International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-8 Issue-10, August 2019

Development of a Low-Cost Heart Rate Monitoring and Transmission System using PPG Signal Processing for Wearable Devices

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Abstract: Photoplethysmography (PPG) technique is used in most of the fitness tracking devices available now-a-days, due to its low cost and simplicity. These PPG signals are obtained from the variations in the blood flow with the help of pulse rate sensor. In this paper, PPG signal is acquired from two PPG sensors worn in the finger and the wrist to get the heart rate and its various parameters. The signal noise is removed with the help of MATLAB with various filters to get the smooth signal. The peak detection is done for heart rate (HR) and peak interval calculation, the spectral estimation is done, the first and second derivatives and the heart rate variability are obtained. The low cost Arduino nano and the Bluetooth module is used for the development and the transmission of HR value from the wearable device through an application developed for it, as well as the values are transmitted remotely with the help of the Global System for Communication (GSM) built in the mobile phone, which can display the value and can also transmit it to any particular person or remote physician who can monitor the person's HR remotely. The complete system developed provides a low cost solution for heart rate detection and monitoring of a person from a distance.

Keywords: MATLAB, Photoplethysmography (PPG) signal Processing, pulse rate sensor, pulse transit time, Resting Heart Rate

I. INTRODUCTION

Fitness tracking is increasingly gaining importance in today's life due to the growing health concerns, in which, heart rate plays a vital role. The heart rate of a person can be determined by calculating the pulse rate, which specifies the functioning of the heart. Generally, pulse rate can be calculated by counting the pulse from one's wrist, using the finger, in 15 seconds and then multiplying it by 4, to get heart rate in beats per minute, that is, the number of times the heart beats. The normal resting heart rate of an adult person is around 60-100 beats per minute. Resting heart rate or RHR is the number of heart beats per minute while the person is at rest. Heart rate monitors usually measure or display real time heart rate as well as record it for later monitoring and analysis. These monitors acquire data from the person at rest or during various physical exercises. The heart rate monitors used in hospitals consists of wires and different types of sensors which usually involve the ECG. The general consumer heart rate monitors for everyday use do not have wires and mostly involve the PPG. These two technologies are used in today's world for measuring heart rate which gives nearly the same basic outcome. The (ECG) Electrocardiography sensor measures the bio-potential or the electrical activity of the heart that arise due to expansion and contraction of the heart. The Photoplethysmography (PPG) sensor uses light to detect the changing blood flow caused by the pumping of the heart. In this paper, PPG technique is used to detect the heart rate with the help of an optical pulse rate sensor and an Arduino Nano board. The PPG sensor gives the voltage level of PPG signals which are sometimes distorted due to noise from the surroundings as well as from breathing and body movement. The noise needs to be removed from the noisy PPG signal to obtain the clear PPG signal which can be used for further analysis. For this, different filters have been used to get the clear PPG signal. Then the peaks of the PPG signal are detected and marked for further calculations. The complete process of signal acquisition, noise removal, peak detection and analysis has been done in MATLAB. The clear signal thus obtained is used to calculate the heart rate in beats per minute (bpm) and to carry out the different analyses of the PPG signal. The heart rate thus obtained is transmitted back to the Arduino Nano board through the USB cable. Then Bluetooth is used to transmit the value to an Application which is specially designed for this purpose. The Application then takes the cell phone number to which the data is to be transmitted remotely and sends a message of the heart rate in bpm. This is done with the help of the GSM communication network inbuilt in the mobile phone. Section II gives the literature survey of the previous work done on the PPG signal processing for heart rate detection and analysis. Section III gives a description of the PPG technique and its working to detect the pulse rate from the finger. Section IV describes the methodology used for acquiring the PPG signal, the processing techniques used to remove the noise using MATLAB and discusses the technique which is used for heart rate detection from PPG signal, the feature extraction and the spectral analysis of the PPG signal and the heart rate variability, as well as gives a brief description about its outcomes. Section V describes the hardware used to establish communication for transmission of the HR value of the person to a remote physician and section VI discusses the results obtained from the PPG signal processing and its analysis for heart rate parameters. Finally section VII gives the conclusions drawn from the overall process and the system developed.

