SIGNAL PROCESSING TECHNIQUE FOR CONTINUOUS BLOOD PRESSURE MEASUREMENT

A thesis submitted in partial fulfillment of the requirements for the award of the degree of

B.Tech.

in

INSTRUMENTATION AND CONTROL ENGINEERING

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BONAFIDE CERTIFICATE

This is to certify that the project titled **SIGNAL PROCESSING TECHNIQUE FOR CONTINUOUS BLOOD PRESSURE MEASUREMENT** is a bonafide record of the work done by

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in partial fulfillment of the requirements for the award of the degree of **Bachelor of Technology** in **INSTRUMENTATION AND CONTROL ENGINEERING** of the **NATIONAL INSTITUTE OF TECHNOLOGY, TIRUCHIRAPPALLI,** during the year 2019-2020.

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ABSTRACT

The aim of this project is to measure blood pressure continuously with the help of ECG and PPG signals extracted from the human body. The pulse transit time (PTT)is calculated as the time interval between the peak of the R-wave in electrocardiogram (ECG) and the fingertip photoplethysmogram (PPG). Later, this can be calibrated to find blood pressure.

Since we are dealing with physiological signals, we mainly concentrate on how these signals can be processed in order to ensure not only accurate BP measurement but also for various other medical applications. The mainly used methods include Cluster analysis and segmentation. Cluster Analysis method is used to process the signals first. Later the baseline wander is estimated and then subtracted from the signals in order to remove the baseline wandering to make the signals more useful and accurate for any purpose.

This project finds its use in various medical applications to control and prevent hypertension and cardiovascular diseases (CVD). The processed signals were verified with various metrics to analyse the performance of signal processing techniques used.

Keywords: Electrocardiogram(ECG), Photoplethysmograph(PPG), Blood Pressure(BP), Signal Processing

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ABBREVIATIONS

BP	Blood Pressure
ECG	Electrocardiogram
PPG	Photoplethysmogram
CVD	Cardiovascular disease
PTT	Pulse Transit Time
BW	Baseline Wander
AC	Alternating Current
DC	Direct Current
RMSE	Root Mean Square Error
SNR	Signal to Noise Ratio

CHAPTER 1
INTRODUCTION

1.1 General Introduction

Blood pressure (BP) is the pressure of circulating blood on the walls of blood vessels. Most of this pressure is due to work done by the heart by pumping blood through the circulatory system. Used without further specification, "blood pressure" usually refers to the pressure in large arteries of the systemic circulation. Blood pressure is usually expressed in terms of the systolic pressure (maximum during one heartbeat) over diastolic pressure (minimum in between two heartbeats) and is measured in millimeters of mercury (mmHg), above the surrounding atmospheric pressure. Blood pressure is one of the vital signs, along with respiratory rate, heart rate, oxygen saturation, and body temperature.

Blood pressure is a vital sign to monitor the health of an individual, especially to control and prevent hypertension and cardiovascular diseases (CVD). It is important because the higher your blood pressure is, the higher your risk of health problems in the future. If your blood pressure is high, it is putting extra strain on your arteries and on your heart. Over time, this strain can cause the arteries to become thicker and less flexible, or to become weaker.

In Europe, more than 4million deaths each year is caused by CVD. In India, deaths due to cardiovascular diseases rose from 13 lakh in 1990 to 28 lakh in 2016. The number of prevalent cases of cardiovascular diseases has increased from 2.57 crore in 1990 to 5.45 crore in 2016. It is predicted that up to 23.3 million deaths can be caused by CVD until 2030, since the number of peoplewith high BP is doubled the past two decades.

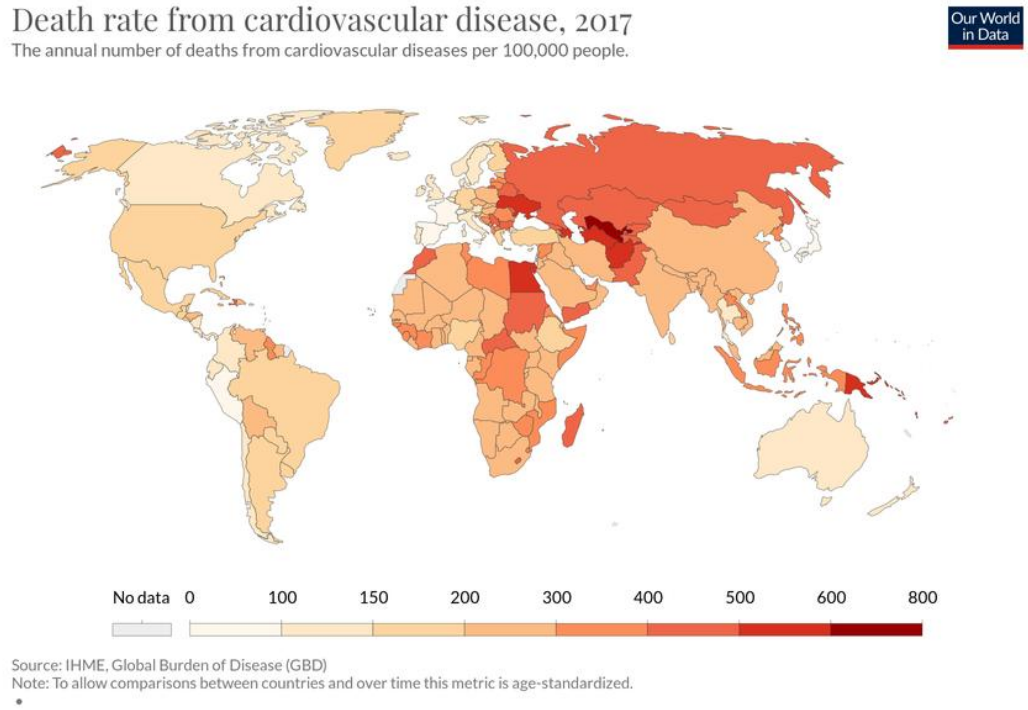

Fig.1.1 CVD Statistics in 2017

If your arteries become thicker and less flexible, they will become more narrow, making them more likely to become clogged up. If an artery becomes completely clogged up (known as a clot), this can lead to a heart attack, a stroke, kidney disease or dementia. More rarely, if an artery has become weakened, the extra strain may eventually lead to the artery bursting. This may also cause a heart attack or stroke.Continuous BP monitoring can also help to predict the likelihood of cardiovascular (blood vessels in the heart) and cerebrovascular (blood vessels in the brain) disease linked to hypertension and organ damage.

1.2 Previous BP measurement methods

Due to an enormous number of people getting under the effect of blood pressure disorders, many researchers are working to improve BP measurement methods inconvenience and accuracy. Several BP measurement methods are now available. The main methods include catheterization, auscultation, oscillometry, volume clamping, and tonometry.

Catheterization is the gold standard method. This method measures instantaneous BP by placing a strain gauge in fluid contact with blood at any arterial site (e.g., radial artery, aorta). However, the method is invasive. Auscultation, oscillometry, and volume clamping are noninvasive methods. These methods employ an inflatable cuff. Auscultation is the standard clinical method. This method measures systolic and diastolic BP by occluding an artery with a cuff and detecting the Korotkoff sounds using a stethoscope and manometer during cuff deflation. The first sound indicates the initiation of turbulent flow and thus systolic BP, while the fifth sound is silent and indicates the renewal of laminar flow and thus diastolic BP. Oscillometry is the most popular non-invasive, automatic method. This method measures mean, diastolic, and systolic BP by also using a cuff but with a pressure sensor inside it. The measured cuff pressure not only rises and falls with cuff inflation and deflation but also shows tiny oscillations indicating the pulsatile blood volume in the artery. The amplitude of these oscillations varies with the applied cuff pressure, as the arterial elasticity is nonlinear. The BP values are estimated from the varying oscillation amplitudes using the empirical fixed-ratios principle. When evaluated against auscultation using an Association for the Advancement of Medical Instrumentation (AAMI) protocol, some oscillometric devices achieve BP errors within the AAMI limits of 5 mmHg bias and 8 mmHg precision. However, oscillometry is unreliable in subjects with certain conditions such as atrial fibrillation, stiff arteries, and pre-eclampsia. Volume clamping is a non-invasive, automatic method used in research. This method measures instantaneous (finger) BP by using a cuff and a photoplethysmography (PPG) sensor to measure the blood volume (see Section V.A). The blood volume at zero transmural pressure is estimated via oscillometry. The cuff pressure is then continually varied to maintain this blood volume throughout the cardiac cycle via a fast servo-control system. The applied cuff pressure may thus equal BP. Volume clamping devices also achieve BP errors within AAMI limits when evaluated against auscultation and near AAMI limits when evaluated against radial artery catheterization.

