DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEVELOPING A PORTABLE PULSE OXIMETER FOR TELEMETRY APPLICATION

by

Kamran SHIRALIYEV

September, 2014
İZMİR

DEVELOPING A PORTABLE PULSE OXIMETER FOR TELEMETRY APPLICATION

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"DEVELOPING A PORTABLE PULSE OXIMETER FOR TELEMETRY APPLICATION"** completed by Kamran SHIRALIYEV under supervision of **ASSOC. PROF. DR. ÖZGE ŞAHİN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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DEVELOPING A PORTABLE PULSE OXIMETER FOR TELEMETRY APPLICATION

ABSTRACT

Pulse oximeter is a common optical medical device that measures the heart rate and oxygen saturation level of the blood in a non-invasive way. The working principle of the pulse oximeter is based on different light absorption characteristics of oxygenated and deoxygenated blood. The red (660 nm) and infrared (895) LEDs are placed in the pulse oximeter probe. The oxygenated and deoxygenated hemoglobin display different absorption characteristics at these light wavelengths. Comparing that difference of absorption coefficient of hemoglobin can produce an estimate of arterial oxygen saturation of blood. When the lights are transmitted through tissues the intensity of the lights are changed due to arterial blood pulse. The change in intensity of the lights is measured by Photoplethysmography (PPG) technique and used for calculating heart rate.

The aim of this thesis is to develop a non-invasive remote portable fingertip pulse oximeter. The main components of our developed device are Pulse Oximeter sensor module and a Fez Spider mainboard. Visual Studio 2010 program and its "C sharp" language was used for programming the mainboard. The bluetooth connection of the device provides the data transfer between device and computer. The data is stored on the computer as xml files.

In this study some physical activities were carried out with participation of 10 volunteers. The indoor and outdoor areas effect to the variability of oxygen saturation of blood during exercises also investigated in this research. The oxygen saturation values of volunteers were monitored during indoor and outdoor exercises and their measurements were stored as an excel file. Then the average of each volunteer's oxygen saturation measurements during indoor and outdoor exercises were calculated and graphical representation of the compared values were obtained.

Keywords: Oxygen saturation, heart rate, photoplethysmography (PPG).

UZAKTAN ÖLÇÜM UYGULAMASI İÇİN TAŞINABİLİR VURU TİPİ OXİMETRE GELİŞTİRİLMESİ

ÖZ

Pulse Oksimetre kandaki oksijen miktarının seviyesini ve kalp atış hızını non-invaziv olarak ölçen, yaygın olarak kullanılan bir optik medikal cihazdır. Pulse oksimetrenin çalışma prensibi oksijenli ve oksijensiz kanın ışığı farklı soğurma karakteristiğini temel almasıdır. Pulse oksimetrenin probunda kırmızı (660 nm) ve kızılötesi (895 nm) LED'ler yerleştirilmiştir. Oksijenli ve oksijensiz hemoglobin ışığın bu dalga boylarında farklı soğurma karakteristiği sergiler. Hemoglobinin bu farklı soğurma katsayılarının karşılaştırılması kandaki oksijen miktarının tahmin edilmesini sağlar. Işıklar dokuların içinden geçerken arterlerdeki darbeler nedeni ile ışığın yoğunluğu değişir. Işığın yoğunluğundaki değişiklik Fotopletismografi (PPG) tekniği ile ölçülür ve kalp atış hızının hesaplanmasında kullanılır.

Bu tezin amacı uzaktan ölçüm alabilen invaziv olmayan taşınabilir bir parmak tipi pulse oksimetre cihazı geliştirmektir. Pulse Oksimetre sensör modülü ve Fez Spider ana kartı geliştirilen cihazın ana bileşenleridir. Ana kartı programlarken Visual Studio 2010 programı ve "C sharp" dili kullanılmıştır. Cihazın bluetooth bağlantısı bilgisayarla cihaz arasında veri transferini sağlar. Veriler bilgisayarda xml dosyası olarak kayıt edilir.

Bu çalışmada 10 gönüllünün katılımı ile bazı fiziksel aktiviteler gerçekleştirilmiştir. Bu araştırmada ayrıca, açık ve kapalı alanın egzersiz sırasında kandaki oksijen miktarının değişimine nasıl etki ettiği de araştırılmıştır. Kapalı ve açık alan egzersizleri sırasında gönüllülerin kanındaki oksijen miktarı gözlemlenmiş ve onların ölçümleri excel dosyasına kayıt edilmiştir. Daha sonra her gönüllünün kapalı ve açık alan egzersizleri sırasındaki oksijen doygunluğu ölçümlerinin ortalaması hesaplanmış ve bu değerlerin karşılaştırılışını gösteren grafiksel bir gösterim elde edilmiştir.

Anahtar kelimeler: Oksijen doygunluğu, kalp hızı, fotopletismografi (PPG).

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CHAPTER ONE
INTRODUCTION

1.1 Description

Remotely monitoring of personal health is more effective for people, especially for overseeing patients or sick children at home. Remote monitoring devices can report periodically and alert if there are serious changes in the health of patients. In those cases the reports can give patients or doctors the opportunities to move quickly and save their lives from danger. These remote devices have the ability to be integrated those home computers, laptops or smart phones and they provide communication over wireless wifi or bluetooth.

We need oxygen to continue our lives. Every time we breathe, we bring oxygen into the lungs and oxygen gets into the blood by our lung capillaries. Blood transports oxygen throughout the body by hemoglobin molecules. No doubt oxygen transportation to cells is vitally important therefore a poor oxygen delivery to cells for prolonged of time causes cells to die. A few methods have been developed for analyzing oxygen delivery and Pulse Oximetry is a common non-invasive method.

The goal of this thesis was to build and develop a portable remotely monitored pulse oximeter. This is an optical medical device that allows the measure of oxygen saturation of hemoglobin in arterial blood in a non-invasive way. The Pulse Oximeter (PO) allows the users to monitor two important physiological indicators of their health. One of them is blood oxygen saturation (SpO2) and the other one is heart rate (HR). Monitoring these parameters are vitally important during a patient's recovery. Pulse oximeters diagnose the lack of oxygen and are used for overseeing patients in some cases like when they are under anesthesia, in natal and during travail. Also in surgical operations and in cardiovascular or pulmonary diseases. It is frequently used in hospitals, in ambulances and in patient transportation. Obviously in the hospitals the nurses could not fully follow monitoring for each patient so pulse oximeter allows them to monitor sudden changes of patient's monitoring values and gives

emergency signals to them in every alarming situation, therefore pulse oximeter is the best way for hospitals to care for their patients. In clinical and homecare application, this device is easy for users to attach to themselves.

The orderly value of the blood oxygen saturation of the healthy human body is around 95% to 99% and if there were serious changes in this value it would be associated with alarming situations. The pulse oximeter can be used to determine the seriousness of the disease and to determine the diagnosis for the patients.

The aim of this thesis was to focus on developing a portable remote fingertip pulse oximeter. The data transfer of developed pulse oximeter provided by bluetooth. That pulse oximeter has ability to store the measurements on laptop as xml files. In this study the experiment was also carried out with that device for two different situations. In this research the changes of blood oxygen saturation (SpO2) values were monitored on volunteer participants during outdoors and indoor exercises. The measurements of volunteer's during indoor and outdoor exercises were monitored and stored on a laptop as excel files. Then the measurements results of each volunteers are evaluated and graphical representation of their oxygen saturation changes during indoor and outdoor exercises were obtained.

1.2 A Brief History of Pulse Oximetry

Measuring arterial blood-oxygen saturation by the method of pulsatile light variations was invented by the Japanese physiological bioengineer Takuo Aoyagi. Takuo Aoyagi was born in Japan, in 1936.He was an electrical engineer and he graduated from Niigata University in 1958.In 1971 he joined the Nihon Kohden Corporation which is a medical electronic company.

Aoyagi's research was interested in using dye dilution to measure cardiac output, therefore he researched and used oximetry literature. In this method a specific wavelength of light is passed through blood and it is detected by photocells. In order to avoid the need for arterial blood sampling various researchers tried to use ear

oximeters for dye measurement. According to the study of Severinghaus & Honda (1986) “the transmitted light signal was noted to exhibit pulsatile variations, which made it nearly impossible to compute cardiac output accurately from these noninvasive dye dilution curves.”

During the research Aoyagi applied his new method of cancelling the pulsatile variations which prevented to compute cardiac output by dilution curves method. He used the red (630 nm) and infrared (900 nm) signals for cancelling the pulse noise. While he was testing his new way, he found out that, when he was holding his breath, a decreasing oxygen saturation reintroduce new pulsatile waves which cause changes the ratio of the two wavelengths densities. This experience gave him new idea that these pulsatile changes during light transmission throughout blood could be used for calculating arterial oxygen saturation. He figured out that the changes of light transmission linked with pulse variations of the arterial blood volume, but there were unpredictable absorptions and that light absorptions of tissue, bone, skin, and pigments would be eliminated from analysis. Severinghaus & Honda (1986) specified this idea in their study: “It was this key idea that permitted the development of instrumentation that required no calibration after its initial factory setting, as all human blood has essentially identical optical characteristics in the red and infrared bands used in oximetry.”

In 1973, Sugiyama, whose working as Aoyagi’s supervisor told Susumu Nakajima, working at the Sapporo Minami National Sanatorium as a surgeon, about Aoyagi’s invention. Aoyagi’s pulse oximeter undeveloped yet but Dr. Nakajima ordered for pulse oximeter because he understood the method was secret and he wanted to test device in patients.

Takuo Aoyagi reported his invention of pulse oximetry to the Japanese Society of Medical Electronics and Biologic Engineering, on 26 April 1974. The Nihon Kohden Corporation submitted the patent application, as titled “Apparatus for Photometric Blood Analysis” to the Japanese Patent Office on March 29, in 1974. On October 9,

1975 the application disclosed and then it was published on August 2, 1978. The application patent granted on April 20, 1979.

Inventor Masaichiro Konishi, who was working at the Minoruta Camera Company (also known as Minolta) , applied to the Japanese Patent Office for patent application, on April 24, 1974 but it was based on similar idea with Takuo Aoyagi. “How this competing application arose and whether Aoyagi's idea was discovered and copied has never been established” according to the study of Severinghaus & Honda (1986). On February 9, 1982 Japanese Patent Office refused Masaichiro Konishi’s patent application but he was submitted his patent application to United States and got patent protection in there.

Aoyagi made prototype pulse oximeter between September 1973 and March 1974. That prototype ear oximeter was used by Dr. Nakajima and his associates at the Sapporo Minami National Sanatorium. Aoyagi and his associates were presented the first commercial ear oximeter, the OLV-5100 (Figure 1.1), in 1975. Nihon Kohden did not continue to improve or market that device and made no effort to patent it abroad, though.

In 1977, the Minoruta Camera Company developed their pulse oximeter with fingertip probe and fiber optic cables and produced it as the Oximet MET-1471 (Figure 1.2). Dr. Nakajima and his nine associates tested and used Minoruta’s fingertip pulse oximeter and then they described it in 1979 (Severinghaus, 2007).

Figure 1.1 Ear Oximeter OLV-5100 (Severinghaus & Honda, 1986)

Figure 1.2 Oximet MET-1471(Konica Minolta, n.d)

1.3 Thesis Outline

The present thesis has been prepared in five chapter. Chapter one contains the history of pulse oximeter, the information about hemoglobin molecule and oxygen saturation. The blood circulation of heart also described in this chapter.

In chapter two the principle and calibration of pulse oximeter are described. This chapter also gives information about limitation and clinical uses of pulse oximeter.

Chapter three contains the design process and development of pulse oximeter.

In chapter four, the experimentation of pulse oximeter is given. The obtained experimental results are also presented and analyzed in this chapter.

Finally, in chapter five, conclusion and future works are presented.

1.4 Hemoglobin

Hemoglobin (Figure 1.3) is a protein molecule in red blood cells which transports oxygen (O2) from lungs to throughout the body and it carries carbon dioxide from the tissues back to the lungs for removing from body. In every red blood cells have

nearly $3x10^8$ hemoglobin molecules and every hemoglobin molecules capable to bind with four oxygen molecules. There are two types of hemoglobin in blood, functional hemoglobin and dysfunctional hemoglobin. In functional hemoglobin, there are two forms of hemoglobin: oxygenated hemoglobin (HbO2), which carries oxygen and deoxygenated hemoglobin (Hb), which after the oxygen of oxyhemoglobin is released in the tissues. The most common dysfunctional hemoglobin types are: Carboxyhemoglobin (COHb), Methemoglobin (MetHb), Sulfhemoglobin (SfHb) and Carboxysulfhemoglobin (COSfHb) and they cannot bind oxygen (Granelli, 2009).

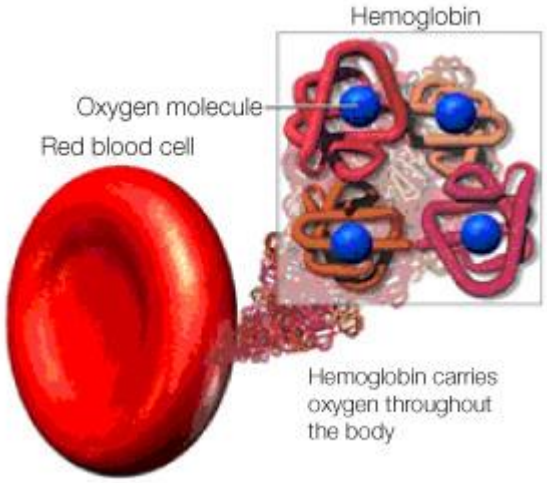

Figure 1.3 Hemoglobin molecule (Domingues, 2009)

The physically binding ratio of oxygen to hemoglobin is 4:1, so four oxygen molecules can bind to one molecule of deoxygenated hemoglobin (Hb) and it form a single molecule of oxygenated hemoglobin (HbO2). The HbO2 can be display different concentration depending on where it is measured in the system. A high concentration of HbO2 have generally seen in arterial blood whereas in venous blood has a low concentration.

Oxygenated (HbO2) and reduced hemoglobin (Hb) change their color when they bind or release oxygen. When the hemoglobin molecule bind with oxygen, it becomes red whereas it releases oxygen it gets darker. This color difference of

hemoglobin also shown in the optic spectral, between 600nm (red) and 1000nm (infrared) wavelengths.

Pulse oximetry is interested in oxygenated hemoglobin and deoxygenated hemoglobin while calculating arterial blood oxygen saturation and based on the light absorption characteristic of oxygenated and deoxygenated hemoglobin. During the light scattering, oxygenated hemoglobin (HbO2) absorbs more infrared light more than deoxygenated hemoglobin (Hb), whereas deoxygenated hemoglobin absorbs more red light more than oxygenated hemoglobin (Avalos, 2011). The absorption curves for oxygenated and deoxygenated hemoglobin are shown in Figure 1.4.

