CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

Simulink Based Modelling of a Pulse Oximeter

A graduate project submitted in fulfillment of the requirements
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in Electrical Engineering

By

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Table of Contents

List of figures

List of tables

Abstract

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The Pulse Oximeter is a medical device which measures the level of oxygen in the arterial blood of the human body. Pulse Oximeter is widely used in hospitals around the world and plays a crucial role in health care system. Since their invention, the pulse oximeter has been revolutionized in many aspects of its hardware and software design. However, there are still some problems that limit their performance. Many researchers and scientists are currently working to improve the performance parameters of pulse oximeter. But due to lack of an accurate Computer Based Simulink Model, the only other way is hardware implementation which is very expensive. Changing the hardware design every time with a new idea is difficult and unrealistic. So, this project focus on designing a Computer Based Simulink Model for Pulse Oximeter with help of which new ideas can be implemented first on a software model before evaluating it on real hardware model. This Simulink Model can also be used in future as enhancement tool for further design and development of Pulse Oximeter. The main aim is to make a Simulink Model of a Pulse Oximeter which provides a modeling environment to implement new ideas and design before evaluating it on hardware model. The project focuses on designing a Simulink Model and its Graphic User Interface (GUI). It shows how different parts are modeled together and their simulation results. The Graphical User Interface will display different graphs depending upon number of oxygen molecules attached with hemoglobin molecule

Chapter 1

1.1 Introduction

Oxygen gas is necessary for human life. Many biological processes depend upon oxygen. Hemoglobin in red blood cells is mainly responsible for transport of oxygen through a human body. So, it is very important to measure the amount of oxygen in blood and obtain critical medical information that will help to improve medical standards.

Health care has emerged as one of the most important aspects of human life. Research has been done to improve the design and technology of medical equipment's. One solution is to look towards improving/developing better medical instruments. These devices will not only revolutionized the field of medicine but also improve quality of human life.

The pulse oximeter is a medical device which measures the oxygen level in arterial blood. The data received from pulse oximeter has a very important role in patient recovery. This data can also be used to examine many other health related problems in human body. From many years, continuous research and change has been done in many aspects of technology. Many new types of pulse oximeters have been introduced in market some having better performance while other emphasizing more on smaller size and less power requirement. Although a lot of development has been done in many aspects but still there are many practical problems related with performance, size, accuracy and reliability of these devices. Each year a lot of new software's and algorithms are introduced to improve the performance.

One solution to these problems is the hardware implementation which is very time consuming and expensive as well. Hardware implementation demands a lot of changes in the circuit, size and technology which is very complex. The main aim of this project is to show a realistic and accurate behavioral model for pulse oximeter devices through which simulation of data can be done through a software as per requirement. The Simulink model of the pulse oximeter explains how different parts of a pulse oximeter have been modeled together. It is also easy to implement changes in the design through a software model instead of a hardware implementation. [2]

1.2 Brief History of Pulse Oximeter

Oximetry is a technology with the help of which the patients' body oxygen level is measured through a translucent site. Oximetry has been around from quite some time and a lot of research has been done in this field. In the early 1930's, a team of German scientists used a spectra photometer to measure light transmission through human body. The main focus was to measure that how the readings differ at different wavelengths of light. In 1935, Carl Matthes came up with a new idea. He built first device which was capable of continuously measuring oxygen saturation level in blood in vivo by trans-illuminating tissue. He used two wavelengths of light i.e. red light and infra-red light. The red light was very sensitive to change in oxygen saturation level. The changes in tissue thickness, hemoglobin content and light intensity on other hand was more sensitive to infra-red light. Still this device was having a lot of limitations as it was difficult to calibrate. Also the absolute value for saturation was not very clear [1].

In 1939, a German scientist research revolutionized the whole idea. First time the use of two LED'S i.e. a red LED and an infra-red LED was used to measure the thickness of blood tissues. During the experiment, he realized that the light passing through finger is attenuated by some factors. The light was not only attenuated by the arterial blood, but this attenuation depends on many other factor. He found that the capillary blood, venous, skin and other tissues (muscles and bones) also attenuate the light to some extent. The attenuation usually in this case depends upon absorption properties which in case vary from person to person due to different pigmentation. This led to a lot of interest in this field. [1]

During World War II, a large number of teams of German as well as British scientists took a deep interest in oximetry. They wanted to design a model with help of which it becomes easy to measure the amount of oxygen required for high altitude pilots in warfare. During 1945, Milikan, a British researcher, designed an ear lobe oximeter. The basic design of this oximeter was very simple. He used a light of two different wavelengths to examine a blood tissue. During his research, he found that the red light was very sensitive to oxy-hemoglobin cells whereas green light was less sensitive to it. It was found out later that oxygen insensitive signal was due to infrared light. One main limitation of Millikan's ear oximeter was that it was not calibrated. In such case, one had to guess the thickness of the ear as well as the normal saturation for each subject [1]. Earl Wood overcome this problem of calibration by measuring the increase in light through a pneumatic cuff when the ear was blanched. In the 1970's Hewlett−Packard developed a device which tried to solve this problem by transmitting light at more than two wavelengths [1]. They had developed an 8-wavelenght oximeter. This oximeter used eight different wavelengths to examine oxygen level in blood tissue. However, due to its large size, high cost it seemed very impractical.

In the late 1970's, the Biox Corporation in Colorado introduced the use of LED'S for the red and infrared source. They used two LED'S to measure the oxygen saturation level. They conclude that the red LED traces the presence of oxygen saturation level in blood whereas it was vice-versa for infrared LED.

Ohmeda Corporation purchased Biox design and continued to make significant development in its size and technology. These devices are known as Pulse Oximeter and are used in hospitals to measure the oxygen level in blood.

Takuo Aayogi found new artifacts while working at Nihon Kohden Corporation. Takuo Aayogi discovered that the pulsatile variation modified the washout curves measurement while working on a dye dilution cardiac output monitor using an ear densitometer. He further discovered that the oxygen saturation level varied the absorbency ratio of these pulsation at different wavelengths. These discoveries were done while attempting to eliminate these variations. He came up with an idea that by balancing the red light signal with infra-red light signal, he might be able to minimize the pulsatile component at the point where dye had no absorption. Then he used the technique of reducing noise in his signal to measure oxygen saturation. This was done because all these compensation were dependent on oxygen. This technique was further refined by the development of microprocessor, photo detector, and light emitting diodes (LEDS). With further development, the pulse oximeter were widely used in hospitals. [1]

1.3 Project Overview

The main purpose of this project is to create a wireless optical sensing module with the help of which human blood oxygenation levels can be continuously monitored and the data which is generated can be wirelessly transmitted to a host machine. The main phenomenon that is involved in this process is called Pulse Oximetry. In the near infrared region, optical sensing has a wide variety of application being used during anesthesia, intensive care, blood pressure calculation. Optical sensing can be used in two modes i.e. transmission mode or reflectance mode for this purpose. The main challenges are to design a model that is convenient to use, consume small power, portable and less in cost. Temperature monitoring, integration with a wireless body area network and data visualization are additional features that can be implemented into this model depending on the requirement. Wireless Pulse Oximetry has become a standard procedure for the measurement of blood oxygen saturation in hospitals operating rooms.

The pulse oximeter is a well-known device for measuring the level of oxygen in blood. It is one of the standard procedure used in the hospital operating room to measure the blood-oxygen saturation level in human body. Deficiency of oxygen known as Hypoxemia in medical terms is treated through pulse oximeter readings. Significant hypoxemic events such as cardiac catheterization, or inserting a catheter into a chamber or vessel of human body is common. Pulse oximeter provides an early warning with help of which hypoxemia can be treated in its initial stage.

An early warning of oxygen deficiency and ventilator malfunction is provided by pulse oximeter. With help of pulse oximeter, it becomes easy and quick to suspect episodes of low blood oxygen level within time. Based on these reading provided by pulse oximeter, a quick and accurate action can be taken for treatment.

Wireless pulse oximeter has many advantages over the other traditional wired units. Wireless pulse oximeter is more convenient and comfortable to use. There is no need to reconnect it each time with human body as a person moves. In addition, a patient oxygen level is monitored 24 hours and based on these reading an appropriate treatment procedure can be done.

The main aim of this project is to show a realistic and accurate behavioral model for pulse oximeter devices through which simulation of data can be done through a software as per requirement. The Simulink model of the pulse oximeter explains how different parts of a pulse oximeter have been modeled together. It is also easy to implement changes in the design through a software model instead of a hardware implementation. [2]

Pulse Oximetry is a non-invasive method that is used to monitor the level of oxygen in a patient's blood and alerts the health care worker if the oxygen level drops below safe level, allowing rapid intervention and further assistance. The Principle of Pulse Oximetry is based on the red and infrared light absorption characteristic. Red and Infrared LED'S are shined through the patient body through a translucent site. A good blood flow is required in order to take proper readings. The main principle involved is that the oxygenated hemoglobin absorbs more infrared light and therefore allows more red light to pass through. It is reverse in case of deoxygenated hemoglobin. Deoxygenated hemoglobin absorbs more red light and allows more infrared light to pass. A clear reading depends upon the blood flow level and sensitivity of the sensor used. The reading of the oxygenation level in blood can be calculated by the amount of light reaching the optical receiver that is mounted on the oximeter. [3]

Pulse oximeter hardware design and Simulink based modeling of pulse oximeter for prototyping and verification will be covered in detail in next chapters.

Chapter 2 will cover the design development, background theory and its concepts, and system design.

Chapter 3 will cover the MATLAB/Simulink based modeling of pulse oximeter.

In this chapter, Section one will give a general introduction about Simulink based behavioral modeling of a Pulse Oximeter, while section two will review the background theory of Pulse oximeter and the equation used to design the system, different parameters required for design.

Chapter 4 will basically explain the Simulink Model of Pulse Oximeter and its GUI interface. This chapter will basically explain the behavioral Simulink model of the Pulse Oximeter and its Graphic User Interface (GUI) controller.

Chapter 5 will show the simulation results.

Chapter 6 will give a summary and conclusion.

Chapter 2

2.1 Design of Pulse Oximeter

The main focus of this project is to create a Wireless Optical Sensing Module such that the human blood oxygen level can be continuously monitored and the data which is generated can be wirelessly transmitted to a host machine.

The main method that is involved in this process is called Pulse Oximetry. Pulse Oximetry is a non-invasive method that is used to monitor the level of oxygen in a patient's blood and alerts the health care worker if the oxygen level drops below safe level, allowing rapid intervention and further assistance. The Principle of Pulse Oximetry is based on the red and infrared light absorption characteristic. Red and Infrared LED'S are shined through the patient body through a translucent site [3]. A good blood flow is required in order to take proper readings. The main principle involved is that the oxygenated hemoglobin absorbs more infrared light and therefore allows more red light to pass through. It is reverse in case of deoxygenated hemoglobin. Deoxygenated hemoglobin absorbs more red light and allows more infrared light to pass. A clear reading depends upon the blood flow level and sensitivity of the sensor used. The reading of the oxygenation level in blood can be calculated by the amount of light reaching the optical receiver that is mounted on the oximeter. [3]

2.2 Background Theory and Concepts

Functional arterial oxygen saturation (SaO_2) is defined as the ratio of oxygenated hemoglobin to the total concentration of hemoglobin. SaO_2 is known as SpO_2 when measurement of oxygen saturation level is calculated through a Pulse oximeter. The wavelength of Red light is between the range of 600-700 nm whereas the infrared light has a wavelength ranging from 850-1000nm. The calculation involves the ratio of red/infrared light absorbed. The Red/Infrared ratio is compared to a table. This look up table consists up of empirical formulas that convert the ratio to a SpO2 value. The Formula is [3]

$$SpO_2 = \frac{[HbO_2]}{[HbO_2]+[Hb]} \quad \text{..... (2.1)}$$

Where SpO2 is the ratio of oxygenated hemoglobin to the total concentration of hemoglobin measured by pulse oximeter

HbO_2 is the amount of oxygenated hemoglobin in blood.
$Hb + HbO_2$ is the total concentration of hemoglobin in blood.
When the SaO_2 is measured using a Pulse Oximeter it is written as SpO2.
The brackets in this equation stands for concentration.

The general formula from which equation 2.1 is derived is given as [3]

$$SaO_2 = \frac{[HbO_2]}{[HbO_2]+[Hb]} \quad \text{..... (2.2)}$$

When the measurement is done using an oximeter, the SaO_2 is replaced by SpO2.

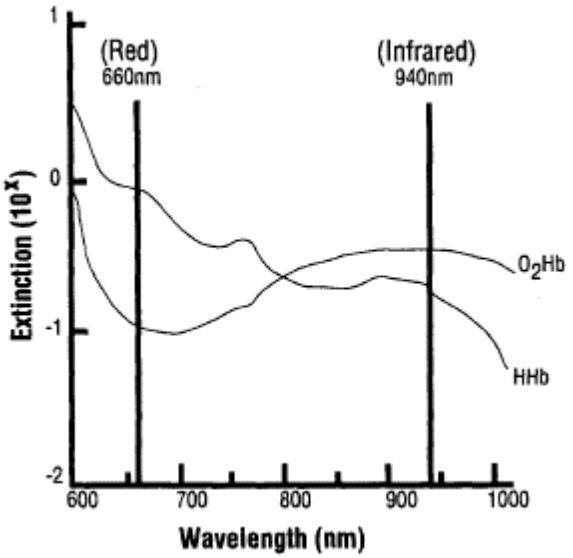

Figure 1: Extinction (absorption) of light from oxygenated and reduced hemoglobin [8]

With a known measurement of red and infrared light transmitted through the finger, an estimate of the ratio between oxygenated hemoglobin and reduced hemoglobin can be determined based on extinction (absorption) curves at the various wavelengths of transmitted light. A typical oximeter works with 660nm red light, and 940nm infrared light. At 660nm, reduced hemoglobin absorbs about ten times as much light as does oxygenated as shown in figure 1.

It is possible to measure the oxygen saturation level in blood due to the optical properties of both HbO_2 and Hb at 500nm-1000nm. This can be done by measuring transmitted light

at two different wavelengths through different tissues normally finger and ear lobe. According to Beer-Lambert's law, the light intensity will decrease logarithmically. This is done by making an assumption that the transmission of light through the arterial bed is influenced by the relative concentration of oxygenated and reduced hemoglobin blood [3] [11]. The transmission of light through the arterial bed also depends upon the absorption coefficients of oxygenated and reduced hemoglobin at two different wavelength. Using these principles, it is possible to obtain an expression for the ration of the intensity of light transmitted at two different wavelength [3] [11]. This expression is given as:

$$R_1 = \frac{\log_{10}(I_1)}{\log_{10}(I_2)} \quad \text{..... (2.3)}$$

I_1 is the light intensity at wavelength 1.
I_2 is the light intensity at wavelength 2.

