B.Sc. Engineering Thesis

Photoplethysmographic Analysis of Optical Signals : A Single Device to Measure All the Vital Signs

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Submitted to

Department of Computer Science and Engineering

in partial fulfillment of the requirements for the degree of

Bachelor of Science in Computer Science and Engineering

Department of Computer Science and Engineering

Bangladesh University of Engineering and Technology

Dhaka-1000, Bangladesh

September 2015

Abstract

Heart rate and blood pressure are two vital signs used to measure basic functions of human body. Heart rate is the number of times heart beats per minute whereas blood pressure is defined as the pressure against the inner walls of the blood vessels. Blood Pressure (BP) is considered to be a strong indicator of an individual's well being and one of the most important physiological parameters that reflect the functional status of the cardiovascular system of human beings. Although some smartphone applications can calculate heart rate, neither of these applications is capable of measuring or estimating blood pressure for their underlying sensor limitations. A short survey was conducted on the performance of the smartphone applications. This paper presents a novel approach to measure heart rate and estimate blood pressure with a single device using photoplethysmography (PPG). This non-invasive device uses infrared light to capture the volumetric change of blood during each cardiac cycle as a PPG signal. Theoretically, any body part can be used to measure heart rate and blood pressure through the sensor of the device, although fingertips and earlobes are commonly targeted. The constructed device measures heart rate with a very acceptable accuracy limit compared to the existing smartphone applications. Some parameters of the PPG signal was correlated with 25 healthy subjects and a good correlation was found to estimate the blood pressure which also provides a very satisfactory accuracy. Finally, an extra module was introduced in the device for remote heart rate and blood pressure monitoring.

Acknowledgements

First of all we would like to thank our supervisor, Dr. A.K.M. Ashikur Rahman, for introducing us to the fascinating field of telehealth monitoring and guiding us on how to perform our research work. Without his continuous supervision, guidance and valuable advice, it would have been impossible to complete the thesis. We are especially grateful to him for allowing us to chose our course of actions with freedom, for enlightening us during the moments of frustration, for his patience throughout the entire research work and for his moral support to the extra-curricular activities that we accomplished aside from the thesis.

We would also like to thank our friends, who despite not working on the same field provided us great support. We are also grateful to all other friends for their continuous encouragement and for helping us in thesis writing.

We would like to express our gratitude to all our teachers. Their motivation and encouragement in addition to the education they provided meant a lot to us.

Last but not least, we are grateful to our parents and to our families for their patience, interest, and support during our studies.

Declaration

This is to certify that the work presented in this thesis entitled "**Photoplethysmographic Analysis of Optical Signals : A Single Device to Measure All the Vital Signs**" is the outcome of the investigation carried out by us under the supervision of Dr. A.K.M. Ashikur Rahman, Professor, Department of Computer Science and Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka. It is also declared that neither this thesis nor any part thereof has been submitted or is being currently submitted anywhere else for the award of any degree or diploma.

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Chapter 1

Introduction

1.1 Motivation

Vital signs such as heart rate, blood pressure, respiratory rate and body temperature are the indicators of a person's essential body functions. *Heart rate(HR)*—the number of times heart beats per minute—is a typical measure of heart conditions. Although heart rate varies with body fitness, the normal range of heart rate among adults is 60-90 beats per minute (bpm) [1]. Heart rate indicates how well the heart is functioning. It helps finding the causes of symptoms, such as an irregular or rapid heartbeat (palpitations), dizziness, fainting, chest pain or shortness of breath. Heart rate also helps to detect diseases like tachycardia (a medical condition where heart rate exceeds the normal range) and bradycardia (a medical condition where heart rate is under the normal range). High heart rate can cause cardiac arrest [2]. During physical exercise it is extremely essential to monitor heart rate [3]. During exercise or immediately after exercise, the heart rate can provide information about one's cardiovascular fitness level and health. Another important fact about heart rate monitoring is Heart Rate Variability (HRV) which is the physiological phenomenon of variation in the time interval between heartbeats. HRV has significant effect on sudden cardiac death, hypertension, psychiatric disorders [4] [5] [6] and it has additionally been used as an indicator of acute and chronic stress [7]. One way to measure HRV is the statistical method in which heart rate monitoring is involved [8].

Respiratory rate (RR) is the number of breaths a person takes within a certain amount of time or more formally, defined as the number of chest movements involving inspiration and expiration per unit time. The RR is measured in units of breaths per minute. It is measured by counting the number of breaths(number of times the chest rise) for a minute, usually when the person is at rest. Respiratory rates will increase as the demand for oxygen increases; it also increases due to illness, intensive physical activity, etc. The average RR reported for a healthy adult at rest is usually given as 12 breaths per minute (12/60 Hz) [9] and the estimates vary between 12-20 breaths per minute, whereas the respiratory rate is higher in the case of young adults, children and babies. As people age, breathing rate declines. In slow rates, more accurate readings are obtained by counting the number of breaths over a full minute. Table 1.1 [10] shows the heart rate and respiratory rate at varying ages showing a gradual decline in the rate with age.

Age	**Heart Rate (beats/min)**	**Respiratory Rate(breaths/min)**
Newborn	100-160	30-50
0-5 months	90-150	25-40
6-12 months	80-140	20-30
1-3 years	80-130	20-30
3-5 years	80-120	20-30
6-10 years	70-110	15-30
11-14 years	60-105	12-20
14+ years	60-100	12-20

Table 1.1: Heart Rate and Respiratory Rate for Different Ages

Blood Pressure(BP), sometimes referred to as arterial blood pressure, is the force of circulating blood pushing against the walls of blood vessels, named arteries. Each time the heart beats, blood is pumped out into the arteries and distributed all over our body. It constitutes one of the principal vital signs. Systolic blood pressure occurs when the heart is pumping and diastolic blood pressure occurs when the heart is resting [11]. By convention, blood pressure is measured in millimetres of mercury (mm Hg) , and is considered normal if it is usually less than or equal to 120/80 mm Hg (120 systolic and 80 diastolic). Pumping Rate, blood volume, resistance, viscosity, etc. are some of the factors which affect the blood pressure of a person. Due to various reasons, the average blood pressure differs from each individual. The pressure values are categorized into five major divisions. Table 1.2 shows the categories of people in

Category	**Systolic (mmHg)**	**Diastolic (mmHg)**
Hypotension	$<$90	$<$60
Normal	90-120	60-80
Prehypertension	121-139	81-89
Stage 1 Hypertension	140-159	90-99
Stage 2 Hypertension	$\geq$160	$\geq$100

Table 1.2: Categories of Blood Pressure

accordance to their blood pressure range.

Blood Pressure (BP) is considered to be a strong indicator of an individuals well being and one of the most important physiological parameters that reflect the functional status of the cardiovascular system of human beings [12]. There is evidence of a direct relationship between blood pressure and cardiovascular diseases which represents nearly 50% of the worlds cause of death by noncommunicable diseases [13]. However, BP is also known to be a very unstable parameter and its variability alone is considered by some to be a separate independent risk factor itself [13]. In addition, conventional methods of monitoring BP in clinics or at home are either limited to simple measurement of systolic and diastolic blood pressure at intervals [14] or uncomfortable and unreliable to use over prolonged periods of time. Due to these enormous importance of heart rate and blood pressure monitoring, we designed a single device to calculate both heart rate and blood pressure which is non-invasive, cost-effective and accurate to a good extent. The main idea lies behind the concept of Photoplethysmography(PPG).

1.2 Existing Methods of Heart Rate measurement

1.2.1 Manual Methods

There exist several techniques for measuring heart rate. Most traditional methods manually measures heart rate by feeling pulse at the spot on the body where artery is close to the surface. Two most common spots are *radial artery* at the wrist and *carotid artery* at the neck. To take the radial pulse, one needs to place the tips of the index and second fingers of one hand on the inside wrist of the other hand. The fingers should be positioned just below the base of the thumb to take the radial pulse at the wrist as shown in Figure 1.1. To take the carotid pulse,

Figure 1.1: Measuring Radial Pulse

one needs to place the tips of the index and second fingers of one hand on the side of the neck just beside the windpipe as shown in Figure 1.2. However, this manual method requires a little skill to locate the pulse first and then counting precisely the subsequent rate. Althugh manual methods are popular, sometimes it might lead to inaccurate result.

Figure 1.2: Measuring Carotid Pulse

1.2.2 Digital Methods

Now-a-days, special devices, such as electrocardiographs, heart rate monitors and pulse oximeters are being widely used to measure heart rate. Among these devices, the working principle of a pulse oximeter is very interesting and is based on the so-called *photoplethysmogram* (PPG)—an optically obtained *plethysmogram* [29]. In its most common (transmissive) application mode, a sensor device is placed on a thin part of the patient's body, usually a fingertip or earlobe, or in the case of an infant, across a foot as shown in Figure 1.3. Ususally the term 'plethysmogram' is a volumetric measurement of an organ and 'photoplethysmogram' is simply an optical way of measuring such volume. We will study PPG in the next section with more details.

Figure 1.3: Measuring heart rate using pulse oximetry

1.2.3 Smart-phone Applications

The rapid improvement in smartphone technology has produced many medical applications [16]. There exist a myriad of applications that use only smart phone and its associated accessories (such as on-board camera) to detect heart rates within acceptable accuracy limit. Smartphone applications for measuring heart rate use almost the similar idea of pulse oximeter [17]. These applications are becoming popular because they require neither any costly equipment like pulse oximeter nor any special skill to measure heart rate in manual method. The requirement for heart rate measurement using smart-phones is just a phone with an on-board camera equipped with a flash (the quality of the camera does not influence much) and a special application installed. If the phone does not have flash then the measurement needs very well-lit condition to get accurate results. There are mainly two ways to measure heart rate via smartphone applications: (i) Contact method (usually suggests to use fingertip) (ii) Non-contact method (usually uses the front camera). In the first method, as the name suggests, a close contact of a body part and the camera is needed. On the other hand, in non-contact method such contact is not necessary. The algorithms and process of measurement in each category are discussed in the later sections.

1.3 Existing Methods of Blood Pressure Measurement

There are two major approaches when it comes to measuring BP:

- direct invasive methods
- indirect non-invasive methods

1.3.1 Invasive Methods

Invasive Methods are generally used in hospitals and intensive care units via the insertion of a catheter into a suitable artery thus providing a "beat-to-beat" record of the patients BP. This method provides more accurate readings, proving to be very useful in patients that are likely to display sudden BP changes (e.g. vascular surgery), patients that require a close BP control (e.g. head injured patients), or in patients receiving drugs to maintain BP [18]. On the downside, being a method that requires the invasion of the body (skin, tissue and vessel wall) with a hollow needle, its application is limited due to the risks and ethical aspects of the associated invasiveness. Therefore, such measurements usually only take place on seriously ill patients.

1.3.2 Non-invasive Methods

Non-Invasive Methods do not require skin penetration but instead the use of a cuff based technique. Although there has been recent developments concerning cuffless measurement systems in a body sensor network (BSN) context, these are not yet available for commercial purposes. There are mainly two types of commercial product of blood pressure measurement.

- Auscultatoric measurement devices
- Oscillometric measurement devices

Auscultatoric measurement devices

Auscultatoric measurement devices determine blood pressure by monitoring Korotkoff sounds. An inflatable cuff is placed around the upper arm at roughly the same vertical height as the heart, normally attached to a mercury manometer. The cuff is fitted and inflated manually by squeezing a rubber bulb or - as it is the case in Tensoval duo control automatically until the artery is completely occluded (about 30 mmHg above the systolic pressure). Then the pressure in the cuff is slowly released. When blood starts to fl ow in to the artery, the turbulent flow creates a pulse synchronic pounding (first Korotkoff sound). The pressure at which this sound is first detected is the systolic blood pressure. The cuff pressure is further released until no more sound can be detected at the diastolic arterial pressure. The process is briefly shown in Figure 1.4. The main shortcomings of this process is we need an expert to measure the blood pressure.

Oscillometric measurement devices

Oscillometric measurement devices use an electronic pressure sensor with a numerical readout of blood pressure. In most cases the cuff is inflated and released by an electrically operated pump and valve, which may be fitted on the wrist (elevated to heart height), although the upper arm is preferred. Initially the cuff is inflated to a pressure in excess of the systolic arterial pressure,

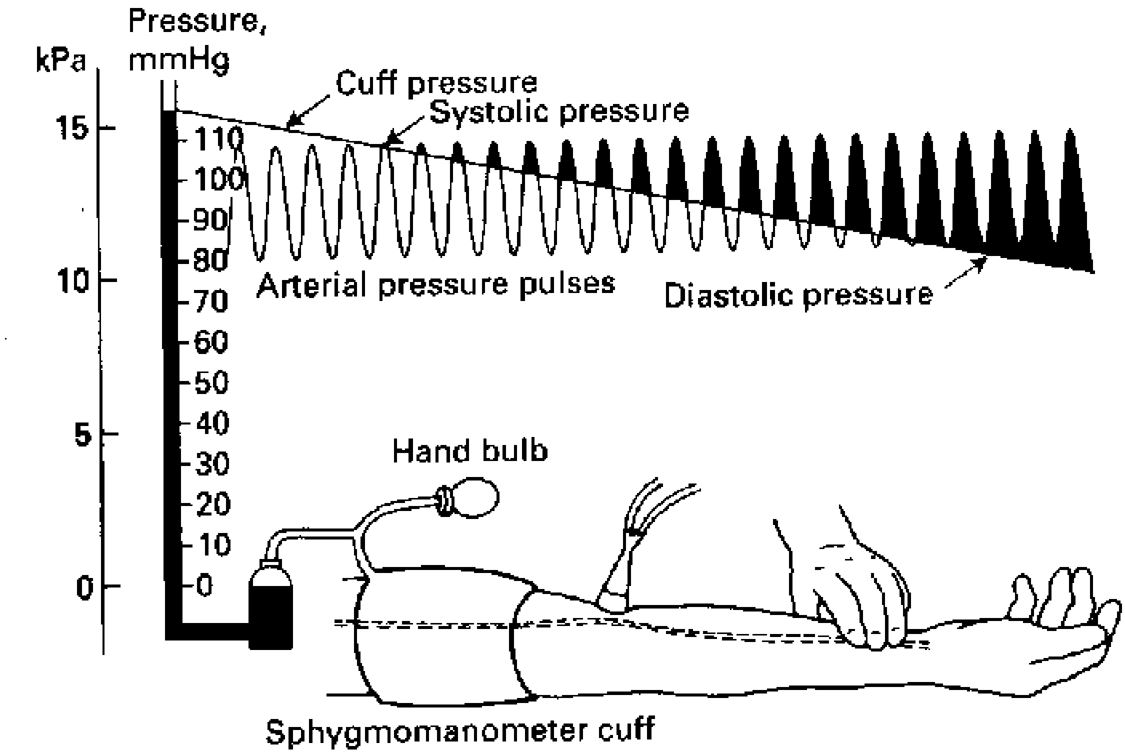


Figure 1.4: Measuring heart rate using pulse oximetry

and then the pressure reduces to below diastolic pressure. Once the blood flow is present, but restricted, the cuff pressure will vary periodically in synchrony with the cyclic expansion and contraction of the brachial artery. The values of systolic and diastolic pressure are computed from the raw data, using an algorithm.

1.4 Summary

Heart rate, blood pressure, respiratory rate and body temperature are the four vital signs of human body. Heart rate of a person can be determined manually or digitally. Photoplethysmography (PPG) is an optical way of volumetric measurement of blood in an organ which is massively used for digital measurement of heart rate. Various Smartphone applications are available for measuring heart rate using either contact or non contact method. Blood pressure of a person can be measured in an invasive way and also in a non-invasive way using cuffs.

