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Rapid Prototyping of Pulse Oximeter

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Abstract—**Measurement of oxygen saturation levels in blood is a vital activity during most medical treatments. A pulse oximeter is a device most commonly used to perform this measurement. It provides convenient, non-invasive and continuous monitoring of oxygen levels in a human body. However, it is often a tedious task to select the appropriate hardware and software components to manufacture a pulse oximeter that gives accurate results. This paper describes a student project, which had the goals to expose the student to this important technique of applying rapid prototyping methods to the design of a state of the art pulse oximeter.**

Keywords—**hardware-in-the-loop, modeling, pulse oximeter, simulation, SpO2, rapid prototyping**

I. INTRODUCTION

Monitoring the oxygenation of a patient's blood forms a crucial parameter during a visit in operating rooms, recovery rooms, Intensive Care Units (ICU), Neonatal Intensive Care Units (NICU), ambulances etc. The percentage of oxygen in blood is of vital importance especially for patients being administered general anesthesia or receiving respiratory care. Since any abnormal oxygen saturation level in a patient's blood needs to be treated immediately, a non-invasive technique capable of continuously measuring oxygen saturation is desired. Pulse oximeters provide a real-time, non-invasive technique for measurement of oxygen saturation in blood.

The working principle of a pulse oximeter is based on the Beer-Lambert's law for spectral analysis. This law states that the concentration of absorbent in solution can be determined as a mathematical function of the amount of light transmitted through the solution, providing that the intensity of incident light, the path length, and the extinction coefficient of a substance at a particular wavelength are known.

$$\begin{aligned} A_{\lambda 1} &= \varepsilon_{o1} l_o C_o + \varepsilon_{r1} l_r C_r + \varepsilon_{x1} l_x C_x + A_{y1} \\ A_{\lambda 2} &= \varepsilon_{o2} l_0 C_o + \varepsilon_{r2} l_r C_r + \varepsilon_{x2} l_x C_x + A_{y2} \end{aligned} \quad (1)$$

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Equation (1) is the mathematical representation of the Beer-Lambert's law to calculate the absorbance (A) of light at two discrete wavelengths as a function of extinction coefficients (ε), path length (l), concentration of the absorbent (c) and wavelength (λ) [1].

The percentage of oxygen in blood measured by the pulse oximeter is the ratio of oxygenated hemoglobin to the total amount of hemoglobin capable of binding with or transporting oxygen. This ratio is commonly expressed as a percentage. This parameter is an indicator of the arterial oxygen saturation, commonly referred to as SaO_2. However, when measured by a pulse oximeter, this is specifically referred to as SpO_2.

$$SpO_2 = \frac{HbO_2}{RHb + HbO_2} \times 100\% \quad (2)$$

Equation (2) represents the ratio SpO_2 where HbO_2 refers to oxygenated hemoglobin and RHb refers to hemoglobin with reduced oxygen.

II. TECHNOLOGY

The signal conditioning units within a typical pulse oximeter are depicted by Figure 1. A pulse oximeter consists of a probe and a signal processing unit. The probe consists of a source of light, typically light emitting diodes (LEDs) and a photodetector. Pulse oximeters generally use a "transmission mode", where the light source and the photodetector are placed on opposite sides of the sample tissue. The photodetector detects the intensity of light transmitted through the tissue. The oximeter probe is usually worn on well-perfused tissue like finger tips or the ear lobe. A red LED emitting light typically at a wavelength of 660 nm and an infrared LED emitting light typically at 940 nm is made incident on the area of tissue it is clipped on. To nullify the effect of ambient light, the LEDs are made to follow a cycle where the red LED is powered on for e.g. 0.4 ms, both LEDs are powered off for 0.4 ms, infrared LED is powered on for 0.4 ms following which both LEDs are powered off again for 0.4 ms. The amount of light transmitted through the tissue is detected by the photodetector. The photodetector converts the amount of light detected into its equivalent electrical signal, e.g. current. The amount of current produced when both the

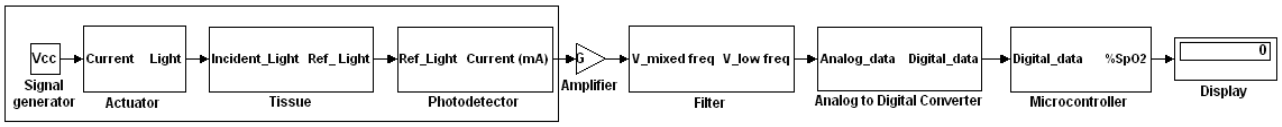

Fig.1. Principle of pulse oximeter as signal flow depicting the probe and the signal processing unit [1] [3]

LEDs are powered off gives an estimate of the intensity of ambient light. [2]

In the measuring unit, the current is converted to equivalent voltage levels. The voltage signal thus obtained is amplified and filtered using a low pass filter. The filtered signal is digitized and then demodulated. From the demodulated data, the electrical signal obtained at ambient light is subtracted from that obtained at each of the two wavelengths of light. This nullifies the effect of ambient light on the measured parameters. A ratio R, which is the ratio of the voltage level at 660 nm to that at 940 nm is calculated. The SpO_2 value corresponding to ratio R is computed using the relationship depicted in Figure 2.