The oxygen saturation level in the blood can be measured from the absorbance coefficients of HbO_2 and Hb at the two wavelengths [4] [5] [7]

$$SaO_2 = (\alpha r_2 R_1 - \alpha r_1)/[(\alpha r_2 - \alpha o_2)R_1 - (\alpha r_1 - \alpha o_1)] \quad \text{..... (2.4)}$$

Where

- αr_1 is the absorption co-efficient of Hb calculated at wavelength 1
- αr_2 is the absorption co-efficient of Hb calculated at wavelength 2
- αo_1 is the absorption co-efficient of HbO2 measured at wavelength 1
- αo_2 s the absorption co-efficient of HbO2 measured at wavelength 2
- R_1 is ratio of $\frac{\log_{10}(I_1)}{\log_{10}(I_2)}$

In Pulse Oximetry, the oxygen saturation level in the blood can be calculated only through that part of the signal which is related to the inflow of the arterial blood at that segment. A pulsatile signal as shown in figure 2 is obtained when light at different wavelenght (IR and red) is transmitted through blood tissue. [11] The signals varies in time in relation to heart beat. This signal can be used to extract the heart rate of an individual .

In this case

Heart Rate = Frequency of signal

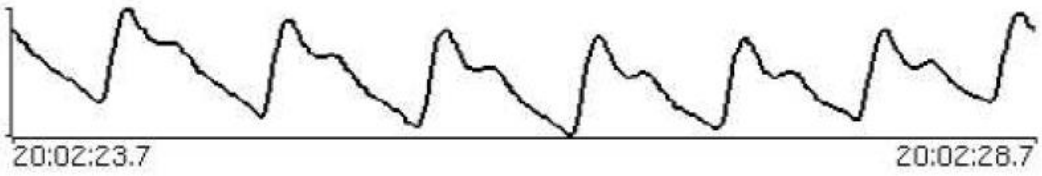

Figure 2: Pulsatile signal resulted when red and infra-red light is transmitted. [9]

It gives an idea of the frequency content of the signal and is also useful when designing our system.

As we can see in figure 2, the pulsatile signal frequency is related to the individual's heart rate. A lot of necessary information can be extracted from this relation i.e. the voltage measurement at any given time from the output signal. As discussed earlier, the intensity of the transmitted light relates to this voltage measurement and can be used to calculate the oxygen saturation reading. Using this relation, the ratio of the intensity of light transmitted at two different wavelength is given by: [6] [7]

$$R = \frac{\log_{10}(I_1)}{\log_{10}(I_2)}$$

Functional arterial oxygen saturation (SaO2) is defined as "the ratio of HbO2 to the total amount of arterial Hb calculated for oxygen binding" [1]. This ration is known as SpO2 when measured through pulse oximeter and is given as:

$$SpO_2 = \frac{[HbO_2]}{[HbO_2]+[Hb]}$$

HbO_2 and Hb molecules strongly absorbs the short light wavelength which in case results in the red color of blood cells. Hb absorbs more red light and less blue light as compared to HbO_2 molecules. That is the reason why venous blood has darker colour as compared to the more oxygenated arterial blood. The color difference in Hb molecules as compared to HbO_2 molecules is key to pulse oximetry.

This process is explained very clearly by Beer-Lambert Law. Beer-Lambert law explains the light propagation in a uniform medium. It states that the intensity I of the light in the medium is directly proportional to the transmitted intensity of light Io. It also states that the intensity I decreases exponentially with the extinction coefficient of the absorbing medium ε, the path length l and concentration of the absorbing medium β. The equation is given as [4] [6]

$$I = I_0 . e^{-\varepsilon(\lambda)\beta L} \quad \text{..... (2.5)}$$

Where I is the intensity of the light in the medium

I_0 is the transmitted intensity.
L is the path length.

Taking log on both sides give us

$$\ln \frac{I}{I_0} = -\varepsilon(\lambda)\beta l = A(\lambda) \quad \ldots\ldots\ldots\ldots\ldots \quad (2.6)$$

$$A_{total}(\lambda) = \sum_{i=1}^{N} \varepsilon\lambda_i \beta_i L \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.7)$$

Where this equation gives the unscattered absorption or optical density
$\ln \frac{I}{I_0}$ is log of the transmitted intensity over the received intensity.

As basic pulse oximetry is an invasive method of transmitting two different frequencies of light through a blood sample containing both HbO_2 and Hb molecules. The amount of light absorbed by these molecules is recorded through a photo detector. The extinction coefficients of both molecules are different at different wavelength. It is possible to calculate the relative percentage of HbO_2 to the total amount of Hb available just by comparing the amount of light absorbed at two different frequencies. As shown in Figure 3, both molecules have different extinction coefficient at each wavelength.

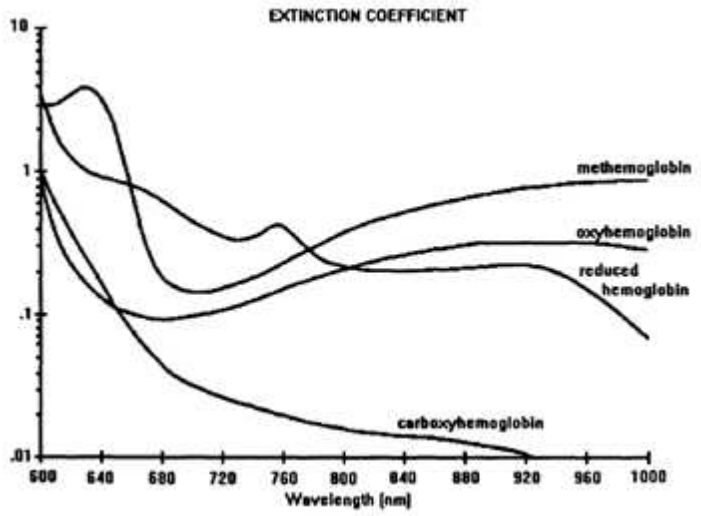

Figure 3: Extinction curves of Hb, HbO2, methemoglobin, and carboxyhemoglobin. From Rusch p 146 [6] [7].

The relationship between each pulse and the light measured by the pulse oximeter depends on amplitude optical pulse. The signal indicating the amplitude optical pulse goes down every pulse and this signal is displayed inverted on a pulse oximeter output.

Skin pigment, bones and arterial and venous blood are the main absorbers of light rather than Hb and HbO2. The light received by the photo detector is heavily attenuated and scattered in many directions as it enters human skin.

Taking into account all these sources of absorption and attenuation, the total absorbance at two different wavelengths is given by [4] [5] [6]

$$A_{total}(\lambda_1) = \varepsilon_{HbO_2(\lambda_1)[HbO_2]} + \varepsilon_{Hb}(\lambda_1)[Hb] + \varepsilon_x(\lambda_1)[X] + A_y(\lambda_1) \quad \text{..... (2.8)}$$

$$A_{total}(\lambda_2) = \varepsilon_{HbO_2(\lambda_2)[HbO_2]} + \varepsilon_{Hb}(\lambda_2)[Hb] + \varepsilon_x(\lambda_2)[X] + A_y(\lambda_2) \quad \text{.....(2.9)}$$

Where x is the variable source of absorbance not from arterial blood.
A_y is nonspecific attenuation.

The oxygen saturation of the arterial blood is one of the main factor in determining SpO_2 . The pulsatile absorbance are only taken in account to isolate the arterial blood oxygen saturation level. This is possible by taking the derivative of above equations. It is possible to calculate SpO_2 when such substances are present in the blood stream, but measurements at additional frequencies are necessary.

In determining SpO_2, we are interested in the oxygen saturation of the arterial blood. To isolate the arterial component, only the pulsatile absorbencies are analyzed. By taking the time derivative of the absorption in Equations 2.8, all the path length independent attenuation terms $A_y(\lambda)$ disappear. Additionally, we will assume that the blood path length changes $\frac{dl}{dt}HbO_2$ and $\frac{dl}{dt}Hb$ are equivalent. [4]

The ratio of the time derivative is gives

$$R = \frac{\frac{dA(\lambda_1)}{dt}}{\frac{dA(\lambda_2)}{dt}} \quad \text{..... (2.10)}$$

$$= \frac{\varepsilon_{HbO_2(\lambda_1)[HbO_2]}\frac{dl}{dt}HbO_2 + \varepsilon_{Hb}(\lambda_1)[Hb]\frac{dl}{dt}Hb}{\varepsilon_{HbO_2(\lambda_2)[HbO_2]}\frac{dl}{dt}HbO_2 + \varepsilon_{Hb}(\lambda_2)[Hb]\frac{dl}{dt}Hb} \quad \text{..... (2.11)}$$

Assuming $\frac{dl}{dt}HbO_2 = \frac{dl}{dt}Hb$,

$$R = \frac{\varepsilon_{HbO_2(\lambda_1)[HbO_2]} + \varepsilon_{Hb}(\lambda_1)[Hb]}{\varepsilon_{HbO_2(\lambda_2)[HbO_2]} + \varepsilon_{Hb}(\lambda_2)[Hb]} \quad \text{..... (2.12)}$$

Recalling that S_PO_2 is the ratio of concentrations, therefore S_PO_2 can be calculated from equation 2.10 as

$$\varepsilon_{HbO_2(\lambda_1)[HbO_2]} + \varepsilon_{Hb}(\lambda_1)[Hb] = R\left(\varepsilon_{HbO_2(\lambda_2)[HbO_2]} + \varepsilon_{Hb}(\lambda_2)[Hb]\right) \ldots (2.13)$$

$$[Hb](\varepsilon_{Hb}(\lambda_1) - R\varepsilon_{Hb}(\lambda_2)) = [HbO_2](R\varepsilon_{HbO_2}(\lambda_2) - \varepsilon_{HbO_2}(\lambda_1) \ldots\ldots (2.14)$$

Adding $[HbO_2](R\varepsilon_{HbO_2}(\lambda_2) - \varepsilon_{HbO_2}(\lambda_1))$ to both sides:

$$([Hb] + [HbO_2])(\varepsilon_{Hb}(\lambda_1) - R\varepsilon_{Hb}(\lambda_2)) =$$
$$[HbO_2](R\varepsilon_{HbO_2}(\lambda_2) - \varepsilon_{HbO_2}(\lambda_1) + R\varepsilon_{HbO_2}(\lambda_2) - \varepsilon_{HbO_2}(\lambda_1)) \ldots\ldots\ldots (2.15)$$

Rearranging Equation 2.15:

$$\frac{[HbO_2]}{[HbO_2]+[Hb]} = \frac{(\varepsilon_{Hb}(\lambda_1) - R\varepsilon_{Hb}(\lambda_2))}{(\varepsilon_{Hb}(\lambda_1) - \varepsilon_{HbO_2}(\lambda_1) - R(\varepsilon_{Hb}(\lambda_2) - \varepsilon_{HbO_2}(\lambda_2))} \ldots\ldots\ldots (2.16)$$

As from equation 2.1

$$SpO_2 = \frac{[HbO_2]}{[HbO_2]+[Hb]}$$

Therefore $$SpO_2 = \frac{(\varepsilon_{Hb}(\lambda_1) - R\varepsilon_{Hb}(\lambda_2))}{(\varepsilon_{Hb}(\lambda_1) - \varepsilon_{HbO_2}(\lambda_1) - R(\varepsilon_{Hb}(\lambda_2) - \varepsilon_{HbO_2}(\lambda_2))} \ldots\ldots\ldots\ldots (2.17)$$

In a pulse oximeter, mono chromatic light emitter diodes (LEDs) and photo diodes are used for measurement of the light absorption phenomena. This whole process is called digital photoplethsymogram (DPP). For accurate calculation of SpO2, the wavelength of LEDs used should be 660nm for red light and 940nm for infrared light [4] [5] [6]. In real world, the relationship between SpO2 and R varies slightly from theory. This is because the bandwidth of LEDs varies in range of 20-50nm. Thus, an accurate relationship between the SpO2 and R must be determined using the following figure 4.

As mentioned earlier, the R value is calculated by taking the normalized ratio of red absorbance to the infrared absorbance as shown in the Figure 4. In this case, the time derivative of the absorbance is analogous to the normalized value. The normalized value is calculated by dividing the AC component of the absorbance at that frequency by the DC component as shown in equation 2.18 [6]

$$R = \frac{AC_{red}/DC_{red}}{AC_{ir}/DC_{ir}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.18)$$

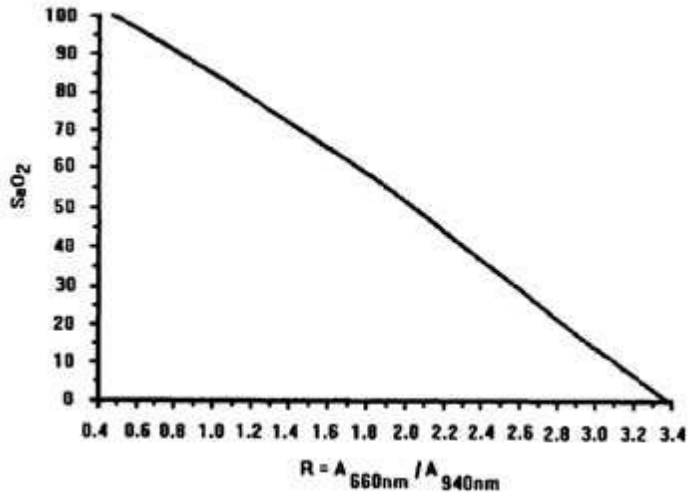

Figure 4: Empirical S_aO_2 vs R taken from Rusch page 148 [6]

Hence SpO2 can be calculated from R using equation 2.19 [6]

$$S_pO_2 = 110 - 25R \quad \text{..... (2.19)}$$

Equation 2.19 corresponds to a linear approximtion to an empirically determined calibration curve. These values are obtained from measurement in healthy volunteers. A measurement system utilising 940nm infra-red light source was used to drive this equation. A significant error in calculation can be expected as at present a 850nm infra-red light source is used. However, equation 2.19 can be used to make a rough estimation about oxygen saturation value. There is no other equation avaliable to give an accurate value of oxygen saturation.

2.3 System Design

A Sensor is placed on a thin part of patient body. The sensor is used to sense the signal. As this signal is analog, an analog to digital convertor (ADC) is used to convert this signal into a digital form and then it is sent to a microcontroller. The user SpO2 level will be detected by the microcontroller based on the data it receives. The output is then transmitted to the host machine and result is displayed. Constant Light absorbers are always present at measuring site i.e. Skin, tissues and arterial blood. The blood across the measuring site is increased by every heartbeat. As during every heartbeat, there is contraction and expansion of veins and arteries. This results into a surge in the arterial blood. This results into more light absorption during the surge.

If the light signal received is analog and examined carefully then there are peaks with heartbeat and troughs. This is the main technique how pulse oximetry works.