However, cuff use has several drawbacks. In particular, cuffs are cumbersome and time consuming to use, disruptive during ambulatory monitoring, especially while sleeping, and do not readily extend to low resources settings. Tonometry is another

non-invasive method used in research that, in theory, does not require an inflatable cuff. This method measures instantaneous BP by pressing a manometer-tipped probe on an artery. The probe must flatten or applanate the artery so that its wall tension is perpendicular to the probe. However, manual and automatic applanation have proven difficult. As a result, in practice, the measured waveform has been routinely calibrated with cuff BP whenever a BP change is anticipated. In sum, the existing BP measurement methods are invasive, manual, or require a cuff. So, none are suitable for ubiquitous (i.e., ultra-convenient, unobtrusive, and low cost) monitoring. Moreover, the calibration process of these devices is still tricky due to their dependency to individual physiological parameter. The requirement of a cuff in BP devices restricts the further reduction in size and limits the ease of their usage.

CHAPTER 2

LITERATURE REVIEW

Continuous blood pressure (BP) measurement allows the investigation of transient changes in BP and thus may give insights into mechanisms of BP control. We validated a continuous, non-invasive BP measurement based on the pulse transit time (PTT), i.e. BP-PTT, by comparing it with the intra-arterial BP measurement.PTT was determined from the electrocardiogram and the peripheral pulse wave.The results encourage the application of PTT-based BP measurement for the evaluation of BP dynamics and pathological BP changes[5].

Ubiquitous blood pressure (BP) monitoring is needed to improve hypertension detection and control and is becoming feasible due to recent technological advances such as in wearable sensing. Pulse transit time (PTT) represents a well-known, potential approach for ubiquitous BP monitoring. The goal of this review is to facilitate the achievement of reliable, ubiquitous BP monitoring via PTT.Ubiquitous blood pressure (BP) monitoring is on the horizon for two reasons. One reason is a profound need. Hypertension is a major cardiovascular risk factor that is treatable, yet high BP detection and control rates are abysmally low, especially in low resource settings. Ubiquitous BP monitoring is expected to improve hypertension detection by providing serial, out-of-clinic measurements in the mass population and could even enhance hypertension control by providing continual feedback to the patient. The second reason is feasibility. There have been many relevant technological advances in the recent past such as in wearable sensing, miniaturization, pervasive computing, and smartphones. Further, there is mounting evidence that pulse transit time (PTT, i.e., the time delay for the pressure wave to travel between two arterial sites) can provide the basis for convenient, cuff-less BP measurement. While major progress on PTT-based BP monitoring has been made, research is still needed to best realize this approach.Several BP measurement methods are now available. The main methods include catheterization, auscultation, oscillometry, volume clamping, and tonometry.

Catheterization is a method that measures instantaneous BP by placing a strain gauge in fluid contact with blood at any arterial site (e.g., radial artery, aorta). However, the method is invasive. Auscultation, oscillometry, and volume clamping are noninvasive methods. These methods employ an inflatable cuff. Oscillometry is the most popular non-invasive, automatic method. This method measures mean, diastolic, and systolic BP by also using a cuff but with a pressure sensor inside it. However, oscillometry is unreliable in subjects with certain conditions such as atrial fibrillation, stiff arteries, and pre-eclampsia. Volume clamping is a non-invasive, automatic method used in research. This method measures instantaneous (finger) BP by using a cuff and a photoplethysmography (PPG) sensor to measure the blood volume. However, cuff use has several drawbacks. In particular, cuffs are cumbersome and time consuming to use, disruptive during ambulatory monitoring, especially while sleeping, and do not readily extend to low resources settings.The PTT-BP relationship has been studied by many investigators over many decades.The arterial wall models establish the relationship between BP and arterial elasticity. The arterial wave propagation models establish the relationship between arterial elasticity and PTT. Based on the models, we then draw conclusions on the optimal arterial sites to measure PTT for cuff-less BP monitoring.Based on these models, PTT can be used to effectively monitor BP if the following conditions are met: (a) smooth muscle contraction and viscous effects are negligible; (b) aging and disease do not alter arterial elasticity; and (c) wave reflection interference is absent. These conditions are best satisfied by measuring PTT through central arteries and via the foot-to-foot time delay between the proximal and distal waveforms and limiting the monitoring duration to a period shorter than aging and disease processes[9].

Physiological signals can often become contaminated by noise from a variety of origins. Many algorithms are described for the reduction of sporadic noise from a continuous periodic signal. Algorithms based on cluster analysis for selecting similar repetitions or pulses from a periodic single exist[6]. These methods select individual pulses without noise, returns a clean pulse signal, and terminates when a sufficiently clean and representative signal is received. These are designed to be sufficiently

compact to be implemented on a microcontroller embedded within a medical device. It has been validated through the removal of noise from an exemplar photoplethysmography (PPG) signal, showing increasing benefit as the noise contamination of the signal increases. The algorithm design is generalised to be applicable for a wide range of physiological (physical) signals.Signal quality or signal-to-noise ratio requires consideration in almost all signal measurements. This is especially true in physiological measurements where the signals tend to be small and prone to measurement artefacts and the noise is often difficult to control. A novel cluster analysis method is described to reduce the influence of noise on photoplethysmography (PPG) signals. PPG is an optical measurement technique that can be used to detect blood volume changes in the microvascular bed of tissue. The peripheral pulse, as measured by PPG, is often used in the assessment of health and disease and can provide important valuable information about the cardiovascular system. The clinical utility of such a device relies on its ability to identify and eliminate noise from PPG signals.Noise minimisation starts with removing the source of the noise; this can be through electrical isolation or, for example, by keeping the subject relaxed and still during measurements to eliminate muscle and movement artefact. There is also inherent noise produced through the amplification of small signals; however modern physiological amplifiers and analogue-to-digital converters tend to minimise this for all but the smallest input signals. When the sources of the noise have been reduced as far as possible, various active noise reduction techniques can be used. The most common kind of noise minimisation is filtering that can be used to reduce any noise frequencies that do not overlap the signal frequencies. More sophisticated methods such as wavelet denoising can be employed where filtering is insufficient. Physiological signals, in particular ECG and PPG, have been the focus of noise reduction using a signal quality index, whereby each pulse has attributed a signal quality, which is then used to assess the validity of that pulse. Cluster analysis is a method of arranging features into groups such that those with similar characteristics lie within a single group[6]. Many physiological signals are prone to baseline wandering also. Baseline Wander is a low frequency noise having non-linear and non-stationary nature. Theclassical methods such as high-pass filtering cannot

provide fullseparation of the signal from low-frequency noise. There is an approach to estimate the Baseline Wander basedon piecewise linear estimation and nonlinear smoothing. Thegeneral idea is to estimate baseline wander locally using linear models[7].

CHAPTER 3

MOTIVATION

Blood pressure is a vital sign to monitor the health of an individual, especially to control and prevent hypertension and cardiovascular diseases (CVD). Ubiquitous BP monitoring is expected to improve hypertension detection in the mass population and could enhance hypertension control by providing continual feedback to the patient. With continuous BP measurement, cardiovascular diseases can be treated more efficiently.

In Europe, more than 4million deaths each year is caused by CVD. In India, deaths due to cardiovascular diseases rose from 13 lakh in 1990 to 28 lakh in 2016. The number of prevalent cases of cardiovascular diseases has increased from 2.57 crore in 1990 to 5.45 crore in 2016. It is predicted that up to 23.3 million deaths can be caused by CVD until 2030, since the number of people with high BP is doubled the past two decades.

Due to an enormous number of people being affected by blood pressure disorders, many researchers are working to improve BP measurement methods convenience and accuracy. One of the conventional BP measurement methods is mercury sphygmomanometer. This measurement is based on inflating a cuff around the corresponding arm to impede the blood flow in the artery. Another well-known method that is used occasionally for day to day home healthcare is automatic BP meters. Oscillometry is similar to the auscultatory technique which uses a cuff around the arm or wrist. Other methods include catheterization, volume clamping, and tonometry.