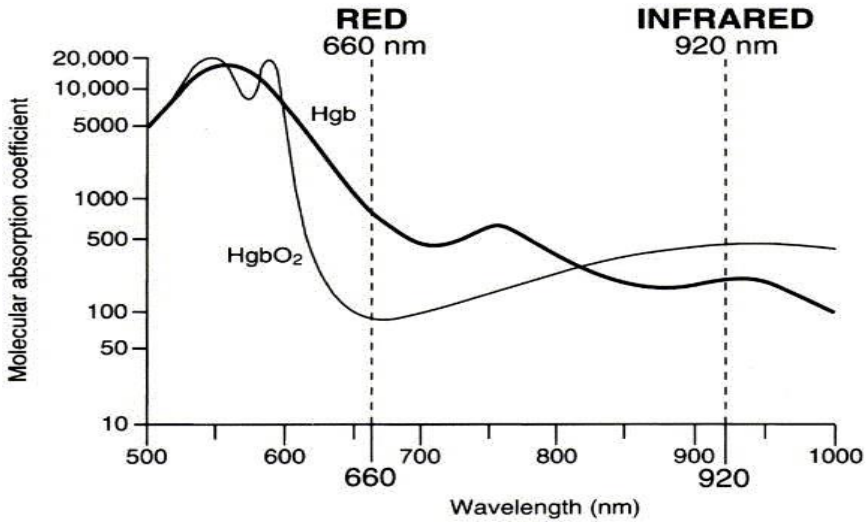

Figure 1.4 Absorption curves for both types of hemoglobin (Single wavelength pulse oximeter, 2012)

We can see in Figure 5 that, oxygenated and deoxygenated hemoglobin display different optical spectra in the specific wavelengths range, from 600 nm to 1000 nm. The pulse oximetry based on the difference absorption of these two wavelengths for calculating blood oxygen saturation.

However, the blood is not include just two types of hemoglobin. There are also another types, such as methemoglobin (MetHb) and Carboxyhemoglobin (COHb) and both of them also absorb light. We can see their absorption curves in Figure 1.5.

It is possible to see some of these spectra are very close to oxygenated hemoglobin that this closeness cause false reading on pulse oximeter. If the doctors suspect that the patient has high level methemoglobin or carboxyhemoglobin in his blood they can use special oximeter which called CO-oximeter. The CO-oximeter uses four or more light wavelengths for measuring abnormal hemoglobin level in patient's blood (Kamat, 2002).

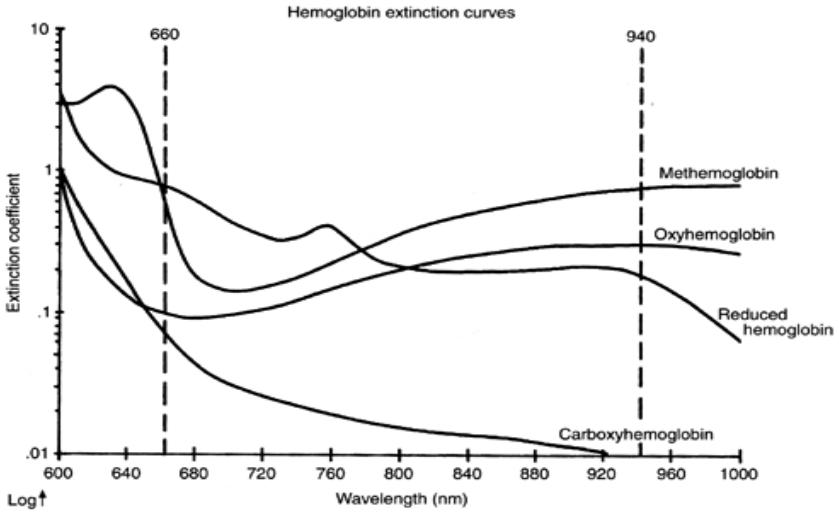

Figure 1.5 Absorption curves of common hemoglobin types (oxyhemoglobin, deoxyhemoglobin, methemoglobin, carboxyhemoglobin) (Pulse oximeters, n.d)

1.5 Oxygen Saturation

Oxygen saturation is described as the ratio of hemoglobin to the total concentration of hemoglobin. Typical pulse oximeters interest just two forms of hemoglobin: oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (Hb). But as described above there is not only two types of hemoglobin. Therefore oxygen saturation can be defined with two way, first one is "Functional" oxygen saturation and other one is "Fractional" oxygen saturation (Seo, 2008). We can see functional oxygen saturation's equation in below:

$$S_pO_2 = \frac{HbO_2}{HbO_2 + Hb} \tag{1.1}$$

"Fractional" oxygen saturation can be described as follow equation:

$$S_pO_2 = \frac{HbO_2}{HbO_2 + Hb + MetHb + COHb} \quad (1.2)$$

Methemoglobin and carboxyhemoglobin have not ability to transport oxygen. Therefore "functional" oxygen saturation can be used for determining percentage of hemoglobin. Pulse oximeter commonly uses functional oxygen saturation. However COHb and MetHb extinction coefficient are not zero and if they present in appreciable concentrations, the pulse oximeter reading would be inaccurate (Kamat, 2002). In this cases co-oximeters in the laboratory can be used. That oximeters take into all four types of hemoglobin during calculation oxygen saturation and they use Equation 1.2.

1.6 Blood Circulation of Heart

The circulatory system consists of three components: the heart, blood vessels and blood. The blood travels continuously through the circulatory system, and it has two loops (Figure 1.6): the pulmonary circulation which blood travels between heart and lungs and the systemic circulation which blood travels between heart and organ systems. The right side of heart pumps blood into pulmonary circulation, during this circulation the drop of blood expels CO_2 from blood by lungs and picks up fresh supply of O_2 to the left atrium by the pulmonary veins. The left side of heart pumps blood into the systemic circulation. Heart pumps blood from left side to body by aorta.

The blood enters heart through two large veins which are called as the inferior and superior vena cava. Blood flows from right atrium to right ventricle through right atrio-ventricular valve (AV), also called tricuspid valve. When ventricle is full the right atrio-ventricular valves close. Blood leaves right ventricles through the pulmonary valve and to pump into pulmonary artery to the lungs, where CO_2 expel and blood oxygenated.

The pulmonary veins carrying reach oxygenated blood to the left atrium and blood flows from left atrium into left ventricle through the left atrio-ventricular valve (also called mitral valve). When the ventricles is full left atrio-ventricular valve close. Then ventricle contracts and pumps blood into the aorta and to the body. Blood leaves heart through the aortic valve.

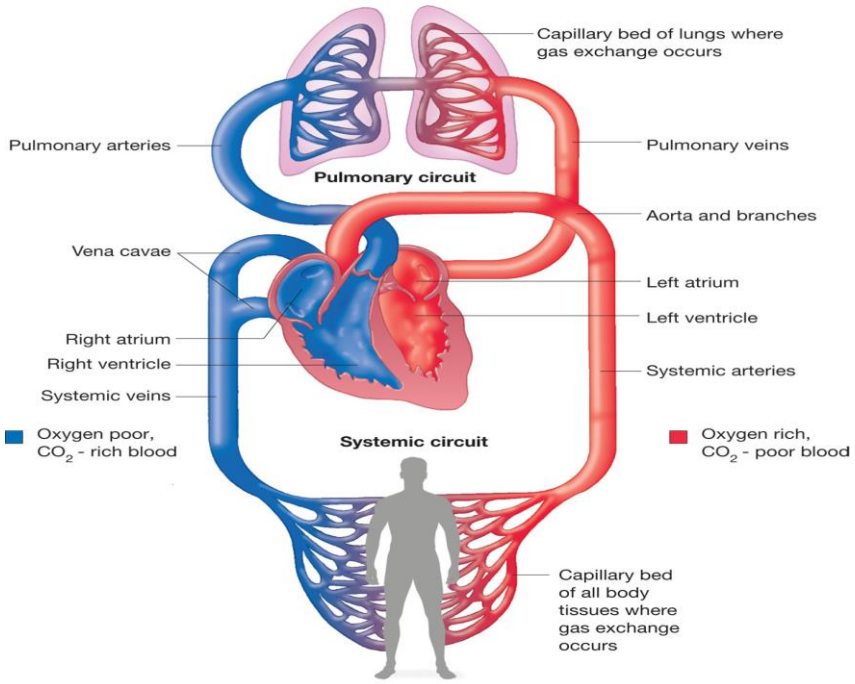

Figure 1.6 Pulmonary circulation and systemic circulation (Biology forums gallery, n.d)

Each complete turn of filling and pumping is called a cardiac cycle. The rhythmically relaxation and contraction of heart create two phases in cardiac cycle: diastole and systole (Figure 1.7).

1st Diastole Phase:

In the diastole phase, atria and ventricles are relaxed and atrio-ventricular valves of both side are open. The atrio-ventricles valves allows blood flow from atria to ventricles. Deoxygenated blood flows into right atrium by superior and inferior vena cava, then blood flow from right atrium into right ventricle. The right atrio-ventricular valve avoid backflow from right ventricles to right atrium.

1st Systole Phase:

During the systole phase the right ventricle contracts and the atrio-ventricular valves close, semilunar valves open. Right ventricle pump deoxygenated blood into the pulmonary artery. The blood backflow avoid by pulmonary valve. Blood carrying to lungs by pulmonary artery, then blood picks up oxygen and it return back to heart by pulmonary veins.

2nd Diastole Phase

In this period the semilunar valves shut and atrio-ventricular valves open. The pulmonary veins carrying blood into left atrium, at the same time blood from vena cave also fill the right atrium. The left atrio-ventricular valve allow blood flow from left atrium to left ventricle and it also avoid backflow into left atrium.

2nd Systole Phase

In this phase atrio-ventricular valves shut and semilunar valves open. The left ventricle contracts and pumps oxygenated blood into aorta. In this case aortic valve avoid backflow into the left ventricle. The aorta branches carrying blood to the body and expended blood is return the heart by the vena cava (Bailey, n.d).

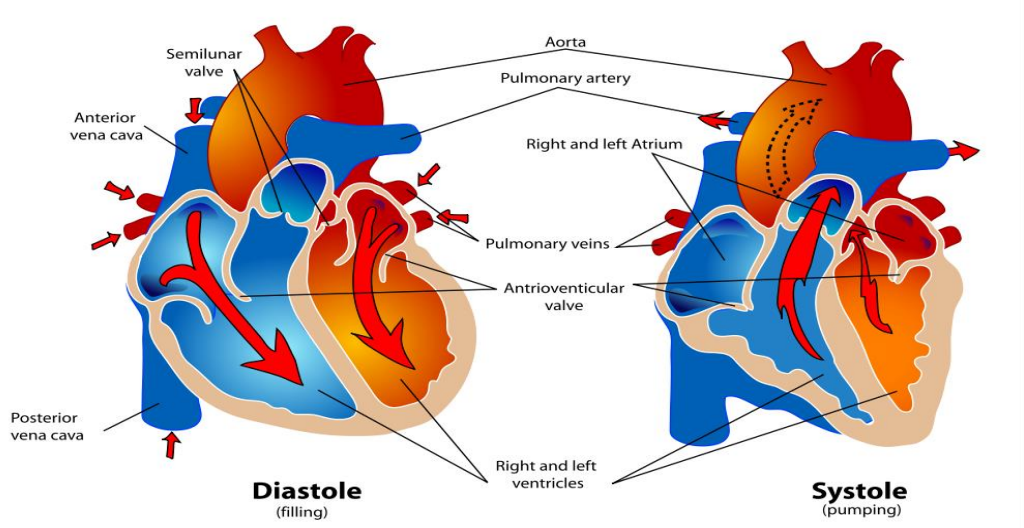

Figure 1.7 Diastole and Systole phases (Cardio-pulmonary resuscitation, 2013)

As we know that changes of arterial blood volume during systole and diastole occur each heartbeat and pulse oximeter based on that arterial blood pulsations. Photoplethysmography (PPG) technique is used to measure that pulsation, each PPG waveform represents the cardiac cycle and it can be used for calculating heart rate.

CHAPTER TWO
PRINCIPLES OF PULSE OXIMETRY

2.1 Introduction

In this chapter, we consider the principle of pulse oximeter. The principle of pulse oximeter based on spectrophotometry and optical plethysmography (PPG) techniques. Detection of oxygen saturation by the spectrophotometry is based on Beer-Lambert law. Pulse oximeter uses the plethysmography (PPG) technique for measuring the pulsatile changes in arterial blood during each heartbeat. The extensive explanation of that methods will be described in the following section. The following sections will also illustrate the calibration, clinical uses and limitation of pulse oximeter.

2.2 Principle of Pulse Oximetry

Pulse oximeter is an optical medical device that measuring the oxygen saturation in arterial blood (SpO2). Pulse oximeter probes can be position on the extremity sides of the body, usually finger, ear, toe and a photodetector is placed on the opposite side in probe (Figure 2.1).

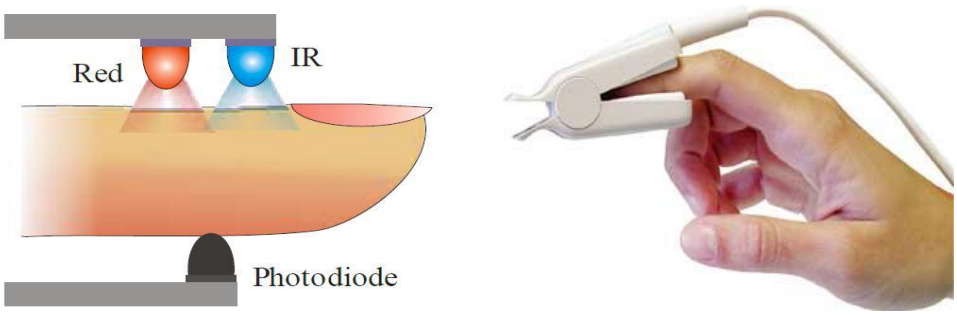

Figure 2.1 Typical pulse oximeter finger probe and configuration (Morey, 2010; Medical equipments, n.d)

A principle of pulse oximeter is based on spectral analysis and it combines two technologies: spectrophotometry and optical plethysmography.

Spectrophotometry: “A spectrophotometer measures light intensity as a function of the color, or more specifically, the wavelength of light” according to the study of Granelli (2009). The spectrophotometer has two classes: single beam and double beam. Single beam spectrophotometer uses for measuring the absolute light intensity, whereas double beam spectrophotometer using for measures the ratio of light intensity from two different light paths. The pulse oximeter uses double beam for measuring arterial blood oxygen saturation (SpO2).

Optical Plethysmography: A plethysmograph is an instrument for measuring changes in volume within whole body. A photoplethysmography (PPG) is a specific plethysmography which uses optical techniques. Pulse oximeter uses this PPG technique for measuring the pulsatile changes in the arterial blood with each heartbeat.

Pulse oximeter uses two different wavelength of light: a red wavelength λ_1 (660 nm), λ_2 infrared wavelength (940 nm) and they emitted from two different light emitted diodes (LEDs). This diodes are sequentially shone through tissues and the transitive light detected by the photo detector. These two specific light wavelength chosen for different light absorption characteristic of HbO2 and Hb molecules. HbO2 and Hb display a big difference in light absorption: HbO2 absorb more infrared light than Hb, whereas Hb absorb more red light than HbO2 (Figure 2.2) (Lopez, 2012).