Two Different Methods can be used in this process i.e. Transmission method or Reflectance method. In the transmission method, the LED'S and optical receiver (photo detector) are placed opposite to each other. In the Reflectance method, both LED'S and photo detector are placed on the same side.

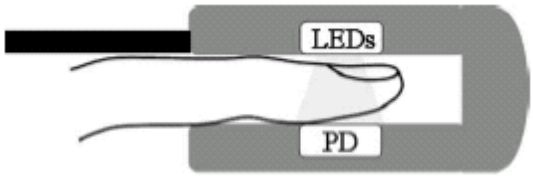

Figure 5: Transmission type Finger Clip Sensor

The most common used method usually is that a sensor is attached to a finger as shown in Figure 5 so that the oxygenation level of the blood flowing through the finger can be calculated.

A fingertip pulse oximeter is a device which attach onto a patient's finger and has a small computer. The device transmits light from one end and measure its value at other end. The light is measured over many pulses and corresponding to it, oxygen saturation value is given as output. The main components required for the design is a red LED, an infrared LED and a receiver which will be a photodiode in this case. The two LED'S are used to measure the oxygenation level in blood depending upon the infrared or red light pattern. The amount of each type of light detected is then sent to the photodiode. The calculation is mostly ratio based. The main focus here is to use transmission method. In this method, a light source is shined into the skin and depending upon the oxygenation level appropriate readings are taken. The reading from the patient's fingertip is measured by Pulse Oximeter. The data received by the Pulse Oximeter will be then sent to a micro controller.

As the data will be transmitted wirelessly to a host device, an ADC will be required to convert the signal in proper form. The ADC will convert the analog data to digital form before sending it to microprocessor. A Bluetooth will be implemented for the wireless communication.

The power of a microcontroller can be conserved by keeping the device in the standby mode when it is not collecting data. The main requirement in this process is that the design needs to be non-invasive, durable and wearable. It should have good battery life and collect appropriate data for final reading.

The main focus in this project is to design a system that is more convenient, comfortable and easy to implement. There are many tradeoffs involved in this project. As the data is sent wirelessly to a host machine, the noise and temperature variation has a big role to play. The user movement can significantly affect the resulting data. Moreover the change in sunlight, the sensitivity of the sensor and photo detector is major factor that can affect the data significantly. Therefore, the resulting system might not be as accurate as some previously used methods.

One another method is Wrist band oximeter. In this case, the whole design procedure is same as that of Finger clip oximeter. Here the location of oximeter is wrist instead of finger. The Wrist Band Oximeter is a small device wired on wrist and is used in measuring and displaying the oxygenation level in blood. It works on the SPO2 technique. The basic design procedure is the same in this case also. The two LED's i.e. Red LED and Infrared LED are used. The data is measured through a photo receiver. The data is sent wirelessly to a host machine either by using a low power Bluetooth device or IEEE 802.15.4-2003 standard WPAN. The light is sensed by each LED depending upon the wavelength and oxy-hemoglobin level in the blood. The data received is represented in a form of ratio of oxy-hemoglobin to de-oxy hemoglobin and is compared to a table. The table reading is standardized. The Oximeter model works in two modes either transmission mode or reflection mode.

In this design, the short of the wrist is strapped through the spring bar on the rear of the Wrist Oximeter. Then the wrist strap is pulled until it is securely attached with the Wrist Oximeter. A sensor is the plug into a connector at the top of the strap. The location of the device is very important.

The location chosen should have a high concentration of blood running through it for proper reading. Wrist is an appropriate location for this invasive method as it has large junction of blood vessels. The photo receiver after taking the readings will send it to the microcontroller for processing them and then it will be transmitted wirelessly to host machine.

Wireless Communication can be done through a Bluetooth Low Energy device or Zig bee IEEE 802.15.4-2003 standard WPAN. The data is converted in the digital form by an ADC and then will be displayed on a screen. The power range of the device will be 5V.

The design will be enclosed in a simple box with rounded edges and holes cut out of the top to mount sensor on it. The host machine will have a display that is capable of showing both the percentage of oxygenated hemoglobin to de-oxy hemoglobin. The ratio is compared to imperial table and final reading will be taken from that table. The patient will be remotely monitored by a receiver. The receiver should be very sensitive and should have high sensing range.

The main function of the microcontroller is to enable the system designer to simultaneously interface with sensor, digital component and analog signals.

The senor is used to take reading and this is fed to photo receiver. The information will be fed only at certain intervals. The receiver will have a backup battery in case of power shortage. As the data received by the photo receiver from sensor is in form of light, the sensor unit consists of a light to voltage convertor.

Figure 6 shows the Analog processing block diagram of a sensor. This analog topology is used for the signal processing of the sensor. It basically consist of red LED, infrared LED and a photo detector.

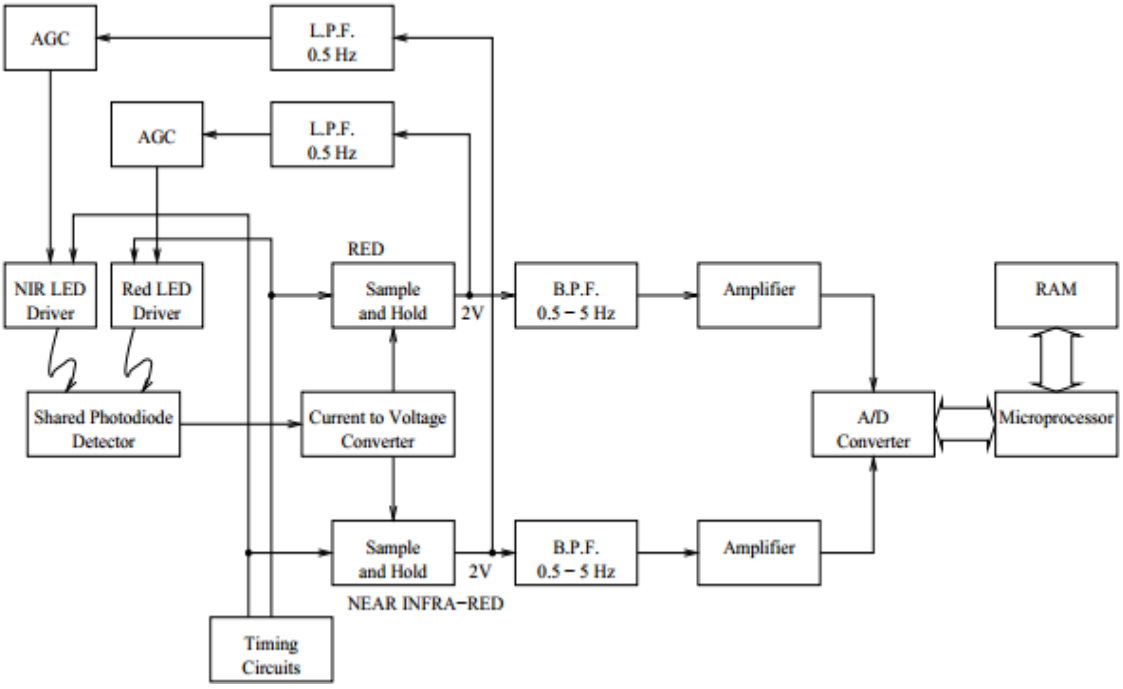

Figure 6: Analog processing block diagram of a sensor [12]

In this design, the signal processing of the sensor is done through analog topology. The two sample and hold circuits (Red LED Circuit and IR LED Circuit) are used to de-multiplex the signal received by the two LED's. The LED's works in two modes ON and OFF.

An ambient light cancellation circuit is used to subtract light when LED is off and the data received is buffered into the memory for future observations. The low pass filter is used to remove any noise that might have occurred due to processing the signal through sample and hold circuit. Some noise is also introduced by the environment factors. A dc feedback circuit is used to adjust the two LED's input depending upon the current output obtained. The high pass filter is used to remove any DC component present in the signal.

In order to build Earlobe or finger clip Pulse Oximeter, detectors and miniature light sources are used. The main reason is that these components are small and unobtrusive. Red LED and infra-red LED are readily available. Red LED has a bandwidth spectrum around 640nm whereas for infra-red LED, the bandwidth spectrum is around 960nm. A very sensitive detector (such as a photomultiplier tube) is used to detect the small amount of power that is transmitted through finger. The detector used should be very sensitive as the average power obtained from standard LED's is very small. [12]

This problem can be overcome by using a high intensity Red LED. This special purpose LED has an internal lensing system to give high intensity output [12]. Similarly, there are some high current NIR LED's. These LED's are designed to be pulsed. The peak power obtained from these high current NIR LED can be increased without increasing the average power. A photo detector such as a photodiode can be used to detect the transmitted light through the finger. This photo detector should be a simple, solid-state and compact device. [12]

A single photo detector can be used in the pulse oximeter design if both light sources are pulsed together. This is done as visible and NIR wavelength are responsive to silicon devices. This mode of operation help to obtain a high-intensity light output [12]. A current of up to 1A over a low duty cycle can also be obtained with the NIR LED. An amplifier is used to amplify the transmitted light detected by photo detector. Then a current to voltage convertor is used to convert this transmitted light to a voltage. Then the signal of each transmitted wavelength is fed to two identical sections. [12]

Then a sample and hold circuit is used. The sample and hold circuit reconstitute the waveform at two different wavelengths. The control pulses for the corresponding sample and hold circuit is provided by the timing circuit. This timing circuit is also used to control the red and NIR LED drivers. The dc component and the high frequency noise from the output of these circuits are filtered by the band pass filter. The resulting signal is a cardiac synchronous information which is further amplified. Then this signal is converted into a digital format and then analyzed by the microprocessor. [12]

It can be seen in figure 6 that a low pass filter is used. The output from each sample and hold circuit is fed to the low pass filter. The light intensity from the corresponding LED is adjusted by an Automatic Gain Control (AGC) Circuit, It is first stage of an AGC circuit and helps to keep the dc level at the same value (2V). This value remain same whatever the skin characteristics or thickness of the patient finger. [12]

Then the resulting signal is amplified by feeding it with proper gain constant. The resulting signal is fed to the display device. The gain feedback is used to keep the DC level same during processing. The output is then wirelessly transmitted to the display device. The output can be monitored on a computer, smart phone or any display device as per the design requirement. A Bluetooth device is used for the wireless transmission.

Next chapter will basically discuss about the SpO_2 level, infra-red light absorption, red light absorption, equations, and various other parameters required for the design of Simulink Model of Pulse Oximeter. It will explains the fundamental concepts and lay a solid formation for the design of Simulink Model of Pulse Oximeter.

Chapter 3

3.1 Introduction to Simulink Model of Pulse Oximeter

In the past 20 years, measuring the arterial oxygen saturation (SpO_2) level of patients has become one of the most vital and easiest parameter to obtain and analyze. As mentioned in chapter 2, pulse oximetry has now become a standard procedure to obtain information including the efficiency of pulmonary gas exchange and the adequacy of alveolar ventilation, blood-gas transport and tissue oxygenation. From past 20 years, the pulse oximeter has been revolutionized in many aspects [13]. Many new designs and parameters have been introduced in the market. Many researchers are currently working to improve the performance parameters of pulse oximeter. The only way for evaluating the robustness of these new algorithm are hardware implementation. But changing the hardware implementation with new algorithm every time is both expensive and time consuming. So the main focus in this chapter is to provide a realistic and accurate behavioral model for pulse oximeter devices which can be used as a productivity enhancement tool for the design of new pulse oximeter. [13]

Pulse Oximetry is a non-invasive method for measuring the oxygen level in the blood. It basically measure the SpO_2 level (Oxygen Saturation Level) in the blood. In order to understand how SpO_2 is obtained through pulse oximeter, one must be familiar with the underlying technology [13]. Photoplethysmography (PPG) is a simple and low cost optical technique that can be used to measure volume changes in tissues by analyzing changing volume of an optically absorbent or reflectance substance such as blood. It is often used non-invasively to make measurements at the skin surface [13]. The arterial blood volume changes with each heartbeat [13]. The changes in blood volume due to arterial pulsation modifies the absorbance/transmittance of light passing through the tissue. It is assumed that the pulsatile change in PPG waveform solemnly depends upon the change in volume of blood due to each heartbeat. Therefore, the heart rate of a patient can also be determined by measuring changing absorbance/ transmittance light characteristics through pulse oximeter. Furthermore, the SpO_2 level can be estimated from amplitude ratio and corresponding PPG waveform DC components. This technology can be extended to determine SpO_2 level by understanding the absorbance/transmittance characteristics of oxygenated and deoxygenated blood. [13]

Hemoglobin is a protein molecule that carry most of the oxygen in the blood. Hemoglobin is basically found in red blood cells (Erythrocytes). It consists of a single heme group containing a central iron atom. Basically, Hemoglobin is composed of four protein chains known as globulin chains. It has the ability to bind one oxygen molecules to each of its four subunits.

Each globulin chain contains an important central structure called heme molecule. These heme molecules contains iron that plays vital role in transporting oxygen. The oxygen binding takes place in this central iron atom. The iron contained in the blood is responsible for the red color of blood.

3.2 Different SpO_2 level depending upon oxygen hemoglobin molecule bind

Depending upon the SpO_2 level, there are different types of oxygen bounding hemoglobin groups circulating in the blood stream.

Case 1:
If 4 molecules of oxygen bound together, it is known as completely oxygenated hemoglobin.

Case 2:
If 1-3 molecules of oxygen bound together, it is known as partially oxygenated hemoglobin.

Case 3:
If 0 molecules of oxygen bound together, it is called de-oxygenated hemoglobin.

Oxygenated and de-oxygenated hemoglobin molecules act uniquely when exposed to light. These molecules possess unique optical characteristics when exposed to red and infra-red light. Oxygenated hemoglobin transmits red light and absorbs infra-red light, while de-oxygenated hemoglobin absorbs red light and transmit infra-red light. [13] This phenomenon is utilize to obtain an accurate, non-invasive measurement of SpO_2. The following table shows the oxygen molecule binding with hemoglobin molecule and absorption of red and infra-red light in accordance with these bonds.

Red Light Absorption (%)	Infra-red Light Absorption (%)	Number of Oxygen Molecules attached with Hemoglobin.	De-oxy hemoglobin bond (No Oxygen Hemoglobin bond)
0	100	4	0
25	75	3	1
50	50	2	2
75	25	1	3
100	0	0	4

Table 1: Relationship between Red light absorption, Infra-red light absorption and Oxygen hemoglobin molecule bind

Pulse oximetry is a non-invasive method to measure the level of oxygen in the human blood. Pulse oximetry is basically performed in two ways: absorbance pulse oximetry and reflection pulse oximetry. In the absorption pulse oximetry, two LEDS at two different wavelengths (Red LED at a wavelength of 660 nm and infra-red LED at a wavelength of 940nm) are placed on the test site. The LEDS are cycled on and off at up to 480 times per second. The transmitted red and infra-red signals passes through test site. The test site is usually a translucent area with a good blood flow. The signal that passes through the test site received by a photo diode. [13]

As discussed earlier, the oxygenated blood absorbs infrared light and passes more red light. Whereas the de-oxygenated blood absorbs more red light and passes infra-red light. So the light received after passing through test site varies in intensity depending upon the oxygen molecules present in blood at test site.