1.5 Objective of Thesis

Our objective is to construct a single device to measure both heart rate and blood pressure which will bring about some major changes compared to the available ones. Firstly, this is a cost-effective option to measure heart rate and blood pressure. Whereas the price of the devices already available in market ranges from 25 USD to 100 USD, the device that has been constructed in this project cost roughly from 3 USD to 5 USD. Secondly, the device provides an easy way to interface with personal computers and mobile phones. This opens up opportunities to perform further analysis on the recorded data. Thirdly, although there are a few analog devices to measure heart rate and blood pressure, the patient needs help from another person to do so. In this device the patient can measure his/her vital signs by his/her own. This device can be used without any need of assistance from others. Finally, the device is easy to use. The user only needs to place a fingertip on a sensor, as opposed to enclosing fingertip inside a cap or wearing a cuff.

1.6 Thesis Organization

This thesis is organized as follows. Chapter 1 gives a brief discussion of the existing techniques to measure heart rate and blood pressure. Chapter 2 gives a concrete definition of photoplethysmography followed by the idea behind measuring heart rate and estimating blood pressure. The chapter also discusses the basic idea behind measuring blood pressure using PPG and ECG signal. It also discusses the algorithm of measuring heart rate using smartphone application. Chapter 3 presents a short survey of the performance of the various applications capable of measuring heart rate. Chapter 4 is the heart of this book. In chapter 4 the circuit construction procedure along with its three phase is presented in details. The necessary ideas like peak detection, linear correlation is explained in this chapter. The chapter also presents the procedure of wireless transmission with nRF24L01. In chapter 5, we present the accuracy of our device for measuring heart rate and estimating blood pressure. Chapter 5 summarises our thesis work states our strengths and weaknesses and states future work directions.

Chapter 2

Background Theory

The main idea behind measuring heart rate and blood pressure in our process is photoplethysmography(PPG). A PPG signal is generated from the constructed device which is further processed to measure heart rate and estimate blood pressure. The mechanism of smartphone applications differ to a great extent from our constructed device. We will discuss these issues in this section.

2.1 Photoplethysmography

Photoplethysmography (PPG) is an optical measurement technique that can be used to detect blood volume changes in the microvascular bed of tissue [19]. It has widespread clinical application, with the technology utilized in commercially available medical devices, for example in pulse oximeters, vascular diagnostics and digital beat-to-beat blood pressure measurement systems. The word plethysmograph has been derived from two Greek words - ‘plethysmos’, meaning increase; and ‘graph’, meaning write [20]. The basic form of PPG technology requires only a few opto-electronic components: a light source to illuminate the tissue (e.g. skin), and a photodetector to measure the small variations in light intensity associated with changes in perfusion in the catchment volume. PPG is most often employed non-invasively and operates at a red or a near infrared wavelength. Plethysmography is the volumetric measurement of an organ, resulting from fluctuations in the amount of blood or air it contains. The change in blood volume is synchronous to the heart beat, so it can be used to detect heart rate. Photoplethysmography is just a means of plethysmography that uses optical techniques. There are two basic types of photoplethysmography: transmittance and reflectance [21, 22]. Reflectance photoplethysmography has been used in this project. In reflectance photoplethysmography, a light source and a light detector are placed on the same side of a body part [23] - for example, underneath the fingertip as shown in figure 2.1. The light source generally used is an infrared light emitting diode, and the detector generally used is a phototransistor.

When the fingertip is illuminated by the source, three things will happen depending on the volume of blood in the fingertip: certain amount of the light will be absorbed, certain amount

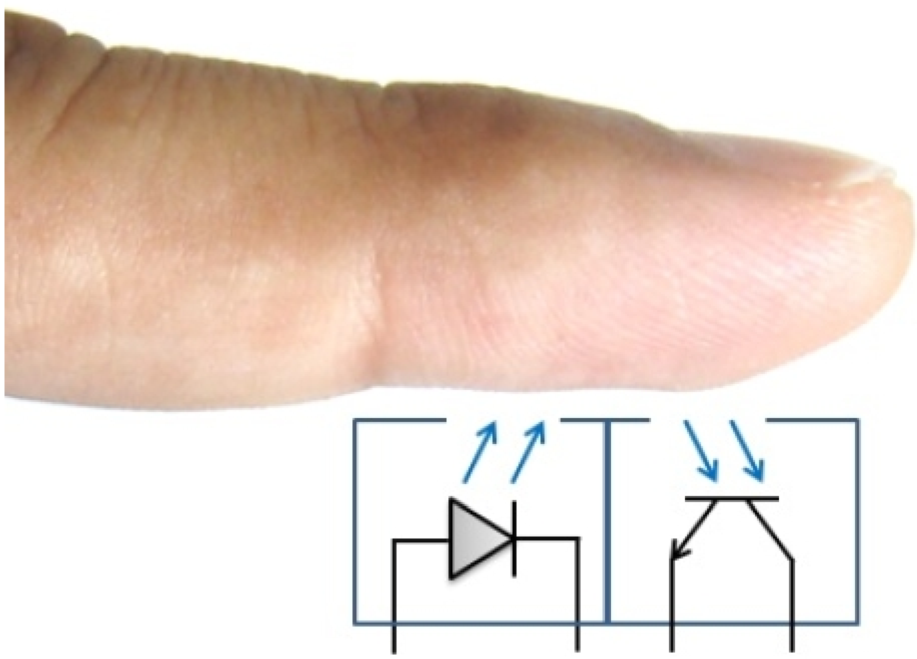


Figure 2.1: Reflective photoplethysmography.

of the light will be transmitted, and certain amount of light will be reflected [24]. The intensity of the reflected light varies with the volume of blood in the fingertip, which in turn varies in accordance with heart beat. Specifically, lower intensity of reflected light indicates higher volume of blood and vice versa [25]. A plot of this varying intensity of light with time is known as photoplethysmographic signal [26]. The time period of each pulse in the signal is dictated by heart beat and the amplitude by the concentration of various constituent parts of arterial blood [27]. The PPG signal is composed of two components: AC and DC [28]. The AC component is superimposed on the DC component. The AC component is the result of pulsatile changes in arterial blood volume [29]. As this arterial blood volume is synchronous with the heart

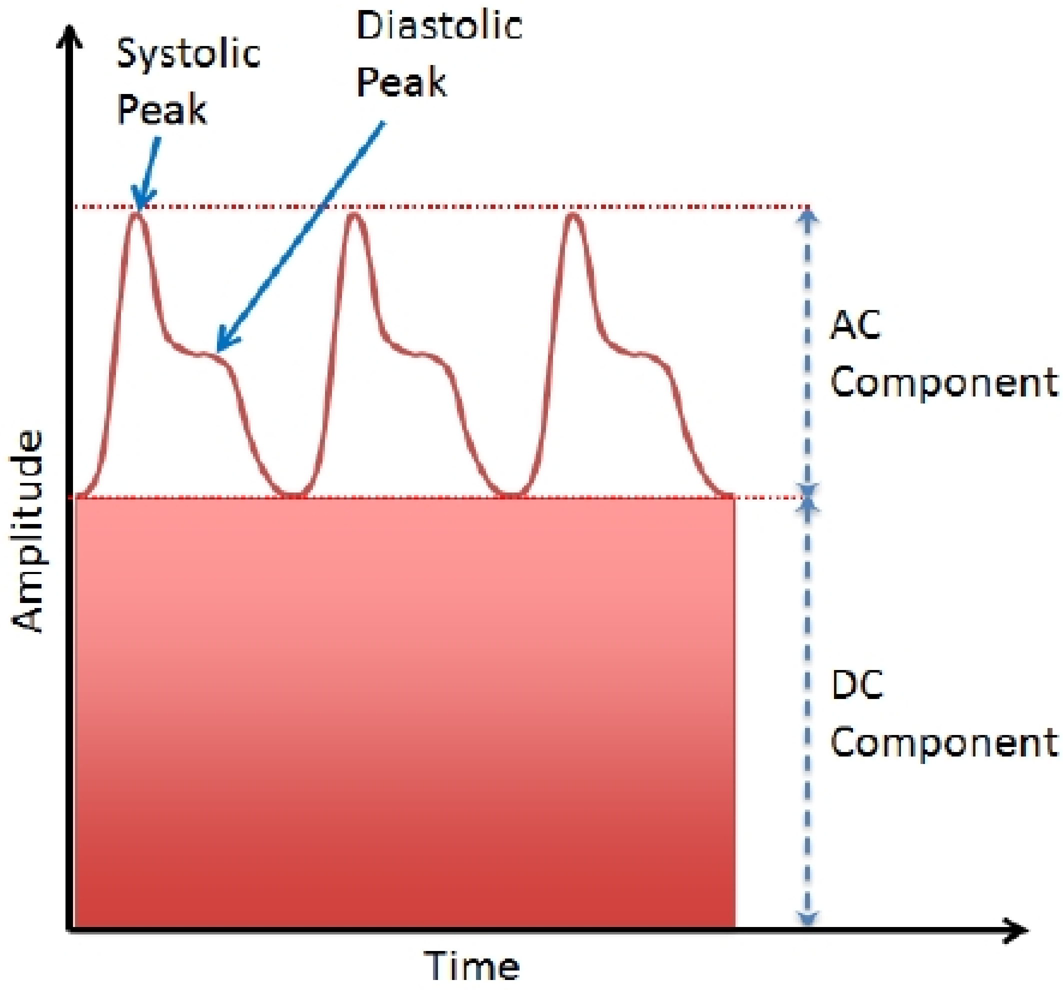


Figure 2.2: PPG signal.

beat, the AC component can be used to measure heart rate. The DC component relates to the tissues, bones, and average blood volume [30]. This DC component must be removed to analyze the AC component. As it happens, the AC component is a very small portion of the whole signal. As a result the resulting PPG signal must be filtered and amplified before it can be utilized in detection of heart rate. Figure 2.3 shows a PPG signal as seen in a DSO NANO V3 oscilloscope. This signal is refered as the PPG Signal.

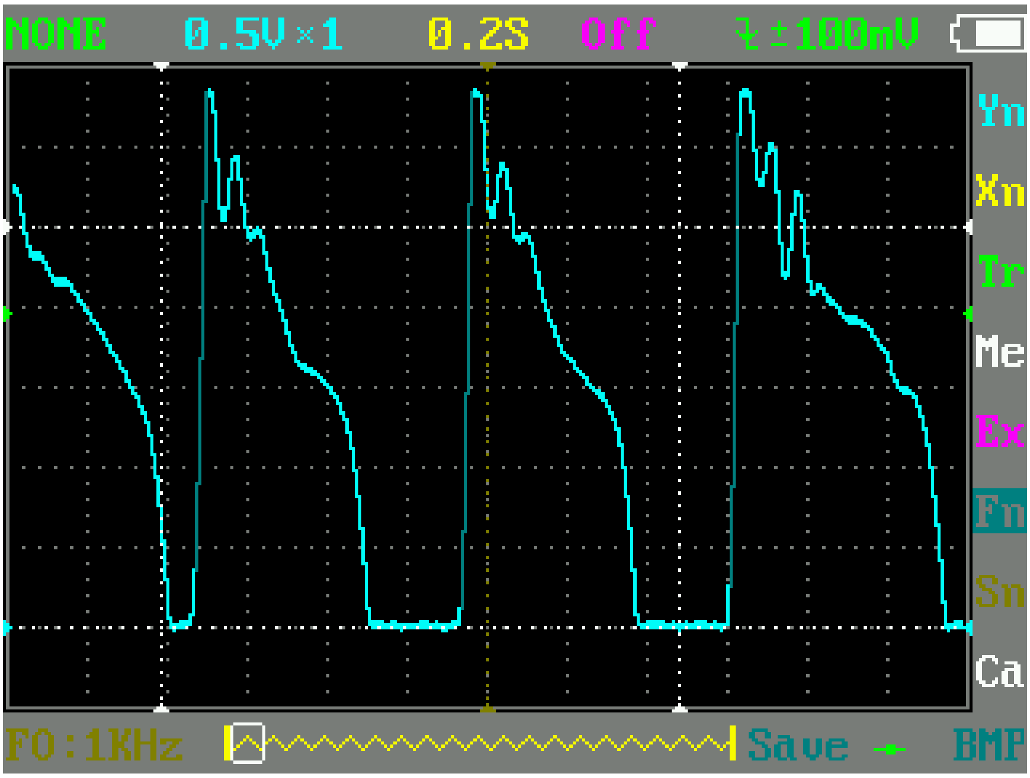


Figure 2.3: PPG signal in oscilloscope.

2.2 Heart Rate Measurement from PPG Signal

The peripheral pulse wave, as detected via PPG, characteristically exhibits systolic and diastolic peaks as shown in Figure 2.2. The systolic peak is a result of the direct pressure wave travelling from the left ventricle to the periphery of the body, the diastolic peak (or inflection) is a result of reflections of the pressure wave by arteries of the lower body [31]. Each Systolic peaks denotes a heart beat. If, we can calculate the time interval between two systolic peaks then we can calculate the heart rate in beats per minute(bpm). Let us consider T be the time intervals between two systolic peaks. Then we can define heart rate by the following equation

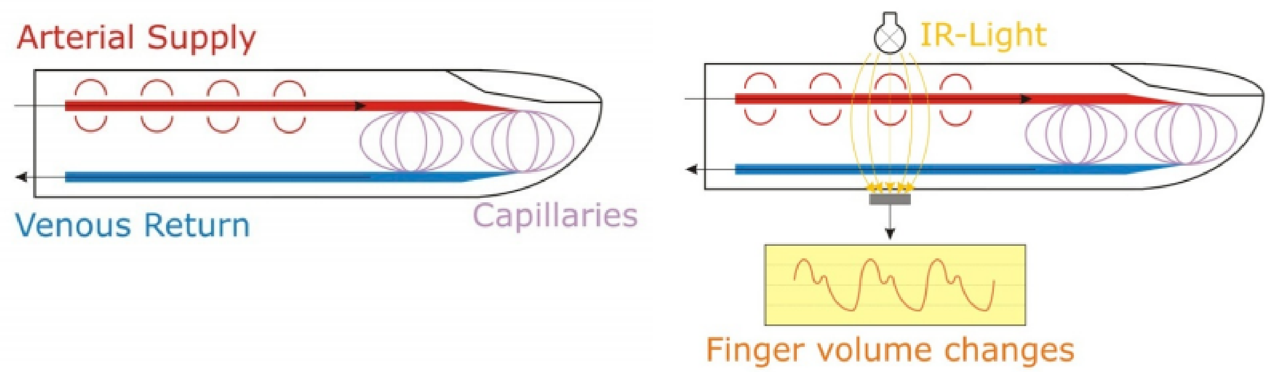
$$HR = \frac{60}{T} \tag{2.1}$$

To calculate the time interval T, we need to detect the systolic peaks. We will discuss the peak detection algorithm we used in later sections in more details.

2.3 Blood Pressure Measurement from PPG Signal

2.3.1 Volume-clamp method

This method was introduced by Pez in 1973 and is based on the principle of dynamic vascular unloading of the finger arterial walls using an inflatable finger cuff with a built-in photoplethysmographic (PPG) sensor [29]. Plethysmographic devices can't measure blood pressure, but they can measure blood volume changes. Yet, these volume changes can't be transformed into pressure, due to the non-linearity of the elastic components of the arterial wall, as well as the non-elastic parts of the smooth muscles[32]. So, to linearize this phenomenon a counter pressure as high as the pressure inside the artery needs to be applied as shown in Figure 2.4 . Blood volume can be kept constant if the same pressure is applied from the outside. Therefore, the continuously changing pressure that is needed to keep the arterial volume constant corresponds to the intra-arterial pressure and thus it is an instantaneous, continuous measure for arterial blood pressure [32]. This is the principle behind the vascular unloading technique shown in Figure 2.5.