Manuscript published on 30 August 2019.
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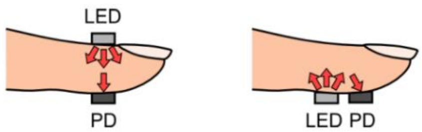
II. RELATED WORK

For the measurement of heart rate signal, PPG technique has been widely used due to its non-invasive nature as well as its simplicity of usage for heart rate detection. The most common technique for heart rate measurement is the ECG, but it requires the electrodes to be physically connected to the body at different points with the help of some specific gel, to get the correct electrical signals from the heart. Therefore PPG provides a good solution, as it just needs to be kept on the finger or the wrist to measure the heart rate, especially for wearable fitness devices. The different works involving the use of PPG signals for heart rate detection and analysis have been discussed below. The authors in [1], used the Arduino board and the optical pulse rate sensor to detect pulse from finger and processed the PPG signals in MATLAB and displayed it in the PC. The frequency domain analysis and the extraction of HRV signal was done. The Wavelet transform and de-noising algorithm was used for the removal of artifacts. The time domain analysis was done by parameter extraction and Poincare plotting and the frequency domain analysis was done by the Power Spectral Density (PSD) method. According to the authors in [2], there are various methods and advances in PPG signal acquisition and analysis which are discussed and conclusions are also drawn from it. The methods such as time domain analysis, performed using statistical and geometric indices and frequency domain analysis were explained. It also concluded that the PPG technique is given preference over the ECG and that its benefits are more than ECG, as compared to the electrodes attached to the body in ECG technique. It also provides a review of the literature related to PPG in last 20 years. The authors in [3], presented a chest wearable blood pressure monitoring system that measures arterial stiffness by calculating pulse transit time (PTT). Data transmission was done wirelessly to the PC and pre-processing of ECG signals was done to remove data noise from it. Pans-Tompkins algorithm was used for R-wave detection and a low pass filter used for removing the noise of PPG signal and then 1st order derivative was applied to PPG signals for peak detection. In [4], the NIELVIS-II+ was used as DAQ board for connecting PCG and PPG devices with the PC for signal acquisition which was given to MATLAB for further processing and heart rate extraction. Baseline drift removal was done by Moving Average filter and noise cancellation by discrete wavelet transform method. The analysis done was helpful for correlating PPG and PCG signal features simultaneously. In [5], the authors developed an adaptive noise cancellation algorithm in MATLAB which extracts the HR frequency. It uses a STM32F407VG micro-controller, a wearable PPG wristband and an embedded three axis accelerometer for data acquisition. The frequency spectrum estimation was done by fast Fourier transform (FFT). In [6], the authors used two PPG signals to estimate the BP and HR. A low pass filter was used for the noise removal of the PPG signal. The number of peaks were calculated by the threshold method. The peak location, peak time and peak time difference was used to determine the Pulse Transit Time (PTT) using LabVIEW. Linear regression analysis method was used to obtain the blood pressure using MATLAB. The averaged PTT values were sent through the GSM. According to the authors in [7], the PPG de-noising which was done, offered significant accuracy and the analysis on the clean PPG signal for medical inference provided higher performance efficacy. The various types of analysis were done on PPG segments, the feature extraction was used for the dissimilarity measure, an outlier detection method was used for noisy segment identification and the clinical utility assessment was done for CAD detection. In [8], the PPG signal acquisition and preliminary level analysis was done with a portable data acquisition system, which was developed for collection of PPG signals through USB interface. The first and second difference points for all points of the PPG signal were detected. The heart rate, peak to peak time, stiffness index and the crest time averaged over all PPG cycles were calculated.

III. PHOTOPLETHYSMOGRAPHY

Photoplethysmography or PPG is a simple optical technique that is used to detect the changes in the blood volume in the microvascular bed of tissue [10]. It is a non-invasive technique which is often used to measure the blood volume at the surface of the skin. The PPG is a low cost technique which is widely used in medical applications to measure the blood pressure, heart rate, oxygen saturation and many other parameters related to the cardiac activity of the body, as well as in many commercially available wearable fitness tracking devices. Photoplethysmography can measure the heart rate by detecting the changes in the blood volume [2]. The photoplethysmogapy signal can be acquired with the help of a PPG optical pulse rate sensor. The PPG sensor consists of a visible green light LED, a photodiode and some noise removal circuitry for acquiring the PPG signals. The green light emitted by the LED is absorbed by the blood flowing through the vessels under the skin. The changes in the blood flow results in the variation of the light absorbed by the blood which is then given to the photodiode. The photodiode is either arranged in a same plane as the LED, called as reflection type of PPG sensor or at the opposite plane of the LED, called as the transmission type of PPG sensor. Accordingly, the green light is either reflected back to the photodiode or is transmitted directly to the photodiode after being absorbed and varied by the blood flow. In the reflection type of sensor, the finger is placed on the sensor and the LED light variations due to the blood flow are reflected back to the photodiode in the same plane. In the transmission type of sensor, the finger is placed in between the LED and the photodiode and the light variations are transmitted directly to the photodiode in the opposite plane.