Nevertheless, these methods usually have some disadvantages. First, they usually have lower accuracy owing to the annoying interference that raises from smooth muscles inside the arterial wall. Also, the requirement of a cuff in BP devices restricts the further reduction in size and limits the ease of their usage. These instruments are inconvenient, painful and do not allow continuous measurement. In particular, cuffs

are cumbersome and time consuming to use, disruptive during ambulatory monitoring, especially while sleeping, and do not readily extend to low resources settings. There have been many relevant technological advances in the recent past to overcome this disadvantage. Further, there is mounting evidence that pulse transit time (PTT, i.e., the time delay for the pressure wave to travel between two arterial sites) can provide the basis for convenient, cuff-less BP measurement. This technique uses the PPG and ECG signals to continuously estimate both systolic and diastolic blood pressures in real time.

Also, Physiological signals can often become contaminated by noise from a variety of origins. These signals tend to be small and prone to measurement artefacts and the noise is often difficult to control. Physiological signals, in particular ECG and PPG, have been the focus of noise reduction using a signal quality index, whereby each pulse has attributed a signal quality, which is then used to assess the validity of that pulse. So, a novel cluster analysis method is performed to reduce the influence of noise on photoplethysmography (PPG) signals. Further, we estimate the Baseline Wander based on piecewise linear estimation and nonlinear smoothing and process the signal to remove it.

CHAPTER 4

METHODOLOGY

4.1 Introduction

In order to make continuous BP measurement possible, a method of finding BP through the Pulse Transit Time(PTT) is used. It has been reported that the pulse transit time (PTT), the interval between the peak of the R-wave in electrocardiogram (ECG) and the fingertip photoplethysmogram (PPG), is related to arterial stiffness, and can be used to estimate the systolic blood pressure (SBP) and diastolic blood pressure (DBP). For this the required parameters should be derived from the used physiological signals(ECG & PPG). Since physiological signals are involved, they often become contaminated by noise from a variety of origins.Noise minimisation starts with removing the source of the noise; this can be through electrical isolation or, for example, by keeping the subject relaxed and still during measurements to eliminate muscle and movement artefact. However, these signals are prone to various other noises, which are to be eliminated using various signal processing techniques. Here, Cluster Analysis method is used to process the signals first. Later the baseline wander is estimated and then subtracted from the signals in order to remove the baseline wandering to make the signals more useful and accurate for any purpose.

4.2 ECG and PPG signals

4.2.1 ECG

Electrocardiography is the process of producing an electrocardiogram (ECG or EKG). It is a graph of voltage versus time of the electrical activity of the heart using electrodes placed on the skin. These electrodes detect the small electrical changes that are a consequence of cardiac muscle depolarization followed by repolarization during each cardiac cycle (heartbeat). The overall goal of performing an ECG is to obtain

information about the electrical function of the heart. Normal rhythm (as shown in figure below) produces four entities – a P wave, a QRS complex, a T wave, and a U wave – that each have a fairly unique pattern.

- The P wave represents atrial depolarization.
- The QRS complex represents ventricular depolarization.
- The T wave represents ventricular repolarization.
- The U wave represents papillary muscle repolarization.

Changes in the structure of the heart and its surroundings (including blood composition) change the patterns of these four entities. The U wave is not typically seen and its absence is generally ignored.

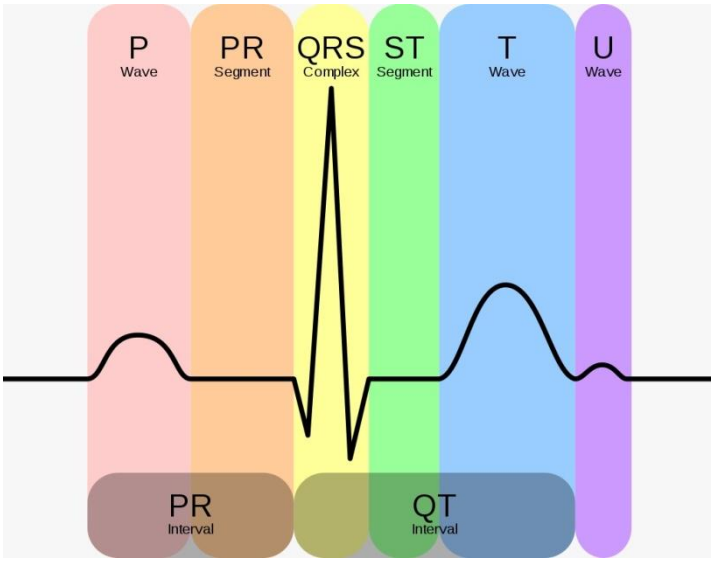

Fig. 4.1 A typical ECG wave

4.2.2 PPG

A photoplethysmogram (PPG) is an optically obtained plethysmogram that can be used to detect blood volume changes in the microvascular bed of tissue. A PPG is often obtained by using a pulse oximeter which illuminates the skin and measures

changes in light absorption. A conventional pulse-oximeter monitors the perfusion of blood to the dermis and subcutaneous tissue of the skin.

Additionally, the shape of the PPG waveform differs from subject to subject, and varies with the location and manner in which the pulse oximeter is attached.PPG shows the blood flow changes as a waveform with the help of a bar or a graph. The waveform has an alternating current (AC) component and a direct current (DC) component. The AC component corresponds to variations in blood volume in synchronization with the heart beat.

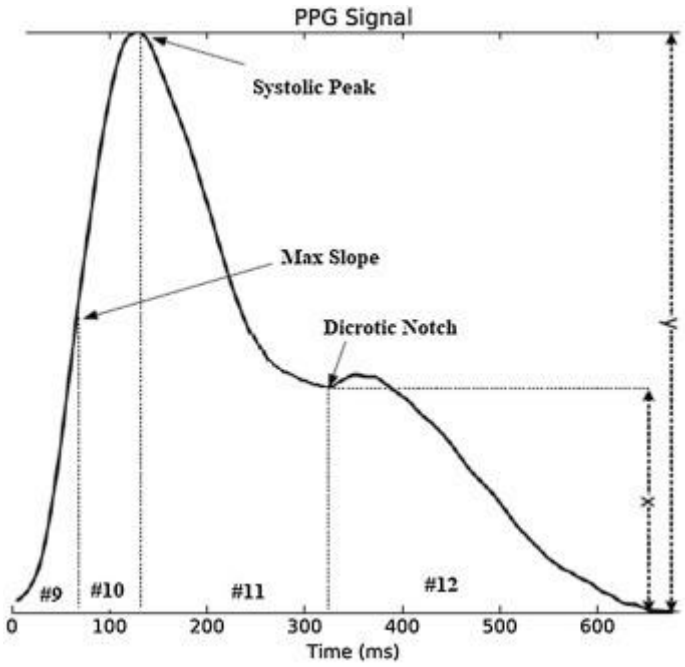

Fig. 4.2 A typical PPG wave

4.3 Sensors Used

4.3.1 Pulse Oximeter Sensor

The **Easy Pulse sensor** is designed for hobby and educational applications to illustrate the principle of photoplethysmography (PPG) as a non-invasive optical technique for detecting cardio-vascular pulse wave from a fingertip. This sensor is used for the extraction of PPG signals from the subject. It uses an infrared light source to illuminate the finger on one side, and a photodetector placed on the other side

measures the small variations in the transmitted light intensity. The variations in the photodetector signal are related to changes in blood volume inside the tissue. The signal is filtered and amplified to obtain a nice and clean PPG waveform, which is synchronous with the heart beat. The original version of Easy Pulse uses the TCRT1000 reflective optical sensor to sense the blood variation in the finger tissue and outputs a digital pulse which is synchronous with the heart beat. Today, we are pleased to announce the release of Easy Pulse Version 1.1, which has some improvements over the original design. The new version provides both analog PPG waveform as well as digital pulse signal as separate outputs.