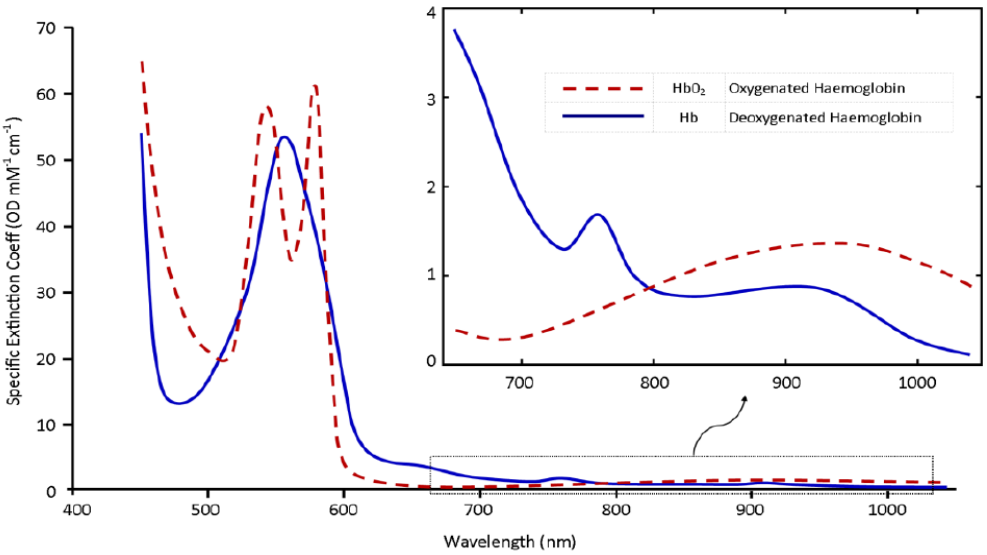

Figure 2.2 Absorption coefficient of HbO2 and Hb (Cloete, 2012)

Detection of oxygen saturation by the spectrophotometry based on Beer-Lambert law and it relates the concentration of solute to the intensity of an uncolored light transmitted through a homogenous solution:

$$I_{trans} = I_0 e^{-\varepsilon(\lambda)cd} \quad (2.1)$$

Where:

- I_{trans} – the intensity of transmitted light $I_{trans} = I_0.e^{-\varepsilon(\lambda)cd}$
- I_0 – the intensity of incident light
- $\varepsilon(\lambda)$ – the extinction of solute
- c – the concentration of medium
- d – the distance which light is transmitted through the medium

Absorbance of medium can be characterized as follows:

$$A = \varepsilon cd \quad (2.2)$$

It is possible to see extinction coefficient of hemoglobin in Table 2.2.

Table 2.2 The extinction coefficient of hemoglobin (Jawahar, 2009)

Extinction coefficient (ε)	Oxyhemoglobin (HbO_2)	Deoxyhemoglobin (Hb)
Red	0.81	0.8
Infrared	0.18	0.29

It is essential to take into account two important factors during determining oxygen saturation, the first one is reflection and scattering of light and the other one is the thickness of the place which changes each pulse associated with increasing and decreasing diameters of arteries due to pressure. So when the light pass through the finger it is absorbed by the different absorbing substances. There are two major component, first one is DC component which consist of the light that absorbed by the bone, skin, pigmentation and other tissues (Zaltum, Ahmad, Joret & Jamil, 2010). The second component is AC component which changes when the diameter of arteries changing during systole and diastole.

The changing of diameter of arterial blood changes the total absorbance by changing the component *d* in equation. This change allows the pulse oximetry to differentiate light absorbance between the pulsatile arterial blood component (AC) and other absorbing substances (bone, skin, venous and other tissues) (Chu, 2006).

We can see AC and DC components in Figure 2.3.

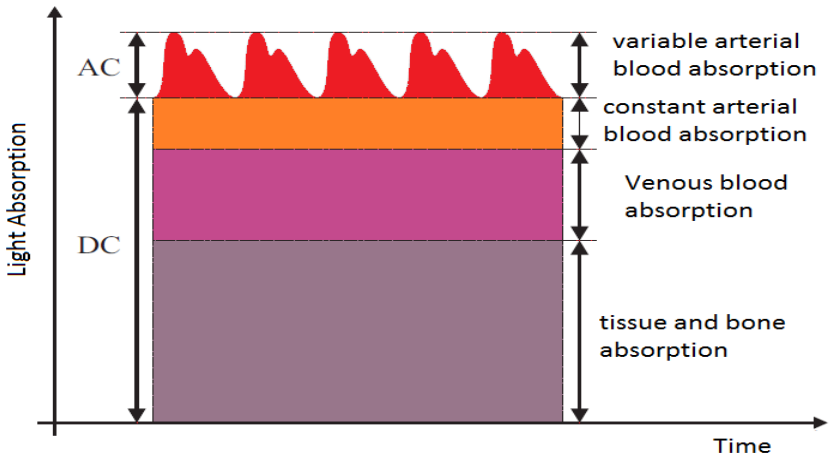

Figure 2.3 Light absorption by tissues component (Avalos, 2011)

When the light pass through the finger the ratio of intensity of transmitted light change due to arterial diameter when diameter is minimum (d_{min}) and maximum (d_{max}). This ratio gives the AC component at one specific wavelength λ as a function of d only. It is possible to see the absorbance at wavelength λ_1 in Equation 2.3:

$$A_1 = \ln\left(\frac{I_{1min}}{I_{1max}}\right) = \left(\varepsilon_{1RHb}c_{1RHb} + \varepsilon_{1HbO_2}c_{1HbO_2}\right)\Delta d_1 \quad (2.3)$$

Where:

- I_{1min} and I_{1max} – the intensities of the transmitted light at wavelength λ_1 during optical path is at d_{max} and d_{min} (Figure 2.4).
- d_{max} – the optical path during systole
- d_{min} – the optical path during diastole
- ε_{1RHb} and ε_{1HbO2} – the extinction coefficient of reduced and oxygenated hemoglobin
- c_{1RHb} and c_{1HbO2} – the concentration of reduced (RHb) and oxygenated hemoglobin (HbO2)
- $\Delta d = d_{max} - d_{min}$

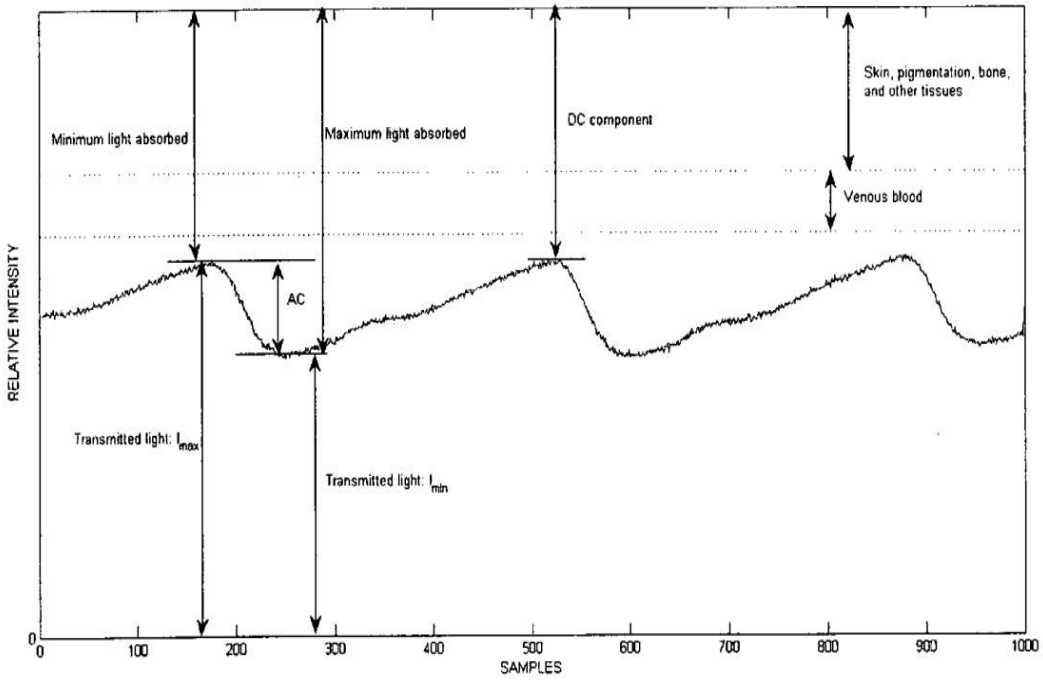

Figure 2.4 Light absorption by the skin, bone, tissues, pigmentation and venous blood and non-pulsatile part of arterial blood (Chu, 2010)

In the same way, the absorbance at wavelength λ_2 is shown below:

$$A_2 = \left(\varepsilon_{2RHb} c_{2RHb} + \varepsilon_{2HbO_2} c_{2HbO_2}\right)\Delta d_2 \tag{2.4}$$

Assuming that the two light sources are placed at the nearly same distance from photodetector, the term Δd_1 and $\Delta\ d_2$ are the same ($\Delta d_1 = \Delta d_2$). So the term Δd_1 and Δd_2 can be eliminated and the ratio of absorbance (also known "ratios of ratio") is as follows:

$$R = \frac{A_1}{A_2} = \frac{\ln\left(\frac{I_{1min}}{I_{1max}}\right)}{\ln\left(\frac{I_{2min}}{I_{2max}}\right)} = \frac{\varepsilon_{1RHb} c_{1RHb} + \varepsilon_{1HbO_2} c_{1HbO_2}}{\varepsilon_{2RHb} c_{2RHb} + \varepsilon_{2HbO_2}\ c_{2HbO_2}} \tag{2.5}$$

The ratio of oxygenated hemoglobin concentration to the reduced hemoglobin concentration use for calculating oxygen saturation:

$$SaO_2 = \frac{C_{HbO_2}}{C_{HbO_2} + C_{RHb}} \times 100\% \tag{2.6}$$

Associated with Equation 2.5 and Equation 2.6 the oxygen saturation can be obtained by:

$$SaO_2 = \frac{\varepsilon_{1RHb} - \varepsilon_{2RHb} R}{\varepsilon_{1RHb} - \varepsilon_{1HbO_2} + \left(\varepsilon_{2HbO_2} - \varepsilon_{2RHb}\right)R} \times 100\% \tag{2.7}$$

However the equations which based on Beer-Lambert law does not take into the multiple scattering light by the red blood cells. There are two relationship in Figure 2.5, one uses Beer-Lambert law, other one based on empirical data. It is possible to see the difference between the ratio R and oxygen saturation of patient (Townsend, 2001).

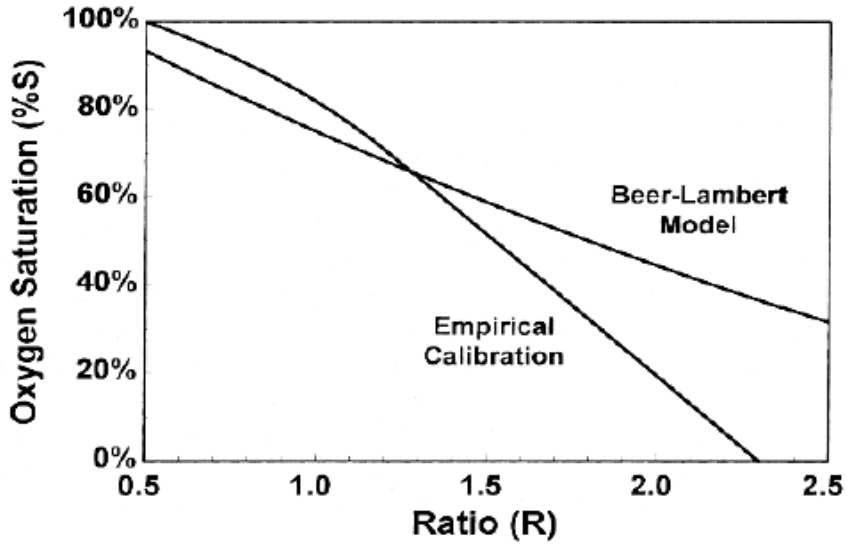

Figure 2.5 The relationship between R and patient's oxygen saturation (Townsend, 2001)

As a result, the instruments which based on Beer-Lambert low tended to give erroneous values during calculating oxygen saturation, especially when the SaO2 values below % 85. The better result for getting true values is experimentally calibration curves.

2.3 Calibration of Pulse Oximeter

According to the study of Sinex (1997), "initially the conversion from absorbency ratios to arterial oxygen saturation was based directly on Beer-Lambert calculation, but the effects of reflection and scattering of light even within the pulsatile fraction of arterial blood led to gross overestimation of oxygen saturation". Most pulse oximeters now use calibration curves which stored in a memory of pulse oximeter by the manufacturers (Figure 2.6). Calibration can be performed with two way: in vivo or in vitro.

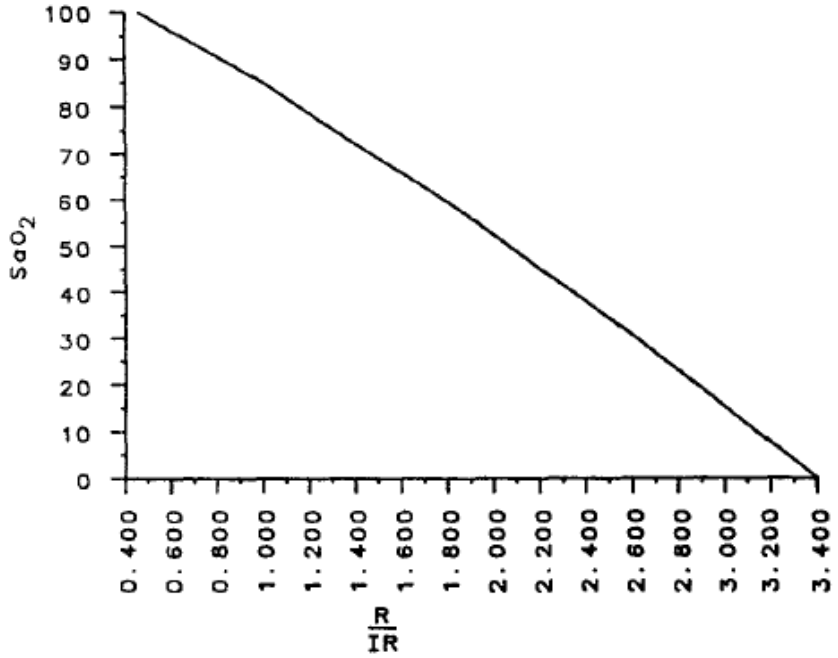

Figure 2.6 A typical pulse oximeter calibration curve (Sinex, 1999)

2.3.1 In Vivo Calibration

In vivo calibration was only method to calibrate pulse oximeter until 1993. During this calibration method the calibration curves obtain by experiments in hospital environment that non-smoking, heathy young volunteers breathing hypoxic mixtures until their oxygen saturation dropped to %80. The volunteer's arterial blood samples are taken and tested to ensure that only normal adult hemoglobin is present and volunteer's methemoglobin and carboxyhemoglobin are within normal limits. The typical values of this hemoglobin are: MetHb <1% and 1%<COHb<2%. The pulse oximeter calibrated by laboratory CO-oximeter or blood gas analysis. The CO-oximeter is using for determine exactly the blood oxygen saturation. During calibration volunteers breathe oxygen-enriched air until their blood samples display 100% saturation. The volunteer's oxygen saturation is gradually reduced by replacing the oxygen in their breathing gas nitrogen. The applying of this procedure is paused each step, it allow time to equilibrate. The device which under the test when display the stable reading, the arterial blood sample immediately taken, then it analyzed by CO-oximeter. The data from each devices is used to generate the

calibration curve and a lookup table is constructed to provide exact mapping of ratios of ratio (R) from the under test device to the corresponding S_aO_2 level (Humphreys, 2007).