Transmission type and Reflection type
Fig. 1. Types of PPG sensor [11]

The PPG sensor provides the change in the voltage level according to the change in the blood flow and thus the PPG signal in voltage values can be obtained from it.

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This signal can be easily acquired and plotted to calculate the heart rate and various other parameters. The PPG signal consists of the cardiac cycles, which comprises of the two main phases, the ventricular diastole and the ventricular systole. The diastole is the relaxation phase, in which the blood pressure decreases and the systole is the contraction phase, where the blood pressure increases in the blood vessels [2]. The PPG signal consists of a lot of valuable information about the cardiovascular system as well as the different features useful for detecting various cardiac conditions.

IV. METHODOLOGY

A. PPG Signal Acquisition:

The PPG pulse rate sensor is used for acquisition of the signals from a person whose heart rate is to be measured. The sensor is attached to any finger from which the values are to be acquired. For this purpose, a low cost, low power Arduino Nano board with ATMEGA328P micro-controller has been used. It takes the analog values of the signal from the sensor and converts it into digital form for further processing and then transfers the signals to the PC via the USB cable.

The PPG sensor has three pins, one analog pin for acquiring the signal, one source pin and one GND pin, which are connected to the respective pins on the Arduino board. A code is written for the Arduino so that the sensor voltage can be measured and acquired at equidistant points in time. The CoolTermWin144 application needs to be executed to start obtaining the values of the sensor through the Arduino connected to the PC. For this, the application is run on the PC which opens a window, where the connection to the Arduino is established through a COM port of the PC. After specifying the baud rate, the capturing of data to text file needs to be started and connected to start receiving the values in the window, which can be saved in proper text format. These values are then loaded into the MATLAB command window of the MATLAB Software for further processing and calculations.

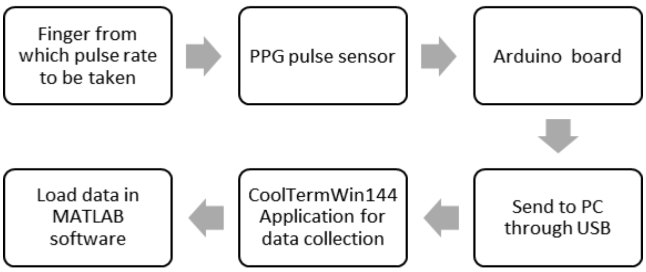

Fig. 2. Flow of the data acquisition

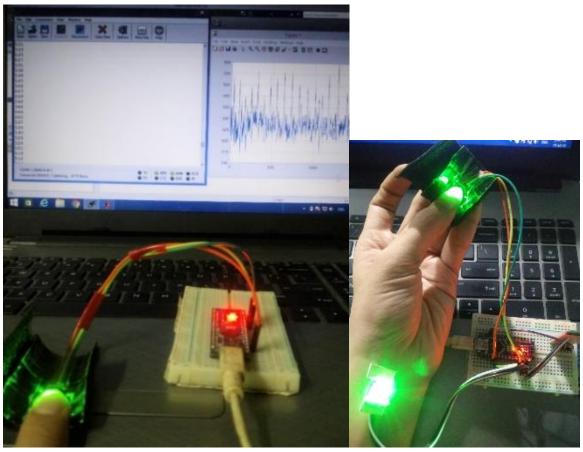

Fig. 3. PPG signal acquisition from the pulse sensor for HR and PTT.

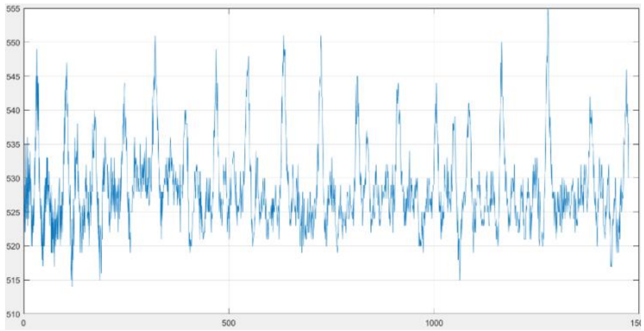

Fig.4. The noisy PPG signal acquired from the pulse sensor

B. Processing of PPG signals:

The PPG signals acquired from the sensor gets affected with noise due to the surrounding external light sources which interfere with the light of the LED falling on the photodiode of the PPG sensor, as well as some body movements which are present while taking the measurements. These light sources and movements get added to the original signal and thus the signal gets contaminated and is not in proper form for extracting the required features. Therefore the PPG signal acquired from the sensor is noisy and in raw form, thus it needs to be processed. This processing involves applying different types of filters for removing the noise and finding the exact peaks which need to be calculated for heart rate measurement. For this, different filters have been used in MATLAB to remove the noisy part and to smoothen the PPG signal so that only the required valuable signal is obtained. The different types of filters which have been used are given below:

1. Moving Average filter:

The moving average filter is used for smoothing data with the use of a given value of point for the moving average. It smoothes the data using a specified number of points to compute each element of the output. It is a specific type of the normal FIR filter. The filter has a sliding window method, in which the specified window length slides through or moves over the samples of data one by one and gives the computed average for the data in the given window.

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Due to the computations involving the past values, a specific amount of delay is added in the original signal value after filtering it with the moving average filter.

2. Savitsky-Golay filter:

The Savitzky-Golay filter smoothes the signal using a polynomial filter, where the polynomial order should be less than the frame length which is odd, and the input signal length has to be greater than or equal to the frame length. The filter performs the filtering by using convolution for convolving the signal with the center row or element of the output of the filter and gives a steady state portion of the filtered signal. The figure below shows the Moving Average filter and the Savitzky-Golay(SG) filter both applied to the noisy PPG signal. The moving average filter used gives less smooth curve than the Savitzky-Golay filter as well as the amplitude of the signal gets affected. Therefore the SG filter is used for smoothing the noisy signal.

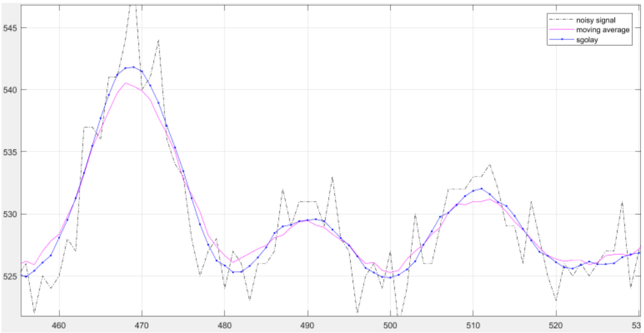

Fig. 5. Moving Average filter and SG filter applied to the noisy PPG signal.

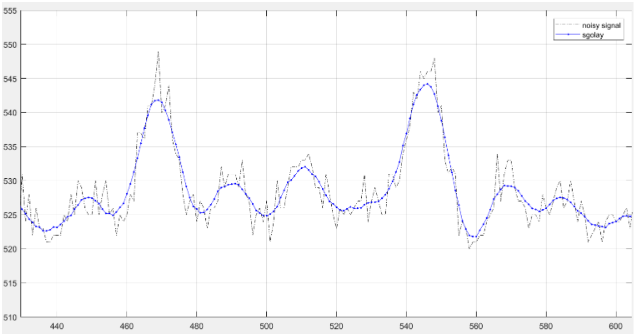

Fig. 6. Noisy PPG signal with Savitzky-Golay filtering

3. Conventional IIR filter:

For this, an Nth order low-pass digital Butterworth IIR filter which returns the filter coefficients in length N+1 for vectors B (numerator) and A (denominator), needs to be designed, where the cutoff frequency is half the sample rate. It filters and smooths the data with the designed filter given by the vectors A and B to create the filtered data. This filter also adds some amount of delay to the original signal.

4. Zero phase IIR filter:

This filter is used to filter the data with the help of a digital filter which needs to be designed. The length of the input data should be more than three times the filter order. It filters the data in the forward direction, then the filtered sequence is reversed and then it is run back through the filter. The filter result gives precisely zero phase distortion, and the magnitude modified by the square of the filter's magnitude response. The startup and the ending transients are also minimized by matching initial conditions. Since there is no phase delay added to the signal using zero phase filtering, the output signal of the SG filter is applied to the zero phase filter. The resulting combination of the filtering then gives the best result as compared to the other filters applied. Figure below shows the differences between the Moving Average, zero phase, conventional, Savitzky-Golay and SG-with-zero-phase filtering applied to the noisy PPG signal.