The ratio of transmitted red and infra-red light received at photo diode are calculated and compared to tables provided by the manufacturer that are based on standard calibration curve derived from various known SpO_2 levels.

The numeric SpO_2 value calculated by the pulse oximeter is the hemoglobin saturation percentage. It is also known as the amount of hemoglobin with saturated oxygen passing through test site. Arterial hemoglobin saturation percentage in case of normal human being is anywhere from 95 to 100 percent. This review which have been discussed so far in this chapter is important. This is because the pulse oximeter calculates the level of oxygen in arterial blood based on the transmitted light in red and infra-red spectral wavelength. While the suggested model calculates the value of transmitted light in both red and infra-red wavelength based on the value of SpO_2. [2]

The two processes are inverse of each other. In order to understand one process, we have to understand the other process.

In chapter 2, the level of oxygen in arterial blood was given by equation [3]

$$S_PO_2 = \frac{[HbO_2]}{[HbO_2]+[Hb]}$$

In this chapter, the above given equation is modified. This is done because the main focus in this chapter is about the concentration of hemoglobin molecules in blood.

Therefore, the level of oxygen in arterial blood is defined as [2]

$$SpO_2 = \frac{C_{HbO_2}}{C_{Hb}} = \frac{C_{HbO_2}}{C_{HbO_2}+C_{RHb}} \quad \text{..... (2.20)}$$

Super script C is used in this equation to emphasize on term concentration in this chapter.
C_{HbO_2} is the concentration of the oxygenated hemoglobin.
C_{RHb} is the concentration of the reduced hemoglobin.
C_{Hb} is the total hemoglobin concentration in blood.

This equation is used to design Simulink Model of pulse oximeter.

Beer Lambert's law explains the attenuation of light through an absorption medium. It is represented as [3] [4] [5]

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

Where
I is the intensity of transmitted light.
I_0 is the intensity of incident light.
$\varepsilon(\lambda)$ is the extinction coefficient of the solute.
β represents the concentration of solute or absorbing medium.
L is the length of the path that the incident light travels through.

This equation explains as the light passes through body, its intensity is attenuated differently. The light passes through different tissues, veins and organs; its intensity of attenuation is derived from above equation. [2] The amount of attenuation that is caused by all other tissues of body other than arterial vessels remains constant. This is because all other tissues of body are assumed to have a constant value of extinction coefficient, length and concentration. The story is completely different in case of arterial vessels. The amount of attenuation of light in arterial vessels changes with time. This is because the diameter of arterial vessels is changing with each heartbeat. [2]

The AC and DC components of the light absorbance are shown in figure

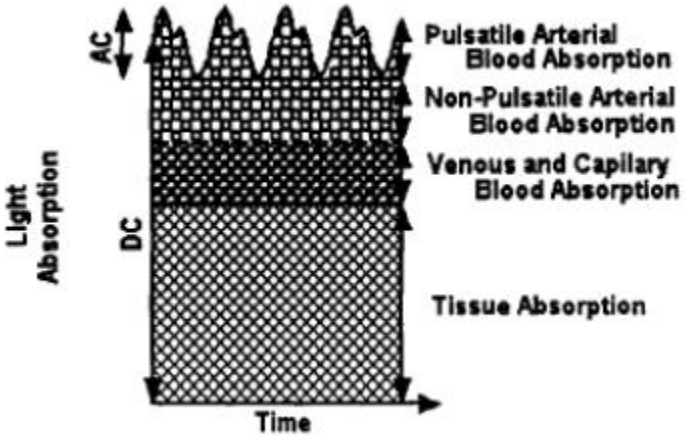

Figure 7: Light absorption versus time showing the primary sources of absorption. [6] Rusch

This causes the amount of attenuation to vary from time to time. The pulse oximeter is still able to distinguish the arterial vessels from other part of the body. The transmitted signal has a small varying part (AC part) due to light passing through arterial vessels. A large constant part (DC part) is generated by the light passing through other body tissues. [2]

This AC part of the signal is used by Pulse oximeter to determine the level of oxygen 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 receiver, it is possible to measure SpO_2 [2]. The normalized value is calculated by dividing the AC component of the absorbance at that frequency by the DC component which is analogous to taking the time derivative of the absorbance as shown by equation in chapter 2. [2]

$$R = \frac{AC_{red}/DC_{red}}{AC_{ir}/DC_{ir}}$$

Where R value is calculated from the digital photoplethysmograms by taking the normalized ratio of the red absorbance to the infrared absorbance (explained in chapter 2 earlier).

In chapter 2, equation 2.17 shows that the arterial oxygen level can be determined by solving for SpO_2 value. The equation 2.17 is [4] [5] [6]

$$SpO_2 = \frac{(\varepsilon_{Hb}(\lambda_1) - R\varepsilon_{Hb}(\lambda_2))}{(\varepsilon_{Hb}(\lambda_1) - \varepsilon_{HbO_2}(\lambda_1) - R(\varepsilon_{Hb}(\lambda_2) - \varepsilon_{HbO_2}(\lambda_2))}$$

This equation shows that it is possible to calculate the value of SpO_2. So the blood oxygen saturation level can be measured if the amount of incident and transmitted light of red and IR wavelength known.

Blood Oxygen saturation level is very important in determining a person's health condition. The normal blood oxygen saturation level for a normal human being is around 95% to 100%. The SpO_2 level range is from 90% to 94% for patient suffering from mild respiratory disease. This condition is known as mild hypoxemia in medical terms. If the blood oxygen saturation level falls below 90%, medical attention is required. The patient is given supplementary oxygen to maintain the appropriate oxygen level.

3.3 SpO_2 level Interpretation

The following table shows different oxygen saturation levels and their interpretation in medical terms.

SpO_2 Level Readings (%)	Medical Interpretation
95-100	Normal
90-94	Mild Hypoxemia
Below 90	Moderate Hypoxemia (Need Medical Attention)
Below 88	Severe hypoxemia (Need Urgent Doctor help)

Table 2: Different oxygen saturation levels and their interpretation in medical term

If the blood oxygen saturation level (SpO_2) falls below 88%, it is serious medical condition. Immediate Doctor attention is required.

The amount of oxygen in air decreases at higher altitudes. It has a significant effect on a person SpO_2 level. A person may have oxygen saturation level of 97% at sea level but it may decrease to 93% at 4000 feet height and may further drop to 88% at 10,000 feet. Sometimes SpO_2 level decreases to about 80% at height above 10,000 feet and this may result in hypoxic condition.

The above discussion shows the importance of a pulse oximeter in a person life.

The main function of blood is to receive oxygen from lungs. Blood then transports this oxygen to other body's tissues. The blood also receive carbon dioxide at the same time from the tissues and bring it back to lungs [14]. The partial pressure of the gas corresponds to the amount of gas dissolved in blood. 100ml of blood per mm Hg (pressure) dissolves only about 0.3ml of gaseous oxygen [14]. Each gas has different solubility rate. This amount corresponds to only about 1/20 of carbon dioxide solubility [14]. This suggests that if solubility were the only way to get oxygen in the blood then human body will not get sufficient oxygen. This is the main reason why hemoglobin (Hb) has an important role as a carrier of oxygen. [14]

Four molecules of oxygen can bind with one molecule of hemoglobin. It means that 1g of hemoglobin can bind to 1.39 ml of oxygen. Thus the hemoglobin contained in 100ml of blood can bind to 20.4ml of oxygen as 15g of hemoglobin is in 1ooml of blood. [14]

The following figure shows the oxygen molecule binding with hemoglobin. This binding takes place in Heme group contained in hemoglobin. Heme group contains a central iron atom where oxygen binding takes place as shown in figure 8.

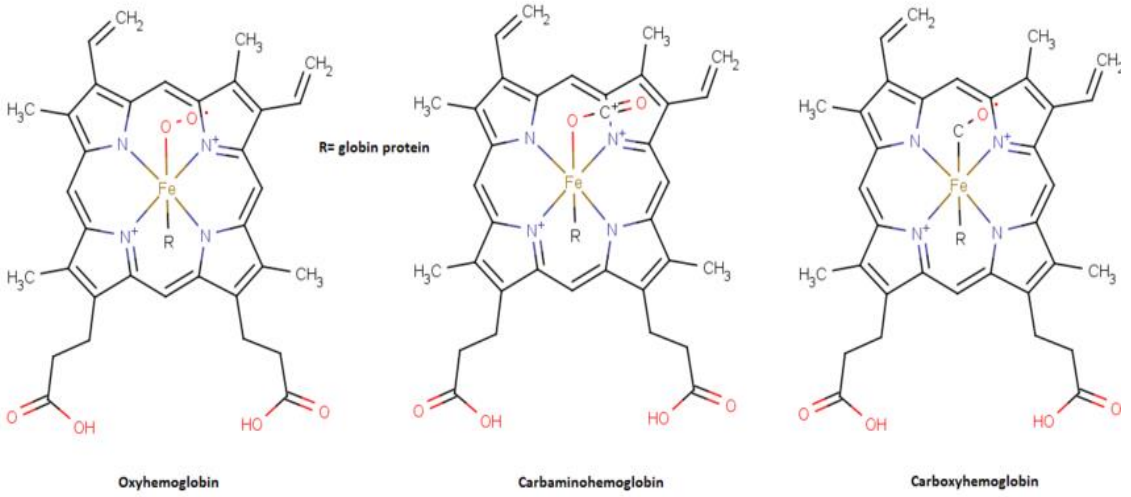

Figure 8: Oxygen molecule binding with hemoglobin (Heme group) [15]

3.4 Relationship between SpO_2 and Heart Rate:

The normal heart rate of a healthy person is 72 bpm. It may vary from 60-100 bpm. The normal oxygen saturation level for a healthy person is 95-100%. Heart rate increases with decrease in SpO_2 level. This can be noticed during exercise. Heart rate variability and exercise are closely related because physical activity places several demand on cardiovascular system. During exercise, muscles need more oxygen and glucose. More oxygen is used therefore resulting in low SpO_2 level. This result in the decrease in the person pH value below normal range and thus increases the heart rate. Therefore, heart pumps faster to deliver more blood to lungs and other organ.

The following table represents the data that was collected in male elite athlete during sports. This study was done at Department of Physical Education and Sport, University Azad of Tehran, IRAN by Professor Hamid Tabatabaei. [10] The table below shows the relation between SpO_2 and heart rate. [10]

SpO_2 %	94-93	92-91	90-88	87-85	84-80	79-77
Heart rate	138-146	147-149	150-154	155-158	159-162	164-167

Table 3: Relationship between oxygen saturation level and Heart rate

Past research done by scientists have shown that there is no direct relationship between heart rate and SpO_2 level. Heart rate increase during exercise depends upon many other parameters. One of several factors may cause a heart rate increase. Physical activity places several demands on the cardiovascular system, which is why heart rate variability and exercise are closely linked. Similarly, there are many other factors that are responsible for increase in heart rate during exercise.

This chapter basically discussed about the SpO_2 level, infra-red light absorption, red light absorption, equations, and various other parameters required for the design of Simulink Model of Pulse Oximeter. This chapter explains the fundamental concepts and lay a solid formation for the design of Simulink Model of Pulse Oximeter.

Chapter 4 will discuss about how to design the Simulink Model of Pulse Oximeter and its Graphical User Interface.

Chapter 4

4.1 Basic idea about MATLAB, Simulink and Stateflow algorithm

In this chapter, a Simulink model of the Pulse Oximeter is presented. This Simulink model is based on the formulae and concepts that were discussed in chapter 2 and 3. This model shows the design of Pulse Oximeter and its background operation concepts. It deals with development concepts and early verification done during a design process. The main aim is to design a model which can be used as a productivity enhancement tool for further research and development process of new pulse oximeter.

MATLAB/SIMULINK is used as a tool software to design the pulse oximeter model. This software is used to process, display and model the data. To understand the pulse oximeter model, the basic understanding of MATLAB and Simulink model is required.

MATLAB is a high level programming language [16]. With the help of MATLAB, one can
Analyze, visualize and explore data
Develop new algorithm for design
Create new models and further develop new applications using Graphical User Interface
Modeling and simulation of data and prototyping its concepts

Simulink is a block diagram environment that provides a graphical user interface (GUI) for building models. [17][16] With Simulink, one can
Model and Simulate dynamic system
Analyze and build Models
Construct interactive graphical model using drag and drop mouse features
Create an up running model in short time

Figure 9 shows a Simulink model of pulse oximeter. This model is based on the equations and formulae derived in chapter 2 and 3. This model is designed using Stateflow Algorithm and gives a clear picture of the device.

Stateflow is a control logic tool based on flow chart algorithm, state transition table, and state machine. It is used to
Model sequential Logic
Simulate combinatorial algorithm and transition table
Combine tabular and graphical time based conditions

4.2 Simulink Model of Pulse Oximeter

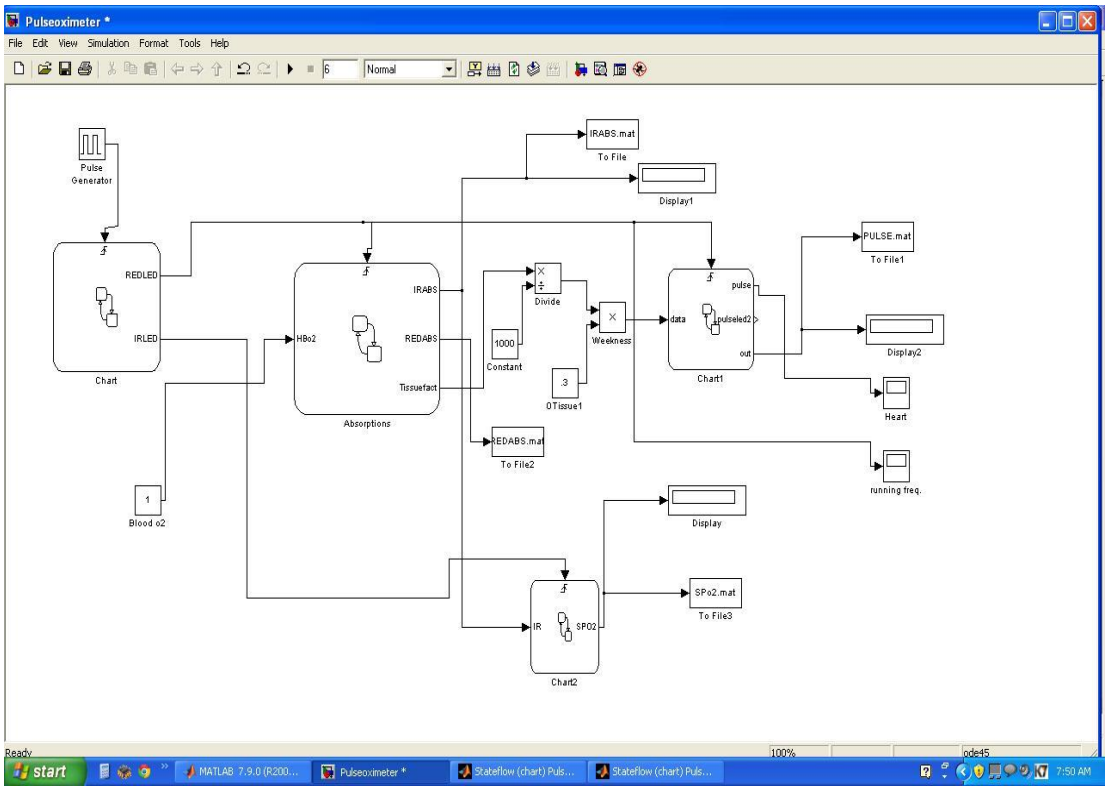

Figure 9: Simulink Based Model of Pulse Oximeter

A brief description of each block of figure is given below:

1. Pulse Generator

A Pulse Generator is an electric circuit that generates a single or multiple pulses that can be adjustable by changing the pulse rate. Pulse generator can use both digital and analog technique to form output pulses. The role of this block is to set timer for pulses on the basis of which IR and RED LED will be ON and OFF.