The formula for using calibration is as follows:

$$S = a - b.R \tag{2.8}$$

Where a and b are coefficients which determine during pulse oximeter calibration, S is variable SpO2 and R is variable ratio. This equation's values obtain by CO-oximeter or second calibrated pulse oximeter from heathy young volunteers.

The coefficient a and b can be calculate as follows equations:

$$a = \frac{\sum_{i=1}^{n} S_i \sum_{i=1}^{n} R_i^2 - \sum_{i=1}^{n} R_i \sum_{i=1}^{n} R_i S_i}{n \sum_{i=1}^{n} R_i^2 - (\sum_{i=1}^{n} R_i)^2} \tag{2.9}$$

$$b = \frac{n \sum_{i=1}^{n} R_i S_i - \sum_{i=1}^{n} R_i \sum_{i=1}^{n} S_i}{n \sum_{i=1}^{n} R_i^2 - (\sum_{i=1}^{n} R_i)^2} \tag{2.10}$$

Where S_i is the SpO2 value that measured by CO-oximeter or calibrated pulse oximeter, R is the ratio which related and correspond to S_i and n is the number of measurement (Domingues, 2009).

The calibrations are performed by manufacturers and it cannot be change by users. Pulse oximeters use this curves for displaying oxygen saturation, that the pulse oximeter calculate the ratio R and then compares R with stored values for displaying SpO2 values. Example if the R was equal to 1 then pulse oximeter will display oxygen saturation as %85 (Figure 2.7).

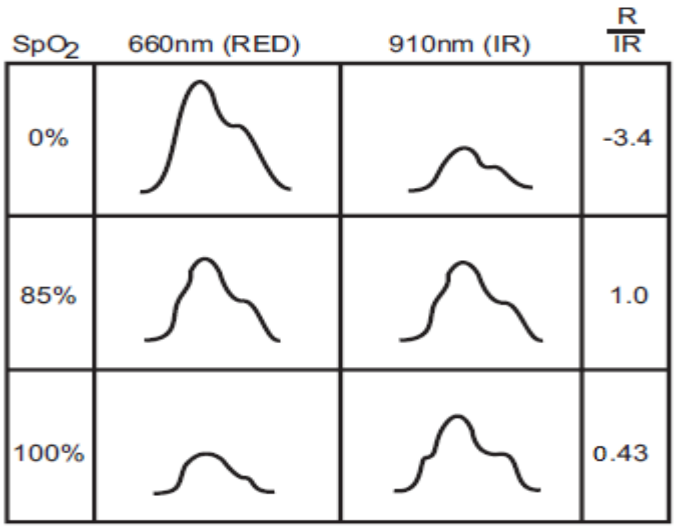

Figure 2.7 Illustration of photoplethysmograms for red and IR wavelength (Mediaid, n.d)

But there is inevitable limitation that pulse oximeters only can measure oxygen saturation as accurate as their empirical calibration curves. The manufacturers don't make volunteers more hypoxic because it is unethical, therefore pulse oximeter's microprocessor has no memory of values below %80 so any saturation under %80 will inaccurately display on pulse oximeter.

The subject groups for calibration are usually include young health volunteers. In the study of Sinex (1999) he specified that: "One manufacturer was even said to have used two Olympic athletes in calibration trials. As such, the applicability of data from such a narrow population to patients at the extremes of ages and with various medical problems has been questioned."

2.3.2 In Vitro Calibration

In this method anticoagulant heparin added blood is used by the system. The blood circulates around a closed loop with minimum damage to red blood cells (erythrocytes) by a computer controlled peristaltic pump. This loop mimics the arterial pulsatile blood flow (Figure 2.8). A mixture of O_2, N_2 and CO_2 provide by a gas-mixing pump and the proportions of this gases defined by users. Here CO_2 uses to provide the realistic carbon dioxide partial pressure and the correct pH. The

oxygen membrane provide the gas diffusion into and out, that membrane oxygenator provides the large permeable interface area. In this membrane oxygenator gas on one side and a thin film of blood on the other side and it mimics the lungs alveolar function. The system uses phantom finger which the device under test attached to. The blood is circulating in this phantom finger. The sample port of the system provides the blood sample which extracted from blood circulation and send this extracted sample to CO-oximeter for analyzing. The fed-back parameters from second modified pulse oximeter is using by computer. The computer varies and controls the gas mixtures and peristaltic displacement's rate, to simulate the heart rate and arterial oxygen saturation which desired.

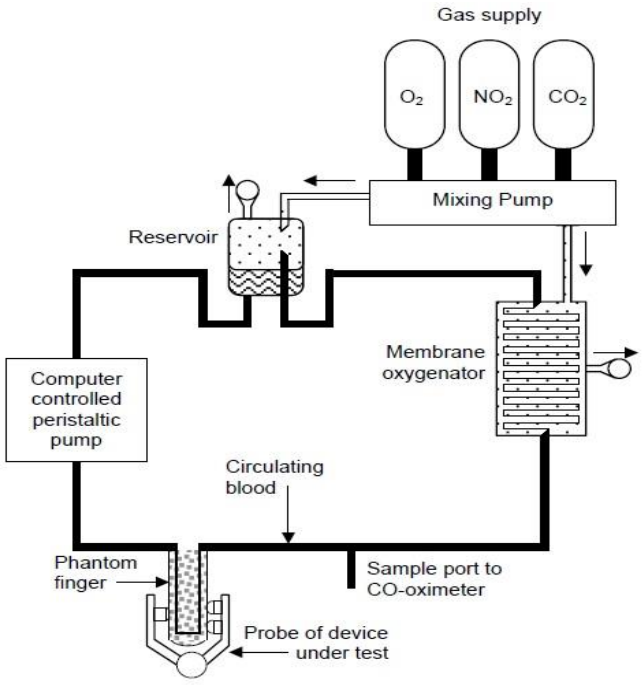

Figure 2.8 In vitro calibration apparatus for pulse oximeter (Humphreys, 2007)

During applying this calibration method, the most important factor is phantom finger which the device under test is attached. This phantom finger should have a similar absorbance and scattering properties as a real finger and during the artificial pulse it should exhibit a similar variance in volume as a real finger (Humphreys, 2007).

2.4 Heart Rate Calculation of Pulse Oximeter

Heart rhythmically pumps blood to the whole body, each complete contraction and relaxation of heart is a single heartbeat and known as cardiac cycle. Cardiac cycle have two phases: diastole phase which the ventricles relaxed and the heart fills with blood and systole phase which the ventricles contract and blood pumps to the arteries. During atrial systole heart receives oxygenated blood from pulmonary circulation into left atrium, when atria enter the systolic period, left atrium pumps this blood into the left ventricle. During ventricular systole, the left ventricles contract and pumps blood to Aorta, which the major artery that supply blood to the body.

Photoplethysmography (PPG) is optical technique that used to detect blood volume changes. The PPG waveform comprises a pulsatile ('AC') physiological waveform attributed to cardiac synchronous changes in the blood volume with each heartbeat. When the blood cross over into the venous return that rhythmical flow getting lost its certainty and it is barely apparent. In this way, it is possible to say that the majority of pulsatile blood flow is due to the arterial blood. So PPG wave mostly represents the blood flow of arteries.

PPG include plenty of information in its height, shape and timing. For example, PPG is described by a second peak in each period of it which called “Dicrotic Notch” (Figure 2.9). “Dicrotic Notch” demonstrate the closure of aortic valve after the end of systole, and it causing a backlash, that backlash is due to the momentarily increasing of blood volume in arteries. That changes of arterial blood volume measured by PPG and that each PPG waveforms represent the repetition of the cardiac cycle and it can be used to calculate heart rate (Jawahar, 2009).

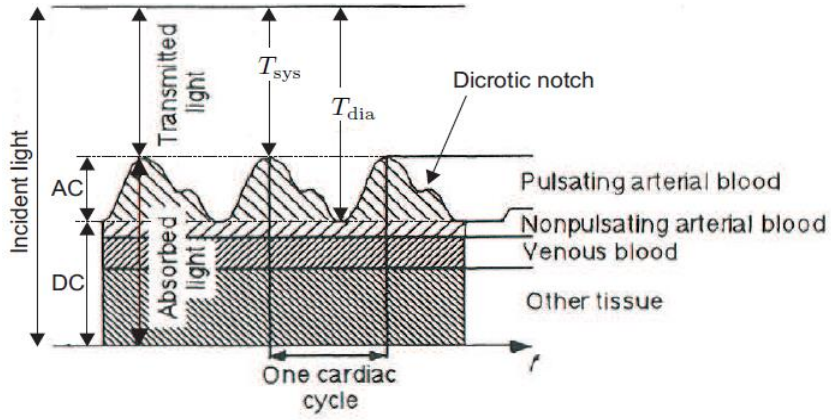

Figure 2.9 Schematic illustration of photoplethysmogram and Dicrotic notch (Haahr, 2006)

In this thesis, the infrared (IR) AC PPG signals used for calculating heart rate. The peak detection algorithm used to calculate heart rate and this algorithm is simple.

In this algorithm buffer including the samples were continuously refreshed with new incoming samples (Figure 2.10).

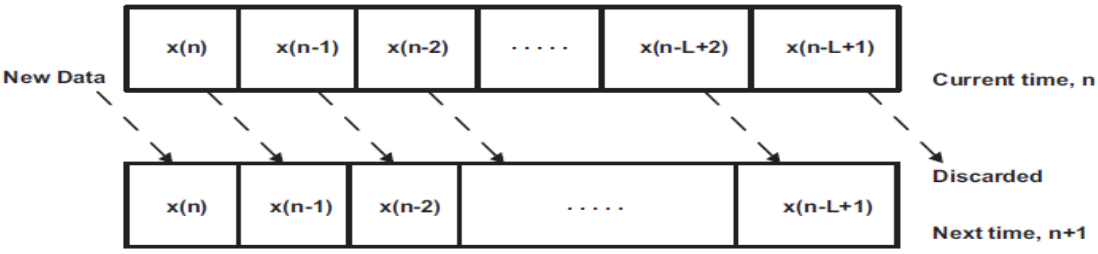

Figure 2.10 Buffer shifting (Texas Instruments, 2010)

The IR signals minimum and maximum threshold values are determined by following formula:

Max Threshold = %40 below the maximum IR value

Min Threshold = %40 above the minimum IR value

During one heartbeat, the index of samples was noted. Then pulse rate detection algorithm detects the numbers of samples between two consecutive threshold (max)

crossing points (Texas Instruments, 2010). The algorithm then calculates the pulse rate by the following formula:

Pulse Rate= (60*Sampling Rate)/Number of samples between threshold crossing point

2.5 Principle of Operation

Pulse oximeters have two methods for determining oxygen saturation: reflectance method and transmission method (Figure 2.11). The transmission is most common method and we also used that method on this thesis.

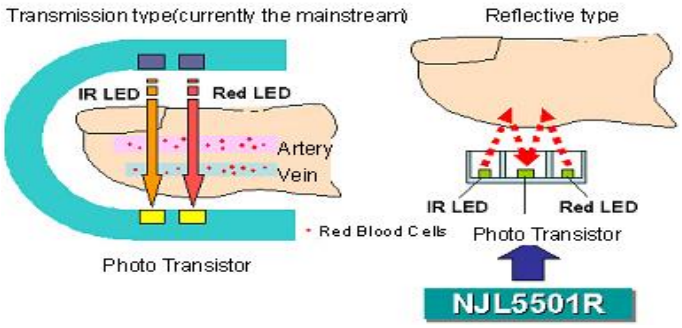

Figure 2.11 Transmission and reflectance types of pulse oximeter (New JRC introduces a reflective optical sensor the NJL5501R well suitable for pulse oximeter and heart rate monitor, 2013)

As we said above two different light emitting diodes positioned in pulse oximeter probe and each LED beam sequentially at frequencies that depend on manufacturer but it may be a several hundred Hz. According to Alexander, Teller & Gross (1989), "in some designs, a third phase of both LEDs off allows the oximeter to detect and compensate for any extraneous light (i.e., not coming from the LEDs) that might cause interference by striking the photodetector (Figure 2.12)."

The photodetector is positioned opposite side of LEDs and after each beam it detected output light at each wavelength (Yun-Thai, 2007). It is possible to see representative schematic of each signals in Figure 2.13.

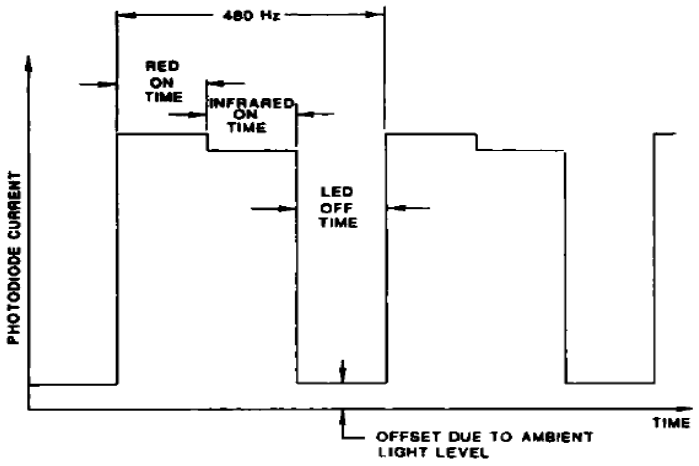

Figure 2.12 LED on-off cycle for a typical pulse oximeter (Alexander & et al, 1988)

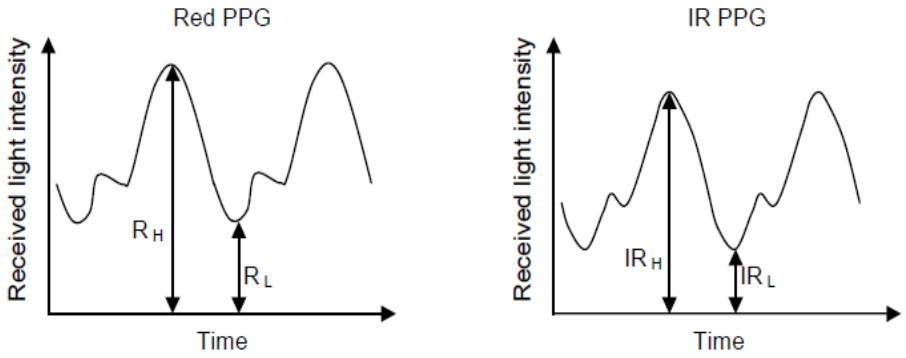

Figure 2.13 Received light intensity from each red (R) and infrared (IR) LEDs (Humphreys, 2007)

That signal peaks due to arterial pressure and represent the blood volume between source and detector is lowest. Therefore light transmittance is highest there. The reduction of transmittance light represented between R_H and R_L. That reduction of transmittance light occur each heartbeat and due to arterial the pulsation of the arterial blood. Based on the Equation 2.5, the ratios of ratio (R) also can be defined as follows:

$$R = \frac{\ln(\frac{R_L}{R_H})}{\ln(\frac{IR_L}{IR_H})} = \frac{\alpha_A(\lambda_R)}{\alpha_A(\lambda_{IR})} \tag{2.11}$$

Finally pulse oximeter correspond that ratios of ratio (R) to the calibration curve and it lead to calculate oxygen saturation.