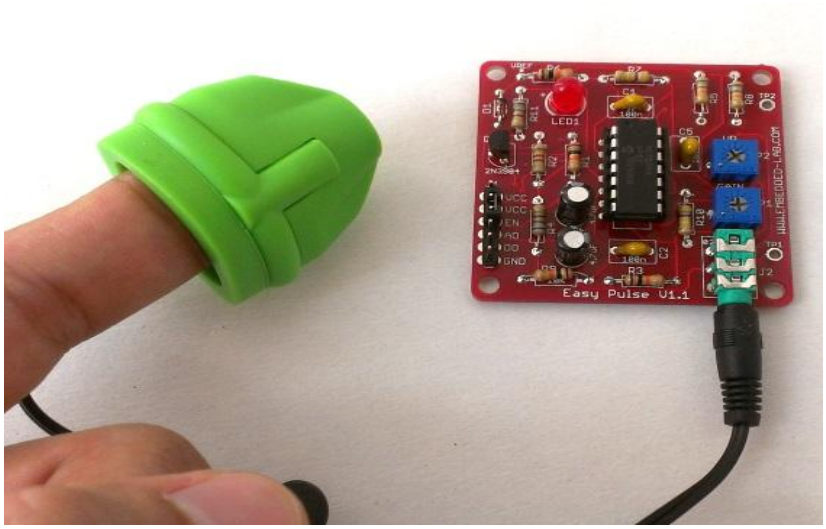

Fig.4.3 Easy Pulse PPG sensor

4.3.2 AD8232 Heart Rate Monitor

The AD8232 is a neat little chip used to measure the electrical activity of the heart. This electrical activity can be charted as an ECG or Electrocardiogram. Electrocardiography is used to help diagnose various heart conditions. This heart rate monitor is used for the extraction of ECG signals from the targeted subject.

Fig.4.4 AD8232 heart rate monitor

The cables are color coded to help identify proper placement as shown in the table based on Einthoven's triangle. The sensors can be placed on the forearms and leg as shown on the diagram on the left. Or they can be placed on the chest near the arms and above the right, lower abdomen (i.e. just above the right hip) as shown on the diagram on the right.

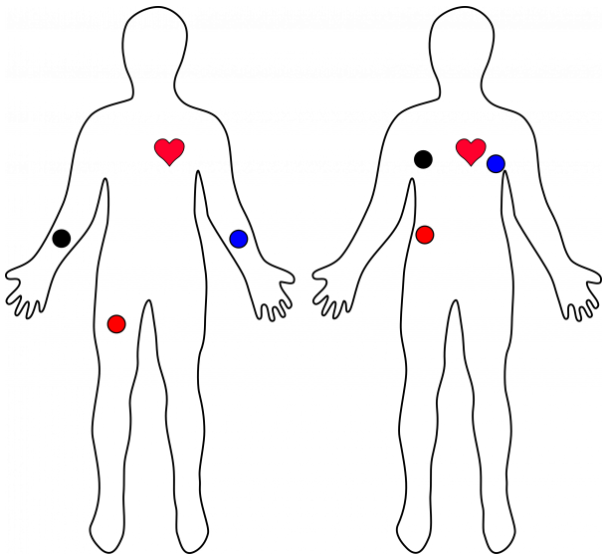

Fig.4.5 Typical Sensor placements

4.4Extraction of signals from human subject

Using the above given sensors, the ECG and PPG signals are extracted from the targeted human subject to whom BP is to be measured.These are the signals extracted from human subject.

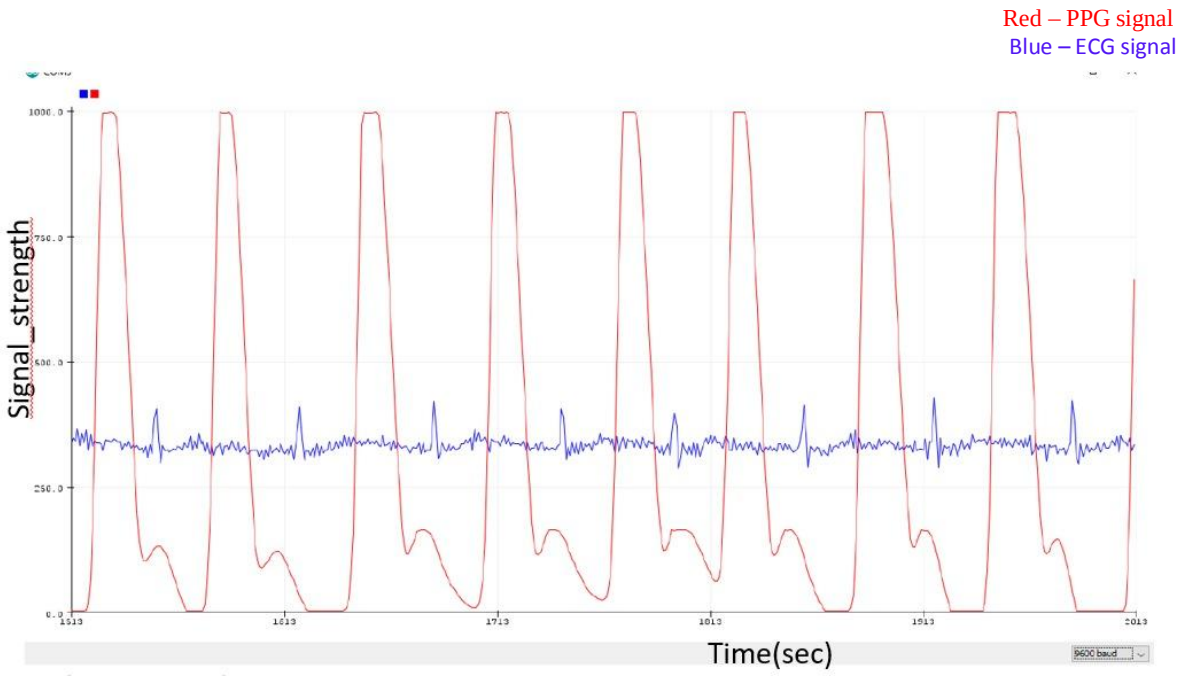

Fig.4.6 Extracted signals

4.5 Normalization and derivation of AC component of PPG signal

It has been reported that the accurate PTT is found by calculating the time interval between R-peak of ECG and the peak of second derivative of the AC component of PPG signal.

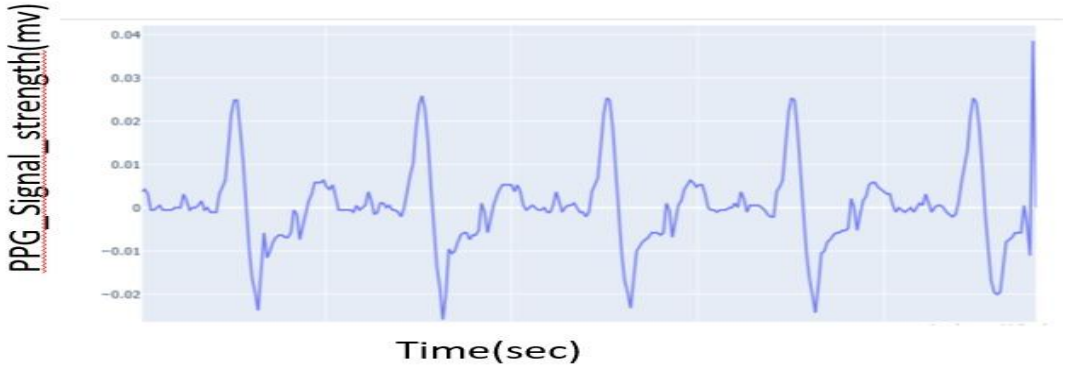

Fig.4.7 PPG signal after derivation

4.6 Finding systolic peaks and valleys of both signals

Systolic peaks and valleys for ECG and PPG signals are found in order to calculate Pulse Transit Time.