Pulse time is selected Time Based in pulse type parameter. The time based pulse type parameter is selected because it allows the Simulink software to compute the block's output only at time when the output actually changes. So it actually computes its output only with change in time interval.

The following figure shows the inner source block parameters of Pulse Generator.

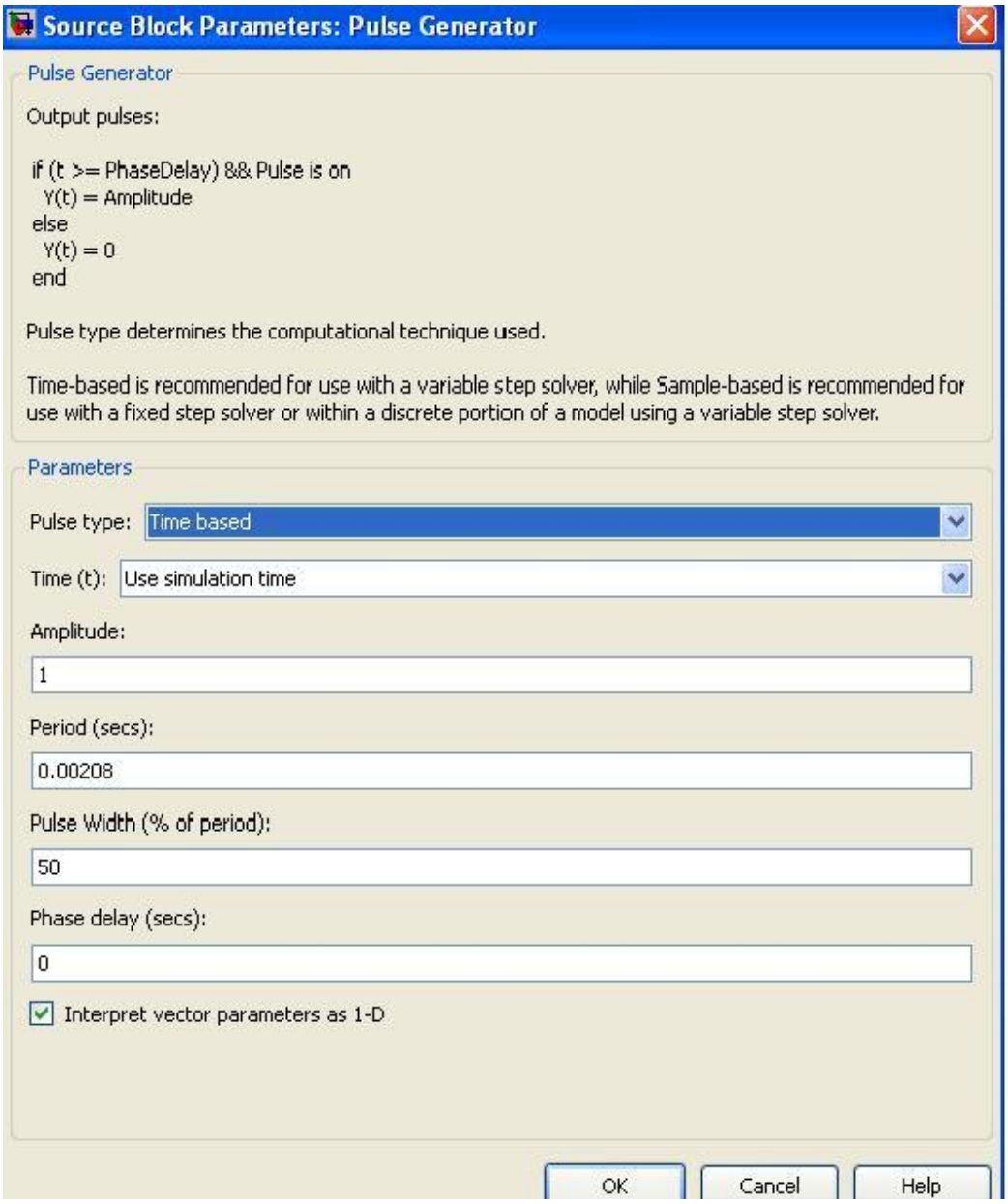

Figure 10: Inner source block parameters of Pulse Generator

For the light to penetrate human body, each LED should blink minimum 480 times per second. If both LED'S blink 480 times per second, the time period accordingly will be 0.00208 seconds.

Time period is inversely proportional to frequency. Frequency of LED in this case is that it blinks 480 times per second.

Amplitude of pulses is selected to 1 as standard

$$T = \frac{1}{f}$$

$$= \frac{1}{480}$$

= 0.00208 seconds

Pulse Width is always measured in percentage. It basically show for how much time duration each LED will remain ON. As the period is equal to 0.00208 seconds. But here pulse width is selected 50%. It means that both LED's will remain ON for 0.00104 sec and OFF for also 0.00104 seconds.
The output of this block has been connected to stateflow chart.

2. Stateflow Pulse Oximeter Chart

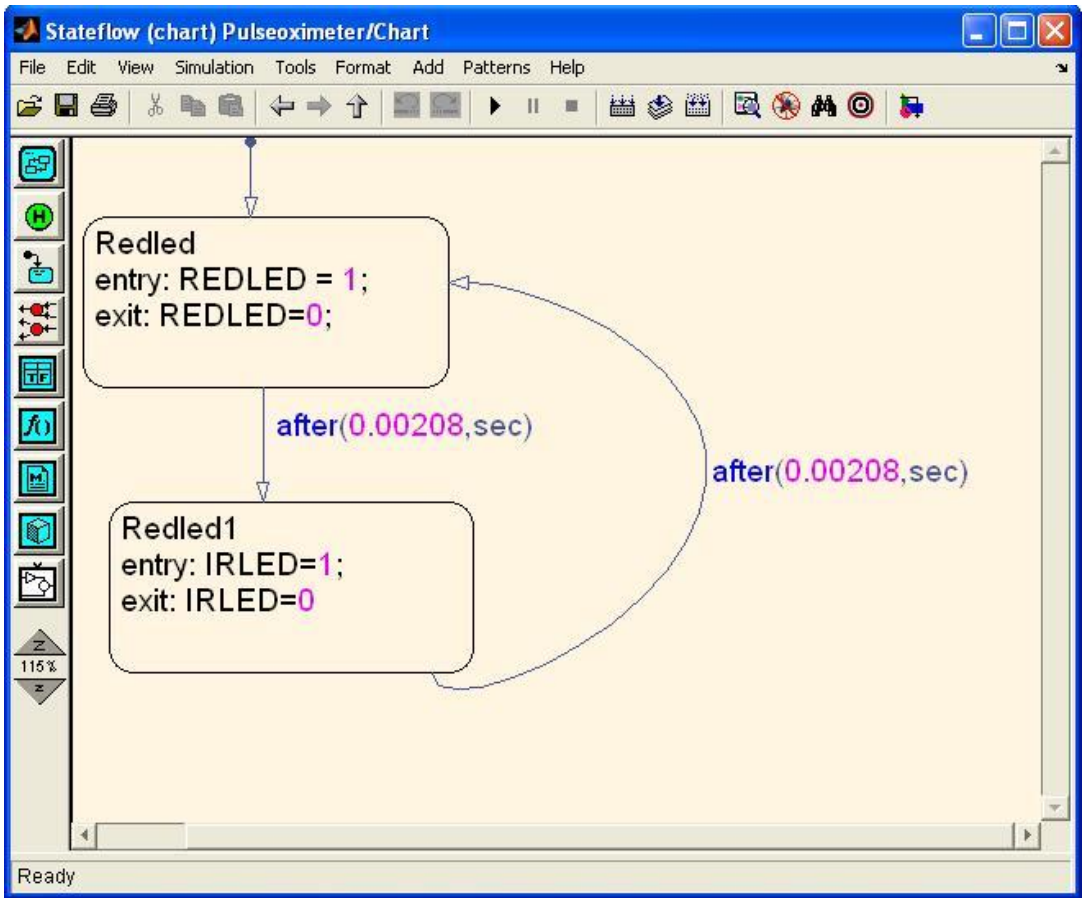

Figure 11: Stateflow Pulse Oximeter Chart

In this block, a stateflow algorithm has been created. Two blocks have been created, one for each LED. Each LED will blink ON and OFF after 0.00208 seconds.

In first block, when REDLED = 1, red LED will blink ON. Red light will penetrate the human body and depending upon its SpO_2 value will be calculated. After 0.00208 seconds, REDLED value is set to zero. It will set LED timer to off.

As it can be seen in the figure, when REDLED = 0, infrared LED (IRLED = 1) goes to 1. It means that now IR LED will be ON and SpO_2 value will be calculated accordingly. It means that now IR LED will be ON for 0.00208 sec and then will be set to zero. So both LED's will be ON and OFF for 0.00208 sec separately.

Input to this block is from Pulse Generator.

Output of this block are two LED'S ON and OFF.

3. Absorption

Absorption stateflow is the main block of this Pulse Oximeter project. A relationship between the IR and RED LED's have been calculated depending upon there ON and OFF state. Accordingly, this stateflow chart have been designed. Total five relations have been shown in the table given below:

Red Light Absorption	IR Light Absorption	HBo2 Molecules bind	Tissue factor
0	100	4	2777
25	75	3	2739
50	50	2	2702
75	25	1	2666
100	0	0	2631

Table 4: Relationship between light absorption, oxygen hemoglobin bind and tissue factor

Here a new term have been used called Tissue factor.

Tissue Factor also called thrombokinose in medical terms is a protease that converts prothrombin to thrombin in the early stage of blood clotting. [19] It basically causes the growth of new blood vessels, found in tissues with high metabolic requirements and also released by macrophages to initiate revascularization in wound healing. [20] The best known function of tissue factor is expressed by cells which are normally exposed to flowing blood. This can change when the blood vessels is damaged or rupture. [19] [21]

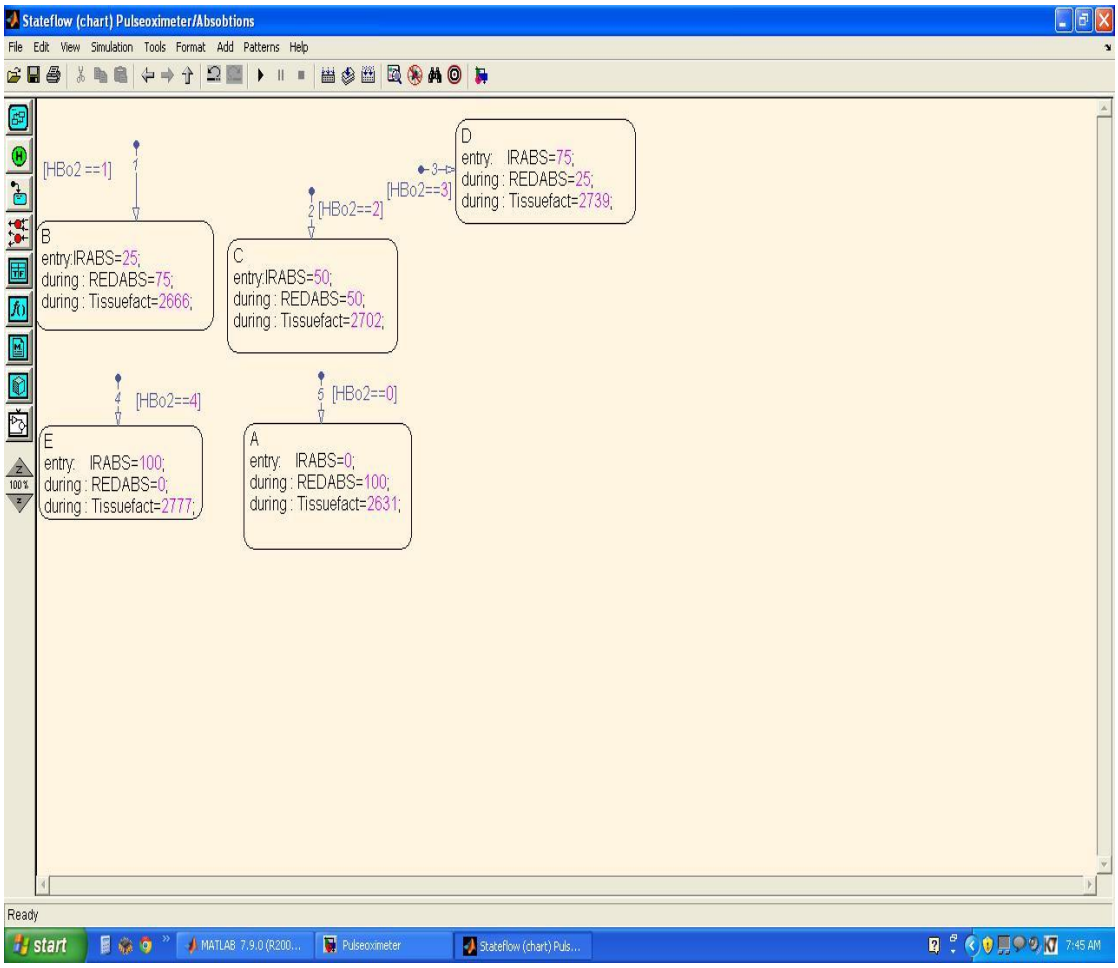

Figure 12: Stateflow Absorption Algorithm

This figure has following inputs and outputs

(a) HBO_2 is the input to this block which is the output from constant value Blood o2. The value to this block is input from the user and which is further connected to stateflow at HBO_2. The value of Block o2 depends upon the number of oxygen molecules attached to the hemoglobin molecule. As shown in the table the maximum number of oxygen molecules attached to hemoglobin can be 4 and the minimum number is zero molecules attached. So depending on this, there are five different possibilities as shown in table before.