2.6 Clinical Uses of Pulse Oximeter

As we know pulse oximeter measures oxygen saturation in arterial blood. It is widely used in respiratory patient monitoring. When patient has hypoxia it is mean the oxygen saturation of patient is decreasing. It is possible to see forms of hypoxia in Table 2.6.

Table 2.6 Types of hypoxia

Types of hypoxia	Clinical situations
Hypoxic hypoxia	Arterial blood is poorly oxygenated.
Anaemic hypoxia	There are insufficient red blood cells to transport the required oxygen.
Circulatory hypoxia	Cardiac output is insufficient or there is failure in tissue perfusion.
Histotoxic hypoxia	Tissue is unable to use the oxygen supplied to it.

Pulse oximeters are widely applied in hospital. We considered some of them like the patients who suffer from chronic respiratory diseases. COPD (Chronic Obstructive Pulmonary Disease) is a chronic respiratory disease. During treatment of COPD, pulse oximeters are useful in stable patient with severe disease and in patients who worsening or other signs of acute exacerbations. It is also a device for patients can be used at home to control their disease under physician guidance (Global Primary Care & Patient Education, 2010).

In patients with asthma, pulse oximeter also uses as compliment of peak flow meter during determine the severity of asthma attacks.

The other disease that pulse oximeter is also useful in is acute respiratory infection. It is useful in determining a seriousness of diseases and evaluating the situations that how to refer patients for further treatment.

We can see uses of pulse oximeter in several various primary care situations as follows:

- Determining baseline values for patients in stable diseases
- Monitoring of patients during exercise-related dyspnea
- Assessment of seriousness, during asthma attach
- Triage of patients for arterial blood gas measurement, referral to emergency department and determining initiation of acute oxygen therapy.
- Monitoring patient after initiation of oxygen therapy or response to therapy
- The patients who suffer from severe acute wheezing, particularly children
- Monitor to patients after severe asthma attack
- Determining the seriousness of a lower respiratory tract infection
- Determining of significant respiratory tract infection for children who has breathlessness
- A part of feature treatment for children with acute asthma (Cloete, 2012).

In normal conditions, when oxygen parietal pressure is 160 mmHg, blood keeps 100% of oxygen saturation. Blood oxygen saturation keeps 95% of saturation even if parietal pressure decreasing till at half. In decreasing of oxygen parietal pressure until 65 mmHg, oxygen saturation still keeps 90% of saturation. Under 65 mmHg the degree start to steep downward part of the curve (Figure 2.14). A little drop of parietal pressure as 10 mmHg causes decreasing of oxygen saturation to %80.

Thus, it is expected in healthy person oxygen saturation of blood could be 95% or above. If the saturation start to decrease under 95% it should be investigated but if saturation falls below 90% some quick treatment should be applied.

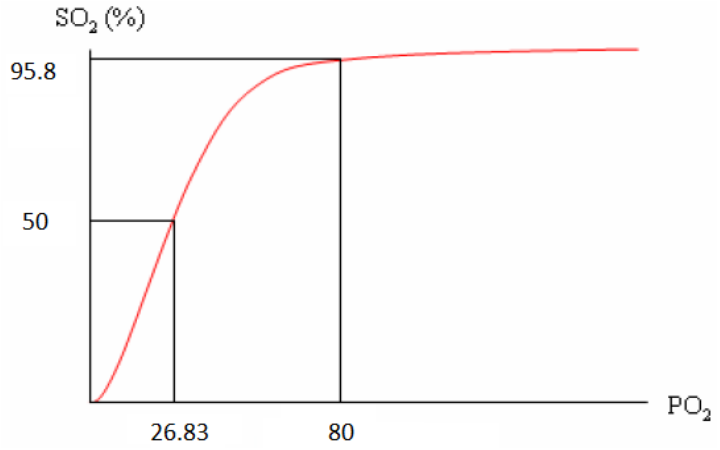

Figure 2.14 Illustration of relationship between PO_2 and SO_2 (Seo, 2008)

2.7 Limitation of Pulse Oximeter

Pulse oximeter working principle based on Beer-Lambert law. It is possible to see in Figure 11 that Beer-Lambert curve is different from empirical curve. The passing light through finger is not only absorbed and transmitted it is also scattered and reflected. Beer-Lambert's law does not take into that scattering and reflection characteristics of tissues during calculating oxygen saturation. It is causes pulse oximeters inaccuracy. Thus pulse oximeter must be calibrated with empirical calibration. However that calibration also display inaccuracy under 80% oxygen saturation because the researches ethically cannot make volunteers more hypoxic. So pulse oximeter lost his accuracy under %80 of oxygen saturation (Granelli, 2009).

The other thing that causes pulse oximeter false reading is optical interface. The blood doesn't include only two types of oxygen, there is also dyshemoglobins and they also absorb the light. Especially MetHb and COHb effect absorption, MetHb absorbs an equal extent of light at both wavelength, COHb absorbs red light similarly oxyhemoglobin. Because of that extra absorption pulse oximeter likely to display false reading. The CO-oximeter is using for determinate to amount of COHb and MetHb in blood.

The other limitation of pulse oximeters is inaccuracy during hypoxia. Hypoxia is the lack of oxygen in cells. We can see types of hypoxia in Table 2.5. In this types,

pulse oximeter only can measure hypoxic hypoxia. However pulse oximeter display reading during other types of hypoxia. Therefore patient may be has hypoxia despite the SpO_2 reading of pulse oximeter.

The motion artifact is also most common limitation of pulse oximeter and it is significantly causes false reading and erroneous alarm. Pulse oximeter based on pulsatile changes of arterial blood. Therefore any changes in peripheral blood flow by movement affect accuracy of reading. During hypotension, hypothermia, the lack or low amplitude of pulse signals cause low signal-to-noise ratio.

The skin pigmentation and nail polish also cause the inaccuracy of pulse oximeter, especially on dark skinned persons. On dark skinned persons pulse oximeter display great inaccuracy, because pulse oximeter put higher current through LEDs in response to low detected lights, so it cause changes of output spectrum of LEDs. The variability of LED's peak wavelength affects the measurement (Chu, 2010).

Ambient light also effect pulse oximeter readings, especially fluorescent and xenon arc surgical lambs cause low SpO_2 readings.

We can see same sources of errors in Table 2.7.

Table 2.7 Sources of errors (Chu, 2010)

Error Sources	**Effects on SpO_2**	**Responses**
Hypotension	Possible loss of signal	Correct underlying problem (e. g. give fluid challenge, lighten anesthesia), vasopressors
Vasoconstriction (reduction of blood flow to arterial bed)	Possible loss of signal, reduction of SpO_2	Change to more central site
Hypothermia (reduction of blood flow: seen in Pts. w/Raynaud's disease)	Possible loss of signal, reduction of SpO_2	Keep patient and extremities warm
Shivering/muscle twitching	Changes in pulse size, possible loss of signal	Warm and/or sedate patient
Carboxyhemoglobin	Falsely high SpO_2 reading	Increase ventilation, eliminate rebreathing
Methemoglobinemia	Falsely low readings approaching 85%	Administer methylene blue
Venous pulsations	Falsely low readings	Change site
Blood pressure cuff on monitored arm	Loss of signal decreases SpO_2	Change site
Arterial lines on monitored arm	Loss of signal decreases SpO_2	Avoid use of arteries in monitored area
Intense bright light (e. g., fiber optic fluorescent lights)	Lower SpO_2 reading	Avoid exposure of photodiode to light

CHAPTER THREE
DESIGN AND CONSTRUCTION

3.1 Introduction

This section will illustrate the design process and development of pulse oximeter for this thesis. The main components of our developed pulse oximeter are Fez spider mainboard, Pulse Oximeter module, Bluetooth module, Multicolor led module, Display module, Button module and power supply module. Description of all this modules are in below sections.

3.2 Modules of Developed Pulse Oximeter

Pulse Oximeter Module – This module is the main component of device and it is provide convenient noninvasive measurement (Figure 3.1). The oxygen saturation measurement accuracy of this sensor module is ±2 digits in the range of 70%-90%, the oxygen saturation measurement is unspecified between 0%-69% ranges. The accuracy of heart rate measurement is ±2 bpm in the range of 20-250bpm. The block diagram of pulse oximeter module is shown schematically in Figure 3.2.

Figure 3.1 Pulse Oximeter Module (Gadgeteer, n.d)

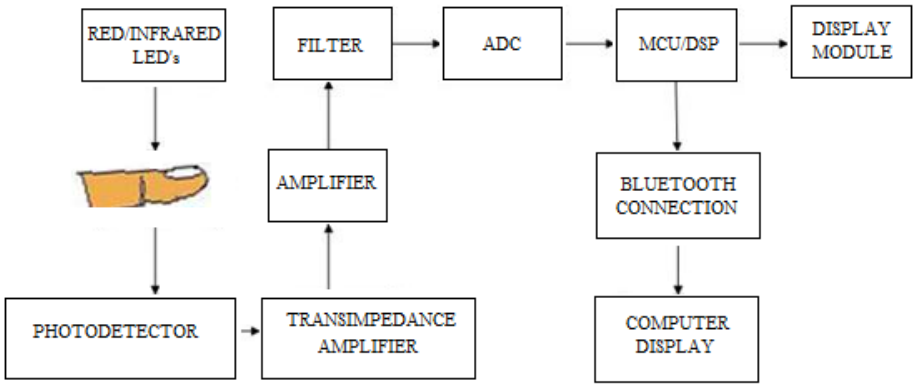

Figure 3.2 Representation of pulse oximeter block diagram

The finger probe has a photodetector and two LED's: one red (R) and one infrared (IR). The red light wavelength is 660 nm whereas infrared light wavelength is 895 nm.

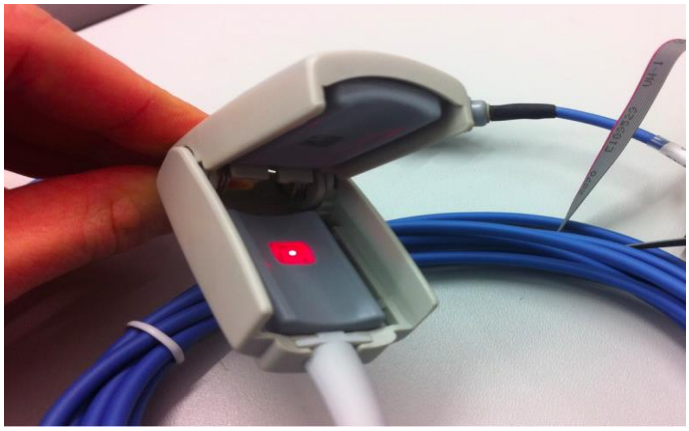

Figure 3.3 Pulse oximeter's finger probe (Getting started with seed pulse oximeter, 2012)

LED's of probe shine by turns. The each LED is switched on every 2ms and LED's switch on in a pulsed fashion. We can see the timing diagram of LED's as follows:

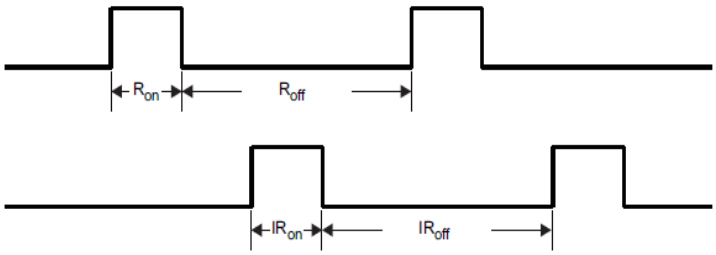

Figure 3.4 LED's timing diagram (Texas Instruments, 2010)

Where,

R_{on} / IR $_{on}$ = 450µs

R $_{off}$ / IR $_{off}$ = 1550µs

The front end board of pulse oximeter process the signals which received from the finger probe, it amplifies and digitizes the signal. It is possible to see the pulse oximeter front end board architecture in Figure 3.5.

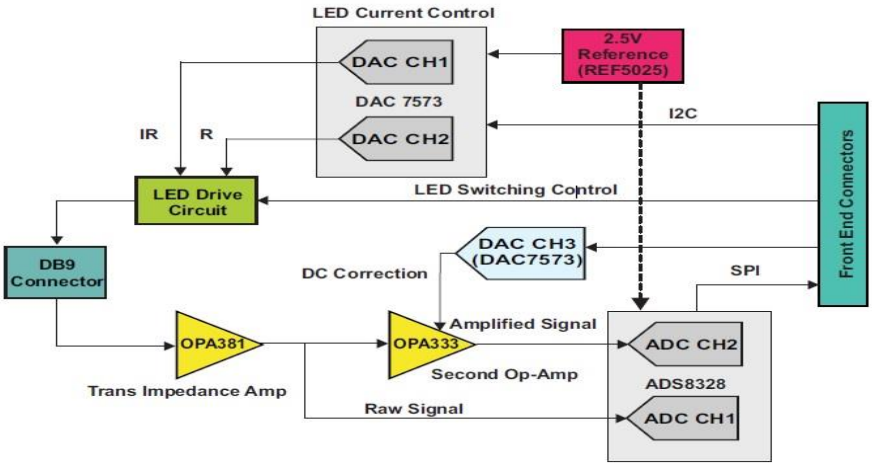

Figure 3.5 The front-end block diagram of Pulse Oximeter (Texas Instruments, 2010)

The digital signal processor (DSP) software controls the red (R) and infrared (IR) LED's on and off switches. It is possible to see LED's switching control circuit diagram in Figure 3.6.