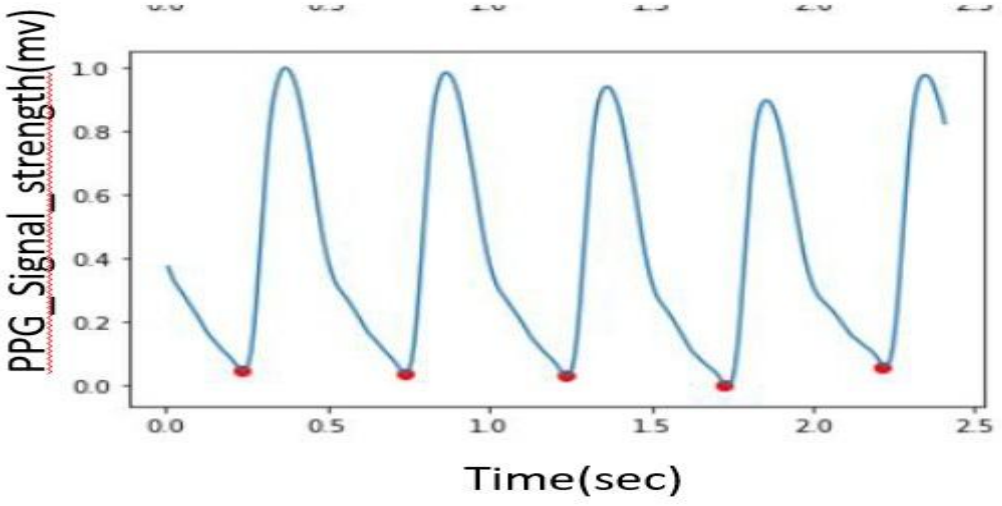

Fig.4.8 Valleys of PPG signal

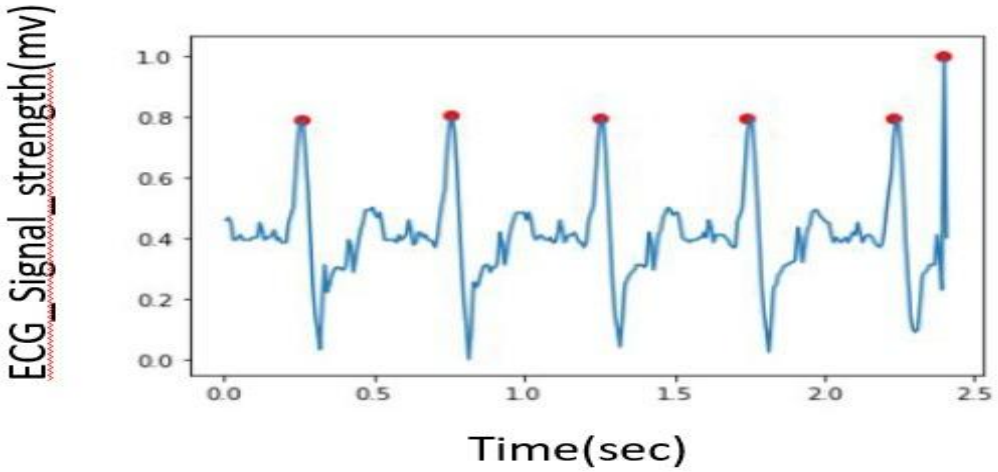

Fig.4.9 Peaks of ECG

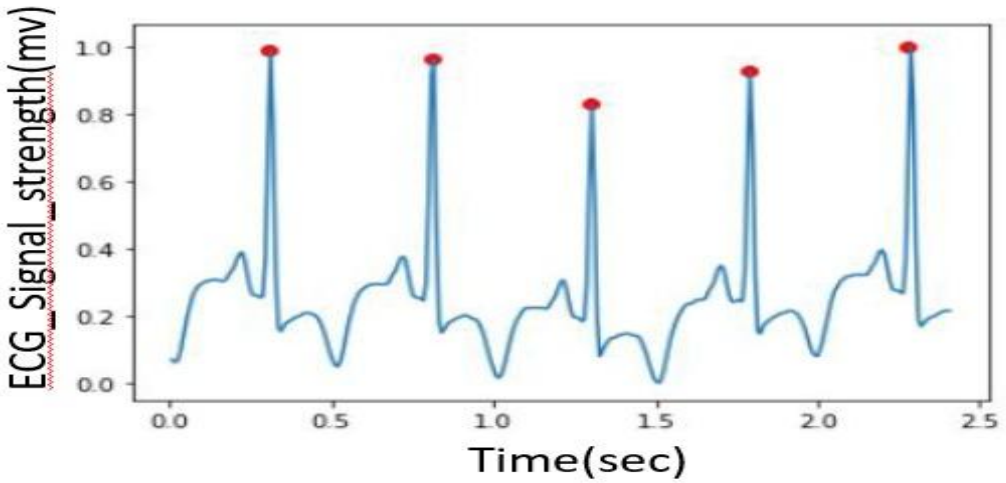

Fig.4.10 Valleys of ECG

4.7 Finding Pulse Transit Time(PTT) :

It has been reported that the **pulse transit time** (**PTT**), the interval between the peak of the R-wave in **electrocardiogram** (**ECG**) and the fingertip photoplethysmogram (**PPG**), is related to arterial stiffness, and can be used to estimate the systolic blood pressure (SBP) and diastolic blood pressure (DBP).

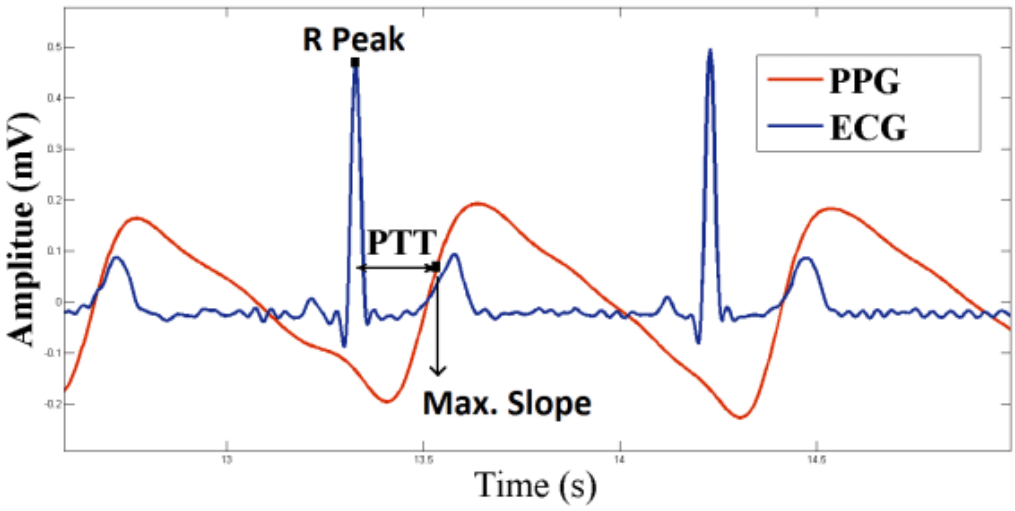

Fig.4.11 Calculation of PTT

4.8 Signal Processing

(Note: Since we do not have the sensors to extract the signals, due to current situation of Covid-19, hereon we use the signals from the physionet database available online)

Physiological signals, in particular ECG and PPG, have been the focus of noise reduction using a signal quality index, whereby each pulse has attributed a signal quality, which is then used to assess the validity of that pulse.

Two signal processing techniques are used to filter, remove noise and baseline wander and process the signals to be useful for various medical purposes. One is the Cluster Analysis. The other being Baseline wander removal technique.

