and A_2, of the mixture at two wavelengths.
3. Solve the system from (4) & (5).

$$Hb0_2 = \frac{A_2\varepsilon_1^{Hb} - A_1\varepsilon_2^{Hb}}{\varepsilon_2^{HBO2}\varepsilon_1^{Hb} - \varepsilon_2^{Hb}\varepsilon_1^{HBO2}} \tag{6}$$

where $[Hb0_2]$ is concentration of oxy-haemoglobin.

$$Hb = \frac{A_1\varepsilon_2^{HbO2} - A_2\varepsilon_1^{HbO2}}{\varepsilon_2^{HbO2}\varepsilon_1^{Hb} - \varepsilon_2^{Hb}\varepsilon_1^{HbO2}} \tag{7}$$

where [Hb] is concentration of deoxy-haemoglobin.

$$SpO_2 = \frac{Hb0_2}{Hb+Hb0_2} * 100\% \tag{8}$$

where SpO_2 is the oxygen saturation in blood.

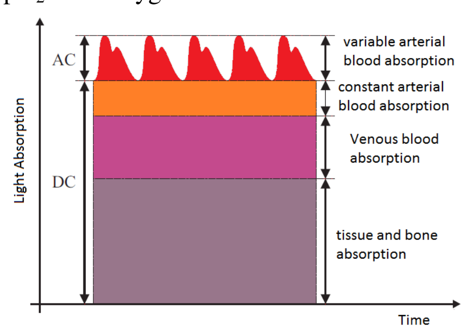


Fig. 3 Light Absorption by different tissues [12].

Fig. 3 shows light absorption by different tissues. The DC component represents the light absorption of the tissue, venous blood, and non-pulsatile arterial blood. The AC component represents the pulsatile arterial blood. The pulse oximeter analyzes the light absorption of two wavelengths from the pulsatile-added volume of oxygenated arterial blood (AC/DC) and calculates the absorption ratio using "9" [12].

$$R = \frac{\frac{I(ac)}{I(dc)}(RED)}{\frac{I(ac)}{I(dc)}(IR)} \tag{9}$$

$$R = \frac{(Vmax(red) - Vmin(red)) * Vmin(IR)}{(Vmax(IR) - Vmin(IR)) * Vmin(red)} \tag{10}$$

Equation 10 is the modified equation to calculate the R Ratio.

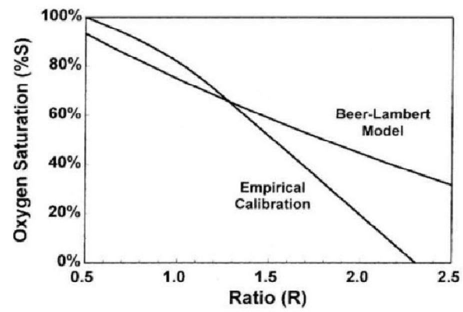


Fig. 4 Relation between R and SpO2 from Beer-Lambert law [12].

Fig. 4 shows the relationship between ratio of absorbtion between Red wavelength and infra red wavelength.

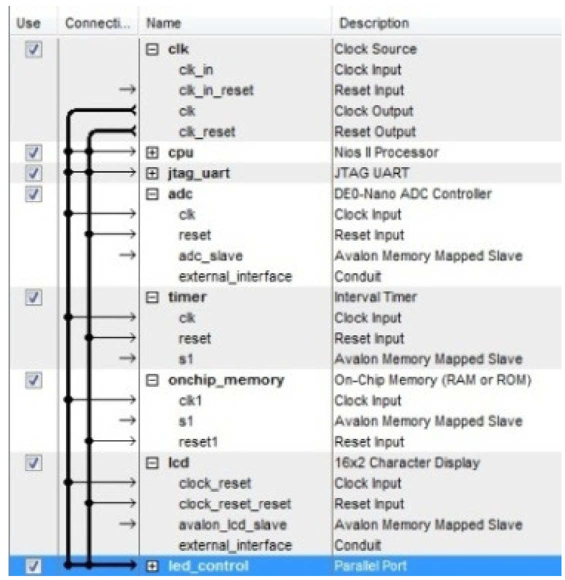
$$SpO_2\% = 112.5 - R*25 \tag{11}$$

Equation 11 is the empirical equation to calculate the SpO_2.