(b) Another input to this chart is from stateflow Chart output i.e. REDLED. This input will depend upon the amount of red light absorbed by the oxy-hemoglobin blood. If the amount of oxygen concentration (SpO_2) in blood is less then more red light will be absorbed. If the amount of oxygen concentration (SpO_2) in blood is more then less red light is absorbed and input will be different.

We have used REDLED as input but IRLED absorption can also be used as input to this block. In that case, it will be opposite.

(c) If the amount of oxygen concentration in the blood is higher, more infra-red light will be absorbed. The absorption of infra-red light will be less, if oxygen concentration in blood is less. As it can be seen in the table that both red light absorption and infra-red light absorption is interlinked with each other.

(d) According to relation stored in the absorption stateflow chart, three outputs will come and that are:
IRABS (Infra-red light absorption percentage)
REDABS (Red light absorption percentage)
Tissue Factor (which will be used to calculate heart rate calculation)

When four oxygen molecules are attached with hemoglobin molecules i.e. HBO_2 = 4, IRABS (Infra-red light absorption percentage) is 100. It shows high concentration of oxygen in blood. So REDABS (Red light absorption percentage) is 0. Tissue factor is 2777 and that is a standard value.

Now as seen in next block, when HBO_2 value is 3 (three oxygen molecules bind with hemoglobin), the IRABS decrease to 75 percentage. It indicates a decrease in oxygen concentration in blood and REDABS increase to 25 percent. Tissue factor decrease to 2739 indicating that the coagulation of blood in vessels decrease. Protein in blood and Platelets forms a clot to stop excessive bleeding in case of injury.

In next block HBO_2 = 2, so it can be seen that both IRABS AND REDABS is 50 percent. Tissue factor decrease further to 2702. So it can be seen that as the HBO_2 value keep decreasing i.e. less number of oxygen molecules attached to hemoglobin molecules, the percent of REDABS keep increasing indicating less amount of oxygen saturation level in the blood. In the final block, when there is no oxygen bind with hemoglobin (HBO_2 = 0), 100 percent of red light is absorbed and vice versa no IRABS takes place. Tissue factor decrease more indicating less blood coagulation in blood vessels.

(e) Output from this chart are connected to GUI program using .mat files named IRABS.mat and REDABS.mat.

(f) One of the output is also connected to Chart2 which will help to calculate oxygen saturation level in blood (SpO_2)

4. Display1

This block is used to show IR light absorption percentage.

Input to this block is from IRABS. IRABS.mat file can be seen in this model. It is used as an input for Graphical User Interface (GUI).

5. Chart2 Stateflow Block

Chart2 Stateflow Block is used to calculate the SpO_2 (Oxygen Saturation level in blood). The input to this block is from Absorption i.e. IR Absorption (IRABS).

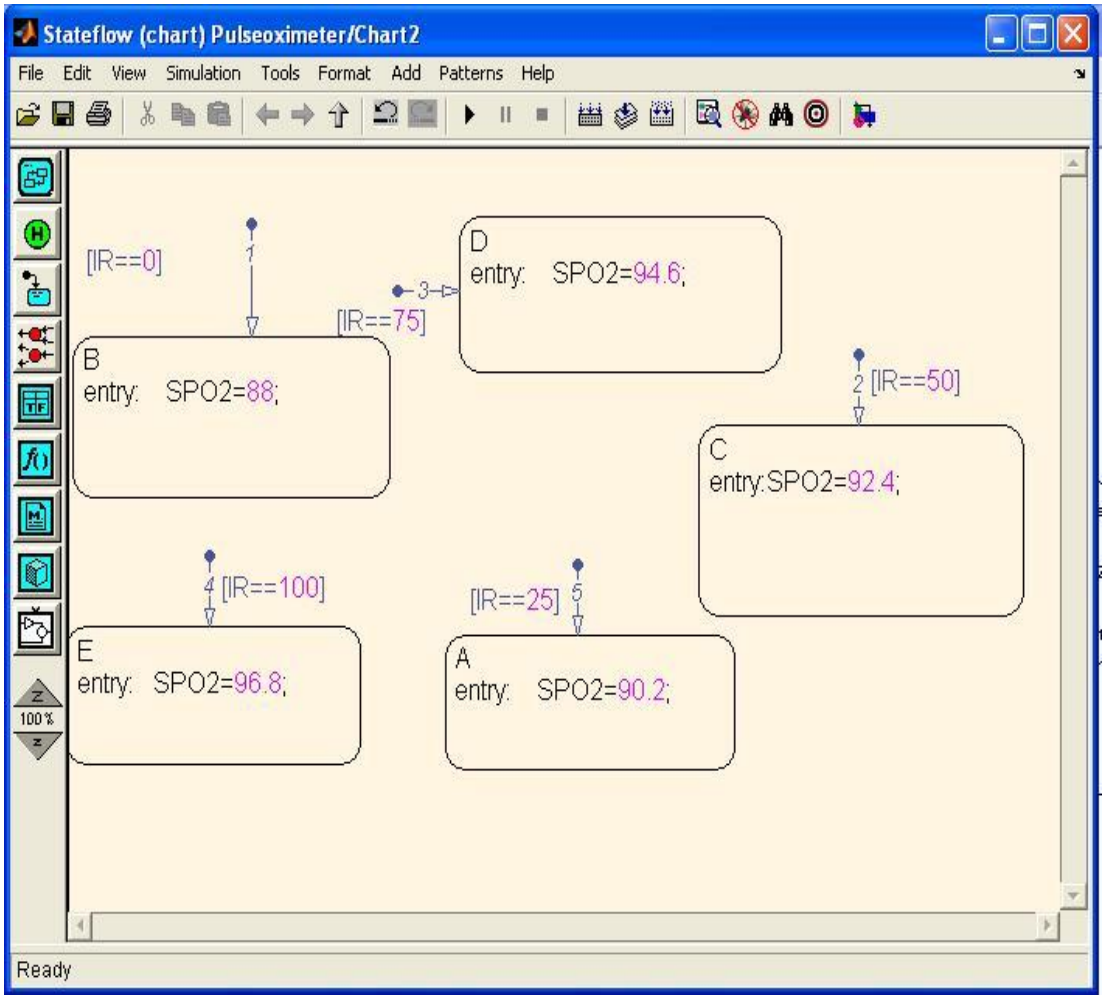

Figure 13: Stateflow Pulse Oximeter Chart2

In the figure above, it can be seen that when Infra-red light absorption is 100 percent (IR=100) i.e. four molecules of oxygen bind with hemoglobin. The blood has high concentration of oxygen in it. Therefore, SpO_2 (Oxygen saturation level in blood) is 96.8. This is the normal condition.

Now it next block when IR Absorption drop to 75 percent and in that case Red light absorption will be 25 percent, the SpO_2 value drop to 94.6. Here it can be seen from SpO_2 value decrease that less infra-red light is absorbed due to less oxygen hemoglobin bind (HBO_2 = 3). As there will be more decrease in infra-red light absorption, the SpO_2 will keep decreasing too. It shows that oxygen saturation level in blood is decreasing with decrease in oxygen hemoglobin bind. A block in the chart illustrate that when there will be no oxygen molecule bind with hemoglobin, there will be no IR Absorption. This chart can also be designed using red light absorption (REDABS). In that case, SpO_2 (Oxygen Saturation level in blood) will decrease with increase in red light absorption (REDABS). So the result will be same regardless of what input is fed to this block i.e. REDABS or IRABS.

This chart clearly shows the relationship between the SpO_2 level and IR light absorption.

6. Display Block

This block is used to show SpO_2 level in blood. The output from SpO_2 block is linked with GUI.m file using SpO_2.mat file. This file is used to create o Graphical User Interface of SpO_2.

7. Constant, Divide, 0Tissue1 and Weakness

Constant, Divide and 0Tissue1 block are used to calculate the timing on the basis of which it is possible to calculate the weakness in the pulse which will further input to Chart1 at data1. On the basis of this timing, it is possible to calculate heart rate.

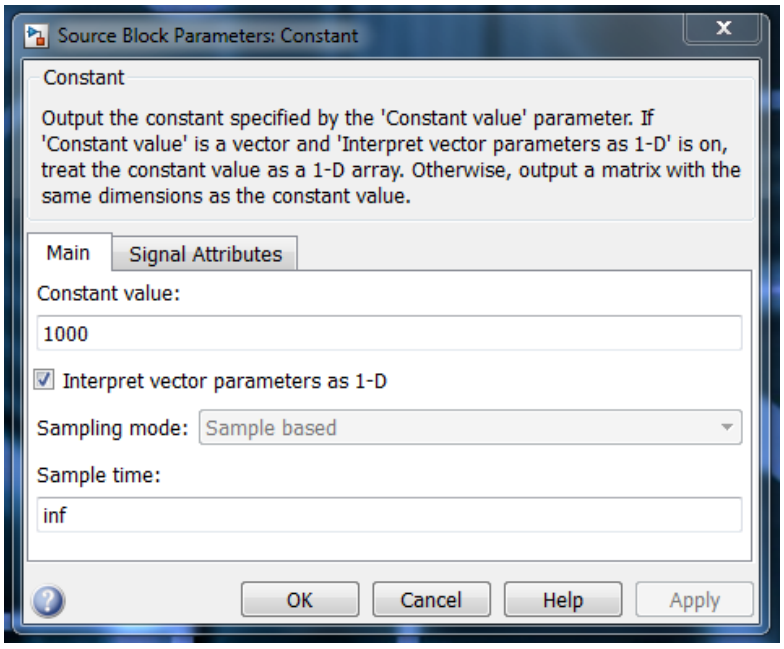

Figure 14: Source Block Parameter Constant

In the figure 14, the constant value has been taken equal to 1000. This is done in order to adjust the value of Tissue factor to smaller scale so that on the basis of which the weakness factor can be calculated easily. If this constant value is not assumed in this model then it will result in larger value of weakness, which it case will make the model more complex. The output from this Constant block act as input to Divide block. The sample time is selected infinity to have a wider range of values. The figure of Function Parameter Divide block is shown below

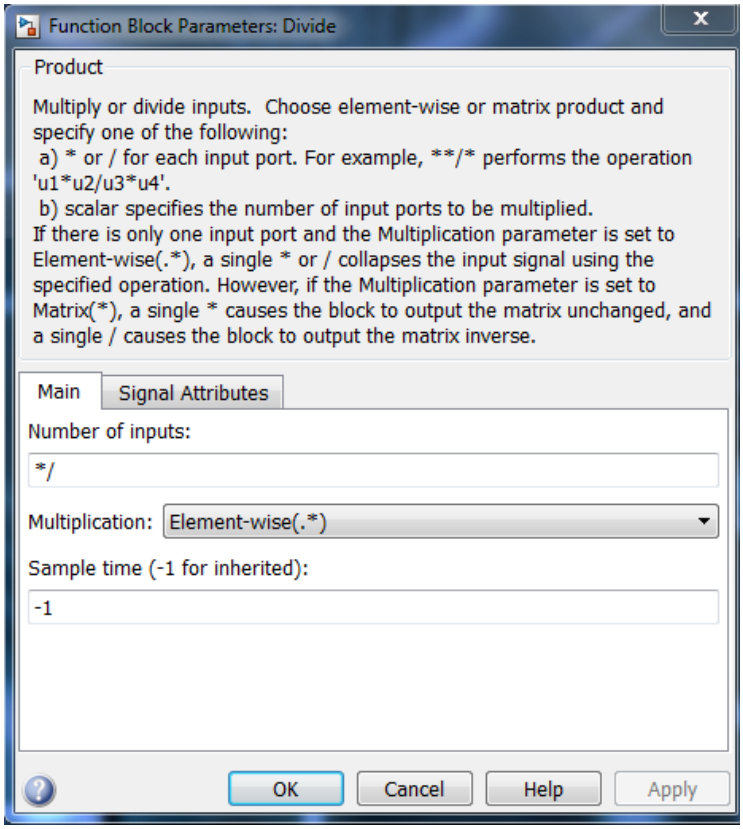

Figure 15: Functional Block Parameter Divide

Divide Block has two inputs. One input is from Constant block and other input is from Tissue factor. The function is this block is to multiple tissue factor value with 1/1000. The output will be tissue factor value decremented by 1000. This will help in scaling the model to smaller values. The multiplication is selected Element-wise. Element-wise multiplication multiples Array A with Array B and returns the result in C. As in figure 12, it is clear that Tissue factor value is changes with change in the HBO_2 value (Number of oxygen hemoglobin bind molecules). So the Divide Block output will be changing in accordance with different Tissue factor value.

The sample time is selected -1.

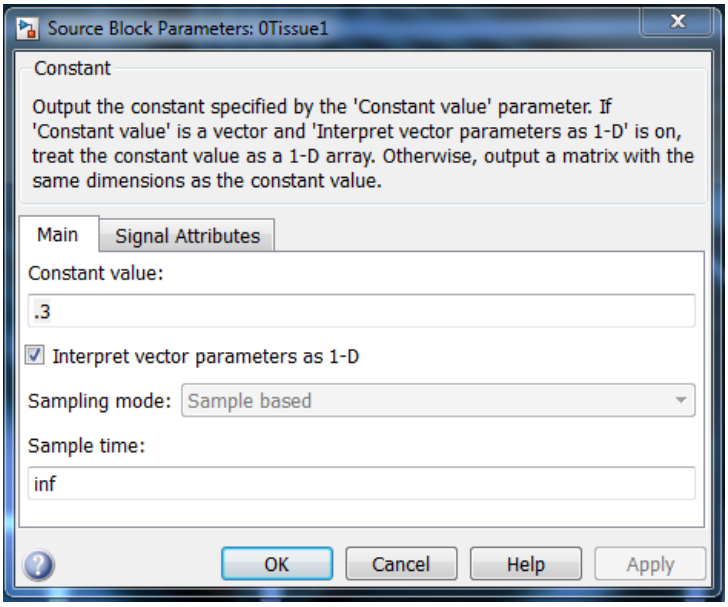

Figure 16: Source Block Parameter 0Tissue1

This block is used to calculate the timing on the basic of which weakness is calculated. This weakness will be the input to Chart1 Stateflow. This timing will help to calculate the value of heart rate. This block act as input to Weakness Block.