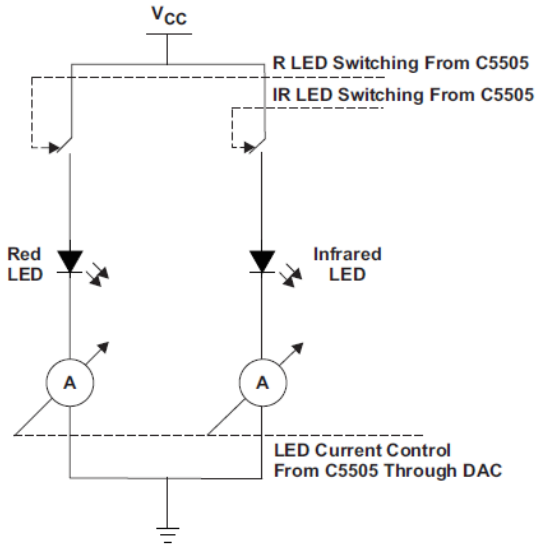

Figure 3.6 LED switching control circuit (Texas Instruments, 2010)

The passing light detected by the photodetector in the opposite side of probe. Usually photodetector used photodiode, when the emitted light reduced by the tissues it detected and photodetector generate a low current. Then the amplifier uses to amplify the low amplitude signal and convert the current to voltage. Generally pulse oximetry uses transimpedance amplifier to convert current to voltage. The OPA381 is used as the transimpedance amplifier on this thesis. The transimpedance amplifier configuration is shown in Figure 3.7.

In this operation input current is converted to output voltage and output voltage as given by:

$$V_{out} = I.R_f \tag{3.1}$$

Where R_f is the feedback resistance.

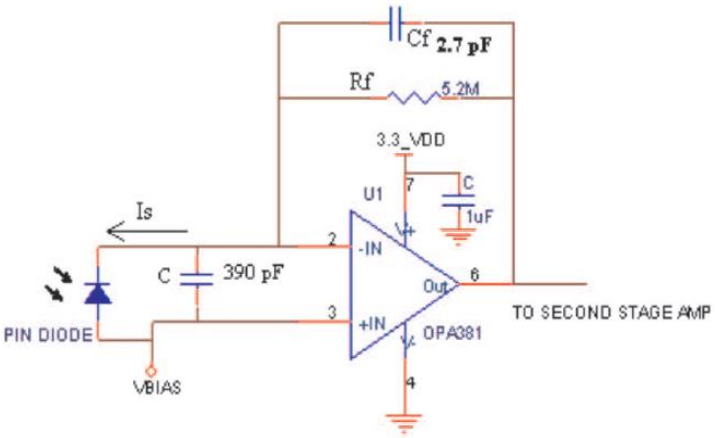

Figure 3.7 Transimpedance amplifier (Texas Instruments, 2010)

Where C $_f$ is the feedback capacitor and R $_f$ is the feedback resistor. The input signal from photodetector is a few micro amps. A high-value feedback resistance (R $_f$) of the order of 5.2 M is used for converting the input current into an output signal of a few volts. This stage provide maximum gain because adding more gain after the transimpedance stage usually generates poor noise performance.

Feedback capacitor (C $_f$) is using for minimization peak gain and improving stability. C $_f$ also limits bandwidth, reducing noise. The capacitance value of C $_f$ is 2.7 pF, whereas larger feedback capacitance limits the operation bandwidth.

The first stage amplifier pass output to second stage amplifier. The second stage amplifier is OPA333, we can see it in Figure 3.8.

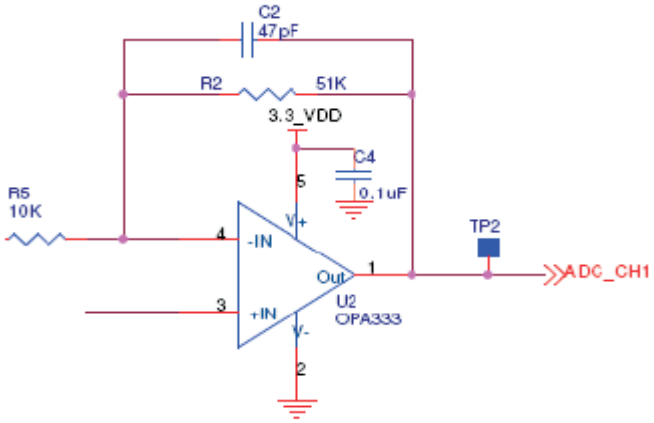

Figure 3.8 Second amplifier (Texas Instruments, 2010)

The non-inverting output of second stage amplifier is fed by regulatable DC voltage so that the output of the second stage amplifier contains complete AC component of the signal in the working range of the analog-to-digital convertor (ADC). The regulatable DC voltage generated by digital-to-analog convertor (DAC).

The signals from this first stage amplifier and second stage amplifier are fed to two different channels (channel0 and channel1) of analog-to-digital convertor (ADC).

The digital signal processor (DSP) software takes digitized signal and processes it (Figure 3.9). The digital signal processor receives SpO_2 signals from channel0 and channel1. That signals corresponding to the LED (red or infrared) that which ones switch on at that instant. The signal which DSP receives from channel0 is represented raw signal and it is the output of the first stage transimpedance amplifier, whereas the signal from channel1 of ADC is represented as amplified signal and it is output signal from second stage amplifier. The intensity of LED controlled by raw signal level so that the signal remains in a present limit. During calculating SpO_2 values this help to obtain linearity and good resolution from ADC. The amplified signal is using for calculating SpO_2 and pulse rate (Texas Instruments, 2010).

The following activities is processing by the software:

- Led switching
- Intensity control of LED
- Data acquisition: through ADC
- Dc offset setting
- Signal processing (noise filtering, DC estimation, AC separation)
- Extraction of parameter (SpO_2 , pulse rate)
- LCD display control

The infrared (IR) and red (R) LED's ON and OFF switches controlled by LED switching block. The LED intensity control block is using for controlling the R and IR LED's intensity.

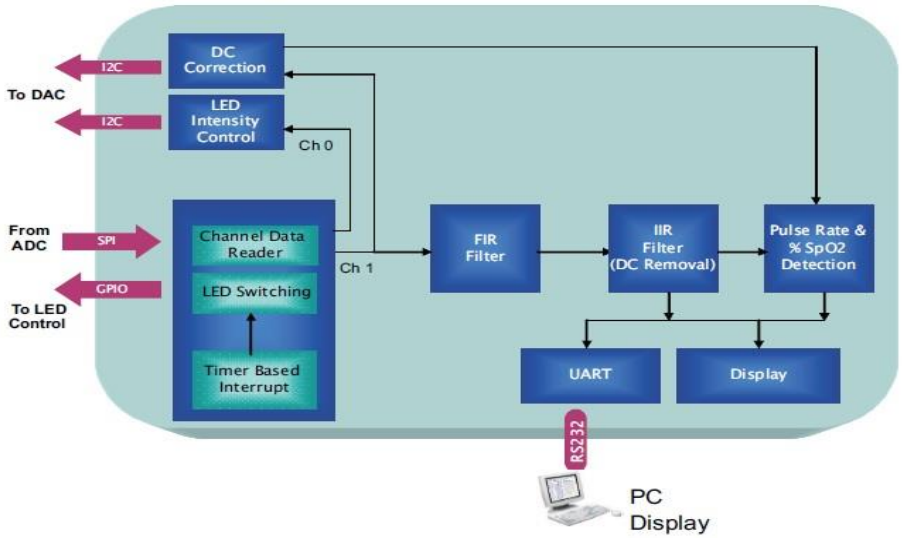

Figure 3.9 Digital Signal Processor (DSP) software architecture (Texas Instruments, 2010)

Data acquisition – The DSP receives R and IR signal from ADC and alternately that signals are read. Both channel0 and channel1 are read during each signal reading, each channel has 16-bit resolution. Both two channels of R and IR signals are read every 2 msec.

FIR Filter (Finite Impulse Response) – That filter used in Digital Signal Processing (DSP) applications. That FIR filter is using for removing unwanted signals and channel1 is fed to the filter. The using filter is FIR hamming low-pass filter and it provides sharp cutoff at 10 Hz with attenuation of about 50 dB. The realization of filter provide by buffer shifting algorithm which described previous chapter (Figure 3.10). The frequency of sampling is 500 samples/second. During receiving every filtered sample the buffer is shifted and add new sample into buffer. We can see the application of LPF as follows:

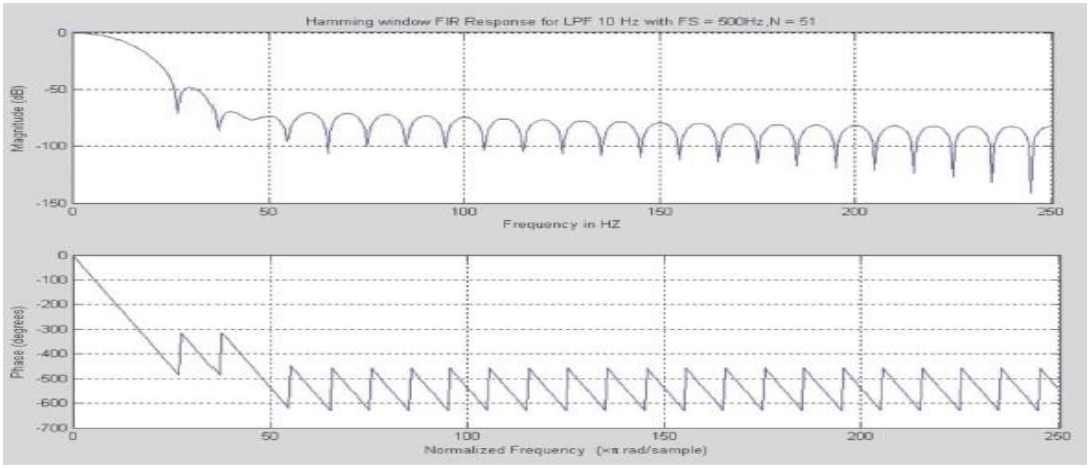

Figure 3.10 LPF application's result (Texas Instruments, 2010)

IIR Filter (Infinite Impulse Response) – this filter is using for removing DC signal. The IIR filter use the following function:

$$H_{(z)} = \frac{Y_{(z)}}{X_{(z)}} = \frac{1 - z^{-1}}{1 - \alpha\, z^{-1}} \tag{3.2}$$

Alpha is chosen 0.992 for providing 22dB Dc attenuation. The frequency response of filter is shown in Figure 3.11.

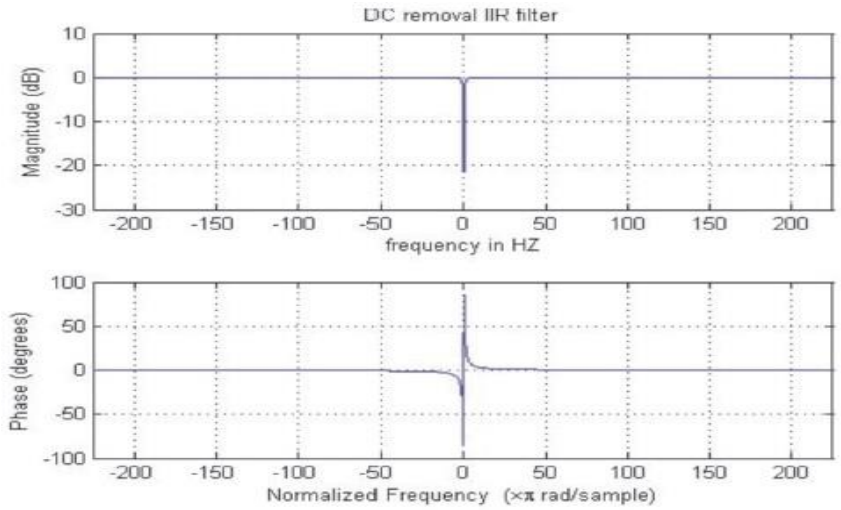

Figure 3.11 Response of DC removal filter (Texas Instruments, 2010)

We can see 1 Hz signal response via the IIR DC removal filter in Figure 3.12.

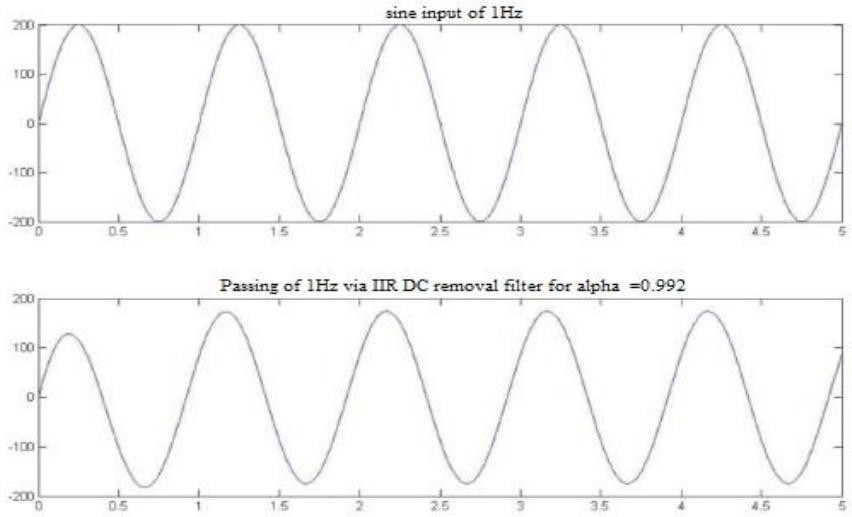

Figure 3.12 IIR DC removal filter signal response (Texas Instruments, 2010)

The R and IR signals are detects over a period of three heart beats, then ratio of signals are calculated and the look-up tables using for obtaining SpO_2 values.

Character Display Module – It is 16×2 character display module and has controllable blue back light. That module provide to display SpO_2 and heart rate values. It is possible to see that module in Figure 3.13.

Bluetooth module – Bluetooth is a common wireless protocol that found in small devices. It has many types of profiles but Serial Port Profile (SSP) is mostly used on the embedded systems. The SSP provide the turns of bluetooth connection into a serial wireless connection. On this thesis this module was used to transfer data from device to PC (Figure 3.14).

Figure 3.13 Character display module (Ghi electronics catalog, n.d)

Figure 3.14 Bluetooth module (Ghi electronics catalog, n.d)

Multicolor Led Module – This LED module provide us a different LED colors (Figure 3.15). It is up to us that which color we need during LED blinking. On this project we used it for definition of pulse oximeter probe position. If the probe is attached it would turn on green color, when the probe is detected it would turn on blue color.

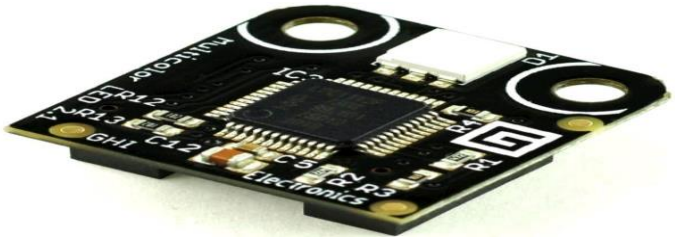

Figure 3.15 Multicolor led module (Ghi electronics catalog, n.d)

Button Module – This module provide us to control the system working. We push the button when we need to interrupt or start the system to perform certain function (Figure 3.16). On this thesis we used that module for controlling the bluetooth module's connection state, when we push the button if the bluetooth is connected program give that message: "You pressed the button but BT (bluetooth) was connected, so not activating pairing mode", if the bluetooth is not connected the program give that message: "You pressed the button and BT (bluetooth) was not connected, so I go to pairing mode".

