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Simulink Based Behavioural Modelling of a Pulse Oximeter for Deployment in Rapid Development, Prototyping and Verification*

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Abstract— **The pulse oximeter is a well-known device for measuring the level of oxygen in blood. Since their invention, pulse oximeters have been under constant development in both aspects of hardware and software; however there are still unsolved problems that limit their performance [6], [7]. Many fresh algorithms and new design techniques are being suggested every year by industry and academic researchers which claim that they can improve accuracy of measurements [8], [9]. With the lack of an accurate computer-based behavioural model for pulse oximeters, the only way for evaluation of these newly developed systems and algorithms is through hardware implementation which can be both expensive and time consuming. This paper presents an accurate Simulink based behavioural model for a pulse oximeter that can be used by industry and academia alike working in this area, as an exploration as well as productivity enhancement tool during their research and development process. The aim of this paper is to introduce a new computer-based behavioural model which provides a simulation environment from which new ideas can be rapidly evaluated long before the real implementation.**

Keyword—**pulse oximeter, modeling, sao2, code development, Simulink, MATLAB.**

I. Introduction

The pulse oximeter is a medical device which measures the oxygen level in arterial blood. This device is widely used in most hospitals and operating theaters around the world. It has a crucial role in patient recovery and generally in health care system. With advances in technology, the pulse oximeter has been revolutionized in many aspects. In terms of performance many power pulse oximeters have been introduced to the market. Despite these developments, there are still many practical problems that limit their performance and many researchers and practitioners in industry are currently working in this area around the world [2], [6], [7]. Many new algorithms are being suggested by them each year that may improve the performance of the device [8], [9]. The lack of an accurate behavioural model, the only way for evaluating the robustness of these new algorithms are hardware implementation which can be both expensive and time consuming. The main aim of this paper is to provide a realistic and accurate behavioural model for pulse oximeter devices which can be used as an exploration as well as productivity enhancement tool for the practitioners and researchers in the field during their research and development process of new pulse oximeters.

The order of sections and their brief contents are as follows: Section II reviews the background theory of the pulse oximeter; equations in this section are regularly referenced in the later sections. Section III is dedicated to the behavioural Simulink model of the pulse oximeter and its Graphic User Interface (GUI) controller; it explains how different parts of the pulse oximeter device have been modeled, with section IV exposing the simulation results in both the ideal and noisy conditions with section V is dedicated to conclusions.

II. Background Theory

This section is a review of the pulse oximetry concept. This review is important because the pulse oximeter calculates the level of oxygen in arterial blood (SaO2) based on the transmitted light in the red and Infra Red (IR) spectral wavelength while the suggested model calculates the value of the transmitted light in both red and IR wavelength based on the value of SaO2. Therefore these two processes are inverses of each other and understanding one of them facilitates the understanding of the other one.

The level of oxygen in arterial blood is defined as follows [3]:

$$SaO2 = \frac{C_{HbO2}}{C_{Hb}} = \frac{C_{HbO2}}{C_{HbO2} + C_{RHb}} \qquad (1)$$

Where C_{HbO2} is the concentration of the oxygenated hemoglobin, C_{RHb} is the concentration of the reduced hemoglobin and C_{Hb} is the total hemoglobin concentration. A pulse oximeter measures this value by shining red and IR light to a part of the body (usually fingertips) and measuring either reflectance or transmission of them. The transmitted or reflected light will be attenuated differently by different body tissues as well as arterial blood and the pulse oximeters are able to detect the SaO2 value based on this attenuation [5].

The attenuation of light through an absorptive medium follows the Beer-Lambert's Law. This law relates the concentration of a solute in a solvent to absorption of the light that passes through the solution. The relationship between these two is represented in (2) [1], [2]:

$$I_{\lambda out} = I_{\lambda in} 10^{-\varepsilon_\lambda c l} \qquad (2)$$

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Where $I_{\lambda out}$ is the intensity of transmitted light, $I_{\lambda in}$ is the intensity of the incident light, λ is the wavelength of the light, ε_λ is the extinction coefficient of the solute, c is the concentration of the solute and finally *l* is the length of the path that the incident light travels through. The transmission of light 'A_λ' is defined as follows:

$$A_\lambda = log_{10}\frac{I_{\lambda in}}{I_{\lambda out}} = \varepsilon_\lambda c l \quad (3)$$