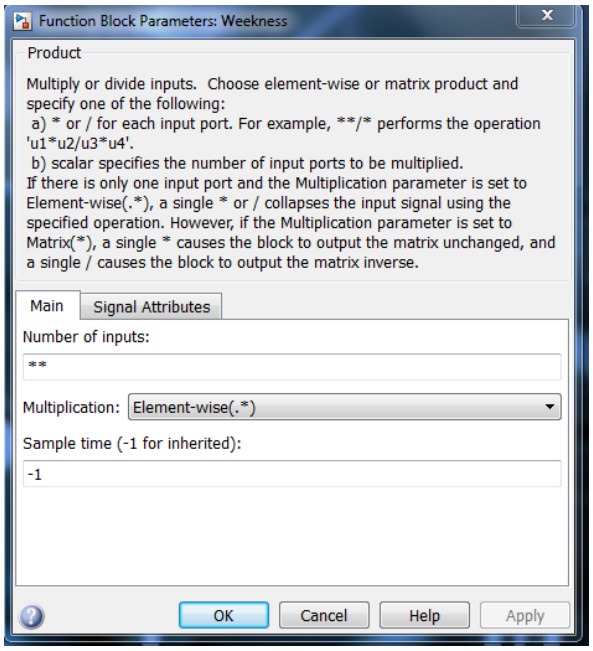

Figure 17: Function Block Parameter Weakness

Figure 17 shows inner parameter of Weakness Block. The input to this block is scaled tissue factor value and 0Tissue1 value. In the "Number of inputs" parameter, the value is equal to two multiplication signs. It indicate the multiplication operation of two input values and the resultant output is fed to Stateflow Chart1.

8. Chart1 Stateflow block

This Block is used to calculate heart rate and frequency of pulses related to it.

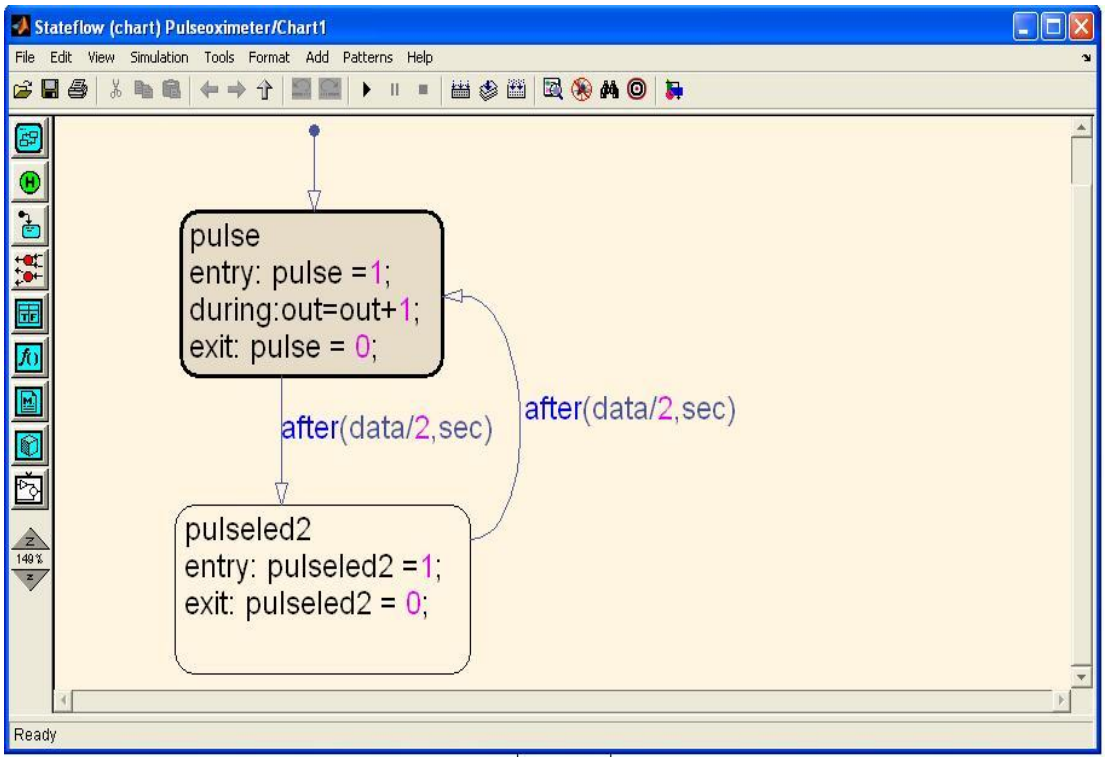

Figure 18: Stateflow Chart1

The input to this block is from the weakness block. The other input to this block is from REDLED of Chart block. The weakness depends on the tissue factor. As the tissue factor decrease, the coagulation of blood in vessel will also decrease. This will decrease the value of weakness block. This will result in increase in heart rate to increase the tissue factor to a normal value. The input to this block is from weakness block, which will be a value on the basis of which ON and OFF timing of heart beat pulses at output pulse is calculated. The output of pulse is further connected to CRO named as Heart.

To link GUI for displaying heartbeat, we have created one .mat file named as PULSE.mat file. The data from this file is being used in GUI.m file for heart rate display.

Display2 block is used to show PULSE. Mat file data.
The role of this chart is to calculate number of heart beats per min. In this chart, a variable pulse is incremented each time a source pulse will come and its output is in the form of number that is used in matlab.m file for calculating heart rate.

The m file represents the coding part for calculating the heart rate based on the value that is input through pulse chart.

The next chapter will show the different simulation results.

Chapter 5

5.1 What is Graphical User Interface?

The presented model has more than 15 parameters explained in it. It is very time consuming to assign value to these parameters separately. A Graphical User Interface has been developed inside MATLAB/Simulink environment to view the results. Graphical User Interface will help to have an intuitive understanding of this model. It will help to explain each parameter used in this accurately.

A Graphical User Interface (GUI) is a user friendly interface with help of which human can interact with computer more easily. With help of GUI, many operations can be performed more intuitively. GUI also allows user to change different parameters in pulse oximeter model and accordingly observe their output. It make is possible to do changes in model design in real time simulation. [22]

5.2 Simulation Results

Figure 19 will show the developed GUI

(a) GUI with Blood O2 = 4

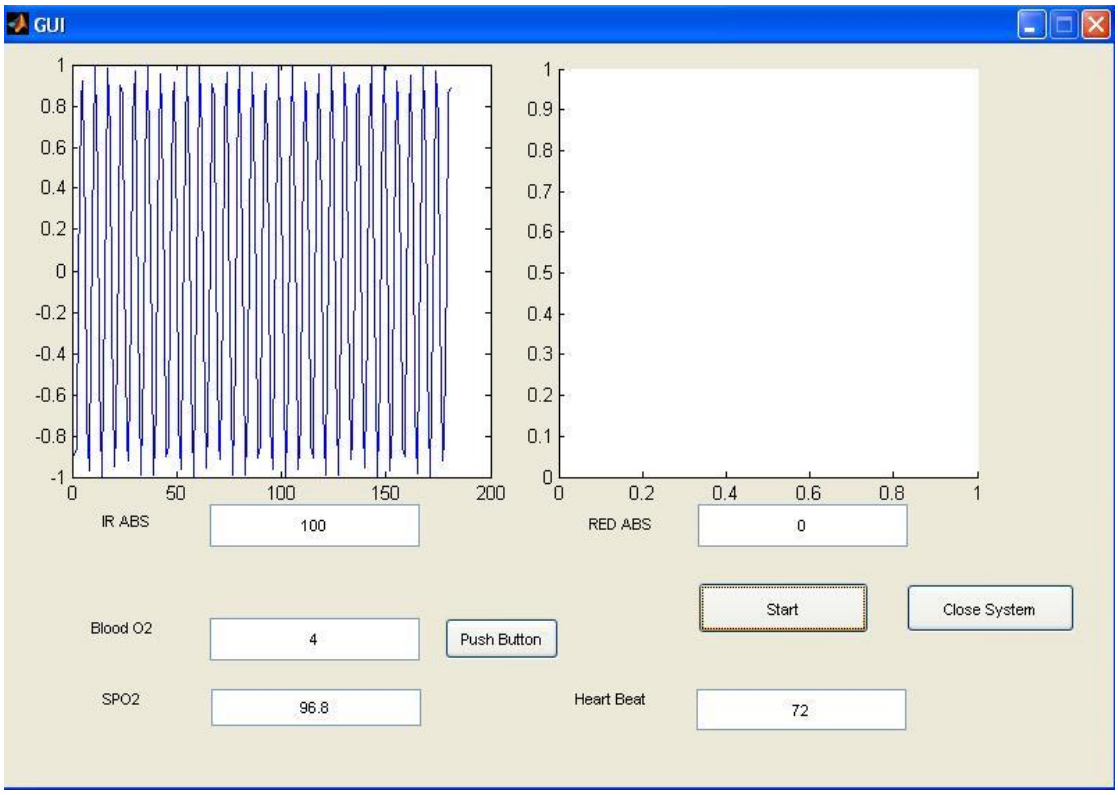

Figure 19: Graphical User Interface with Blood O2 = 4

As it has been discussed previously in this chapter that the IR and Red light absorption depends upon the amount of oxygen concentration SpO_2 in the blood. The SpO_2 level further depends upon the number of oxygen molecules attached with the hemoglobin molecule in blood. The results simulated in this model will clearly illustrate the relationship between SpO_2, Blood O2, IRABS and RED ABS

Figure 19 shows the Graphical User Interface. In this GUI figure, the Blood O2 level is 4. It means that four molecules of oxygen are attached with hemoglobin. So the blood has a high concentration of oxygen in it which is illustrated by SpO_2 value equal to 96.8. This is normal level of oxygen in a healthy person. It has been explained in previous chapters that infra-red light is absorbed more by the oxy-hemoglobin blood whereas red light is absorbed less by the oxygen saturated hemoglobin blood. It can be clearly seen in GUI figure 19 that infra-red light absorption is 100 (IRABS = 100) percent as maximum number of oxygen molecules attached to hemoglobin can be 4. So it is the condition with highest oxygen saturated blood and no red light absorption (REDABS = 0). There is a push button to start the simulation process. Heart rate shown at this SpO_2 level is 72. After the simulation time assigned, the simulation process will stop and results will be generated. The Close system is to stop the process in between the simulation process to view results that different intervals of time.

(b) GUI with Blood O2 = 3

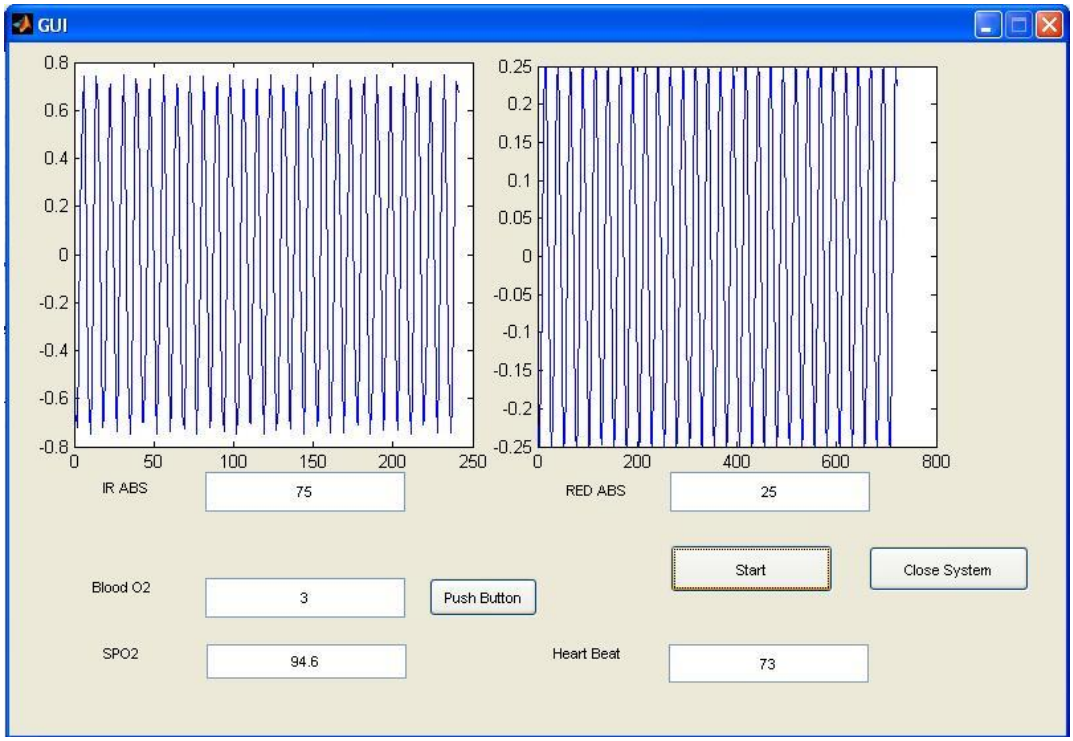

Figure 20: Graphical User Interface with Blood O2 = 3

In the GUI Figure 20, the Blood O2 = 3, it means that now three molecules of oxygen are attached with hemoglobin molecules. So, it is partially oxygenated blood. In this case as can be seen in the figure 16 that the Infra-red light absorption (IR ABS) is 75 percent. It has decreased from 100 to 75 percent. This is because now less molecules of oxygen bind to hemoglobin. So in this case RED ABS will increase to 25 percent. Now it can be clearly seen that there is a drop in SpO_2 level. The graph showing the RED ABS is now showing some frequency. The frequency shows the absorption rate in accordance with red light. Whereas in figure 19, the RED ABS graph was empty showing no absorption. Also increase in heart rate is very less. It clearly show that there is no direct relationship between the heart rate and SpO_2 (Oxygen Saturation level). Heart rate usually depends upon a lot of other factors. This Simulink Model is designed to show the oxygen level of blood. So, the other factors relating to heart rate are not taken into deep consideration in this model. That is one of the primary reason that why there is no significant change in the heart rate with regards to increase or decrease in SpO_2 level.

(c) GUI with Blood O2 = 2

In the figure 21, Graphical User Interface for Blood O2 = 2 is shown.