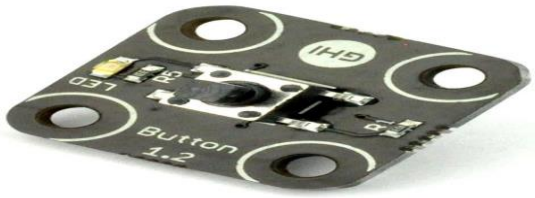

Figure 3.16 Button module (Ghi electronics catalog, n.d)

UC Battery 4×AA Module – This module is the power option for our device. It uses four AA type batteries to run the system (Figure 3.17). This module also has USB connector for deploying and debugging application to mainboard. The switch of that module is using for select the power source, USB or battery.

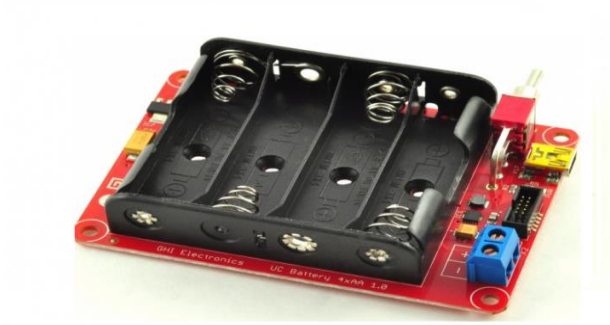

Figure 3.17 UC 4×AA battery module (Ghi electronics catalog, n.d)

Fez Spider Mainboard – The Fez Spider built around EMX module (Figure 3.18). The EMX module is a combination of hardware (ARM Processor, Flash, RAM, Ethernet PHY…etc.) on a very small SMT OEM 8-Layer board (Figure 3.19). All of our above modules are connected to Fez Spider mainboard. The EMX module is very sophisticated part of hardware. This module remarkable simple platform, it provide the users apply in any hardware design. The EMX module has standard 16 MB SDRAM and 4 MB external flash. The system need 3.3 V power consumption.

The EMX module utilize the LPC2478 microcontroller. This LPC2478 72Mhz ARM7 32Bit processor is the core of the EMX module, and it include a memory acceleration interface with 128Bit internal FLASH memory.

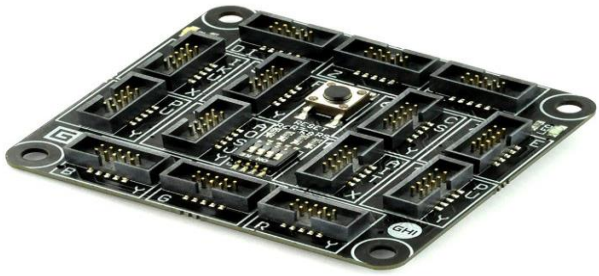

Figure 3.18 Fez spider mainboard (Ghi electronics catalog, n.d)

Figure 3.19 EMX module (Ghi electronics catalog, n.d)

All this modules are connected with fez spider mainboard and fastened on the board. The final form of pulse oximeter is shown in Figure 3.20.

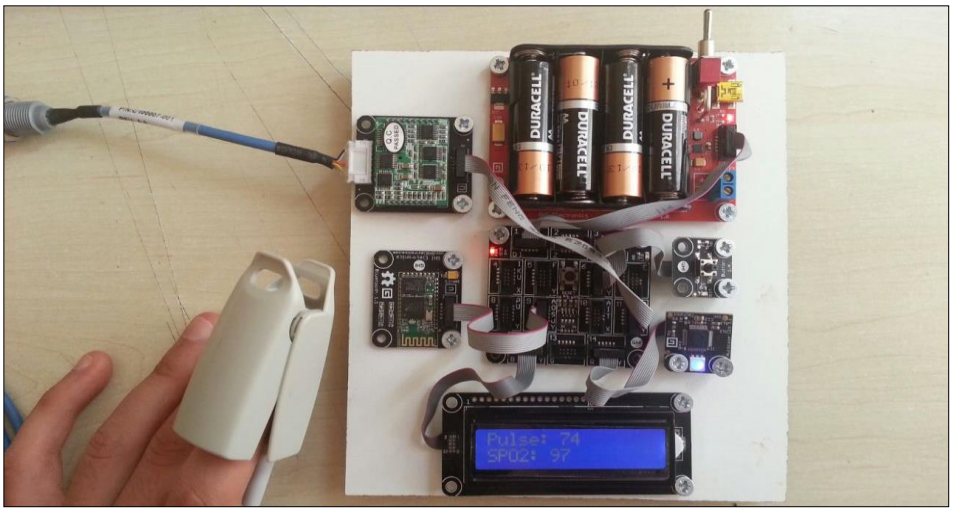

Figure 3.20 The final form of pulse oximeter. The heart rate (74) and SpO_2 (97) values are displayed on character display module

3.3 Software Design of Pulse Oximeter

The software of pulse oximeter was written by visual studio 2010 c#. Our developed pulse oximeter based on Microsoft .Net Gadgeteer. It is an open source platform for building small electronic devices and it based on the use of the .Net Micro Framework and Visual Studio. Microsoft .Net Micro Framework is an application of .Net Framework. It supports the development of any code in C# and debugging that code on device or emulator.

.Net Gadgeteer provides a hardware interfacing platform for users to build and develop their projects.

The *Visual studio 2010 ultimate* program was used during programming the pulse oximeter. The Gadgeteer modules can be add from visual studio's toolbox to designer screen. The connections of all modules must be connected on the designer screen before debugging the code to the device. The device connection to the PC is provided by the battery module's USB connector.

The designer screen of visual studio is shown in Figure 3.21.

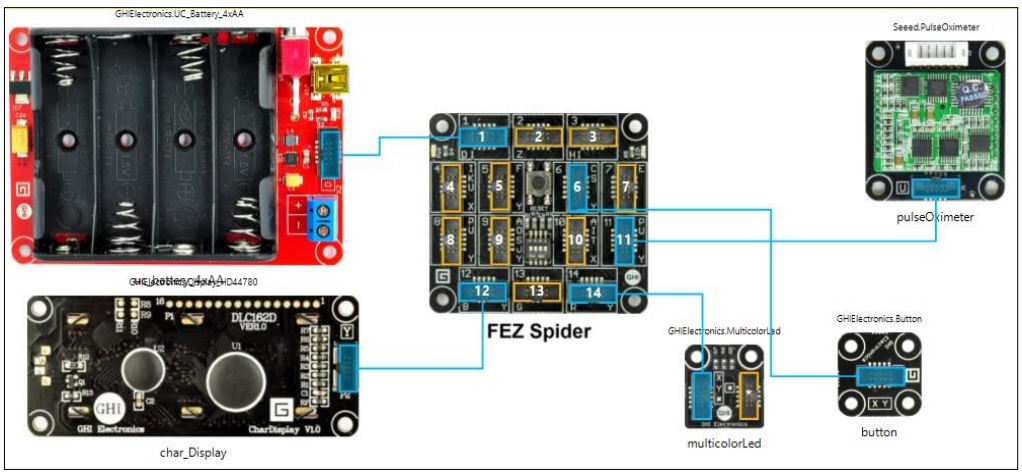

Figure 3.21 Designer screen of visual studio and connections of modules

The device connected to PC over the USB connector then the code deployed to the mainboard. When the device connected to PC by USB, the button module

provide us to control and see the bluetooth connection state on output screen of visual studio and program give the message according to bluetooth connection state. (Figure 3.22, 3.23).

Figure 3.22 When we press the button if the bluetooth is connected, program gives that message

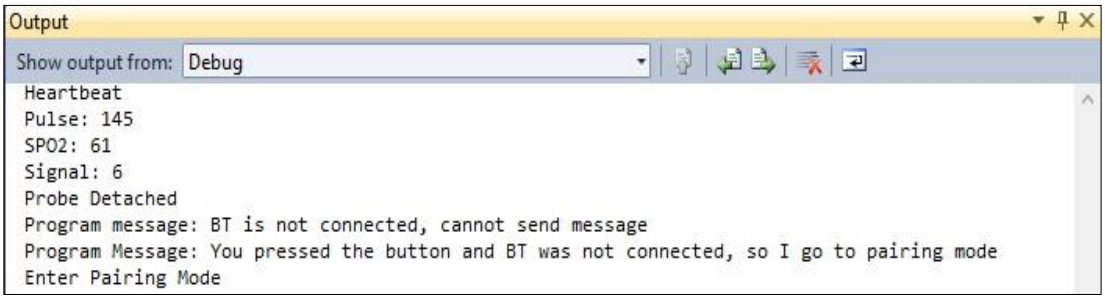

Figure 3.23 When we press the button if the bluetooth is not connected, program gives that message

After successfully deploying code to the device, it is ready to measure values. The output screen of visual studio also display the signal strength. It is possible to see some measured values in Figure 3.24.

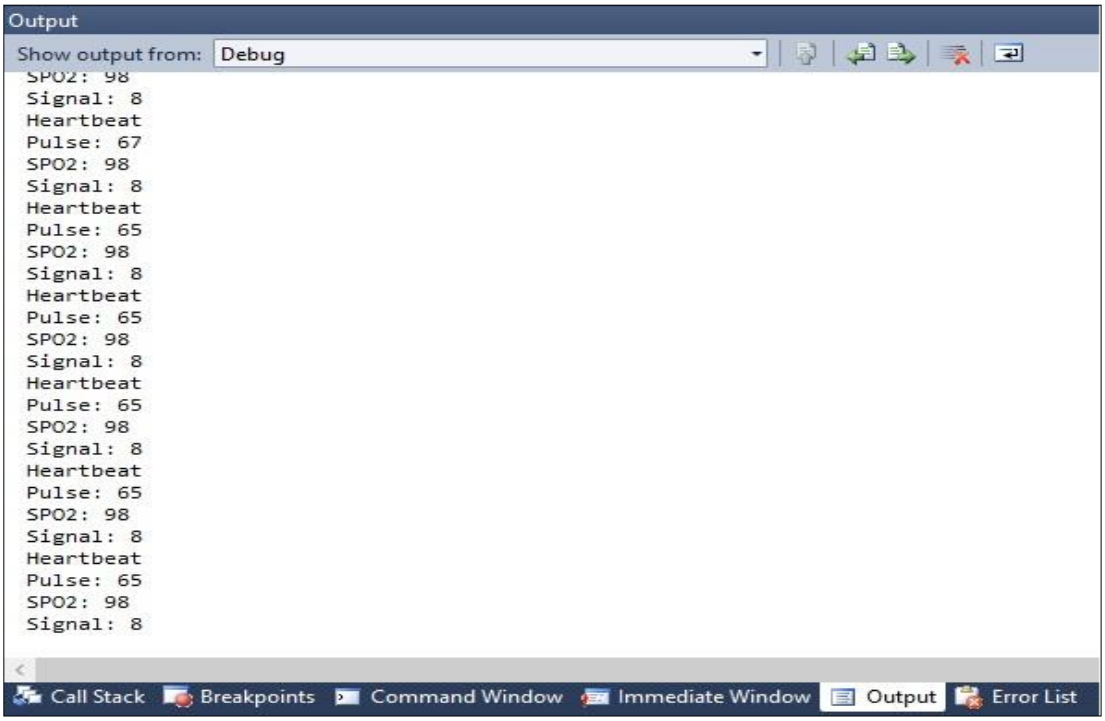

Figure 3.24 The measured values on the output screen of visual studio

After debugging the USB connection of device was removed and the device power provided by the external UC Battery module. When the device power, bluetooth automatically try to make connection with PC. If it cannot make bluetooth connection successfully, the button module is using for restart the bluetooth connection.

The measured values of pulse oximeter was transferred to the PC over bluetooth module. The “Bluetooth Serial Accept” program provided the data transfer between device and PC. That program stored the values as *xml* files.

CHAPTER FOUR
MEASUREMENTS OF OXYGEN SATURATION BY PULSE OXIMETER DURING EXERCISE

4.1 Introduction

This chapter consider the test and experimentation of the developed pulse oximeter. The experiment involved the measuring of arterial oxygen saturation during exercise in indoor and outdoor areas. Ten volunteers joined our experiment. The list of volunteers and their characteristics are displayed in Table 4.1. The experiment was carried out at Dokuz Eylul University, at the department of Biomedical Technologies. In this research walking at mid-tempo on a treadmill was chosen as indoor exercise and walking at mid-tempo outside was chosen as outside exercise.

In this investigation the variability of arterial oxygen saturation depending on indoor and outdoor areas were observed and monitored the effect of indoor and outdoor areas to the alteration of oxygen saturation. The experiment was performed on 10 male and female volunteers between the ages of 20 and 35. The SpO_2 values were acquired by pulse oximeter and stored as excel files.

Table 4.1 Characteristic of volunteers

Number of Participants	**Gender**	**Age**	**Smoker/Non-Smoker**
1	male	28	smoker
2	male	21	non-smoker
3	male	24	smoker
4	male	23	non-smoker
5	male	23	smoker
6	male	23	smoker
7	male	23	smoker
8	male	35	smoker
9	male	25	non-smoker
10	female	27	smoker

4.2 Tests of Developed Pulse Oximeter Accuracy

At the beginning of this research the accuracy of the developed pulse oximeter was tested at a private hospital. The SpO_2 and heart rate values of healthy volunteer were measured with the hospital's pulse oximeter and our developed pulse oximeter at the same time. The measurements were taken from four volunteers at the different times during the day. It is possible to see the measuring devices below.