To reduce the effect of absorption of light by the surrounding tissue, measurements are only made on detection of an arterial pulse. Blood has a light absorption coefficient greater than that of the surrounding tissue. An arterial blood pulse increases the volume of the artery due to an increase in the volume of blood. This results in greater absorption of light by blood as compared to that by the surrounding tissue.

III. MODELING

During the project, a pulse oximeter was implemented and simulated using MATLAB Simulink. Figure 3 represents the Simulink model of the implemented components. The model simulates the working of a photodiode, the tissue, on which the light is incident and the photodetector, which senses the light transmitted through the tissue.

The simulation involves transmission of light at two discrete wavelengths. The light is made incident on the tissue i.e. sample blood. The intensity of light transmitted through the tissue is detected by the photodetector. The photodetector translates the amount of light it receives into an electrical output e.g. current. The output from the photodetector may further undergo amplification, filtering and computation as per the designed signal conditioning unit to yield the SpO_2 content in the sample blood.

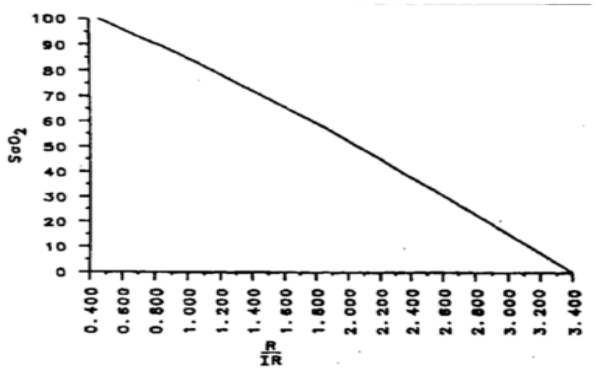

Fig. 2. Relationship between the ratio of red (R) and infrared (IR) to oxygen saturation (SaO_2). [2]

IV. SIMULATION

The simulation for each of the subsystems is described as follows:

A. Photodiode

The photodiode consists of two LEDs. In the model depicted in Figure 4, a red LED and an infrared LED are simulated for emitting light at wavelengths of 660 nm and 940 nm respectively. The typical forward biasing voltage for the red LED is 1.8 V while that for the infrared LED is 1.3 V. The LEDs are sequenced such that both the LEDs are powered off for 1 ms, the red LED is powered on for 1 ms, both LEDs are powered off again for 1 ms and finally the infrared LED is powered on for 1 ms. This cycle is continuously repeated. The LEDs are simulated to be powered on or off by providing a forward bias or a reverse bias to them respectively.

The LEDs are kept normally reverse biased by supplying a constant potential of 2 V at both, the anode and the cathode. To forward bias an LED, the potential at cathode is dropped to produce the required forward biasing potential difference across the diode. The voltage drop (V_F) across the LED is multiplied by the forward current (I_F) to simulate the intensity (P_{out}) of light emitted by the LEDs.

$$P_{out} = I_F V_F \tag{3}$$

The light emitted by the two LEDs is summed and given as an input to the subsystem representing "*tissue.*"

B. Tissue

Tissue" forms a relatively complex subsystem in the model as depicted in Figure 5. It receives three inputs (i) the light emitted by the LEDs on the tissue, (ii) the volume of blood flow through the artery, and (iii) a signal for selecting the frequency spectrum of ambient light.

The light emitted by the LEDs is represented by a stream of rectangular waves while the blood flow is simulated by a continuous stream of sawtooth waves. The rectangular waves indicate the intensity of light at red, infrared and ambient light