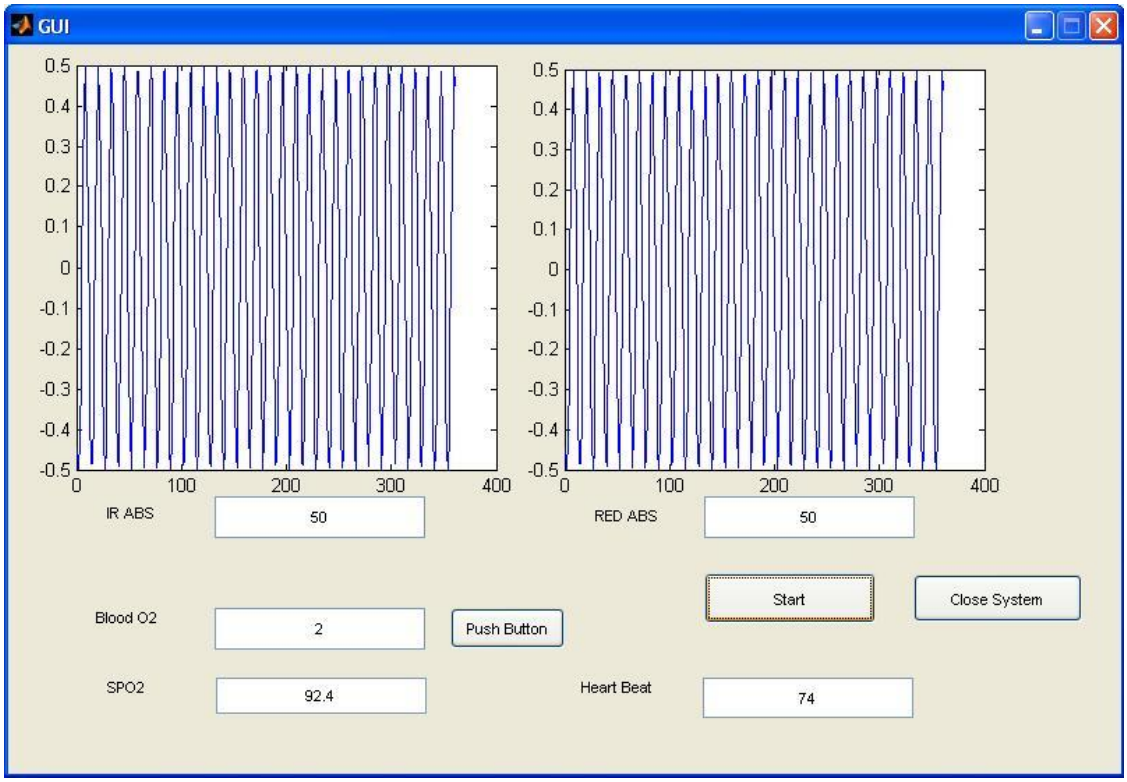

Figure 21: Graphical User Interface with Blood O2 = 2

It means two molecules of oxygen attached with hemoglobin molecule. So it can be seen clearly from the figure that now only 50 percent of Infra-red light is absorbed and also RED ABS increase to 50 percent. It is because now the percentage of oxygen saturation level in

blood has decreased. Now the blood will allow more infra-red light to pass than before so its absorption has decreased to 50 percent. The absorption rate in both graphs for IR ABS and RED ABS are linear. It can be seen clearly that the rate of absorption in both graphs are same as equal amount of red light and infra-red light in absorbed with Blood O2 level equal to 2. The amplitude of absorption is 0.5 in both graphs. The SpO_2 level has dropped further to 92.4. Again there is very slight increase in heart rate because all other heart dependent factors are not taken in consideration.

(d) GUI with Blood O2 = 1

Figure 22 represents Graphical User Interface with Blood O2 = 1 which means only one molecule of oxygen bind with hemoglobin molecule.

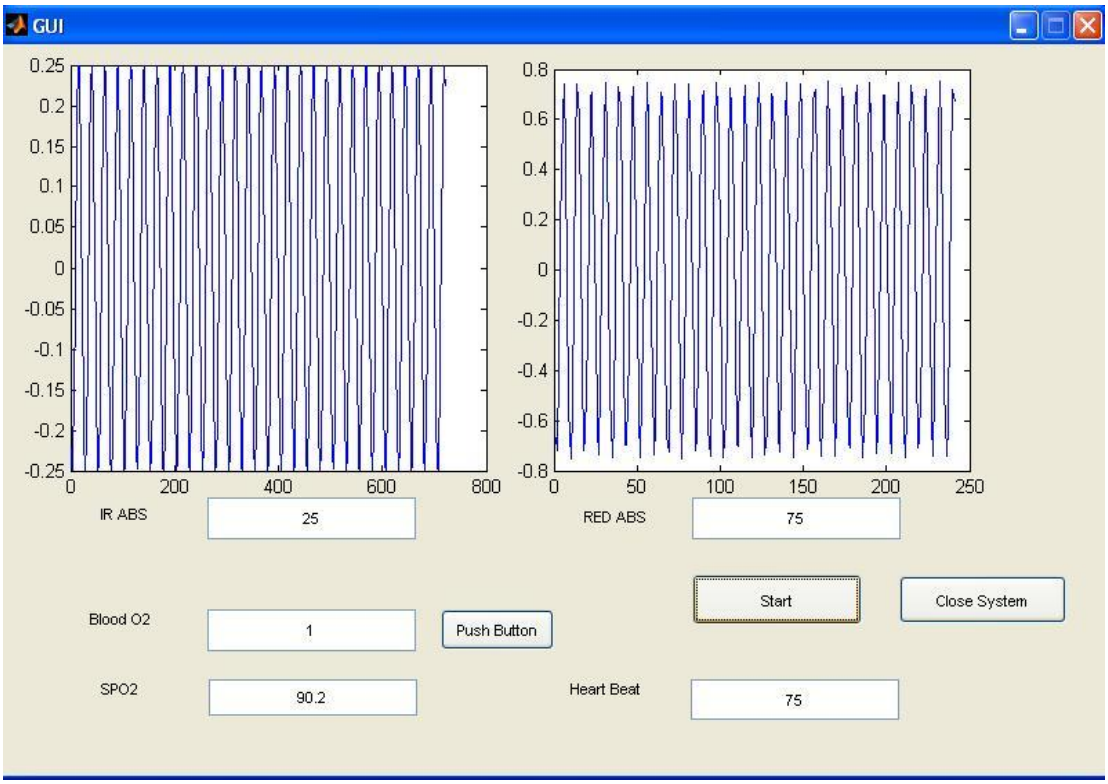

Figure 22: Graphical User Interface with Blood O2 = 1

In this GUI figure, the RED ABS (red light absorption has increased to 75 percent due to decrease in the oxygen saturation level in the blood. It can be seen the due to less Blood O2 level, the IR ABS is only 25 percent.
So now blood is allowing more infra-red light to pass whereas red light absorption is more. This is the main concept behind the Pulse oximeter model which is clearly shown in all these GUI figures. The RED ABS graph also show more absorption as the amplitude and frequency of absorption is more in that case. Heart rate has increased by a small value

which is common. The main focus is to examine the SpO_2 value. It has decreased to 90.2. So it a condition of Moderate Hypoxemia. SpO_2 value is quite helpful in examine the condition of human body.

(e) GUI with Blood O2 = 0

Figure 23 represents Graphical User Interface with Blood O2 = 0.

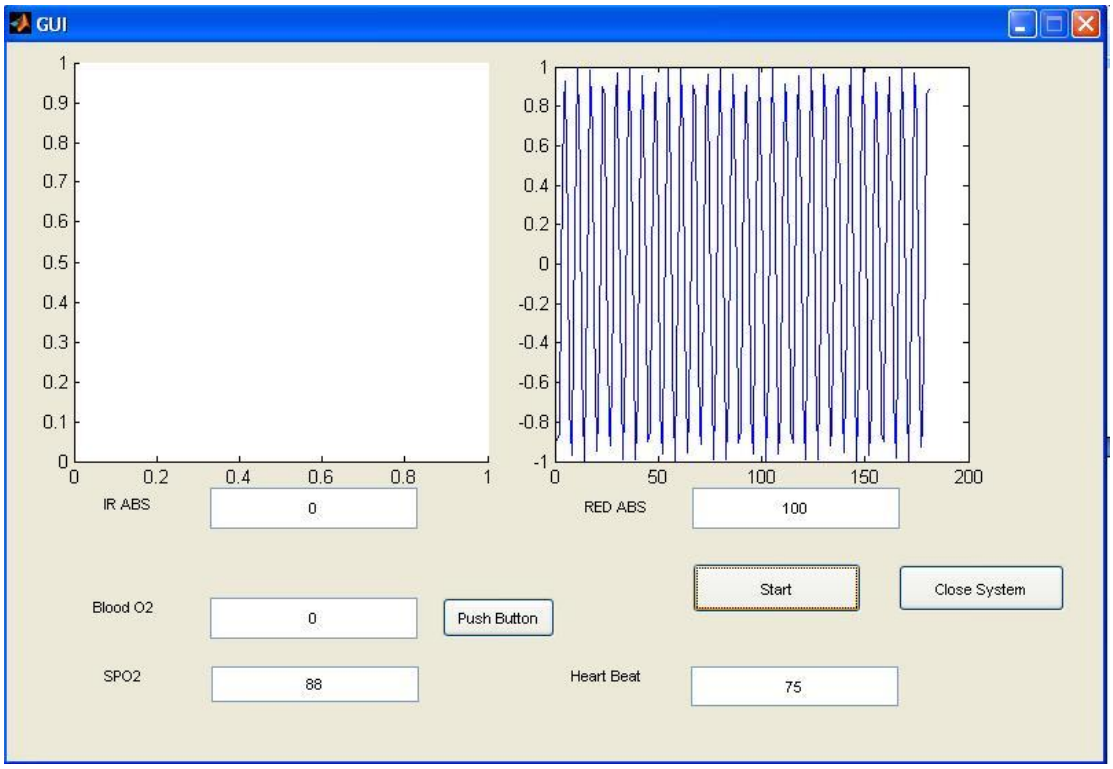

Figure 23: Graphical Interface User with Blood O2 = 0

Blood O2 = 0 is the condition with no oxygen molecule bind with hemoglobin molecule. This is very severe condition. In medical terms, this condition is known as severe Hypoxemia. It needs immediate doctor concern. The graph of IR ABS is blank. It show that no infra-red light is absorbed by blood because oxygen saturation level is blood is very low. So the 100 absorption can be seen in RED ABS graph. Red light will be absorbed to maximum in this condition. So, the SpO_2 value has dropped further to 88. It indicates a low oxygen saturation level in blood. Heart rate value is 75 as the heart rate dependent parameters are taken into account in this model.

From all the results of GUI, it is clear that this Simulink model accurately calculate the SpO_2. The infra-red light absorption, red light absorption and oxygen saturation level can be calculated using this Simulink model. This model shows a relationship between all these parameters. It can be seen from the results that changing one parameter directly or

indirectly changes the value of other parameter. The main focus of this model was to measure the SpO_2 depending upon the red light and infra-red light absorption. This result has been correctly depicted in this model.

It can be seen that there is no significant change in the heart rate. This is because heart rate depends upon a lot of other factors. These factors were not taken into consideration while designing this model. If heart dependent factors would have taken into deep consideration, it would have made the Simulink model more complex. Also then it would have been difficult to calculate the right SpO_2 value. Also in previous research gone by scientists, there have been no direct relationship between heart rate and SpO_2 value. These two factor do not depend upon each other directly. But due to complex human body mechanism, there is great chance for heart rate and SpO_2 to be depending on each other indirectly.

The main focus of this Simulink Model is to calculate the SpO_2 level. The GUI result show that this Simulink Model is capable of calculating the SpO_2 level accurately. So, this model can be used in future reference to calculate SpO_2 value.

Chapter 6

Conclusion

An accurate Simulink Model of Pulse Oximeter has been presented. This Model gives a better understanding of the concepts and theory used in Pulse Oximeter. It clearly explain the relationship between SpO_2, infra-red light absorption, red light absorption and oxygen hemoglobin molecule bind. The Graphical User Interface allows the user to change the Simulink parameters in real time and then observe their effects on output. The results help to explain result in detail. This Model is very flexible as it allows the user to change the parameters before final hardware implementation. It speed up the design process and implementation. This Simulink Model can also be used in future as enhancement tool for further design and development of Pulse Oximeter. This Simulink Model of Pulse Oximeter also provides a modeling environment to implement new ideas and design before evaluating it on hardware model. It can easily evaluate the robustness of new algorithm. With further modification, this Model can be used to measure accurate heart rate, blood pressure and other blood content.

Bibliography

[1] Pulse Oximetry Dr. Vijaylakshmi Kamat
chua2.fiu.edu/Nursing/anesthesiology/.../PULSE%20OXIMETRY.pdf
www.ijaweb.org/article.asp?issn=0019-5049;year...46;...Kamat, June 2002.

[2] Simulink based behavioral modelling of a Pulse Oximeter for deployment in rapid development, prototyping and verification by Shokouhian M, Morling RC, Kale I. (IEEE Paper), 2012.

[3] J. G. Webster, Design of Pulse Oximeters, Series in Medical Physics and Biomedical Engineering. Boca Raton: CRC Press, 1997.

[4] Gail D. Baura. Improved pulse oximetry. In System Theory and Practical Applications of Biomedical Signals, Series in Biomedical Engineering, chapter 4, Pages 66–85. IEEE Press, MA, 2002.

[5] A. Guyton and J. Hall. Medical Physiology. W.B. Saunders Co., 10 edition, 2000.

[6] T. L. Rusch, R. Sankar, and J. E. Shcarf. Signal processing methods for pulse oximetry. Computers in Biology and Medicine, 26(2):143–159, 1996.

[7] E. H. Wood and J. E. Geraci. Photoelectric determination of arterial oxygen saturation in man. 1943.

[8] Yitzhak Mendelson, "Pulse Oximetry", in Wiley Encyclopedia of Biomedical Engineering, John Wiley & Sons, Inc, 2006.

[9] Medical Electronics, Dr. Neil Townsend, 2001.

[10] Evaluate the change of %SpO2 (saturation percent oxygen) and heart rate at lactate threshold in male elite athletes during sport until exhaustion Hamid Tabatabaei, Ph.D. Department of Physical Education and Sport, University Azad of Tehran, IRAN http://www.smas.org/2-kongres/papers/1771.pdf, 2000.

[11] Design of a Wireless Pulse Oximeter for use in a Clinical Diagnostic System by Hamzah Quareshi

[12] Medical Electronic, DR. NEIL Townsend, 2001.
http://www.robots.ox.ac.uk/~neil/teaching/lectures/med_elec/notes6.pdf

[13] Pulse Oximetry Laboratory
Cleve labs Laboratory Corse System – Student Edition
biomed.engr.sc.edu/...lab/lab%20reports/48)%20Pulse%20Oximetry.pdf, 2006.

[14] http://www.maxtecinc.com/docs/pulsox/aboutPulseOximetry.pdf, Oct 2010.

[15] http://en.wikipedia.org/wiki/Hemoglobin, 9 January 2013.

[16] www.mathworks.com/products/matlab, 1984-2013.

[17] ewh.ieee.org/r1/ct/sps/PDF/MATLAB/chapter8.pdf, 1984-2013.

[18] www.mathworks.com/products/stateflow/, 1984-2013.

[19] http://www.thefreedictionary.com/Tissue+factor, 1984-2013.

[20] http://medical-dictionary.thefreedictionary.com/tissue+factor, 2013.

[21] en.wikipedia.org/wiki/Tissue factor, 2013.

[22] http://www.linfo.org/gui.html, 1984-2013.