(a) Finger Physiology (b) Plethysmographic method

Figure 2.4: **Plethysmographic method:** Infrared light, emitted from a LED, is sent through the finger. The light is partly absorbed by arterial blood, which changes according to the pulse. A light detector receives the non-absorbed light on the other side of the finger and therefore produces a continuous pulse signal. Figures adapted from http://www.cnsystems.at/en/vascular-unloadingtechnique.

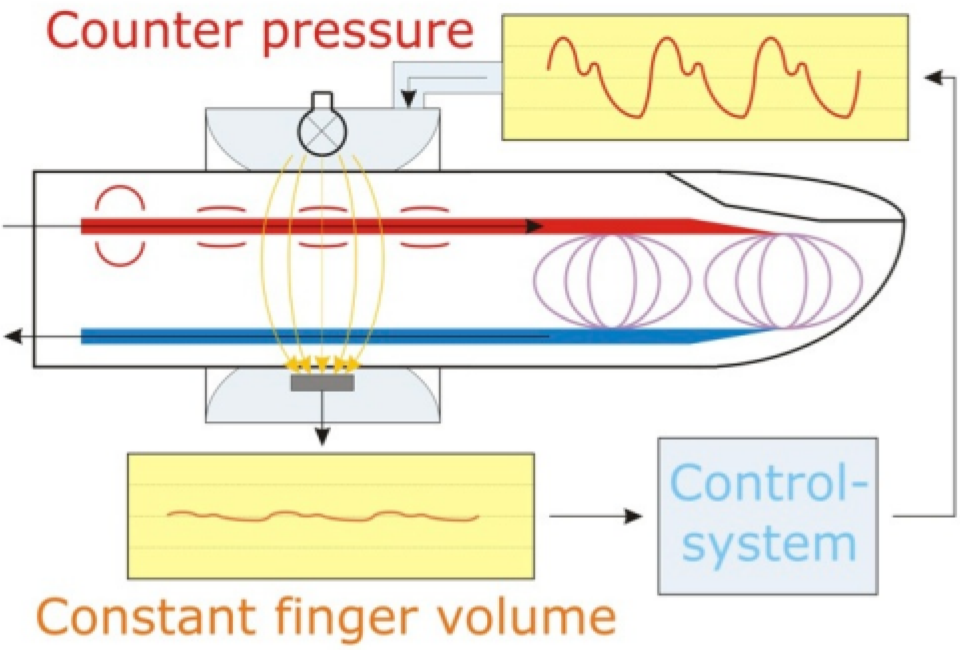


Figure 2.5: Vascular unloading technique: The volume signal is fed into the control system that produces a counter pressure in a cuff placed over LED and light detector. The control condition of the system keeps the volume signal constant at any time by controlling the alterable pressure in the cuff (adapted from http://www.cnsystems.at/en/vascular-unloading-technique).

Finapres (Finapres Medical Systems, Amsterdam, The Netherlands) technology was introduced in the early 1980s providing the measurement of the arterial blood pressure waveform at the finger on a continuous beat-to-beat basis, using the vascular unloading technique described above Figure 2.5. It uses a extremely rapid servo system with the cuff actuator in order to adjust the pressure in the finger fast enough to keep the photoplethysmograph constant.

Finapres cuff pressure has been compared to intra-arterial pressure in a large number of studies in both awake and anaesthetized subjects. Blood pressure variations were introduced by different means [18]. The obtained wave form using this procedure has been found to resemble to the intra-arterial pressure wave in most subjects and is considered to give an accurate estimation of the changes of systolic and diastolic pressure [34]. Still, results have concluded that the finger arterial mean pressure measured with Finapres is 5 to 10 mmHg lower than intra-arterial pressure in the brachial artery. The Finapres system is no longer commercially available, but alternative blood pressure devices have been introduced: the Portapres and Finometer systems (Finapres Medical Systems BV, Holland) and the Task Force Monitor system (CNSystems Medizintechnik, GmbH) [32].

With the development of the Portapres measurement device it was possible, for the first time, to record long-term 24 h blood pressure profiles and obtain daily variations in blood pressure. In consequence, related cardiovascular parameters of healthy subjects and patients during their normal daily activities could be obtained and analysed [34]. It was considered a breakthrough in ambulatory non-invasive blood pressure measurement.

2.3.2 Blood pressure estimation using the pulse transit time

Even though the above described non-invasive methods for measuring BP present good results, their ambulatory characteristics show a number of limitations that makes it unsuitable for individuals to wear in a truely comfortable and reliable way. Furthermore, the vertical offset between the measurement location and the level of the heart is often a source of serious measurement error[35].

Potentially the most useful and convenient indirect parameter for achieving a continuous non-invasive measurement of BP in an ambulatory way that is comfortable and reliable is the pulse wave velocity (PWV) or the inverse, pulse transit time (PTT). PTT is the time it takes a pulse wave to travel between two arterial sites, usually from the aortic valve to the finger [14][11]. The principal factors that determine the speed of propagation of the pulse wave are the stiffness and tension in the arterial walls. In turn, speed propagation of the pulse wave depends to a large extent on blood pressure. An increase in BP means an increase in arterial wall tension and stiffness, thus decreasing PTT, and in reverse a drop in BP decreases arterial wall tension and stiffness, therefore extending PTT [11]. It can then be concluded that PTT is inversely proportional to BP and the falls in blood pressure corresponds to rises in PTT [11].

The theoretical framework behind these statements is known as the Moens-Korteweg equation. It gives us the pulse-wave velocity as a function of vessel and fluid characteristics, thus outlining the relationship between PTT and blood pressure [14]:

$$c = \frac{L}{PTT} = \sqrt{\frac{E.h}{\rho 2R}} \tag{2.2}$$

To find a relation between blood pressure and PTT, the above equation can be used. From this, a logarithmic relation between the two parameters is obtained:

$$P = k_1 \ln(k_2.PTT) \tag{2.3}$$

where k_1 and k_2 are arbitrary constants and P the fluid pressure, in this case BP. BP can be then estimated using a linearised version of the logarithmic model. Different linearised versions of the logarithmic model have been used in various cuffless systems that attempt to estimate BP noninvasively, some of which include additional data features, such as heart rate (HR).

Recently, several methods and devices for cuffless BP estimation using PPG signals, have been proposed in the literature. Experiments have been conducted on groups of subjects, where independent instruments are used to acquire ECG and PPG, thus estimating BP. Simultaneously, a reference method for BP measurement is applied and compared with the estimated values. The most frequently used models based on simplified and linearised versions of the Moens-Korteweg equation 2.2 are:

- Cattivelli and Garudadri [36] use models of the form:

  $$BP = aPTT + b \tag{2.4}$$

  which the authors considered to be more robust to noisy measurements.

- Wong and Poon [38] observed that for some cases, BP was highly correlated with instantaneous heart-rate. Furthermore, they considered the arteries to be purely resistive, thus meaning that BP would increase linearly with heart-rate (HR):

  $$BP = aPTT + bHR + c \tag{2.5}$$

- McCombie et al [37] suggested the following model:

$$BP = \frac{a}{PTT^2} + b \tag{2.6}$$

- Lastly, Fung et al [39] considered:

$$BP = a\ln(bPTT) \tag{2.7}$$

On a different perspective, Ferreira Marques et al [40] proposed an online calculation of BP based on the method first described by Pandian et al [41]:

$$P_{sys} = [k_s \times (C_{dx})^2] + k_{sys\_cal} \tag{2.8}$$

$$P_{dis} = [k_d \times (C_{dx})^2] + [k_{IHR} \times IHR_i] + k_{dis\_cal} \tag{2.9}$$

where C_{dx} is the inverse of the delay between the R peak of the ECG wave and the 50% slope on the ascending PPG part of the PGG wave of each pulse Figure 2.6.

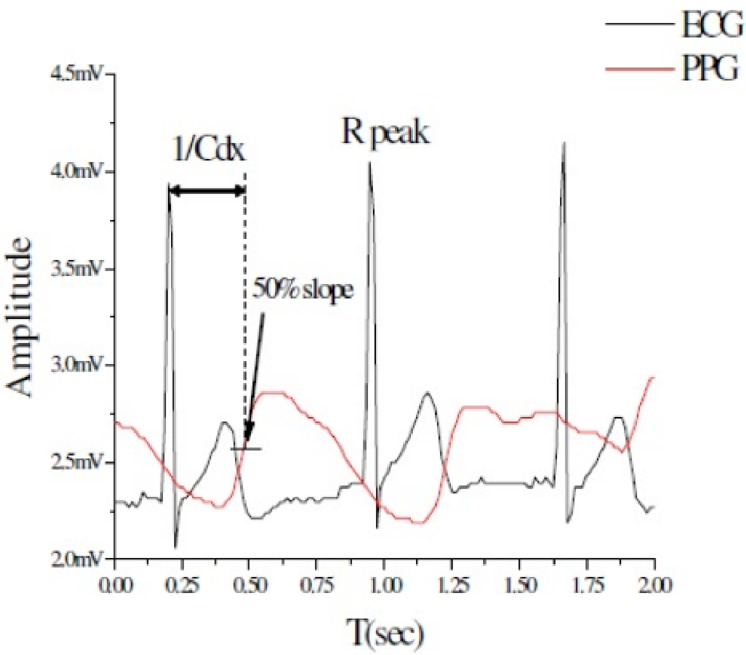


Figure 2.6: Example of PPG and ECG signals

IHR_i is the instantaneous heart rate for the ith pulse, k_s and k_d are fixed constants; k_{sys_cal} and k_{sys_cal} are the systolic and diastolic calibration constants, $k_I HR$ is the constant related to the IHR [40]. The given equations are considered to be the most accurate for calculation of the systolic and diastolic blood pressure [40].

From the above discussions, we can see that to measure blood pressure we need PPG signal and ECG signal. Blood Pressue is closely related to PPG signal as in all the equations we can see the effect of heart rate and PPG signal.

2.4 Smartphone Applications

2.4.1 Contact Method

The working principle of the contact method closely matches with the Eulerian Video Magnification (EVM) [42]. EVM is one way to record motion in video that is imperceptible for a human to see with the naked eye. A sequence of spatial decomposition and temporal filtering is applied to a video file and the resulting file contains all details with magnified motions. As stated earlier, the smartphone application utilizes an imaging acquisition concept similar to the *pulse oximeter*. The subtle difference between a pulse oximeter and the smart phone using contact method is, the former one uses infrared light to determine oxygenated and deoxygenated blood based on the blood opacity, but the later one captures and analyzes images (i.e., video frames) to determine heart rate based on blood opacity.

The process works by placing the subject's index finger on the smartphone camera in such a way that it covers both the camera and flash as shown in Figure 2.7. The finger should not be pressed too hard because it may stop blood circulations. After placing the finger the application starts to capture the frames keeping camera flash turned on. Every time the heart beats, it pushes blood to every part of the human body. When the capillary is full of blood, it will block the amount of light that can pass through. When the blood retracts, more light can pass through the tissue. Clearly this changes in opacity affects the color of the skin and

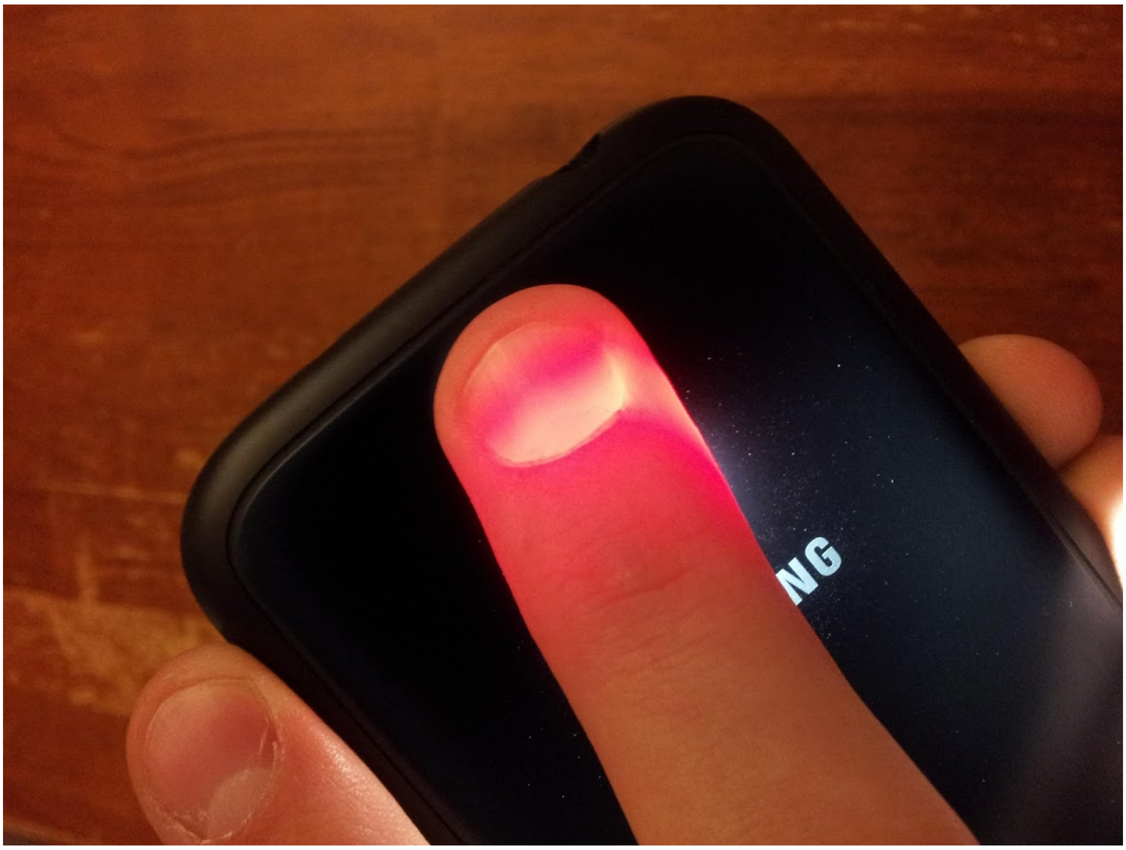


Figure 2.7: How to place the finger while measuring heart rate

can be detected either by analyzing average red components of the RGB values of the frames as in [44] [45] or the average green components of the RGB values as in [47]. Thus a PPG wave shape can be obtained by plotting average red/green values in the subsequent frames as shown in Figure 2.8 [50]. Observe how the signal contains *sharp* local maxima called peaks that quickly changes from large positive values to large negative values. Each peak corresponds to a single heart beat.