4.9 Cluster Analysis

4.9.1 Flowchart of procedure

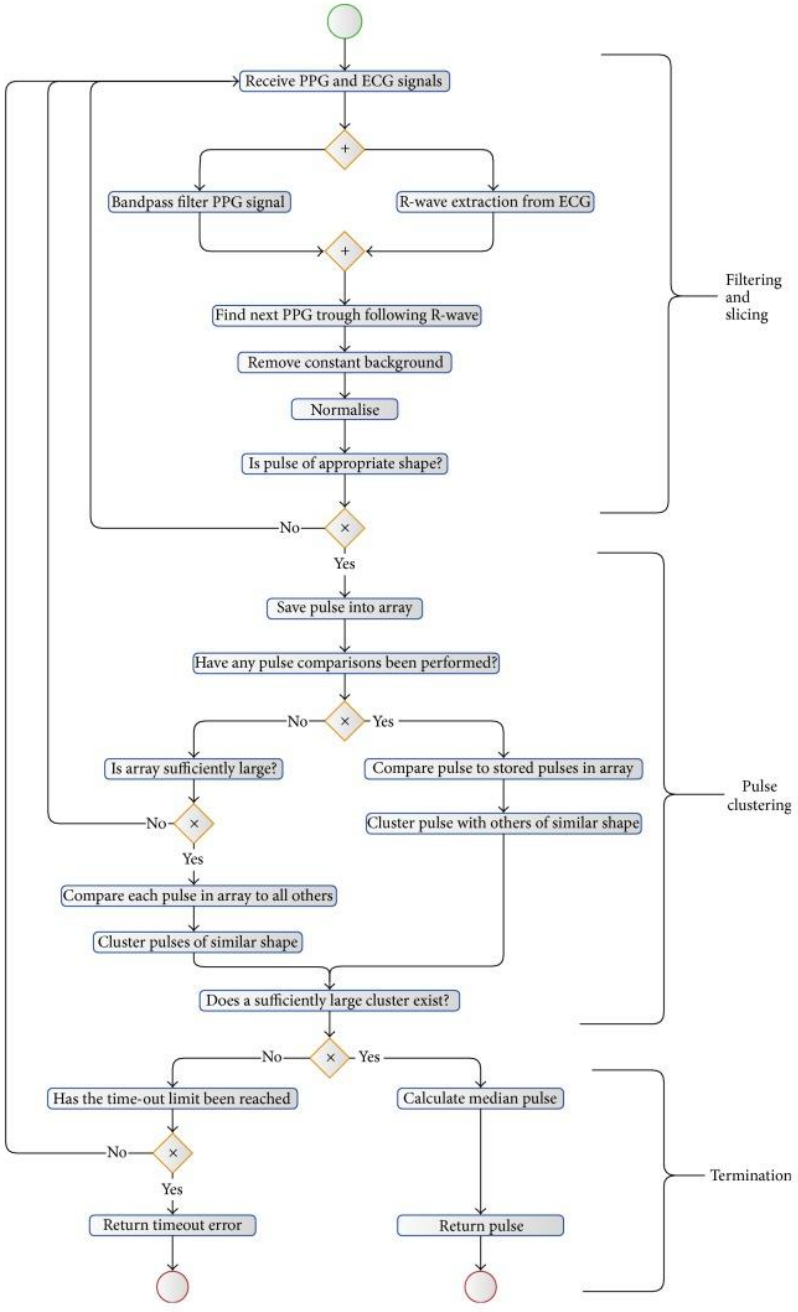

Fig.4.12 Flowchart of the procedure

4.9.2 Introduction

The algorithm was developed to reduce noise from a PPG signal. This signal has a periodic frequency equal to the heart rate of the subject. The signal structure mainly

exists in the low-frequency domain, with the desirable frequencies for analysis lying between 0.15 Hz and 20 Hz. The incoming PPG signal is subject to a digital bandpass filter to remove unwanted noise and signal drift. This is implemented through a low-pass filter and a high-pass filter, designed to minimise both the signal distortion and the signal phase delay. A minimal delay is imperative for any device where a live trace is shown, especially where operator feedback is a possibility (e.g., adjustment of the sensor at the measurement site). Any substantial delay can render such operator feedback confusing and nonintuitive.

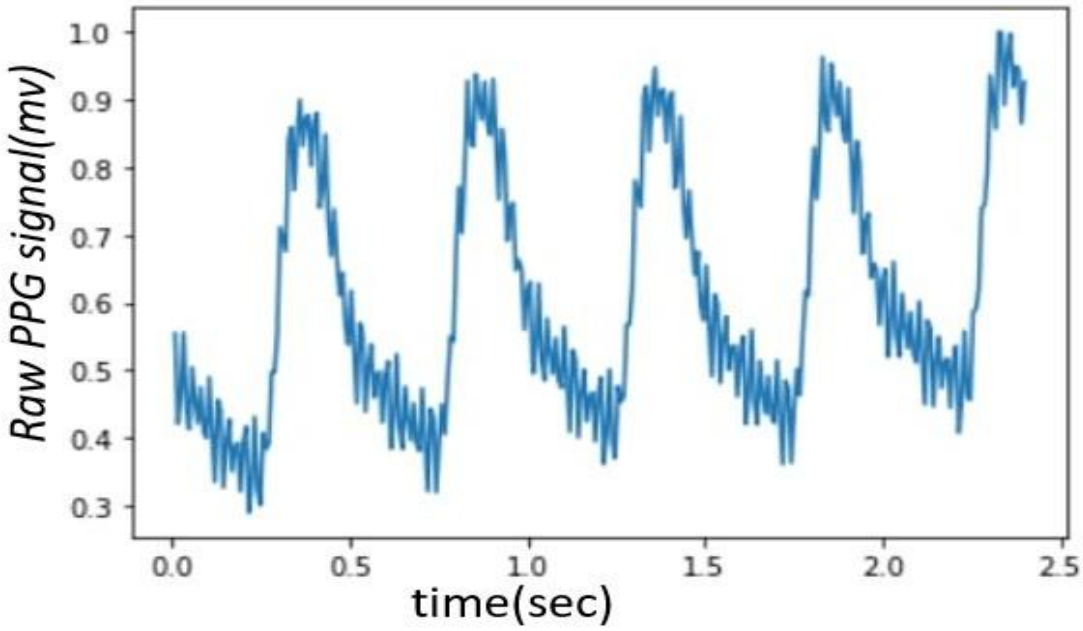

Fig.4.13 Raw PPG signal

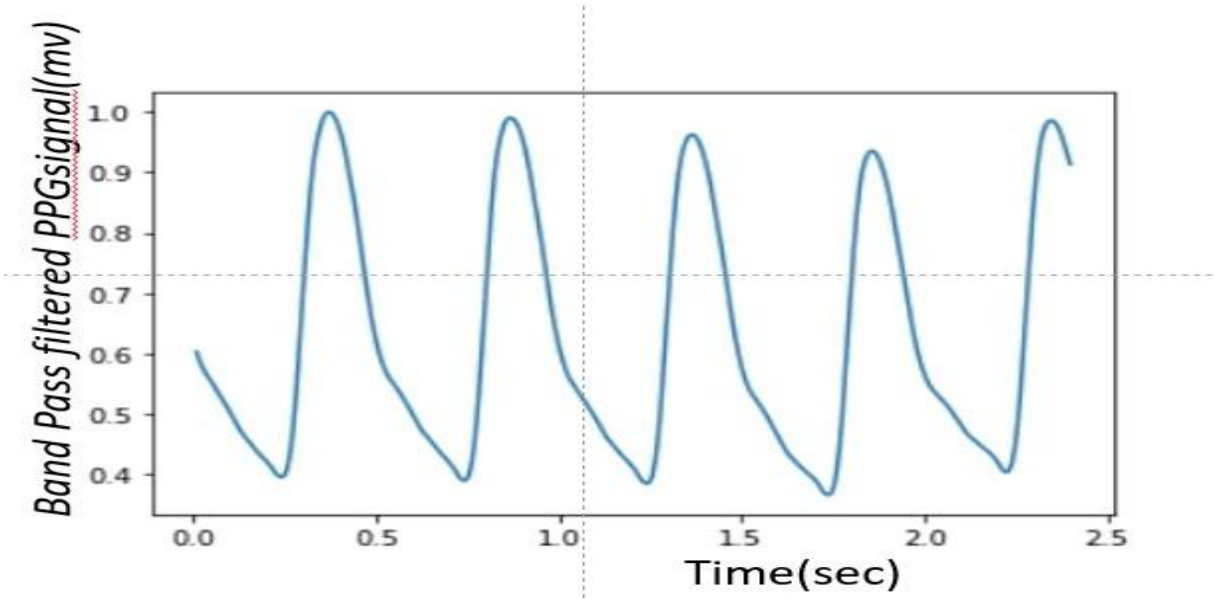

Fig.4.14 Band Pass filtered PPG signal

4.9.3 Pulse Clustering

The algorithm saves the pulse into an array. This pulse is then compared to all previous pulses by comparing the amplitude of each sample within the pulse. In order to compare the pulses, distance metrics were tested, including calculating the Pearson correlation coefficient, the Kendall rank correlation coefficient, the Spearman rank correlation coefficient, and the root mean square error (RMSE). Each of these distance metrics is optimised differently; by using a subset of data and visual comparisons of the clusters, RMSE produced the most appropriate clustering. RMSE also has the advantage of being computationally simple and therefore fast.

Each pulse forms a new cluster and is the centre of that cluster. In addition, each pulse is placed into any other cluster, where the RMSE between this pulse and the pulse at the centre of that cluster is below a threshold value. In this way, N pulses create N clusters, each populated with pulses with an RMSE from the centre pulse less than a preset threshold.