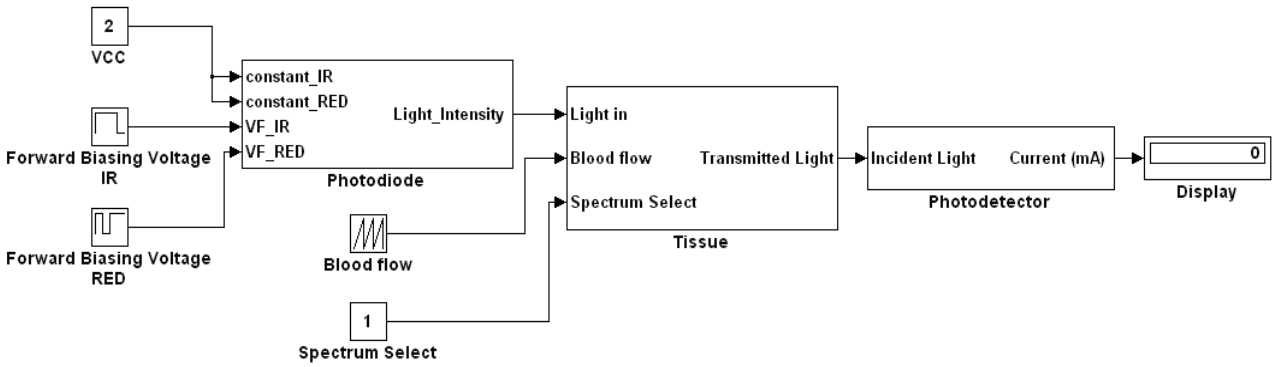

Fig. 3. Simulink model of implemented components

frequencies. The sawtooth wave simulates the gradual increase in blood flow during an arterial pulse. The amount of light absorbed by the tissue is a function of the frequency of incident light and the volume of blood flow.

The subsystem *"Tissue"* is further comprised of two subsystems: (i) Subsystem 1.a, and (ii) Subsystem 1.b.

Subsystem 1.a separates the single stream of rectangular waves into two separate streams of rectangular waves, each representing the intensity of light emitted by the corresponding LED. This corresponds to the demodulation of data in a pulse oximeter.

Subsystem 1.b receives four inputs:

(i) a constant representing the wavelength of light incident on the tissue

(ii) a continuous stream of rectangular waves indicating intensity of light emitted by the red LED

(iii) a continuous stream of rectangular waves indicating intensity of light emitted by the infrared LED, and

(iv) a continuous stream of sawtooth waves representing variations in the volume of blood.

The constant representing the wavelength of light incident on the tissue, serves as an input to two lookup tables. The data in the lookup table was derived by digitizing Figure 6. The digitized data file was imported into the MATLAB workspace. The lookup tables yield extinction coefficients of HbO_2 and RHb at the incident wavelengths of light.

Even though the model is currently using light at wavelengths of 660 nm and 940 nm only, the lookup table is provided to add flexibility to the model so that it may be simulated for different wavelengths of incident light.

The *subsystem 1.b* performs the task of computing the intensity of absorbed light. The extinction coefficient range for RHb and HbO_2 is calculated at 960 nm. The upper limit of the range corresponds to 100% SpO_2 whereas the lower limit of the range corresponds to 0% SpO_2. Similarly, the extinction coefficient range for RHb and HbO_2 is calculated at 640 nm. In this case, the upper limit of the range corresponds to 0% SpO_2 whereas the lower limit of the range corresponds to 100% SpO_2. Multiplication of the range of coefficients by the volume of blood flow simulates the degree of absorption of the incident light by sample blood. As discussed previously, the amount of light absorbed is proportional to the volume of blood. A bias is added at the respective wavelengths and the result so obtained is multiplied by the signal representing incident light. This output, which represents the amount of light absorbed by the sample blood, is given to the subsystem *"Photodetector."*

C. Photodetector

This subsystem, as depicted in Figure 7, converts the intensity of transmitted light into an equivalent electrical signal. This signal is processed to compute SpO_2.

A prototype board, of a physiological infant monitor, which incorporates a discrete pulse oximeter, is used to demonstrate the principles of rapid-prototyping. For this purpose the simulation model of the probe can be replaced with the actual