However, the original captured signal is ususally too noisy and may contain fake peaks due to movements of the finger above camera lens. So the next step is to detect the real peaks. For this purpose the captured signal is usually normalized using smoothing differentiation [48] and then filtered with a moving average filter [49]. Heart rate (HR) can be measured from the time interval between the peaks. The time difference between consecutive peaks is computed which is known as R-R interval (RRI). From the RRI values the HR is estimated using Equation 2.10

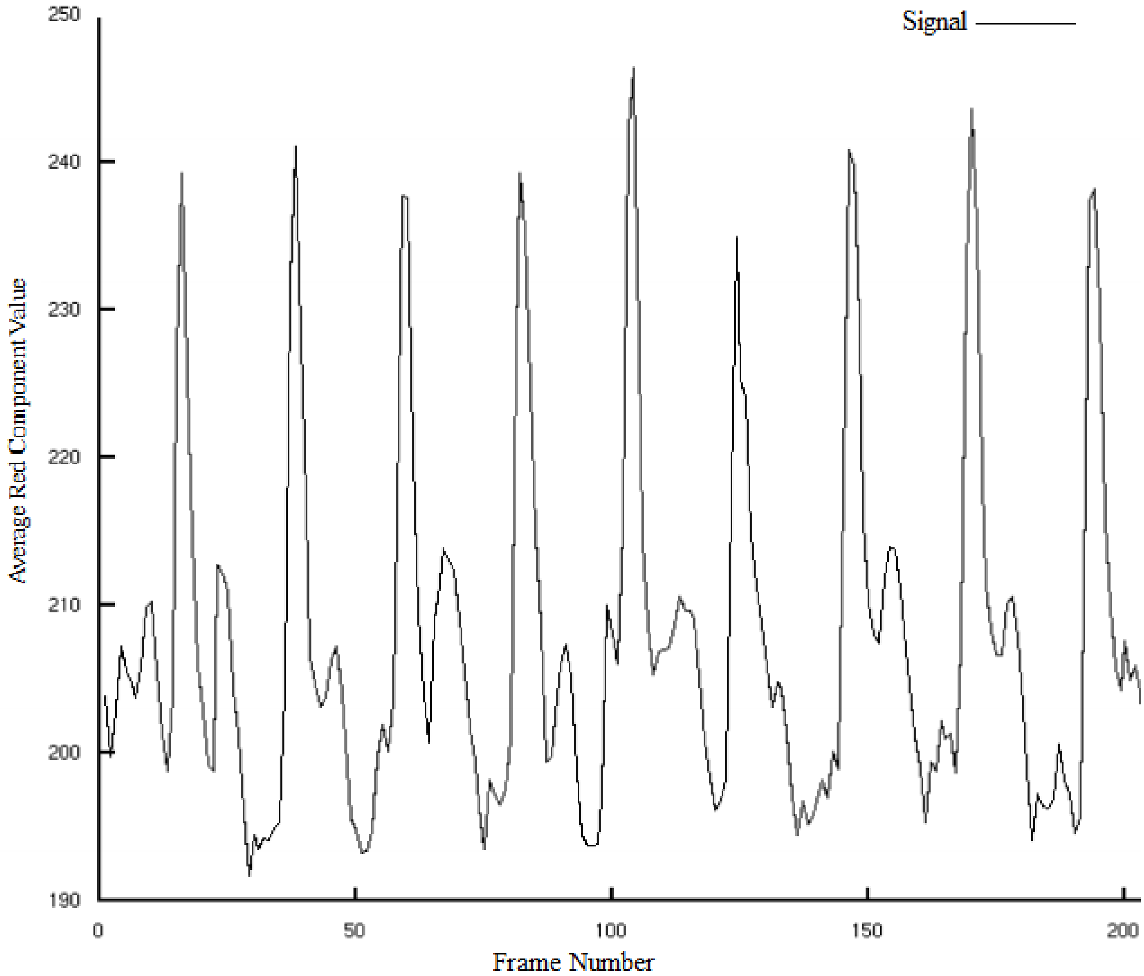


Figure 2.8: Time series of average red component values of the frames

given below.

$$HR = \frac{60}{RRI} \tag{2.10}$$

The RRI in Equation 2.10 is measured in seconds, therefore the numerator is 60 seconds. Sometimes the heart rate can be measured by directly counting the number of peaks present in the PPG. Further improvement on the algorithm was proposed in [50] which is being used by some of the applications.

2.4.2 Non-contact Method

This process works by placing the subject's face in front of the smartphone camera in a predefined way as shown in Figure 2.9. The subject has to hold still for a few seconds to get the

Figure 2.9: User interface of an application which utilizes non-contact method

measurements. The underlying principle for calculating heart rate is similar to contact method. Heartbeat causes micro color changes on the subject's face. The software uses camera to detect these micro changes, with beat-to-beat accuracy. The algorithm is built based on reliable non-contact photolethysmography concept [42] [52] which is validated by Kwon et. al. [53] later on.

2.5 Summary

Photoplethysmography is a popular non-invasive method of measuring heart rate. This can be implemented by measuring the reflected or refracted light intensity of infrared light from human skin. The peaks of the received signal are detected and the corresponding time intervals are used in measuring heart rate and blood pressure. Smartphone applications use this principle to measure heart rate using on board camera.

Chapter 3

Comparison between the smartphone applications : A Short Survey

Detecting heart rate using *only* cameras has an added advantage because in such case the users do not require any additional accessories and/or skills to measure heart rate rather than simply placing his body parts infront of the camera and capturing image/video. Almost all of these applications are based on similar techniques that we described in the previous section. Although there exist a notable volume of research on how to detect heart rates using smart phone cameras, no study has been conducted to compare the accuracy and performance of such available smartphone applications. Although the main focus of this study is related to the performance analysis of these applications, this short survey also answers few important (and exciting) questions to the research community: (1) what smartphone applications are available for detecting heart rates using attached cameras only, (2) what accuracy level do they offer, (3) what are the underlying techniques/algorithms to detect heart rates using simple image/video analysis, (4) are these applications able to capture heart rates accurately under various body conditions, such as sleeping and waking up, and (5) does the accuracy level varies based on smartphone's associated operating system.

In this chapter we describe the experimental set up used for data collection.

3.1 Subjects

A convenience sample of 15 adults, aged 18-55, volunteered and participated in this study. The diverse sample of participants consisted of 6 females and 9 males. The subjects' weight and height were measured before the study. Descriptive characteristics of each subject are presented in TABLE 3.1.

Table 3.1: Descriptive Characteristics of the Subjects

Sex	Age	Height (in)	Weight (lb)
F	25	62	112
F	18	63	110
F	33	59	154
F	23	61	123
F	49	65	154
F	19	64	128
M	23	69	138
M	31	70	165
M	55	66	172
M	38	70	170
M	19	69	128
M	48	64	180
M	28	65	137
M	33	73	202
M	26	69	198

3.2 Devices and Applications Used

Three different smart-phones were used to measure the heart rate of the subjects. The devices are *Samsung Galaxy S II* (8 MP primary camera), *Walton Primo D2* (2 MP primary camera) and *iPhone 4S* (8 MP primary camera). The former two use Android Operating System and the later one uses iOS. All of these devices are equipped with flash and front camera.

Smartphone applications can be found at App Store [54] and Google play [55] for the iOS and the Android platform respectively. For this study five applications were selected for the Android platform based on their rating, number of rating and number of installs. Four of the applications use the contact method and the remaining one uses the non-contact method. Description of the applications are presented in TABLE 3.2 according to the information of Google Play. Out of the five applications, four have the iOS version which were used to conduct study on iOS platform.

Table 3.2: Applications used

Name	Method	Developer	Rating	Installs	iOS
Instant Heart Rate[56]	Contact	Azumio Inc.	4.3	50,000,000	Yes
Runtastic Heart Rate[57]	Contact	Runtastic	4.4	5,000,000	Yes
Heart Beat Rate[58]	Contact	Bio2Imaging	4.2	500,000	Yes
Heart Rate Monitor[59]	Contact	Mobile Essentials	3.5	1,000,000	No
What's My Heart Rate[60]	Non-Contact	ViTrox Technologies	4.0	500,000	Yes

These applications were installed in each of the above mentioned smart-phones. However, it was observed that for the same application the collected data does not vary much with the model of the smartphone being used. For the same application, mean of the readings was noted down which will be discussed in the later sections.

3.3 Procedure

As shown in TABLE 3.2 *Instant Heart Rate, Runtastic Heart Rate, Heart Beat Rate* and *Heart Rate Monitor* use the contact method. For these applications, both the camera and flash of the smartphone were covered with a finger of the subject as shown in Figure 2.7. It is worth mentioning that positioning the finger inappropriately may produce incorrect result. For each subject, two different sets of heart rate measurements were taken. One set was taken just after the subject woke up in the morning and another set was taken at another time during the day while resting.

Again referring to TABLE 3.2 the application named *What's My Heart Rate* uses non-contact method. Well-lit environment is a very important requirement for this application. The subject was asked to sit in a bright place and the heart rate was measured using the front camera as shown in Figure 2.9.

For both the methods the actual heart rate was measured manually (from wrist) for benchmark purpose immediately after measuring with the applications. To authenticate the working procedure, the applications were run on some invalid inputs other than human organs to see whether the applications provide any *false negative* in the results. A white piece of paper, a black piece of paper, laptop monitor, a blinking LED and a printed image of a human were used as these invalid inputs. This study was taken to ensure whether the applications were able to detect human body or not. The result is presented in Table 3.3

Table 3.3: Results for invalid objects as input

Application Name	Black Paper	White Paper	Monitor	Blinking LED	Image
Instant Heart Rate	67	96	95	78	NA
Runtastic Heart Rate	No Reading	No Reading	No Reading	No Reading	NA
Heart Beat Rate	No Reading	No Reading	No Reading	No Reading	NA
Heart Rate Monitor	78	91	75	95	NA
What's My Heart Rate	No Reading	No Reading	No Reading	No Reading	56

3.4 Experimental Results

In this section we present experimental results showing the accuracy comparison of various smartphone applications using contact and non-contact method.

For each application, the two sets of collected data were tabulated along with the manually measured heart rate for comparison. The following five graphs (Figure 3.1 - 3.5) represent the collation between heart rate measured with a particular application and the corresponding standard value measured manually.

The mean square error (MSE) of each application is presented in TABLE 3.4.

Response of the applications when non-living objects were used as subject is illustrated in TABLE 3.3.