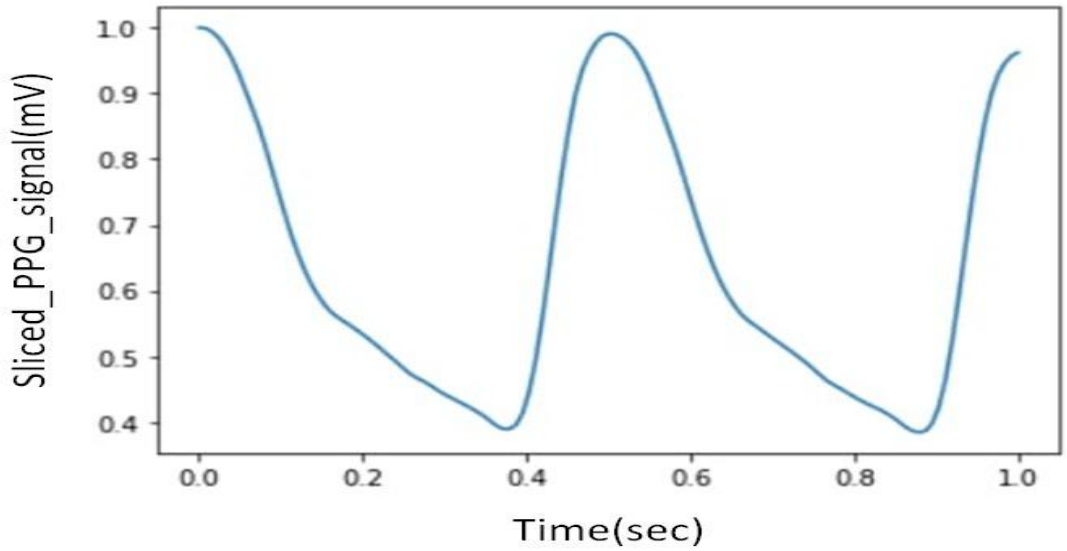

Fig.4.15 Sliced PPG Signal

4.9.4 Termination

After each pulse has been clustered, the number of pulses in each cluster is calculated. If any cluster has sufficient pulses for the algorithm requirements, then the loop is terminated, and an averaged (normalised) pulse is returned. As the pulses are normalised in time, the median pulse is calculated by finding the median of each point on the pulse. If there is no cluster with sufficient pulses, then the algorithm accepts more data, or if a predefined time-limit has been reached, then the algorithm terminates with a time-out error. This protects the algorithm from running continuously with no output.

4.9.5 Algorithm Validation

To validate the algorithm, a clean PPG signal was analysed using the filtering described above, however with the clustering turned off. This returned an averaged representative pulse shape. The signal was then digitally contaminated with noise, and the analysis was repeated with and without clustering. The output of these two methods of analysis was compared to the representative pulse from the clean signal.

4.10Baseline Wandering Removal

4.10.1 Introduction

Baseline Wander is a low frequency noise having non-linear and non-stationary nature. The classical methods such as high-pass filtering cannot provide full seperation of the signal from low-frequency noise. We propose an approach to estimate the Baseline Wander based on piecewise linear estimation and nonlinear smoothing. The general idea is to estimate baseline wander locally using linear models. The proposed approach is experimentally compared with reference methods.

4.10.2Methodology

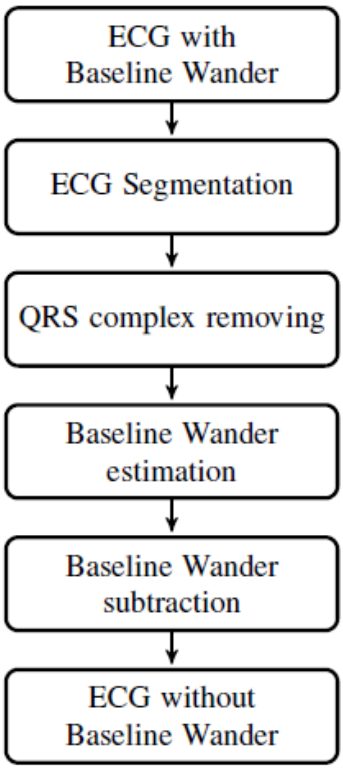

Fig.4.16 Flowchart of methodology

The method is estimation and subtraction of baseline wander from ECG signal. The main elements of our approach are: segmentation algorithm removal of QRS complexes from ECG signal and estimation of baseline wander .The general idea

lying behind the Baseline Wander estimation is to divide ECG signal into small segments and to estimate the BW in these segments. The segmentation is to divide ECG signal into the regions where QRS complexes occur and the areas where the QRS does not appear. The next step in the considered method, is the removal of QRS complexes. We apply the mean interpolation technique. BWs, linearly interpolated in each segment, are concatenated to determine the piecewise linear estimate of Baseline Wander. Since the determined baseline wander is a concatenation of linear functions, it is important to make it smooth. To do this, we use a Savitzky Goaly filter.

4.10.3 Segmentation

We divide the signal into regions where QRS complexes occur and those where QRS does not appear.

The general form of the segmentation algorithm is:

$t_s = [t_s^{(1)}, t_s^{(2)} \ldots\ldots\ldots , t_s^{(m)}]$

Where 'm' denotes the number of QRS complexes, $t_s^{(n)}$ denotes time portion of the signal where the QRS complexes occur .

The segmentation is done by finding the peaks of the inverse signal.

4.10.4 QRS complex removing and Interpolation

The next step, is to remove QRS complexes from ECG recordings. The general form of the algorithm is denoted as:

$y_I = F_I(y_s, y)$: where F_I is the interpolation method.

The interpolation technique used here is as follow :

For t between $t_s^{(n)}, t_s^{(n+1)}$

if : $t <= t_s^{(n)} + (t_s^{(n)} - t_s^{(n+1)})/3$

$y(t) = y(t_s^{(n)})$

if : $t_s^{(n)} + (t_s^{(n)} - t_s^{(n+1)})/3 < t < t_s^{(n)} + 2*(t_s^{(n)} - t_s^{(n+1)})/3$

$y(t) = y(\text{mean}(y(t_s^{(n)}), y(t_s^{(n+1)}))$

if : $t_s^{(n)} + (t_s^{(n)} - t_s^{(n+1)})/3 < t <= t_s^{(n)} + 2*(t_s^{(n)} - t_s^{(n+1)})$

$y(t) = y(t_s^{(n+1)})$

This is done for every consecutive $t_s^{(n)}$.

Below is the figure of signal with baseline wandering.

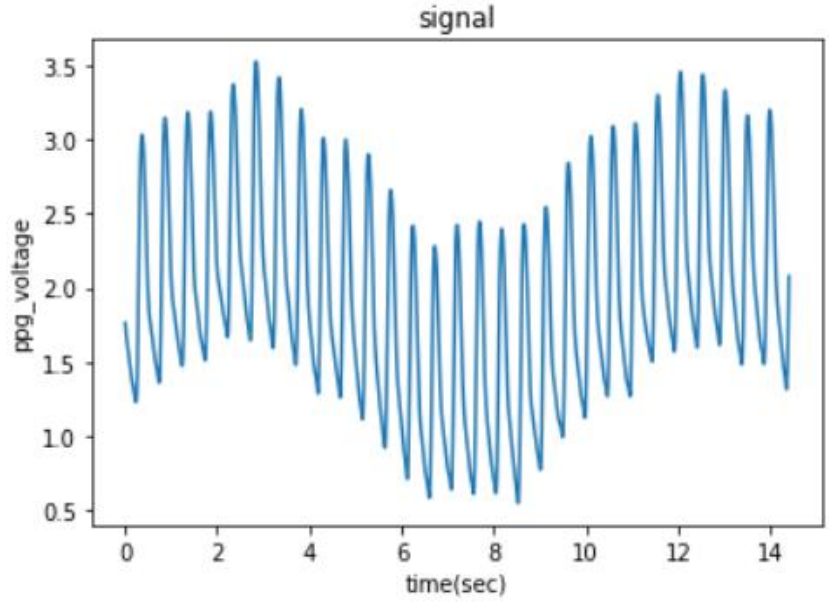

Fig.4.17 Signal with baseline wandering

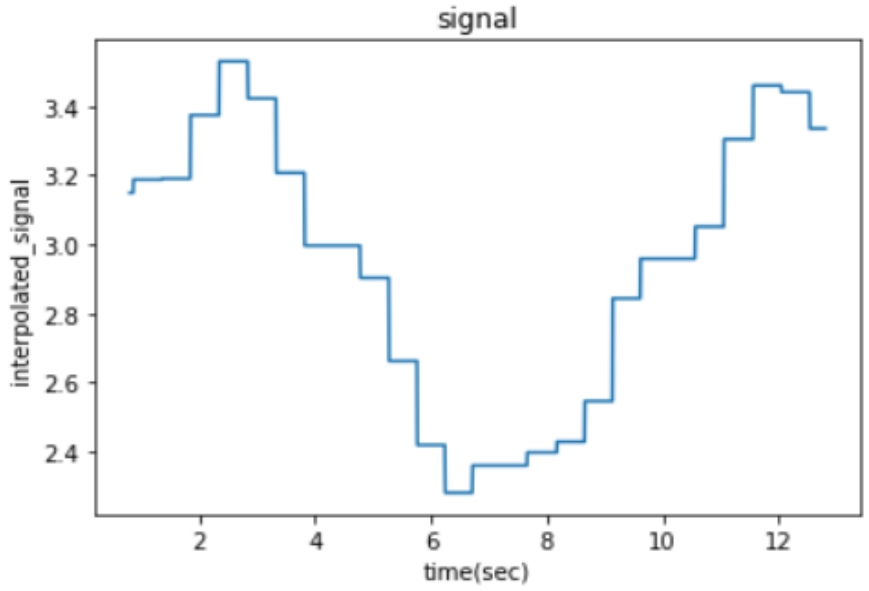

Fig.4.18 QRS complex removed and Interpolated signal

4.10.5 Baseline wander estimation

The interpolated signal is passed through Savitzky Goaly filter. This has the effect of smoothing the signal.