The Beer-Lambert's law can be applied to complex solutions where multiple solutes are solved in a solvent. In these types of solutions (2) and (3) can be rewritten as follows [1], [2]:

$$I_{\lambda out} = I_{\lambda in} 10^{-(\varepsilon_{\lambda 1} c_1 l + \varepsilon_{\lambda 2} c_2 l + \ldots)} \quad (4)$$

$$A_\lambda = \varepsilon_{\lambda 1} c_1 l + \varepsilon_{\lambda 2} c_2 l + \ldots \quad (5)$$

Blood is considered as a complex solution. Based on (5) the transmission of blood for two different light colors will be as follow:

$$A_1 = l(\varepsilon_{1HbO2} c_{HbO2} + \varepsilon_{1RHb} c_{RHb}) \quad (6)$$

$$A_2 = l(\varepsilon_{2HbO2} c_{HbO2} + \varepsilon_{2RHb} c_{RHb})$$

In (6) it is assumed that the concentration of oxygenated hemoglobin and reduced hemoglobin are dominant and the concentrations of other blood contents are negligible. To derive the SaO2 value, it is more convenient to show that the value of C_{HbO2} and C_{RHb} in terms of the SaO2 value and total hemoglobin concentration C_{Hb} is:

$$A_1 = l c_{Hb}(\varepsilon_{1HbO2} SaO2 + \varepsilon_{1RHb}(1\text{-}SaO2)) \quad (7)$$

$$A_2 = l c_{Hb}(\varepsilon_{2HbO2} SaO2 + \varepsilon_{2RHb}(1\text{-}SaO2))$$

Equation (7) can be simplified by defining an extinction coefficient for the total hemoglobin as follows [2]:

$$\varepsilon_{1Hb} = \varepsilon_{1HbO2} SaO2 + \varepsilon_{1RHb}(1\text{-}SaO2)$$

$$\varepsilon_{2Hb} = \varepsilon_{2HbO2} SaO2 + \varepsilon_{2RHb}(1\text{-}SaO2) \quad (8)$$

Based on (8), (7) can be rewritten as:

$$A_1 = \varepsilon_{1Hb} c_{Hb} l \quad (9)$$

$$A_2 = \varepsilon_{2Hb} c_{Hb} l$$

Dividing both sides of (9) will cancel out the effect of light path '*l*' and total hemoglobin concentration 'C_{Hb}' and leaves us with:

$$K = \frac{A_1}{A_2} = \frac{\varepsilon_{1Hb}}{\varepsilon_{2Hb}} \quad (10)$$

The arterial oxygen level can then be determined by solving (10) for the SaO2 value:

$$SaO2 = \frac{K\,\varepsilon_{2RHb} - \varepsilon_{1RHb}}{K\,(\varepsilon_{2RHb} - \varepsilon_{2HbO2}) + \varepsilon_{1HbO2} - \varepsilon_{1RHb}} \quad (11)$$

Equation 11 shows that by measuring the amount of the incident and transmitted light to the *blood* in red and IR separately, it is possible to calculate the SaO2 value. The question now is how the pulse oximeter can derive the incident and transmitted light to arterial blood from the transmitted light through the finger.

Looking at the path of the light in the body shows that as the incident light passes through the different tissues of the body such as fat and muscles, etc, its intensity is attenuated based on the Beer-Lambert's Law represented by (2) and (3). Other than arterial vessels, all other tissues of body are assumed to have a constant value of extinction coefficient, concentration and length and therefore the amount of attenuation that they cause remains constant. For arterial vessels the story is different. Since the diameter of the arterial vessels is changing with each heartbeat, the amount of attenuation which they generate is changing in time. Because of this unique feature of arterial vessels, the pulse oximeter can distinguish them from other body tissues. The transmitted signal from the finger, has a large constant part (DC part) generated by the light passing through other body tissues. In addition to that the transmitted signal has a small varying part (AC part) due to the light passing through arterial vessels.

The pulse oximeters use this AC part of the signal to determine the oxygen level in arterial blood. The maximum and minimum of this AC part shows the incident light and transmitted light for arterial vessels respectively and therefore by measuring these values at the receiver, it is possible to determine the SaO2 value based on (10) and (11).

III. METHODOLOGY

In this section a behavioural Simulink model of the pulse oximeter is presented based on the formulae that were derived in the background section. This model gives one a clear view about the pulse oximeter device and its background operation concept. It is also a power full means for novel exploratory development and early verification during the design process. Figure 1 shows the Simulink model for the pulse oximeter.

This model uses the traditional Time Division Multiplexing (TDM) to drive the LEDs. However the model can also be modified to be used with other modulation techniques such as PDM, FDM and CDM . Here a brief description of each block of Figure 1 is described.

A. LED Block

This block models the LEDs and their driving circuits. The driving signals are generated by a digital control unit. Each driving signal along with its corresponding wavelength is passed through the finger block [3].