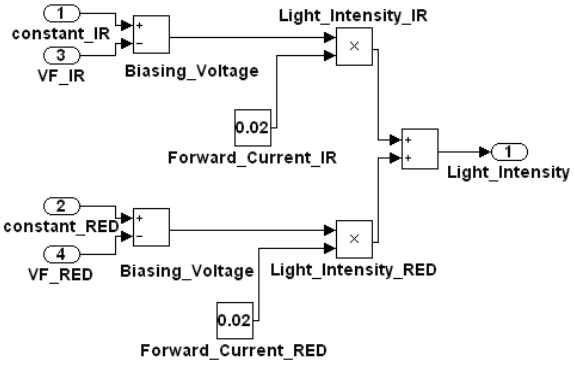

Fig. 4. Simulink model of Photodiode

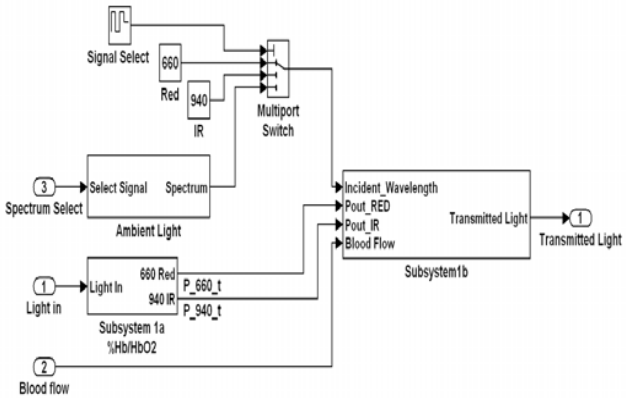

Fig. 5. Simulink model of Tissue

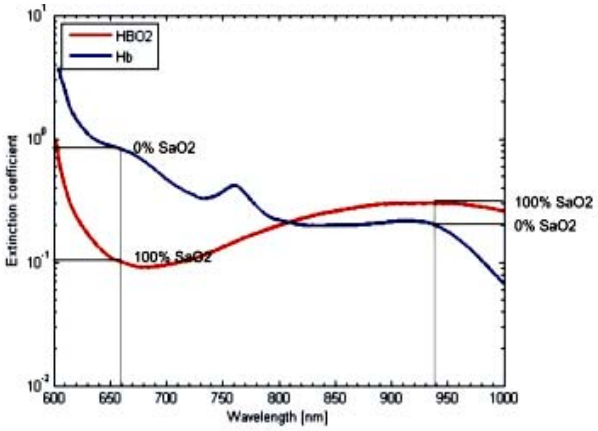

Fig. 6. The extinction coefficients of RHb and HbO_2 as functions of wavelength. [2]

hardware of the infant monitor. To realize this hardware-in-the-loop system a National Instrument MIO board is used. Figure 8 shows the design of a prototype pulse oximeter.

V. CONCLUSION

Pulse oximeters play the vital role of monitoring oxygen saturation levels in blood. The objective of ongoing research in this field is to make pulse oximeters more accurate by nullifying the effects of motion artifacts, differences in skin pigmentation, interference by ambient light etc. The rapid prototyping method discussed in this paper elaborates on simulating a pulse oximeter. Simulation of the hardware and software components of a pulse oximeter is relatively simple compared to the difficulties encountered in simulating the biological processes within the sample tissue. Working on the simulation of a pulse oximeter has given us a better insight into the principle of rapid prototyping and design of biomedical systems. The rapid prototyping method discussed was developed with the objective of accepting data from real

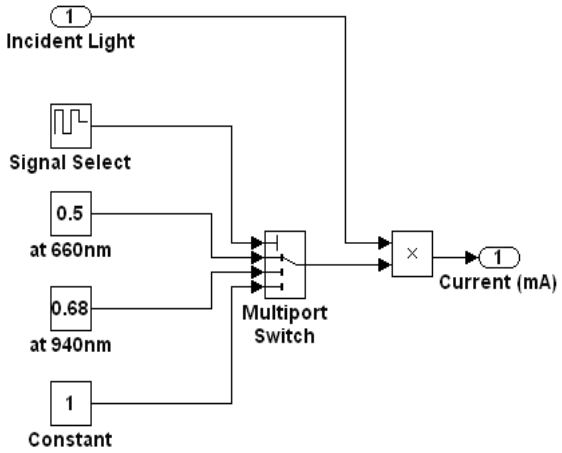

Fig. 7. Simulink model of Photodetector

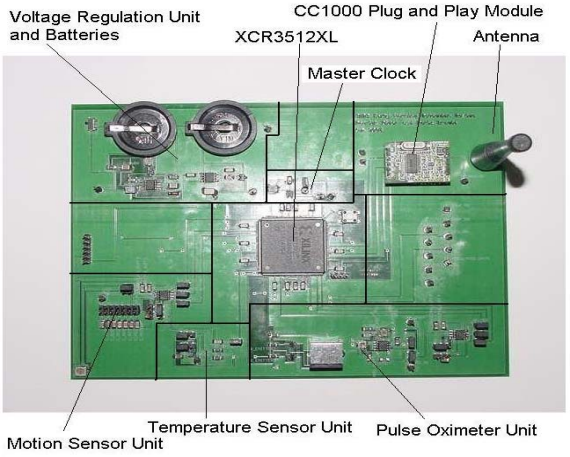

Fig. 8. Design of a prototype board

sensors and observing the results. Analysis of the results obtained from the model would assist an engineer in optimizing his design for a pulse oximeter.

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