The figure shows the plot of the estimated curve.

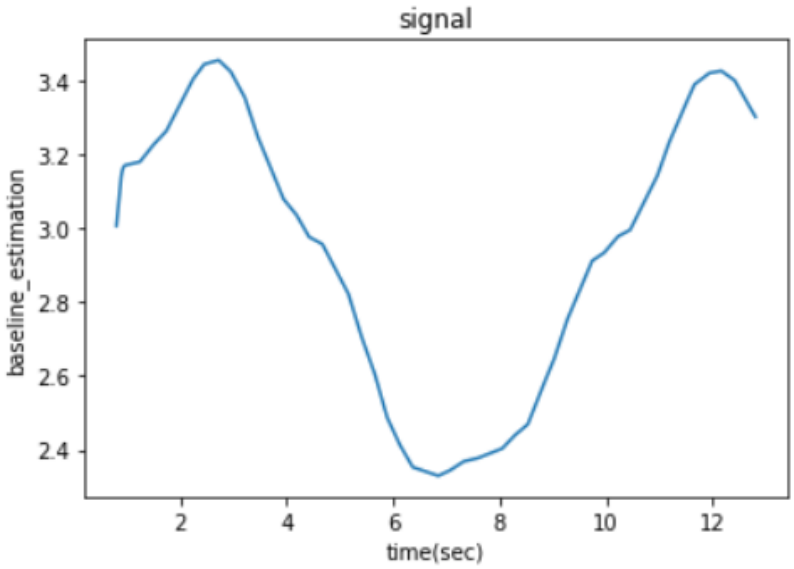

Fig.4.19 Estimated curve

4.10.6 Baseline wander subtraction

The estimated baseline curve is subtracted from the noisy signal to get the ecg without baseline wander.

The plot of the signal without baseline wandering is shown below

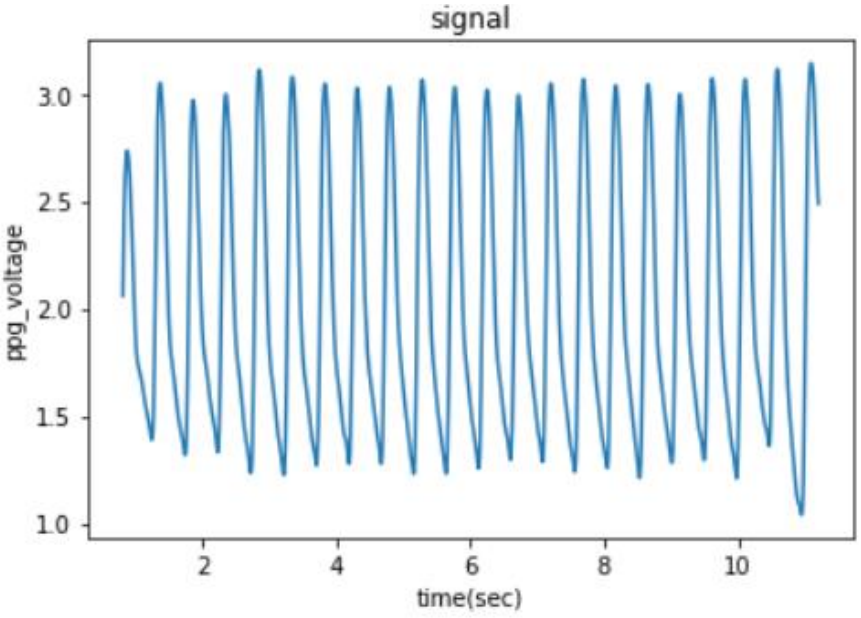

Fig.4.20 Signal without baseline wandering

4.11 Performance evaluation

4.11.1 Performance Evaluation of Baseline Wander

The signal processing performance is evaluated by the following performance indexes:

- SNR (signal-to-noise ratio).
- Root mean square error.

SNR (signal-to-noise ratio):

The signal power and the noise power is compared.

$$SNR = 10\log_{10}\left(\frac{\sum_{t=1}^{T} y(t)^2}{\sum_{t=1}^{T}\left(y(t)-\hat{s}(t)\right)^2}\right)$$

The Root Mean Square Error:

$$RMSE = \sqrt{\frac{1}{T}\sum_{n=1}^{T}\left(y(t)-\hat{s}(t)\right)^2}$$

4.11.2 Performance evaluation result

The dataset used was taken from the Physionet. Three dataset were used and baseline wandering noise was added to it. The noisy signal was then processed by the method described and the above performance evaluation was done to grade the signal processing technique. The result of performance evaluation on the three dataset is shown in the table below.

Table 4.11.2

	Result
dataset 1:	
RMSE	0.0073
SNR [dB]	29.19
dataset 2:	
RMSE	0.0175
SNR [dB]	2.89
dataset 3:	
RMSE	0.0017
SNR [dB]	35.89

CHAPTER 5

CONCLUSION

5.1 Conclusion

From the above process, the Pulse Transit Time has been calculated. Blood Pressure is estimated by calibrating PTT to BP. Since we extract the ECG and PPG signals continuously from the subject, we can calculate the PTT continuously, which means the BP is measured on a continuous time frame. This PTT-based method to evaluate Blood Pressure(BP) continuously could be considered a major advancement, which can be used to treat several cardiovascular diseases. This also helps to predict the likelihood of cardiovascular (blood vessels in the heart) and cerebrovascular (blood vessels in the brain) disease linked to hypertension and organ damage. Also, this method is convenient, accurate and can be used to any kind of subject. This could impact the number of deaths caused by CVDs each year.

Cluster Analysis, a signal processing technique, is performed on a raw PPG signal to remove the noise and it resulted in a clean PPG signal. Later, the PPG signal is processed through segmentation to remove the baseline wander, which if present might affect the final results. Various performance metrics, like signal-to-noise ratio and root-mean-square error, have been tested to check the quality of signal processing. Based on the performance metrics tested (Table 4.11.) it could be stated that the signals have been properly processed and the noise has been greatly reduced. These processed signals are used not only for the estimation of BP, but also for several medical diagnosis. The processed PPG signals are used for measuring oxygen saturation, blood pressure and cardiac output, assessing autonomic function and also for detecting peripheral vascular disease. Estimation of respiratory rate requires the PPG signal to be accurately processed for a finer treatment. Further, ECG signals find their use in indicating the heart rate used to diagnose heart disorders. Every diagnosis related to heart needs the ECG signal. This is the impact of the work created using the PTT based method and the signal processing techniques.

5.2 Future scope

1. Calibration of Pulse transit time to Blood Pressure is to be done.
2. Adaptive calibration can be done inorder to use this system to any human subject irrespective of their individual calibration coefficients. The calibration curve relating PTT to BP is dependent on the distance between the waveform measurement sites,blood density (which is close to that of water), the average cross-sectional area of the arteries between the measurement sites, and the precise function relating BP to compliance. Except for blood density, these parameters are all subject-specific. Experimental data indeed confirm the dependency of the calibration curve on the subject. Hence, a calibration curve that is tailored to each subject would be optimal. However, constructing such a curve would appear to require cuff BP measurements from the subject, and the calibration curve would have to be updated at a rate faster than the arteriosclerotic process (e.g., up to a few years at a time).

5.3 Note

Taking into account the current situation(Covid-19), we have discussed and confirmed with our guide regarding the change of our project from firmware to software.

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