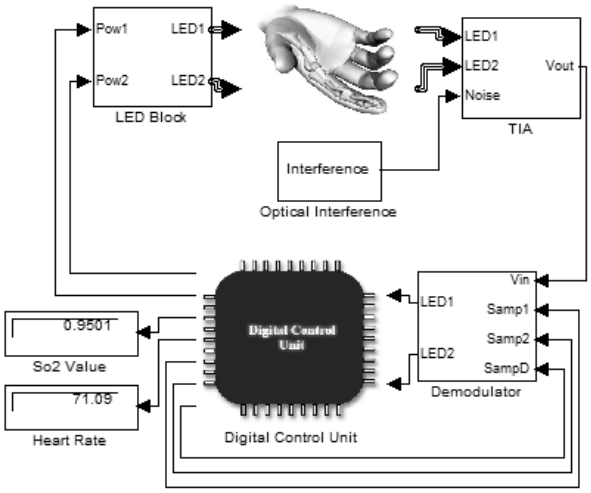

Figure 1. Simulink model of the pulse oximeter

B. *Finger Block*

This block represents the fingertip that the pulse oximeter is attached to. The block is equipped with three important sub-blocks:

- Two look-up tables which provide extinction coefficient of oxygenated and reduced hemoglobin
- Blood flow block which represents the change in diameter of arterial vessel.

The finger block also has some tunable parameters which can be changed during simulation time. These parameters are listed here:

- Current value of SaO2 which is going to be detected by the model.
- The heart rate parameter

Figure 2(a) shows internal structure of the finger block. The finger block can be separated into two parts. The first part generates the transmission of arterial vessels '$A_{Arterial}$' and the second one generates the transmission of other tissues '$A_{Other\ tissue}$'. The transmissions of the other tissues are two constant numbers for IR and red light.

The arterial vessel block shown in Figure 2(b) is responsible for generating the correct value of the transmission of light in both wavelengths for arterial vessels. To accomplish this, the block uses the extinction coefficients of oxygenated and reduced hemoglobin and SaO2 value to calculate the extinction coefficient of total hemoglobin ε_{Hb} based on (8). This task is done inside the EHb block shown in Figure 2(c). The extinction coefficients of total hemoglobin in both wavelengths are then multiplied with the blood flow to produce the transmissions of the arterial vessels in both wavelengths. After generating all transmissions values, transmissions with the same wavelengths are added up together to form the overall transmission for those wavelengths. The finger block then uses (2) to generate the power outputs. These outputs along with their corresponding wavelengths are passed to the Trans–Impedance Amplifier (TIA) block.

C. *Optical Interference*

This block is able to model white noise as well as generating interferences with desirable frequency and power. This block is useful in testing the performance of different techniques in different environmental conditions.

D. *TIA Block*

The TIA block is an accurate model of the photodiode and trans-impedance amplifier. The output of this block is a voltage proportional to the total received power. The output of this block goes to the demodulator block [4].

E. *Demodulator Block*

The demodulator block consists of three ADCs all of which are synchronized with driving signals. The first ADC samples the data when the first LEDs is turned on, the second ADC samples the data when the second LED is turned on and the third ADC samples the input voltage when both LEDs are off. The process of synchronization is done by the digital control unit.

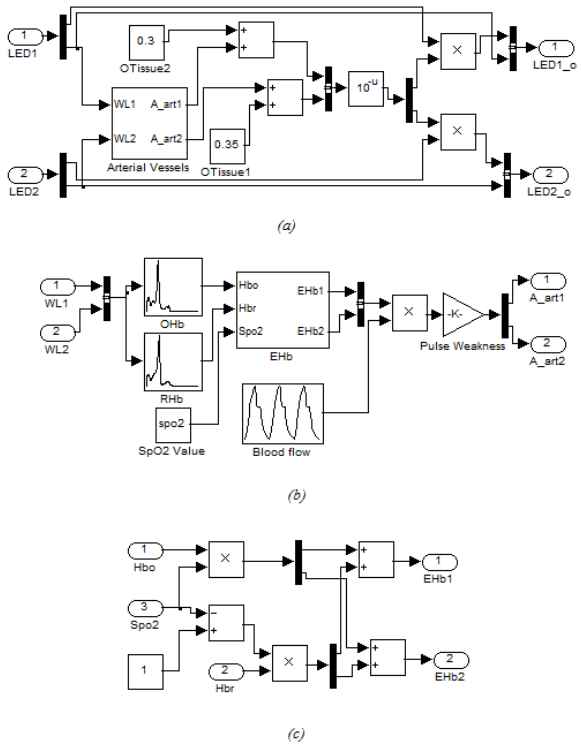

Figure 2. Internal structure of the finger block (a),inside of Arterial vessel sub system (b) and inside of the EHb sub-system(c).