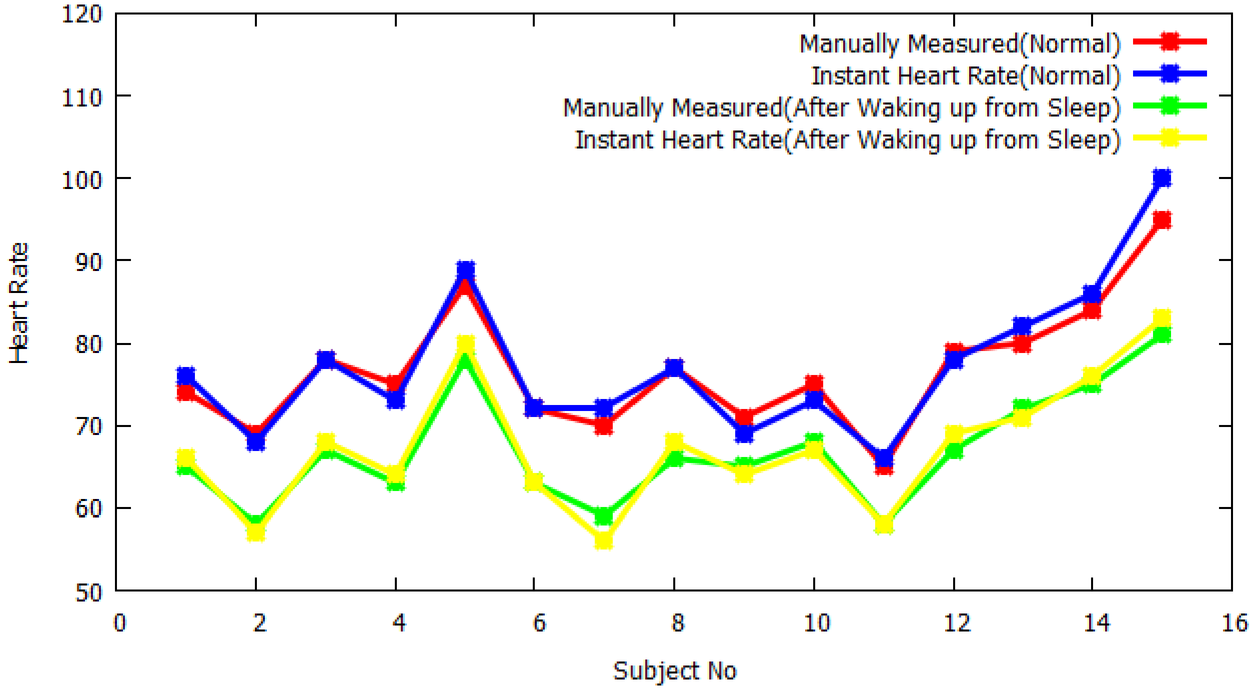


Figure 3.1: Analysis of Heart Rate Using *Instant Heart Rate*

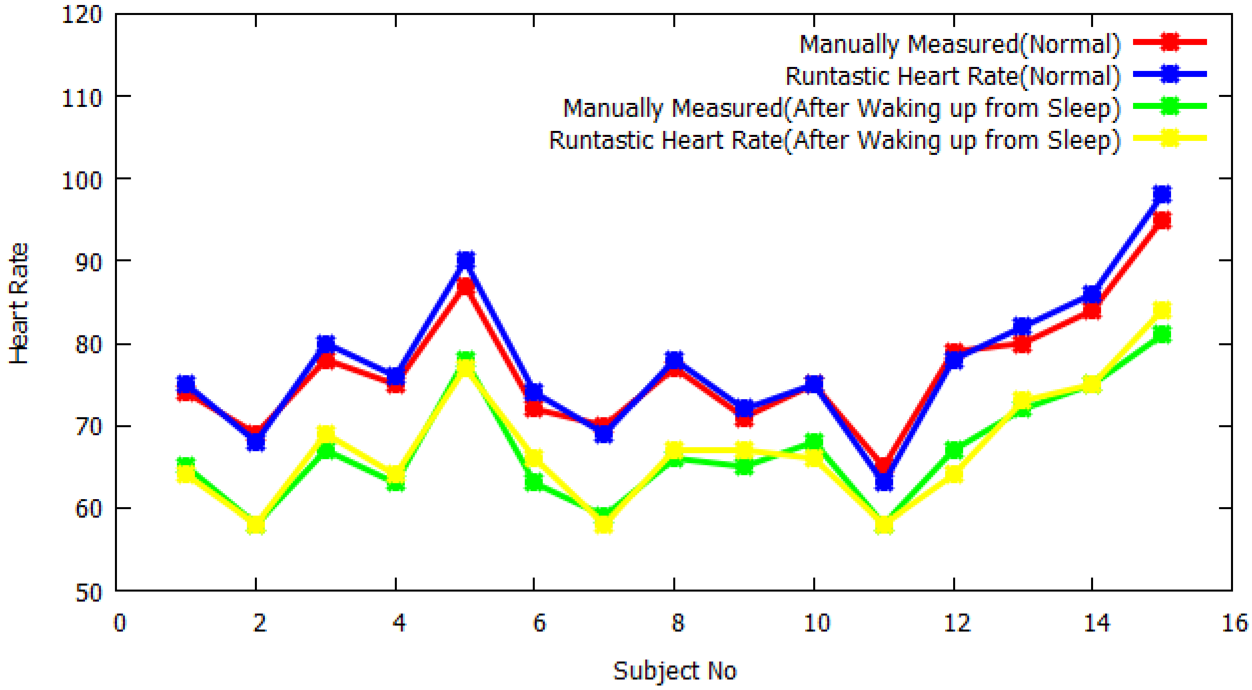


Figure 3.2: Analysis of Heart Rate Using *Runtastic Heart Rate*

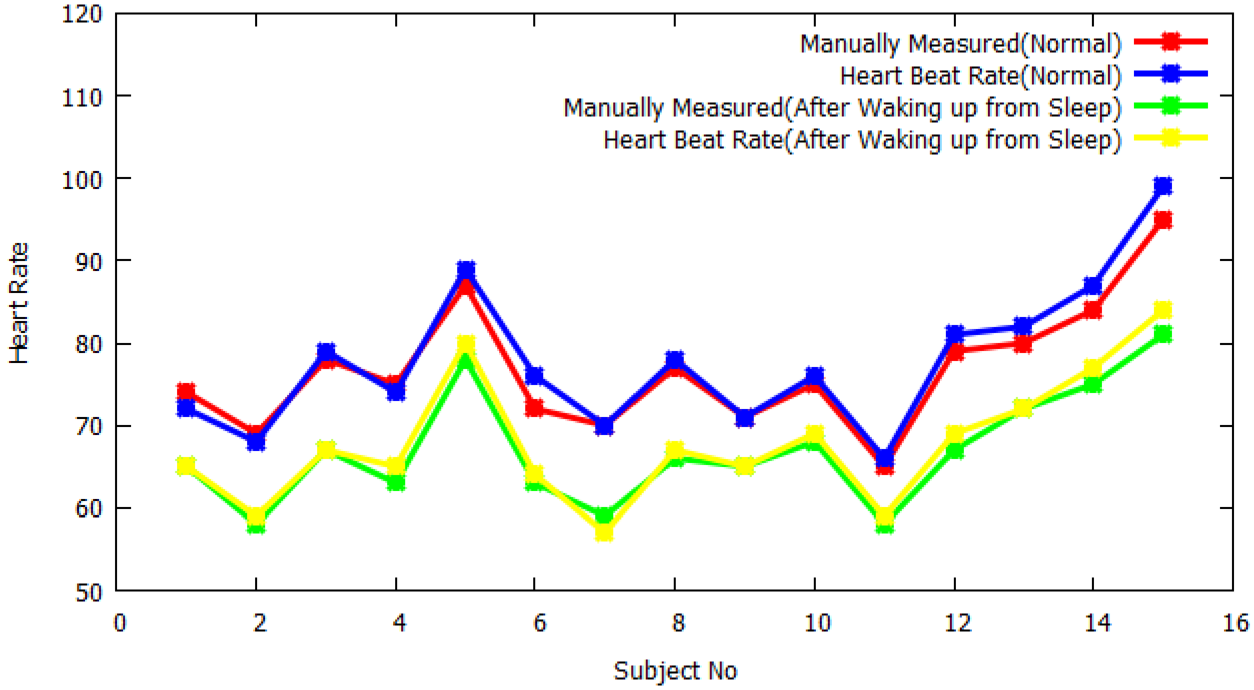


Figure 3.3: Analysis of Heart Rate Using *Heart Beat Rate*

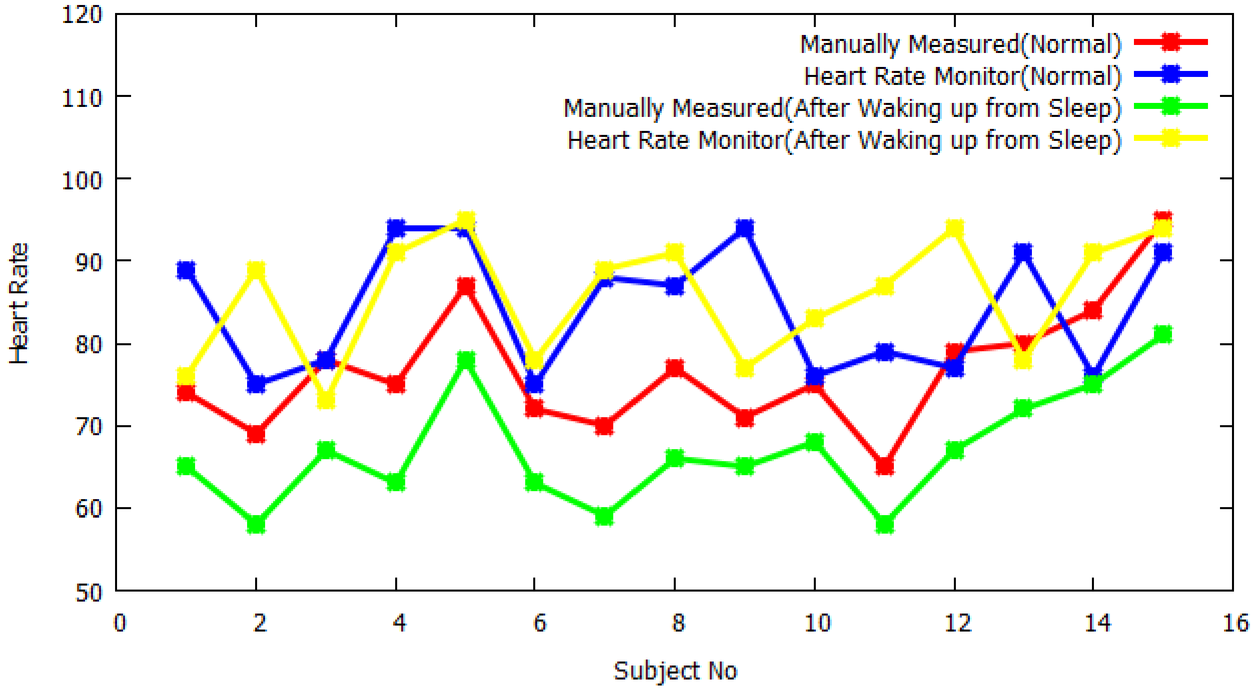


Figure 3.4: Analysis of Heart Rate Using *Heart Rate Monitor*

Figure 3.5: Analysis of Heart Rate Using *What's My Heart Rate*

Table 3.4: Mean Square Error(MSE) of the applications

Application Name	MSE (Normal)	MSE(After waking up from sleep)
Instant Heart Rate	3.4	2.2
Runtastic Heart Rate	3	3
Heart Beat Rate	4.2	2.267
Heart Rate Monitor	135.7	422.7
What's My Heart Rate	48.4	45.53

3.5 Discussion

Referring to TABLE 3.4, it can be noticed that the MSE value of the applications using contact method vary from as small as 2 to a quite large value 422.7. The first three applications *Instant Heart Rate, Runtastic Heart Rate* and *Heart Beat Rate* using contact method seem to produce results in a quite acceptable range. On the contrary, readings by *Heart Rate Monitor* fluctuated irregularly which is the reason for its large MSE value. By careful observation an interesting trend can be noticed from the graphs (Figure 3.1 - 3.5) and MSE values (TABLE 3.4). For each of the applications, deviations tend to be higher for the higher values of heart rates. On the other hand, lower values of heart rates have comparatively lower deviations. This phenomenon can be assumed to be caused by the scaling factor of the time interval used for each application for collecting data. Since the applications take sample for a shorter time period and then convert it into beats per minute, this factor may also be responsible for some of the errors introduced. Fake peaks in PPG signal is another reason for the errors.

Another interesting factor to follow is, *Instant Heart Rate* and *Heart Rate Monitor* responded to an attempt to measure heart rate of non-living objects despite *Instant Heart Rate* provided results very close to accurate value while using fingertip. On the contrary, *Runtastic Heart Rate* and *Heart Beat Rate* did not produce any reading until a valid human body part was detected.

Although the application named *What's My Heart Rate* using the non-contact method provides extra flexibility in measuring heart rate, the performance of the application is not consistent. The effect of ambient light is mainly responsible for this erroneous result. Position and movement of the face and the smartphone may be another cause for this irregular result.

Chapter 4

Our Work

4.1 Circuit Construction

The full circuit has been constructed in three steps: external biasing circuit, first stage signal conditioning circuit, and second stage signal conditioning circuit [61]. The circuit has provision for integration with microcontrollers and single-board computers. In this project the circuit has been integrated with a PIC microcontroller and an Arduino board.

4.1.1 External Biasing Circuit

This part of the circuit provides reading from the sensor. The optical reflective sensor that has been used is TCRT5000 from Vishay. Basically it is a single unit having both the infrared light emitter and the phototransistor placed side by side. The output of the sensor is synchronous to the heart beat. As the sensor is contained in a leaded package, it is less susceptible to ambient light. Another sensor suitable for use here is TCRT1000, also from Vishay. TCRT1000 is less susceptible to ambient light than TCRT5000. While measuring heart rate it is important that the person minimizes movement as much as possible. Generally movements might cause extra changes in blood volume, so the sensors are susceptible to movement. The enable pin can be controlled through a micocontroller. If the only concern is detection of heart beat, the enable

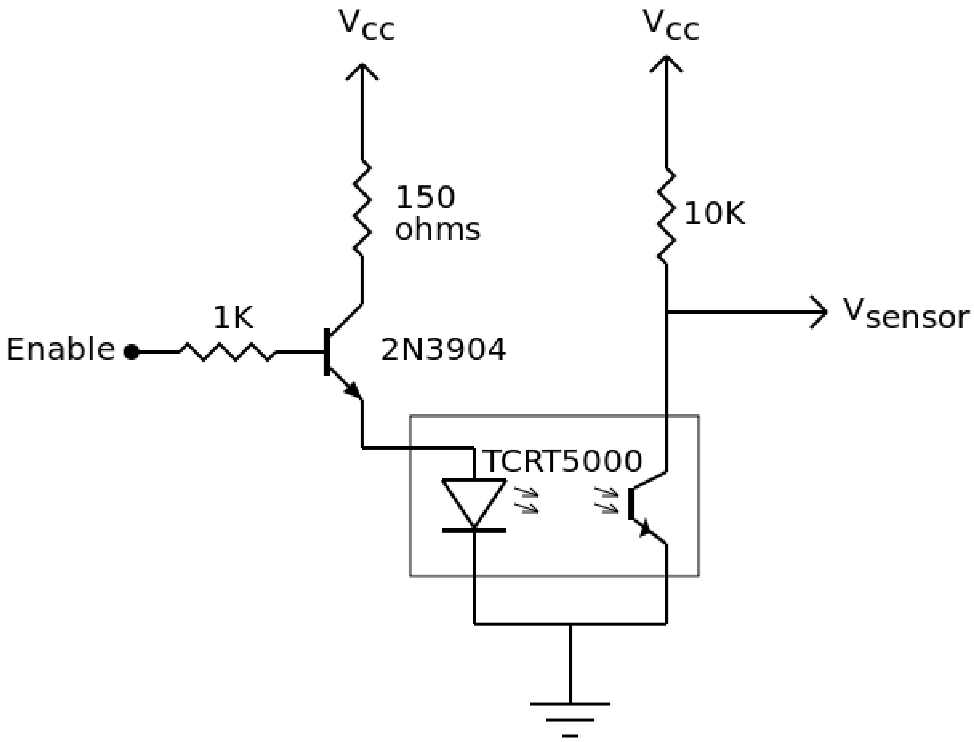


Figure 4.1: External biasing circuit.

pin can be fixed at high logic level. Heart beat can then be understood by observing blinking of an indicator LED at a later part of the circuit.

Although 2N3904 has been used as the required npn transistor, any general purpose npn transistors such as BC547 or 2N2222 can be used.

4.1.2 First Stage Signal Conditioning

This stage of the circuit removes the DC component of PPG signal. It also amplifies the AC component by a factor of 101. A passive high pass filter is used to filter out the DC component. An active low pass filter is used to boost the AC component. The general purpose op amp LM324 has been used to construct the active low pass filter. Other possible options for op amps include, but are not limited to, LM358, MCP6004 and MCP602. In essence a band pass filter has been used to extract required signal. The passive high pass filter has a cutoff frequency of $0.7Hz$. Different combinations of resistors and capacitors can be used to achieve this value.

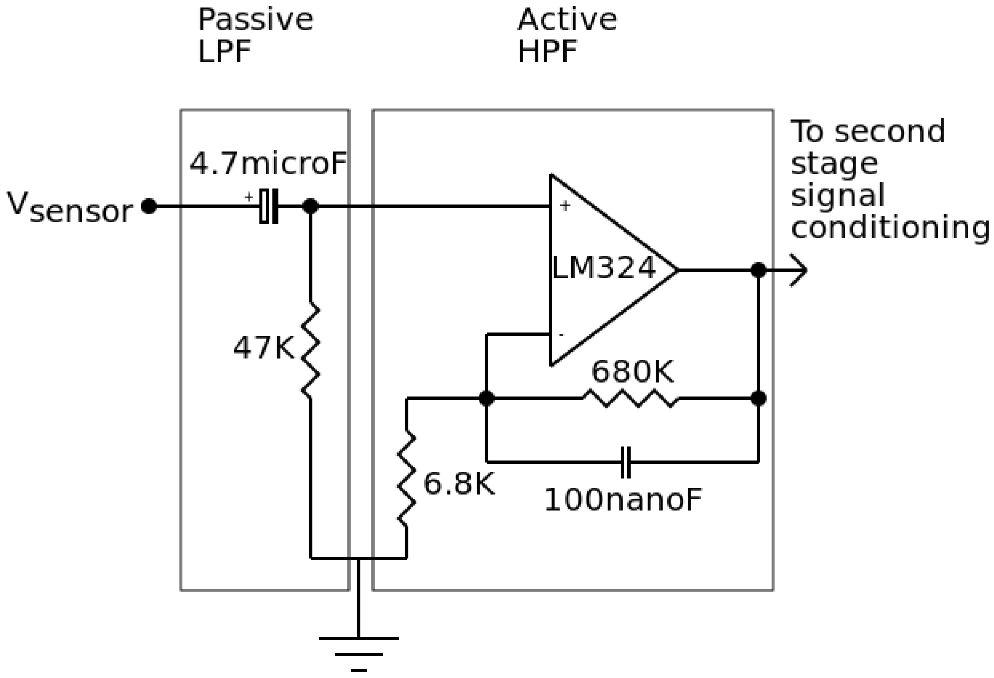


Figure 4.2: First stage signal conditioning.

The particular values used for this circuit are $47K\Omega$ and $4.7\mu F$. The cutoff frequency for chosen values can be found using equation 4.1, where R is the value of resistor and C the value of capacitor.

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 47K\Omega \times 4.7\mu F} \approx 0.7Hz \tag{4.1}$$

The active low pass filter has a cutoff frequency of $2.34Hz$. The particular values used for resistor and capacitor are $680K\Omega$ and $100nF$ respectively. The cutoff frequency for chosen values can be found using equation 4.2.

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 680K\Omega \times 100nF} \approx 2.34Hz \tag{4.2}$$

The gain of this op amp for the chosen values of resistors and capacitors can be found using equation 4.3, where R_2 is the negative feedback resistor.

$$G = 1 + \frac{R_2}{R_1} = 1 + \frac{680K\Omega}{6.8k\Omega} = 101 \tag{4.3}$$

4.1.3 Second Stage of Signal Conditioning

The output of the first stage of signal conditioning is fed into the second stage of signal conditioning. The second stage of signal conditioning is actually a clone of the first stage. So the values calculated at section 4.1.2 are also valid for this stage. This too gives a gain of 101, resulting in final gain of 10201. If such a large gain is not desirable, a potentiometer can be attached between ground and output of first stage signal conditioning. The output of this stage can further be supplied to a non-inverting buffer stage to lower the output impedance. This might be needed if an ADC channel of a microcontroller is used to read the amplified PPG signal. The output of second stage of signal conditioning can be used to drive a LED, which acts as indicator an indicator of pulse.