Figure 4.1 SpO_2 (99) and Heart rate (71) values which was measured by our developed pulse oximeter

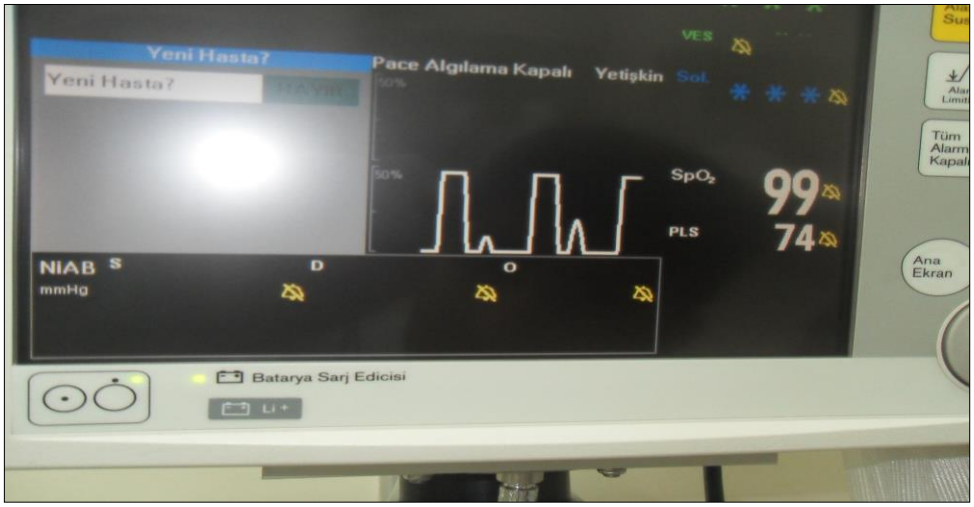

Figure 4.2 SpO_2 (99) and Heart rate (74) values which was measured by the hospital pulse oximeter

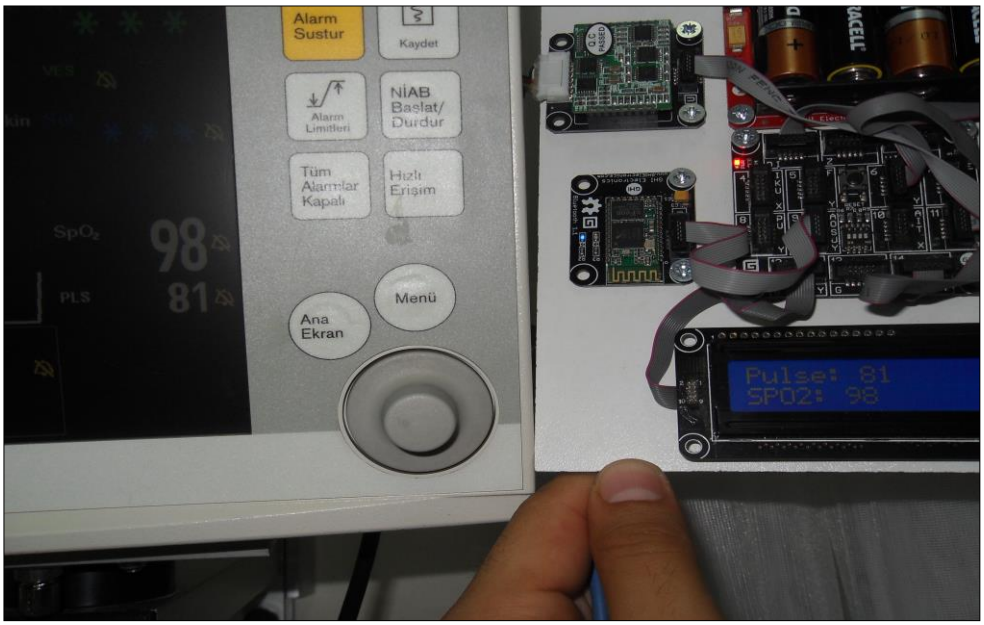

Figure 4.3 SpO_2 and Heart rate values were measured at the same time

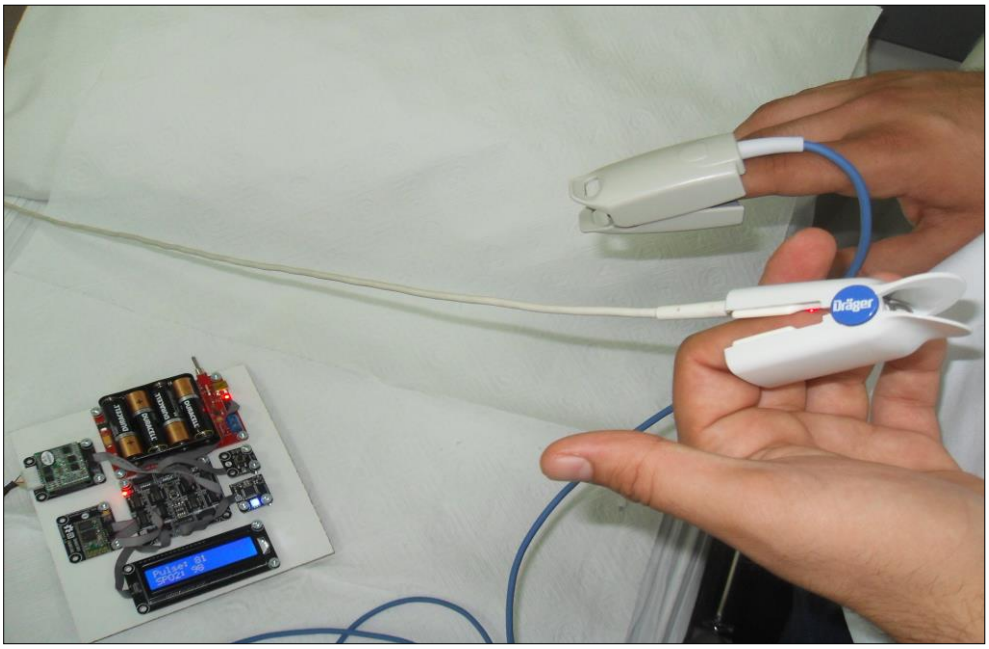

Figure 4.4 SpO_2 (98) and Heart rate (81) measurements measured at the same time

During the tests the SpO_2 values of volunteer were 98% and %99, it is possible to see in above figures that both devices displayed exactly same oxygen saturation values, but there was once a slightly difference between heart rate values.

4.3 Measurements

In this research the experiment's criteria for each indoor and outdoor areas was planned as walking 400 meters for 5 minutes at a 4.8 km/h pace. That experiment was carried out on each of the 10 volunteers and stored their oxygen saturation values during exercises. Their measurements were regularly taken for indoor and outdoor areas. The tests were performed in situations where the volunteers had been at the rest before exercising. The first stage of tests was indoor exercise. At the beginning of the exercise the volunteer's finger was inserted in to the pulse oximeter probe and then they walked 400 meters indoor on a treadmill at a pace of 4.8 km/h for 5 minutes and during exercise their oxygen saturation values were measured by the pulse oximeter and values were stored on a laptop via bluetooth.

In the same way the outside exercise was applied to the volunteers. A 400 meter distance outside was measured and requested volunteers to complete this distance in 5 minutes at a 4.8 km/h pace.

During exercises the pulse oximeter saved values once every five seconds so we got 60 values for each volunteer respectively during indoor and outdoor exercises. Totally 120 oxygen saturation values were obtained for each volunteer. During exercises each volunteer's values were saved as excel files. It is possible to see one of the volunteer's SpO_2 values at the beginning of exercise in Figure 4.5. Then the indoor and outdoor SpO_2 values of the volunteers were compared to observe the difference between them. The obtained results and its analysis can be found in the next section.

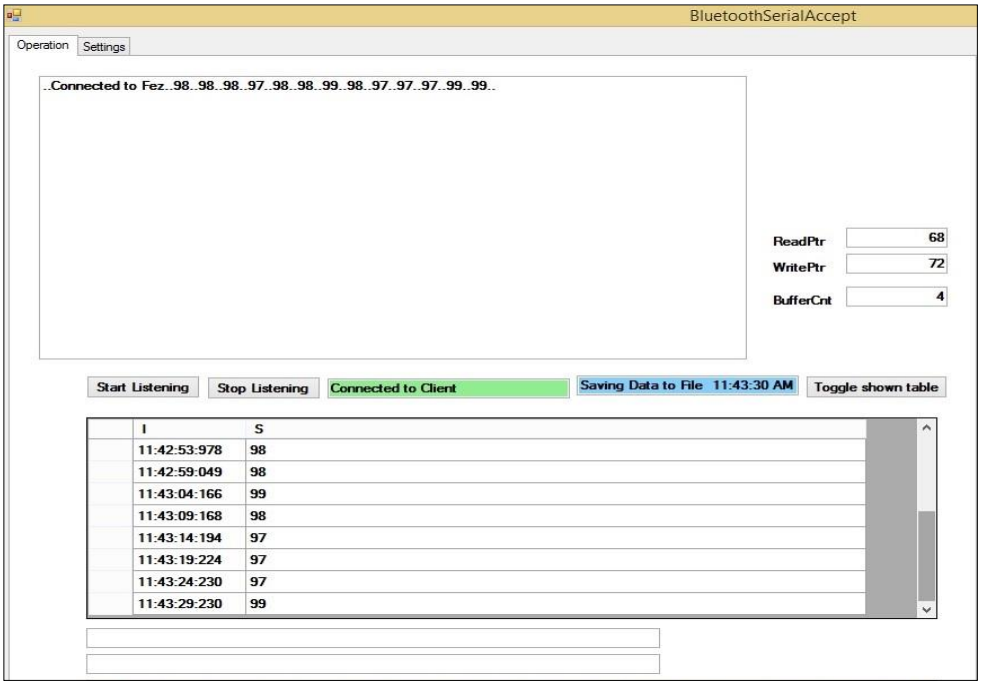

Figure 4.5 Volunteer's SpO_2 values during indoor exercise

4.4 Measurements Results

Once the SpO_2 values were acquired and stored the obtained values from the volunteers are analyzed. The differences of indoor and outdoor exercise measurements were evaluated and analyzed the graphical representation of the values. There were slight differences between indoor and outdoor exercise SpO_2 measurements. The SpO_2 values displayed variations depending on each volunteer. The volunteer's SpO_2 value's average were calculated on excel for each outdoor and indoor exercises to find out how their oxygen saturation was changed. Then the comparison graphic of those values was obtained. The results allow an assessment of oxygen saturation variance and a comparison of them. It is possible to see the graphical representation of the measurements below.

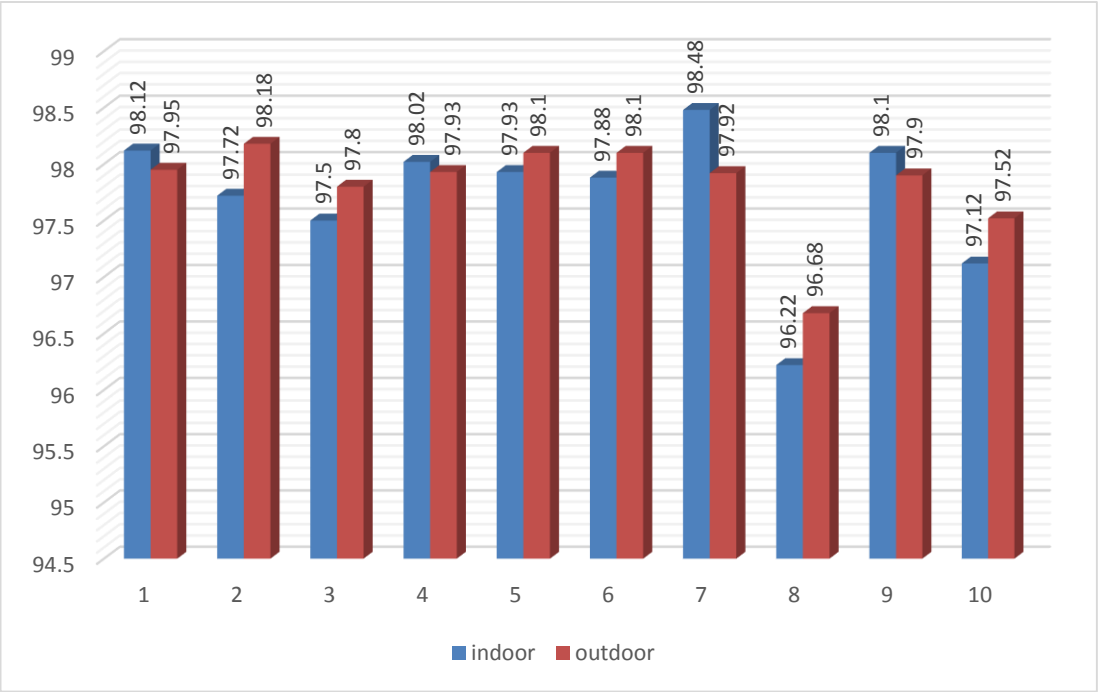

Figure 4.6 Graphical representation and comparison of each volunteer's SpO_2 measurements average

Looking at the graphical representation of the compared values, it is possible to identify the value's differences during indoor and outdoor exercise. Each column represents the volunteer's SpO_2 measurements average. The blue columns represent the volunteer's indoor exercise results average and red columns represent the outdoor exercise results average.

During the outdoor exercise, due to the open air, the oxygen saturation of the blood was expected to increase. The six volunteer's oxygen saturation values increased in outdoor exercise but for four of them it decreased. That decreasing of SpO_2 values was most likely due to inaccuracy of pulse oximeter sensor because during outdoor exercise the pulse oximeter probe was slightly effected by sunshine. The probe is also very sensitive to finger movements, a factor which made noise in the acquired signals, so effecting the processing of signals. There are also other factors that affect the variance of SpO_2 values such as the age, and smoking. The average age of volunteers was 25, seven of them are smokers and three of them do not smoke.

Finally, 600 values were obtained from volunteers for each indoor and outdoor exercises. There were slight difference between monitored values. As normal the oxygen saturation of volunteers displayed variances between 95%-99%. The standard deviation formula on excel was used to find out how spread out the values are in the measurements. The standard deviation of indoor exercises measurements was calculated as 0.947678 and for outdoor exercises it was calculated as 0.756671.

CHAPTER FIVE
CONCLUSION AND FUTURE WORK

5.1 Conclusion

The main objective of this thesis was to develop a portable remote pulse oximeter that receives data from a probe and process it respectively to return the values heart rate and oxygen saturation in blood, then transfer the data to the laptop over bluetooth. It allows the continuous monitoring of heart rate and arterial oxygen saturation.

The design of pulse oximeter was accomplished using the pulse oximeter sensor module, bluetooth module, fez spider mainboard, multicolor led module, display module, button module and power supply module. The Visual Studio 2010 program with C# language was used for deploying the code to the mainboard.

In this study different measuring conditions were applied. The measurements were taken during the physical activity by the pulse oximeter. The physical activity is defined as walking 400 meters for 5 minutes at 4.8 km/h pace in outdoor and indoor areas. The experiment was carried out during the day between 10 am and to 5pm. The virtual reality laboratory at our University was used as an indoor area. During that activity ten volunteers participated in our experiment. The volunteers did their walking in mid-tempo activity on a treadmill in the laboratory. The received values were evaluated on a laptop for each volunteer then the graphical representation of measurements for indoor and outdoor areas was obtained and we were able to compare the measurements.

The accuracy of the developed pulse oximeter was tested at a hospital and obtained the same values.

5.2 Future Work

The developed pulse oximeter stored the values on the laptop over bluetooth connection. It does not have the own memory for storing the values. If there is not a laptop for providing a bluetooth connection the values can be measured momentarily. In future work the memory card module can be add to this device. It would provide the convenience to overseeing patients at home whose oxygen saturation values must be monitored and measured periodically and continuously, so it would allow them to store their measurements outside without a laptop.

The wifi module also can be added to this device. It would provide automatic data transfer over the internet. In a domestic environment it would allow the overseeing patients to automatically share the data with their physician by e-mail or other possible ways such as sending data to the physician’s website.

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