F. *Digital Control Unit*

The digital control unit is responsible for following tasks:

- Generating the LEDs' driving signal.
- Equalizing the DC value of the received signals.
- Synchronizing the ADCs with the driving signals.
- Filtering the outputs of the ADCs.
- Detecting peaks of separated signals

- Calculating the ratio of maximums
- Calculating the SaO2 value based on (11) or a pre-defined look-up table.

G. Graphical User Interface (GUI)

By increasing the accuracy of the model the number of parameters increases gradually. For example the presented model has more than 15 parameters. Assigning values to these parameters one by one for each simulation is a time consuming process. To overcome this problem and to have an intuitive understanding about the effect of each parameter on the outputs of the overall system, a graphical user interface has been developed inside the MATLAB/Simulink environment. The GUI provides a user friendly interface for parameter assignment; it also gathers all the vital information about the pulse oximeter such as the demodulated signals all in one place. Finally it allows the user to change parameters in real-time during the simulations and observes their effect on the outputs immediately. Figure 3 shows the developed GUI.

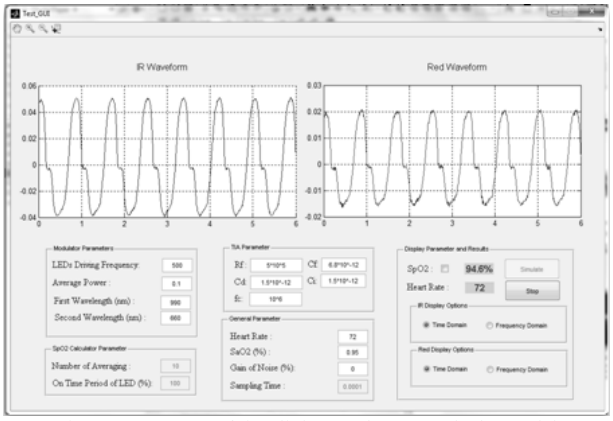

Figure 3. MATLAB/Simulink GUI that controls the model

IV. Simulation Results

To evaluate the accuracy and validity of the model in both ideal and noisy situation, a range of SaO2 values from 80% to 95% has been assigned to the finger block and the pulse oximeter model has been run to detect those values. Figure 4 shows the result of these simulations in both ideal situation and in presence of white noise.

The pulse oximeter can be affected by various unwanted signals such as optical interferences coming from the equipment around the pulse oximeter device or electrical noise coming from circuit components or power supply. Most of these unwanted signals can be modeled and their effect on the accuracy of the device observed and evaluated. Figure 4 depicts the case where white noise has been injected to the system.

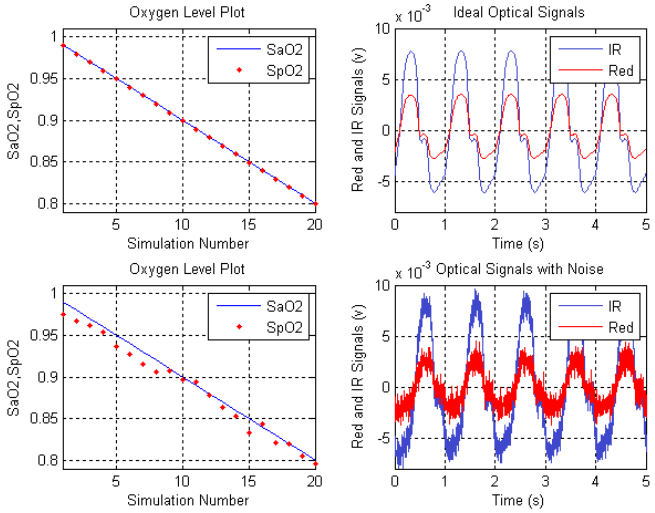

Figure 4. Red and IR signals in ideal and noisy conditions

V. Conclusion

An accurate behavioural model of the pulse oximeter has been presented. This model can be beneficial in many ways. First of all it gives a better and readily understandable insight into the concept and theory behind the pulse oximeter device. Secondly it speeds up the process of design and implementation by providing rapid verification and validation of the newly developed and prototyped algorithms and finally it can easily facilitate the evaluation of the robustness of new algorithm in comparison to preceding ones.

The proposed model can go under further development and improvement in accuracy. For example with some modification, this infrastructure can be used to model other blood content.

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