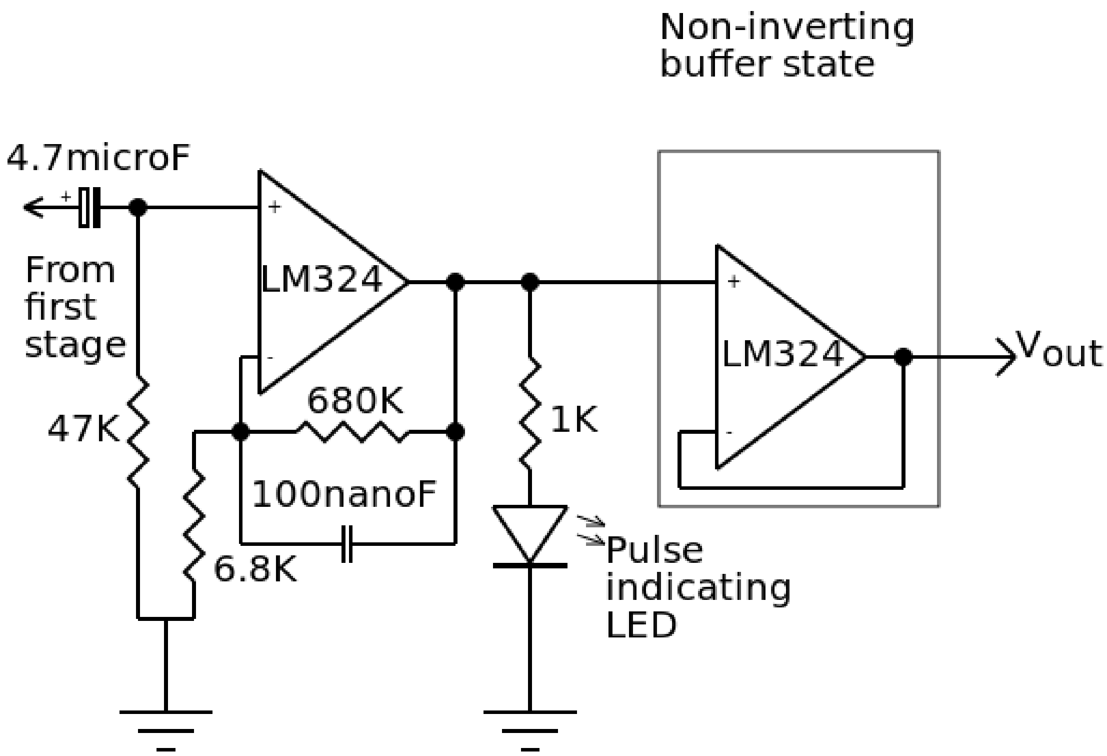


Figure 4.3: Second stage signal conditioning.

4.2 Interfacing to Microcontrollers

Microcontrollers can be used to detect the output of the signal conditioning stage, and count heart beats accordingly. The only module required to count heart beats is the timer module. So any microcontroller having the timer module can be used in this device. This opens up a wide range of choices for microcontrollers, even allowing the use of those that are very simple. A PIC16F648A microcontroller has been used in this project. The connections of the microcontroller can be seen in figure 4.4 along with pin numbers.

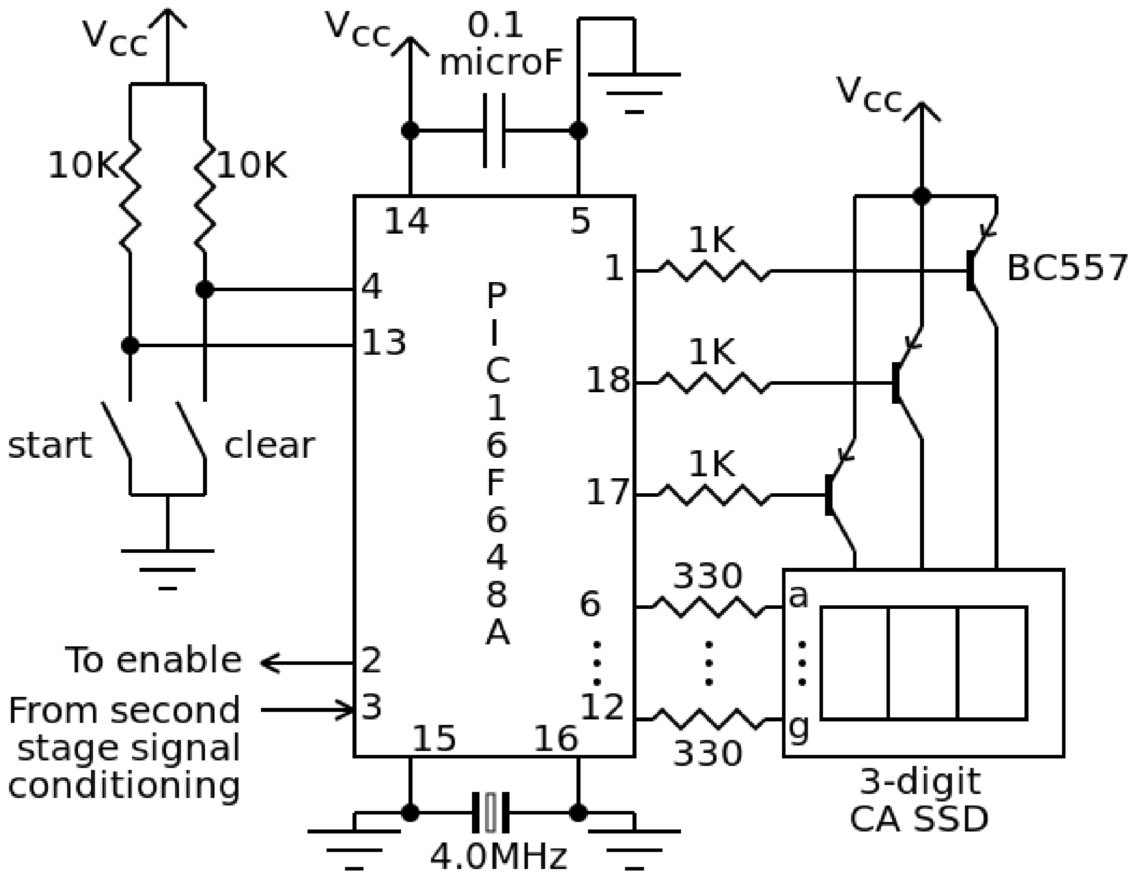


Figure 4.4: Interfacing with PIC16F648A.

The output of the signal conditioning stage is counted for 15 seconds and multiplied by 4 to get the heart rate. The result can then be shown with the help of seven segment displays. In this project three separate displays have been used. Alternatively three displays packaged as a single unit can also be used.

Output from the non-inverting buffer stage can be fed into microcontroller for further analysis. In this project the output of the non-inverting buffer has been fed into an Arduino UNO board. Graphs were obtained from the supplied signal using an existing software [62]. In figure 4.5 the software can be seen in action.

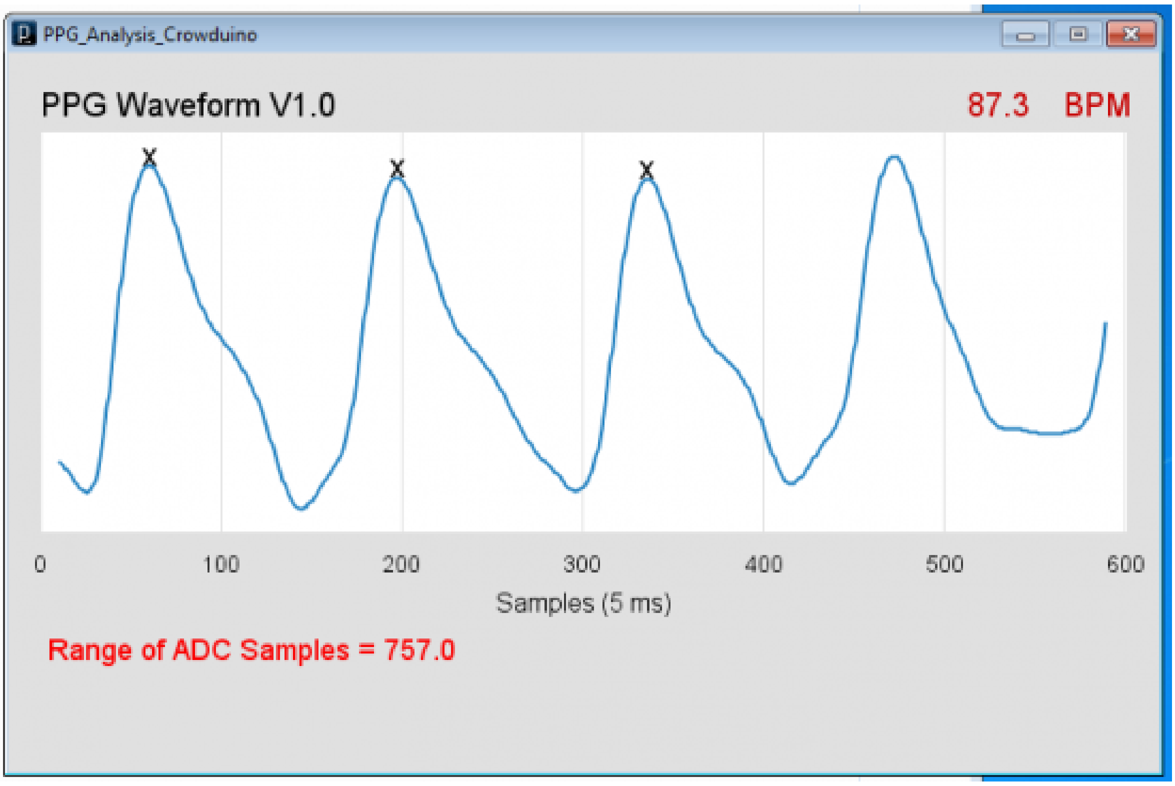


Figure 4.5: PPG waveform and heart rate displayed on computer screen.

Currently the software just shows graph based on the input signal. As a future endeavor an improved software can be created with extra features such as data logging.

To ensure consistency in supplied voltage a decoupling capacitor of $0.1\mu F$ has been used. In DC circuits capacitors act as open circuit. When the circuit is powered up the capacitor starts to acquire charges. If due to noise the supply ever decreases from the previous value, the capacitor discharges to make up for the deviation.

The internal oscillator of microcontrollers generally tend to be susceptible to heat. When the microcontroller is used for a considerable amount of time it generates heat which can affect the functionality of internal oscillator. To avoid this from happening an external oscillator of

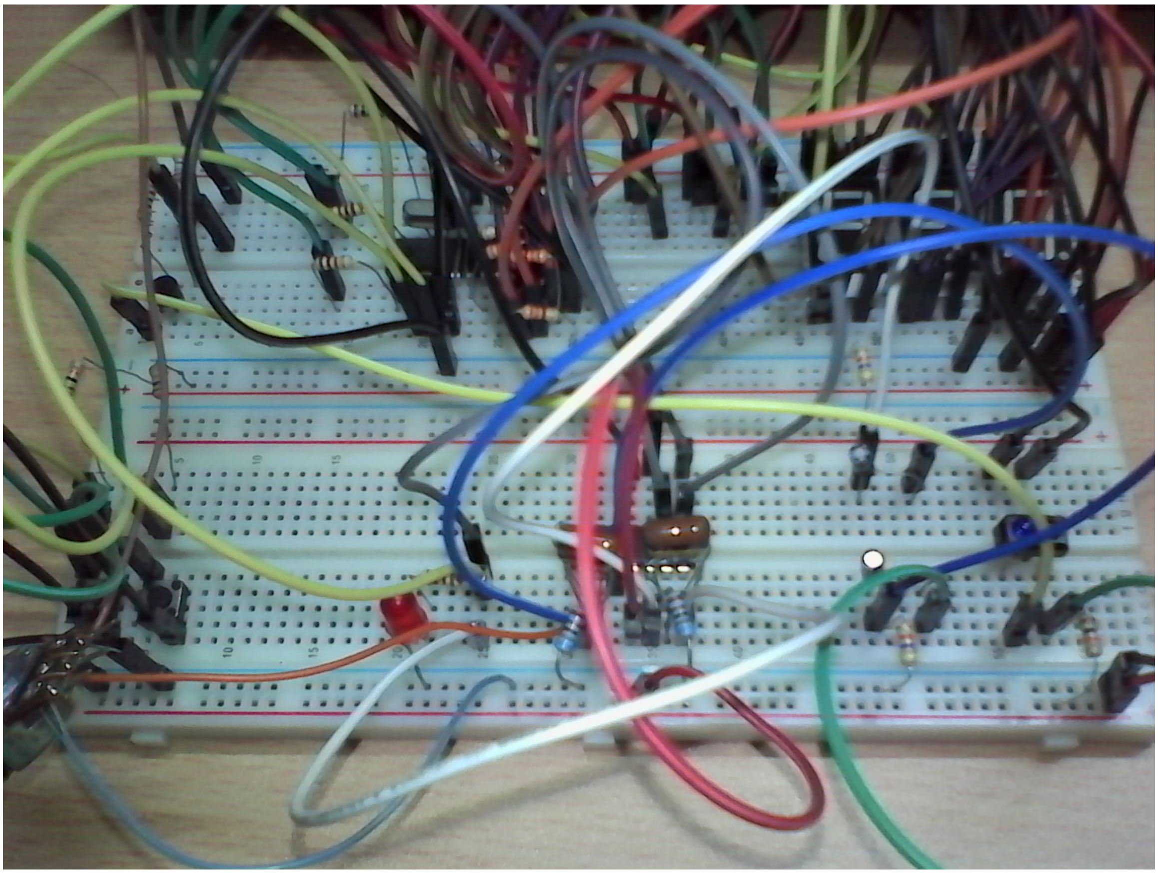


Figure 4.6: Device constructed on breadboards.

4.0MHz has been added.

Three pnp transistors have been used to control the common anode seven segment displays. The BC557 has been chosen as the pnp transistor. Possible alternatives include, but are not limited to, 2N5087 and BC327.

For displaying the result common anode seven segment displays have been used. If desired the output can also be displayed in an LCD module. Three separate seven segment displays have been used to show the result. To minimize the amount of wiring, it is better if three digit packages are used. The three displays are never really driven together. They are lit one by one at a fast pace so as to deceive the viewer's eyes that they are all lit at once.

The Timer0 module of PIC16F648A has been used to count heart beats. The heart beats are counted for fifteen seconds and multiplied by four to get beats per minute (bpm). If it is desired that the microcontroller counts for full one minute, the microcontroller has to be programmed differently.

The circuit has two buttons for controlling its actions. At first the clear button needs to be pressed once. The seven segment displays will light up for a moment. Once they fade away the user can start measuring heart rate. To start counting heart beats the user needs to place finger over the optical reflective sensor and press the push button marked start. The clear button is used to reset the microcontroller's internal registers. If the user wants to discard the current reading midway it can be done by pressing this clear button.

4.3 Cost of the constructed device

Table 4.1 shows the cost of constructing a single device. When, the device will be produced in bulk amount, the price will decrease to a good extent.

Component	**Quantity**	**Price per unit(BDT)**	**Total(BDT)**
Photo reflective Sensor (LTH1550-01)	1	43.64	43.64
Quad op amp (LM324)	1	09.93	09.93
L-shaped connector	4	00.25	01.00
Male connector	3	00.30	00.90
NPN BJT (2N3904)	1	02.59	02.59
LED red - 5mm	1	01.55	01.55
1.0uF capacitor	2	01.00	02.00
0.1uF capacitor	2	01.23	02.46
1kohm resistor	1	00.59	00.59
330ohm resistor	1	00.54	00.54
150ohm resistor	1	00.41	00.41
33kohm resistor	1	00.49	00.49
68kohm resistor	2	00.65	01.30
6.8kohm resistor	2	00.51	01.02
680kohm resistor	2	00.44	00.88
1.98 by 1.87 square inch single layer PCB	1	123.10	123.10
Total			**192.40**

Table 4.1: Cost of Producing a Single Device

4.4 Peak Detection and Heart Rate Measurement

The digital signal received from the constructed device may contain noise. Before any further analysis, reducing the effect of unwanted noise and still keeping the desired attributes of the signal undistorted is necessary. It was observed that the data mainly contains noise of high frequency. Different methods are available for smoothing such curves. In our case, moving average of the data was used.