IV. NIOS II INTERACTION

In our design we have used NIOS II soft-core processor to receive the analog signal for two different wavelengths and do the necessary calculations to calculate the Heart rate and Oxygen saturations using empirical formula.

The SOPC components required for building the Non-Invasive Heart rate and Oxygen saturation meter is shown below in Fig.3. The selected components are 32-bit NIOS II CPU, JTAG UART, On chip Memory, Interval Timer, ADC, CHARACTER LCD. After selecting the SOPC components, the entire NIOS II system is generated. The NIOS II processor is interfaced to the on chip RAM to store the program code and the transmitted signal received from finger probe via ADC.



Use	Connecti...	Name	Description
✓		clk	Clock Source
		clk_in	Clock Input
		clk_in_reset	Reset Input
		clk	Clock Output
		clk_reset	Reset Output
✓		cpu	Nios II Processor
✓		jtag_uart	JTAG UART
✓		adc	DE0-Nano ADC Controller
		clk	Clock Input
		reset	Reset Input
		adc_slave	Avalon Memory Mapped Slave
		external_interface	Conduit
✓		timer	Interval Timer
		clk	Clock Input
		reset	Reset Input
		s1	Avalon Memory Mapped Slave
✓		onchip_memory	On-Chip Memory (RAM or ROM)
		clk1	Clock Input
		s1	Avalon Memory Mapped Slave
		reset1	Reset Input
✓		lcd	16x2 Character Display
		clock_reset	Clock Input
		clock_reset_reset	Reset Input
		avalon_lcd_slave	Avalon Memory Mapped Slave
		external_interface	Conduit
✓		led_control	Parallel Port

Fig. 3 SOPC Block selected to Build System

The generated system is then brought to Quartus Block diagram file window and later the pin mapping is done as shown in fig. 4.

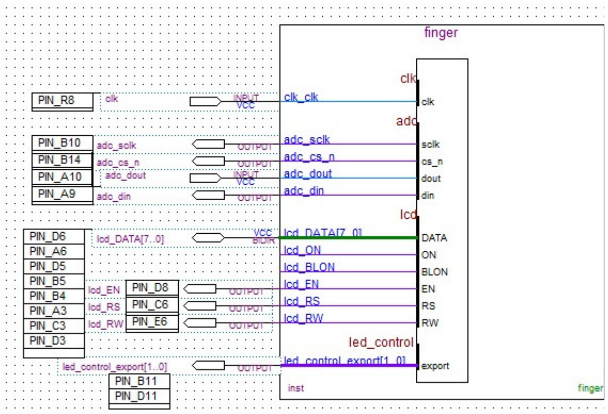


Fig.4 Altera NIOS II soft-core system interface with Finger probe and LCD.

Once the design is compiled, the programming file is ported on Cyclone IVE using USB blaster. Next step is to run the C code on the NIOS II system to get the expected result. Fig. 5 shows the flowchart for the C code which runs on the NIOS II system.