An array of raw (noisy) data $[y_1, y_2, , y_N]$ can be converted to a new array of smoothed data. The "smoothed point" $(y_k)_s$ is the average of an odd number of consecutive 2n+1 (n=1, 2, 3, ..) points of the raw data y_{k-n}, y_{k-n+1}, , y_{k-1}, y_k, y_{k+1}, , y_{k+n-1}, y_{k+n} i.e.

$$(y_k)_s = \sum_{i=-n}^{i=n} \frac{y_{k+i}}{(2n+1)} \tag{4.4}$$

The odd number 2n+1 is usually named filter width. The greater the filter width the more intense is the smoothing effect. It was observed that a value of n=5 served quite well for smoothing the received digital signal.

For measuring heart rate,detection of the peaks of the obtained signal is necessary. A peak is defined as the local maxima in a range of the signal. So, peaks were detected by calculating derivatives of the smoothed data.

The first derivative of the points were calculated by taking ratio of successive data points and their corresponding time interval. Taking first derivative of these values, second derivatives of the data points were also calculated. Peaks were assumed to be the points where the first derivative became sufficiently close to zero (if not equal) and also the second derivative was negative. Now, as we have two different types of peaks, viz., systolic peaks and diastolic peaks, careful measures were essential so that they could be seperated without confusion. Of consecutive systolic and diastolic peak pair, the systolic one is expected to have higher amplitude. In case of any confusion, the value closer to the maximum value of overall data was considered as systolic peak and the other one as diastolic peak. Let us, formally define some parameters of the PPG signal that will be discussed frequently in the later sections.

- The time interval between two systolic peak is known as Time period (T).
- The time interval between two consecutive systolic and diastolic peak is known as Peak to peak interval ($T1$).
- The time interval between between the lowest upstroke and a consecutive systolic peak is known as Systolic time (ST).
- The time interval from a systolic peak to the next lowest upstroke point is known as diastolic time (DT).

These parameters are shown in Figure 4.7. This is sample PPG signal output shown in our java program.

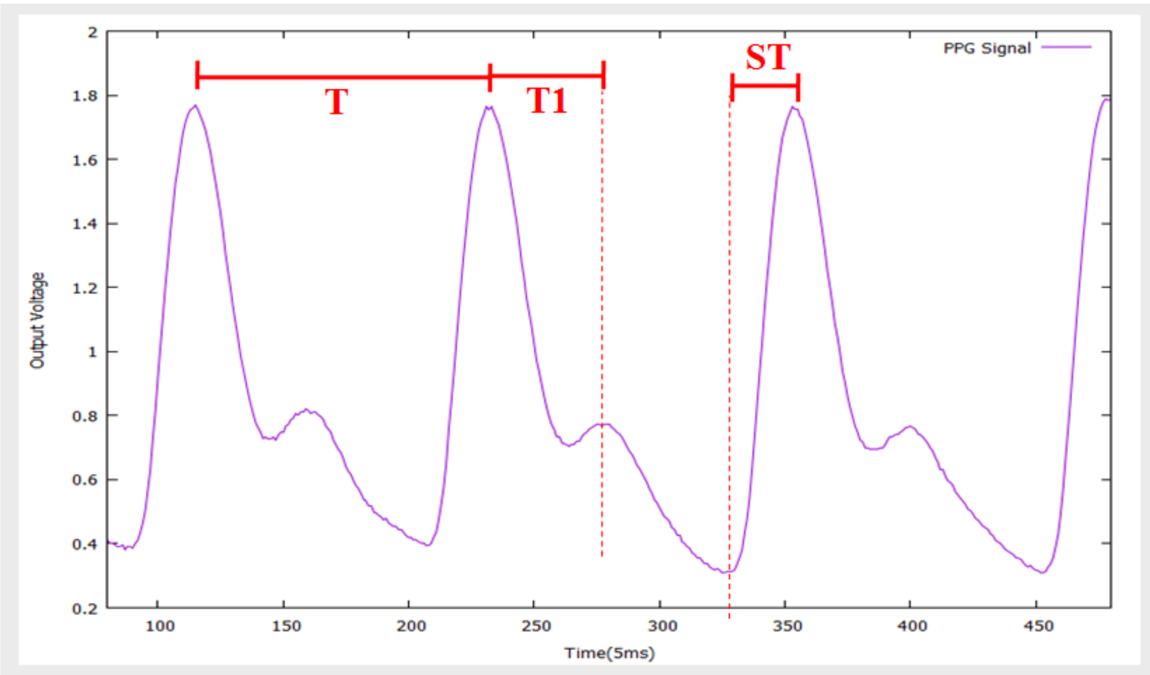


Figure 4.7: PPG signal output from our java program

Detection of the lowest upstroke point was necessary for estimation of blood pressure. This point was considered as the point where there is a sharpe increase of the data values. So a significant value of the second derivative was detection criterion of this point. By calculating T using the above algorithm we calculated the heart rate by the following equation

$$HeartRate = \frac{60}{T} \tag{4.5}$$

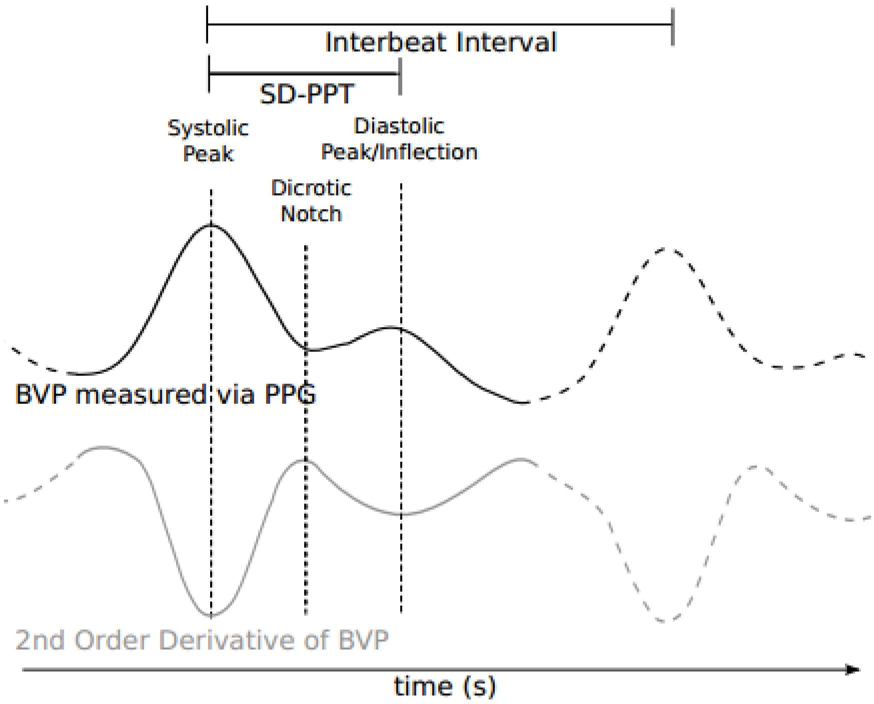


Figure 4.8: PPG signal and its 2nd derivative

4.5 Blood Pressure Estimation

As discussed in section 2.4 systolic and diastolic pressure depends on both ECG signal and PPG signal. We tried to estimate blood pressure using only PPG signal. The waveform obtained from the PPG circuit and the blood pressure values given by sphygmomanometer were simultaneously recorded several times for 25 subjects. The recorded readings of BP and the important parameters of PPG wave (systolic upstroke time (ST), diastolic time (DT), the time delay between the systolic and diastolic peak (T1) and the time period of the PPG signal (T)) were averaged for all the subjects. Thereafter, the systolic blood pressure (SBP) and diastolic blood pressure (DBP) were estimated by taking the correlation of the recorded SBP and DBP with the parameters of PPG wave and then finding the linear regression with them. The process to finding ST, DT and T1 has been discussed in the previous section. The values are shown in Table 4.2

Table 4.2: Actual Pressure and Parameters of PPG Signal of the Subjects

Subject No	SBP	DBP	T	T1	ST	DT
1	120	70	165	50	29	136
2	110	70	128	47	25	103
3	125	85	135	55	30	105
4	130	85	140	56	32	108
5	135	85	138	56	31	107
6	110	70	162	50	29	133
7	125	75	155	48	30	125
8	130	85	128	56	33	95
9	120	70	150	48	31	119
10	135	75	124	55	33	91
11	130	80	153	58	37	116
12	150	90	178	60	40	138
13	130	80	137	54	33	104
14	135	85	148	58	34	114
15	150	85	150	59	34	116
16	120	70	166	49	29	137
17	110	60	135	52	29	106
18	135	75	170	54	32	138
19	120	75	157	53	30	127
20	160	90	139	58	42	97
21	140	90	147	59	40	107
22	120	70	148	49	30	118
23	115	75	167	55	26	141
24	160	85	143	57	41	102
25	130	80	146	52	34	112

In this study, however, PTT has not been used as a parameter for estimation of blood pressure, rather, the basic parameters of the PPG waveform such as ST, DT and difference between the systolic and diastolic peak (T1) have been used to find the correlation co-efficient (with SBP and DBP) and consequently the regression equations. This approach not only minimises the cost of using ECG but also is more practical as it requires only one channel. Following are the findings of our study:

- Firstly we tried to correlate SBP and DBP with ST/T (the fraction of time needed in systolic upstroke) and T1/T (the fraction of time between systolic and diastolic peaks). We found the following equations :

$$P_{sys} = 72.92 + 480.03 \times \frac{ST}{T} - 135.273 \times \frac{T1}{T} \tag{4.6}$$

The above equation had R^2 value of 0.46.

$$P_{dis} = 46.74 + 28.59 \times \frac{ST}{T} + 70.37 \times \frac{T1}{T} \tag{4.7}$$

The above equation had R^2 value of 0.48.

R^2 is the measure of goodness of the fitted curve and these values did not show promising results.

- Then we tried to correlate SBP and DBP with ST/T, DT/T and T1/T. This did not improve the R^2 value. After that, the individual values of ST/T, DT/T and T1/T were correlated with SBP and DBP which also did not show any convincing result.

- Lastly we correlated SBP and DBP with the actual times ST, DT and T1. Our correlation showed that, DT had little impact on the measurement of blood pressure. However, correlation with ST and T1 showed very promising result. We found the following equations :

$$P_{sys} = 12.84 + 0.78 \times T1 + 2.296 \times ST \tag{4.8}$$

The above equation had R^2 value of 0.809.

$$P_{dis} = -5 + 1.224 \times T1 + 0.534 \times ST \tag{4.9}$$

The above equation had R^2 value of 0.711. These are two equations we used to estimate the systolic and diastolic blood pressure. Figure 4.9 shows the typical output of our java program.

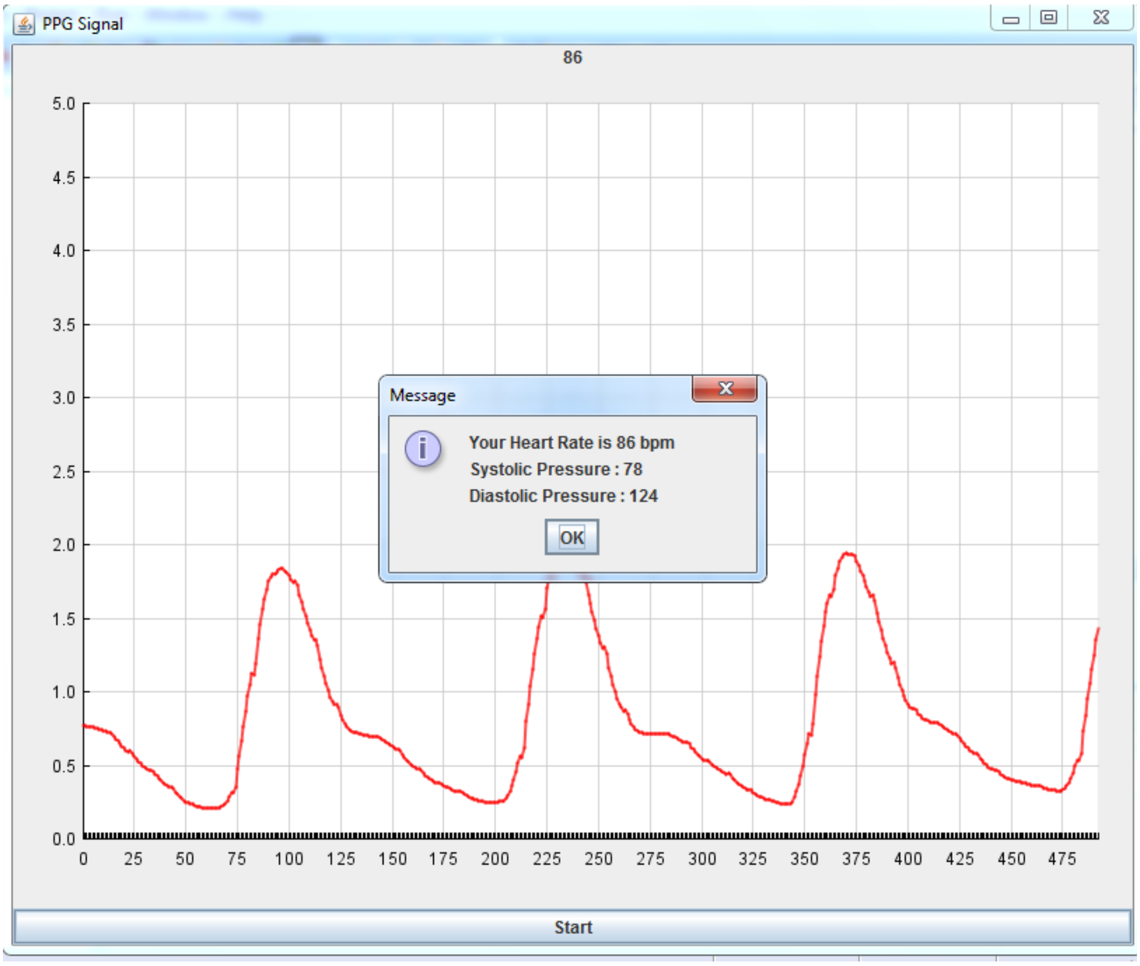


Figure 4.9: A typical output from our java program

4.6 Wireless Communication

A wireless transmission system of the signal received from the constructed device was incorporated so that health conditions of several patients in a hospital can be monitored by a doctor sitting at a distant place as shown in Figure 4.10. For such a configuration remote monitoring is really important. So, wireless transmission of data is incorporotated. There are several ways that can achieve wireless transmission.

Figure 4.10: A typical scenario of wireless transmission

A single chip Radio Frequency transceiver named nRF24L01 was used for this purpose. Figure 4.11 shows an nRF24L01 module.

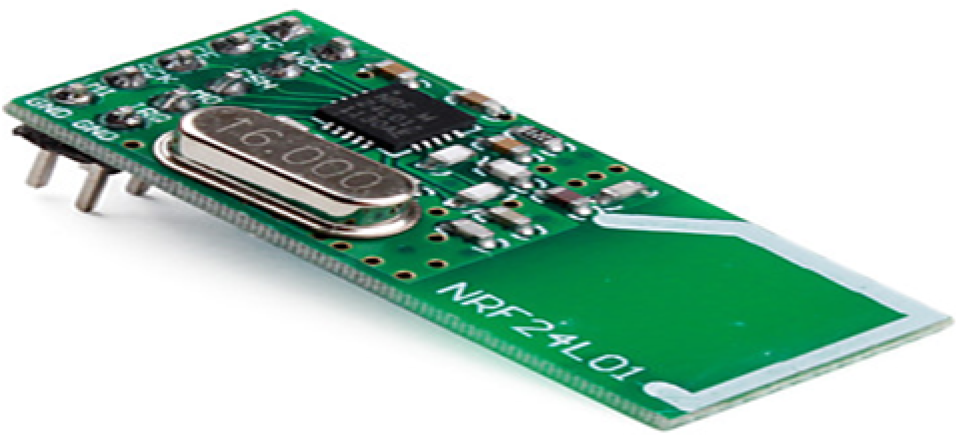


Figure 4.11: An nRF24L01 module

Figure 4.12 shows the block diagram of an nRF24L01 module. The nRF24L01 is a single chip 2.4GHz transceiver with an embedded baseband protocol engine (Enhanced ShockBurst), designed for ultra low power wireless applications. The nRF24L01 is designed for operation in the world wide ISM frequency band at 2.400 - 2.4835GHz. An MCU (microcontroller) and very few external passive components are needed to design a radio system with the nRF24L01.The nRF24L01 is configured and operated through a Serial Peripheral Interface (SPI.) Through this interface the register map is available. The register map contains all configuration registers in the nRF24L01 and is accessible in all operation modes of the chip.

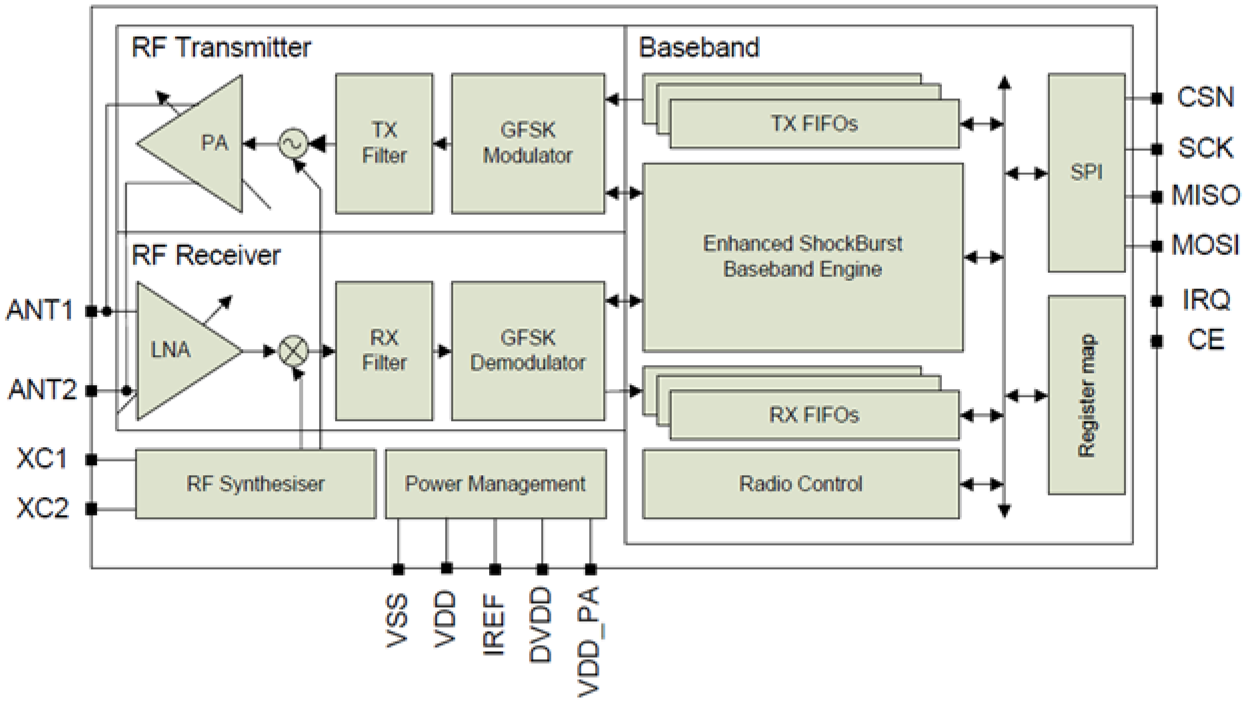


Figure 4.12: Block diagram of nRF24L01

The embedded baseband protocol engine (EnhancedShockBurst) is based on packet communication and supports various modes from manual operation to advanced autonomous protocol operation. Internal FIFOs ensure a smooth data flow between the radio front end and the systems MCU. Enhanced ShockBurst reduces system cost by handling all the high-speed link layer operations. The automatic packet transaction handling works as follows:

- The user initiates the transaction by transmitting a data packet from the PTX to the PRX. Enhanced ShockBurst automatically sets the PTX in receive mode to wait for the ack packet.
- If the packet is received by the PRX, Enhanced ShockBurst automatically assembles and transmits an acknowledgment packet (ACK packet) to the PTX before returning to receive mode.
- If the PTX does not receive the ACK packet within a set time, Enhanced ShockBurst will automatically retransmit the original data packet and set the PTX in receive mode to wait for the ACK packet

The radio front end uses GFSK modulation. It has user configurable parameters like frequency channel, output power and air data rate. The air data rate supported by the nRF24L01 is configurable to 2Mbps. The high air data rate combined with two power saving modes makes the nRF24L01 very suitable for ultra low power designs. Internal voltage regulators ensure a high Power Supply Rejection Ratio (PSRR) and a wide power supply range.

4.7 Summary

A device was constructed to measure heart rate and blood pressure non-invasively and also transfer the data over wireless network. The circuit of the device consists of an external biasing circuit and two stages of signal conditioning. It can be interfaced to a microcontroller or personal computer for further analysis. An IR sensor was used to implement the PPG principle. The cost of the device was significantly low. Number of peaks per unit time was used to calculate heart rate. Systolic and Diastolic time intervals were used to measure blood pressure. The systolic and diastolic time was correlated with SBP and DBP to get the estimated blood pressure. Finally, an nRF24L01 module was incorporated to transmit data wirelessly.

Chapter 5

Accuracy of the device

5.1 Heart Rate Measurement

Subject	**Measured (device)**	**Measured (app)**	**Actual**
1	88	92	88
2	78	76	79
3	74	74	74
4	87	92	88
5	106	106	106
6	80	80	81
7	83	80	83
8	78	76	79
9	72	69	72
10	75	73	75
11	102	100	102
12	76	78	77
13	101	99	100
14	81	81	82
15	78	80	78
16	89	88	89
17	92	92	94
18	85	83	85
19	77	77	77
20	75	78	75
21	78	78	79
22	83	83	83
23	78	77	79

Table 5.1: Measured heart rate via app, our device and actual heart rate of the subjects

Table 5.1 shows the actual heart rate, measured heart rate with our device and measured heart rate with *Instant Heart Rate* application obtainded from 23 samples.

The accuracy of our constructed device is around 99% whereas the accuracy of the smartphone application is around 97%. Clearly, our constructed device has better performance than the application.

5.2 Blood Pressure Measurement

Let us recall the blood pressure estimating equations :

$$P_{sys} = 12.84 + 0.78 \times T1 + 2.296 \times ST \tag{5.1}$$

$$P_{dis} = -5 + 1.224 \times T1 + 0.534 \times ST \tag{5.2}$$

Equation 5.1 has a R^2 value of 0.809 and Equation 5.2 has a R^2 value of 0.711. The rms error, standard error and R^2 value of equation 5.1 and 5.2 are shown in Table 5.2.

Table 5.2: rms error, std. error and R^2 value of our estimation

Pressure (Equation)	R^2	rms error	standard error
P_{sys} (equation 5.1)	0.809	6.041	6.44
P_{dis} (equation 5.2)	0.711	4.21	4.49

We estimated the pressures of the subjects and the estimated result is shown in Table 5.3

Our estimated equation is a plane 3-D surface. Our estimated systolic and diastolic pressure original systolic and diastolic pressure is shown graphically in Figure 5.1 and 5.2 respectively.

Table 5.3: Actual Pressure and Parameters of PPG Signal of the Subjects

Subject No	Actual SBP	Actual DBP	Estimated SBP	Estimated DBP
1	120	70	119	72
2	110	70	107	66
3	125	85	125	78
4	130	85	130	81
5	135	85	128	80
6	110	70	119	72
7	125	75	119	70
8	130	85	132	81
9	120	70	122	70
10	135	75	132	80
11	130	80	143	86
12	150	90	152	90
13	130	80	131	79
14	135	85	136	84
15	150	85	137	85
16	120	70	118	70
17	110	60	120	74
18	135	75	129	78
19	120	75	123	76
20	160	90	155	88
21	140	90	151	89
22	120	70	120	71
23	115	75	116	76
24	160	85	152	87
25	130	80	132	77

5.3 Summary

The performance of our device was quite good for heart rate measurement. It was quite accurate comparing to the existing smartphone application. In case of blood pressure we assumed linear regression. However, this approximation shows quite promising result. The rms error and standard error was significantly low and the margin of error was within an acceptable range.

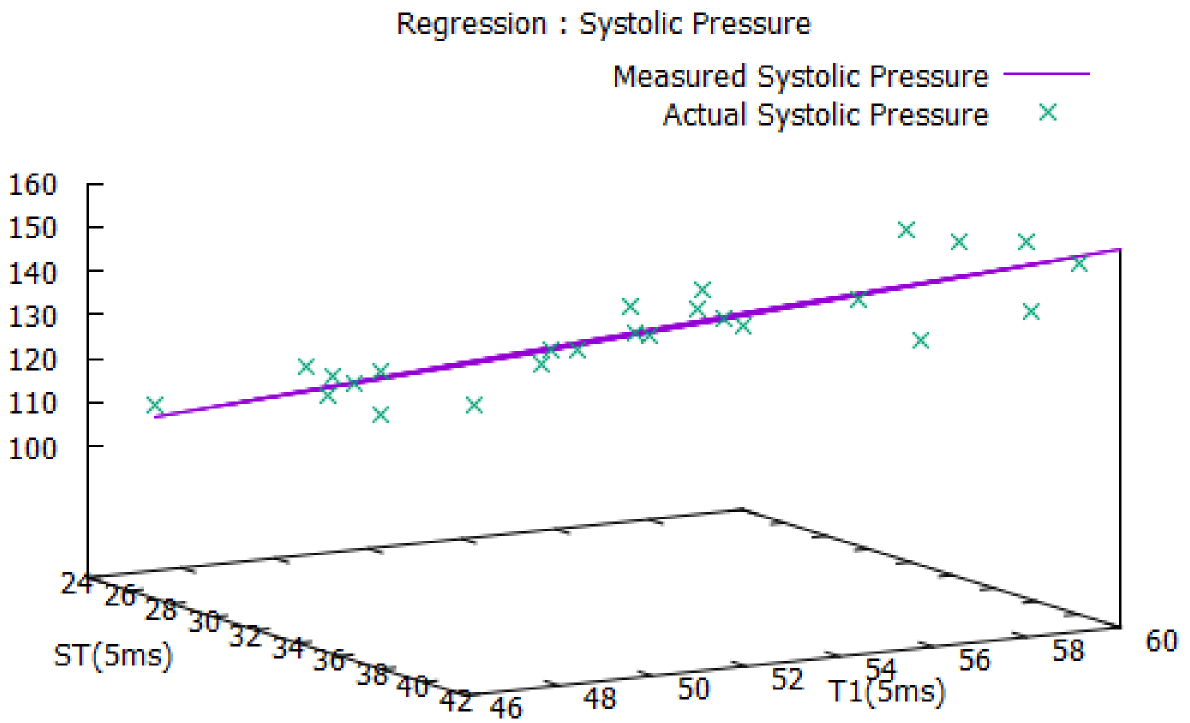


Figure 5.1: Measured systolic pressure and actual systolic pressue

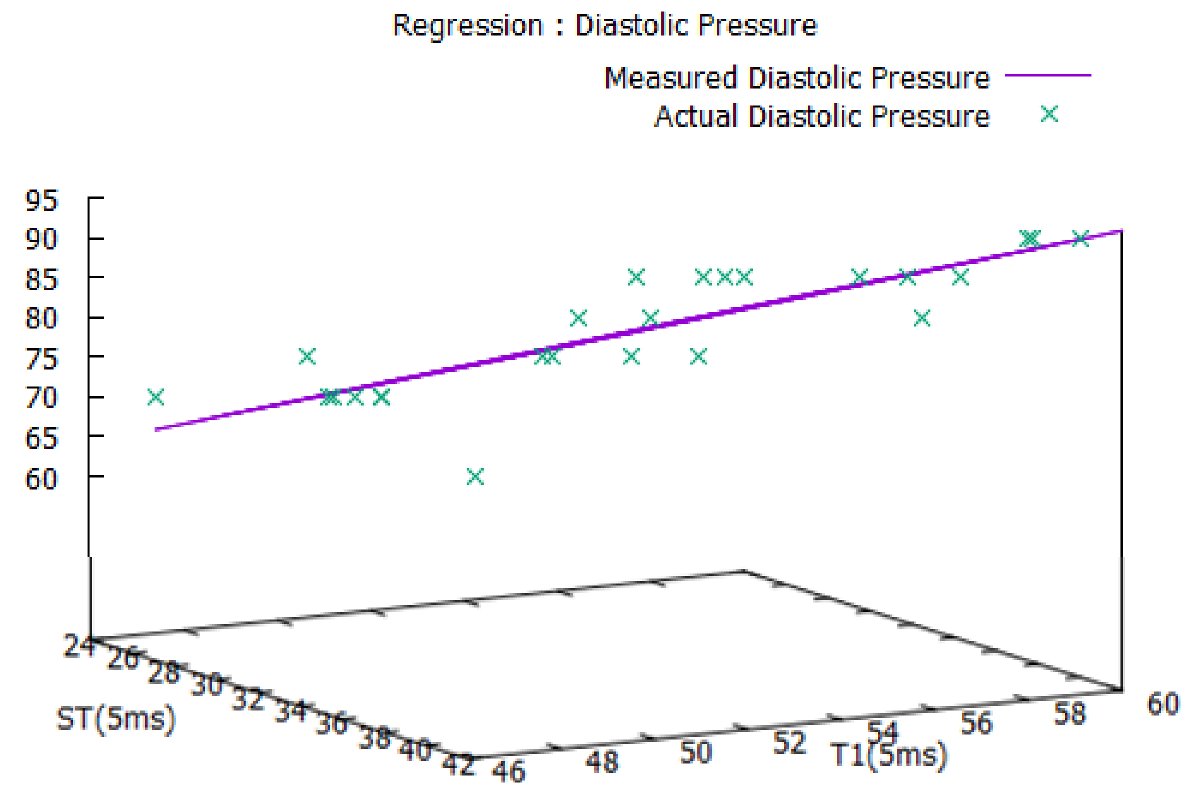


Figure 5.2: Measured diastolic pressure and actual diastolic pressue

Chapter 6

Conclusion and Future works

We proposed a unique device to efficiently measure heart rate and blood pressure. Given the great practical interest on these two vital signs, the proposed device opens the way to provide a cost-effective and non-invasive way of measuring the said vital signs. In addition, the device provides us the option to interface with computers and is accurate to a great extent. We were also able to successfully transmit PPG signal over wireless communication.

As a future enhancement, the device can be set up at each bed of a hospital ward, where the data will be fed to a central computer for mass patient monitoring. The device is still under experiment for blood pressure estimation. We need to collect a bulk amount of data to verify its performance. We assumed linear regression for blood pressure measurement. More sophisticated regression might improve the performance.

It is possible to interface the device with smartphones over bluetooth module. The bluetooth module might be bypassed by using OTG cable. Depending on the power consumption, we might or might not need external power supply. Current studies show that PPG can be used to measure respiratory rate, which is another vital sign. If this can be incorporated in the device, we will be able to measure three of the four vital signals with a single device.

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