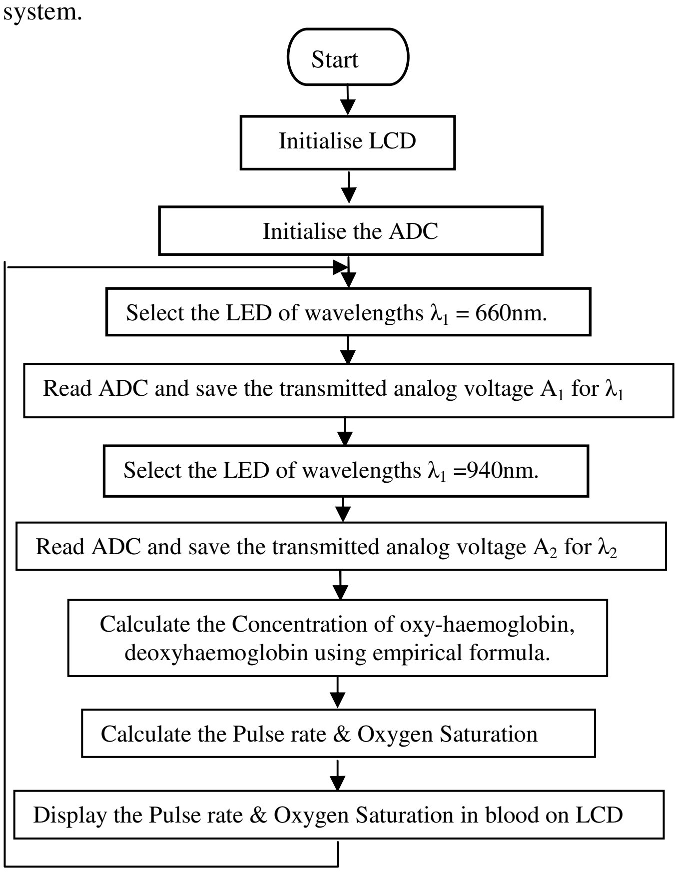


Fig 5.Flowchart for Non Invasive Heart rate and Oxygen Saturation Meter.

First the LCD is configured as 8 bit data, display on and cursor on. The ADC is also configured to read the transmitted analog voltages from the finger probe with signal conditioner. The two wavelengths (660nm / 940nm) will be selected by the soft-core processor one at a time and the readings for each wavelength will be saved in A_1 to A_2 (Absorbance from λ_1 to λ_2). The concentrations of oxy-haemoglobin, deoxyhaemoglobin species are calculated using empirical formula equations. Finally, the Heart Rate and Oxygen Saturation are displayed on the LCD.

V. Result And Discussions

The Quartus II software was used for building the Non Invasive Heart rate and Oxygen Saturation which was downloaded onto NANO DE0 Board. Finally it was connected to the Finger probe with two LED's and a photo detector along with signal conditioner to get the desired heart rate and oxygen saturation for 10 subjects with 50 measurements. It was found accurate with less error when compared with standard pulse oximeter. Also Total haemoglobin can be calculated by using appropriate formulas. Further work can be improvised by including more wavelengths to calculate total Haemoglobin along with Multivariate regressions.

The PPG Signal was observed during each heart beat for two different wavelengths of LED's (660nm and 940nm) using Audacity software on PC and also using Digital Storage Oscilloscope.

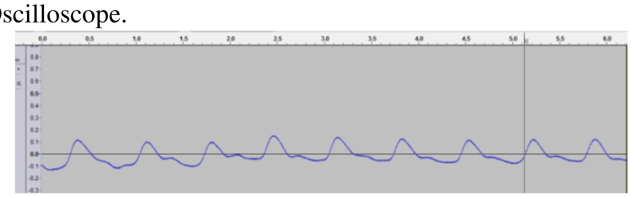


Fig. 6 PPG signals for 660nm LED

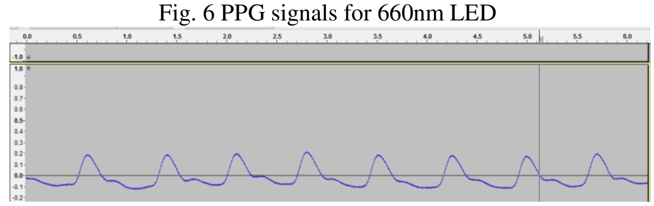


Fig. 7 PPG signals for 940nm LED

Fig. 6 shows that Red LED at 660nm has a small PPG signal compared to Fig. 7 with IR LED at 940nm. From the above figure it shows that more IR light transmitted through finger compared to Red LED.

Table I
HEART RATE AND OXYGEN SATURATION

Subject	With finger Red (660nm)		With finger IR (940nm)		Ratio R	SpO_2 %	Heart Rate	SpO_2 %	Heart Rate
	V_{min} (V)	V_{max} (V)	V_{min} (V)	V_{max} (V)		Using NIOS II Based Heart Rate & Oxygen Saturation		Using Operon Pulse Oximeter	
1.	0.6	1.4	0.8	3.2	0.5	99.13	76	99	76
2.	0.6	1.55	0.8	3.0	0.576	98.10	74	98	74
3.	0.5	1.3	0.8	3.0	0.582	97.95	73	97	74
4.	0.6	1.4	1.0	3.4	0.556	98.61	76	97	76
5.	0.4	1.1	0.7	2.7	0.613	97.18	74	97	73

IV. CONCLUSION

The Development of a Soft-core system for Heart rate and Oxygen Saturation was efficiently designed using Altera NIOS II on Nano DE0 Board. The code was written in C language and was loaded into the FPGA for measuring Heart rate and oxygen saturation. Further Work has to be carried out to predict the Total Haemoglobin using Multi-variate regressions with less error.

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