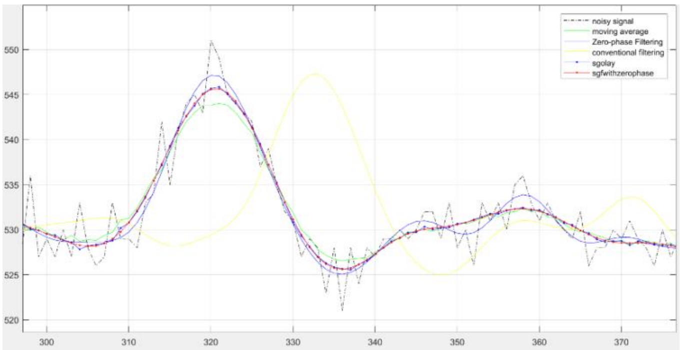

Fig. 7. PPG signal with Moving average, zero phase, conventional and SG and SG-with-zero-phase filtering

The figure below shows the differences in the waveform of the signal in SG filtering and SG-with-zero-phase filtering. The combined filtering effect gives more smooth signals as compared to applying the S-G filter only.

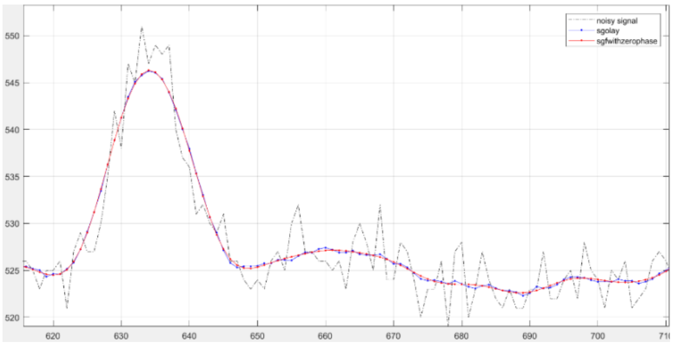

Fig. 8. PPG signal with SG and SG-with-zero-phase filtering

C. Peak detection:

The PPG signal consists of the systolic and the diastolic peaks which together forms the cardiac cycle. The systolic peak has higher amplitude than the diastolic peak therefore its detection is easier than the diastolic peak. The systolic peak is detected from the filtered PPG signal by applying the minimum peak height and the minimum peak distance as the limits to obtain the actual PPG systolic peak only. The peaks can also be detected with the application of peak prominence, where a threshold is set. The number of systolic peaks detected in one minute gives the heart rate of a person in beats per minute.

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The peaks detected and marked in the MATLAB window are shown below. The peaks are obtained for time duration of 15 seconds. The histogram of the peak intervals has been plotted to analyze the variations in the distance of peaks and the number of peaks. The average peak distance has been calculated for the number of peaks. The peak cycle differences for each of the cycles and the mean cycles are also calculated.

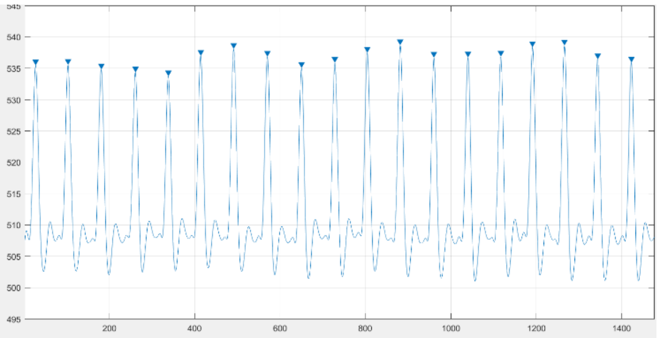

Fig. 9. Filtered PPG signal with peaks detected and marked

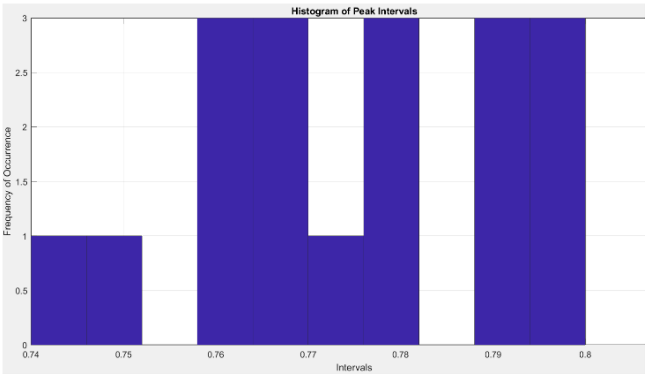

Fig. 10. Histogram of the peak intervals of the PPG signal

D. Feature Extraction and Signal Analysis:

The PPG signal after the processing and filtering gives the information about the systolic and the diastolic peaks only. These peaks are useful in the detection of the signal parameters such as the heart rate (in bpm), the peak to peak intervals, the peak height, the peak width and the pulse intervals. These parameters are used for the calculation of various indices such as the reflection index and the large artery stiffness index [9]. The PPG signal gives the movement of the blood flow from the heart to different parts of the body such as the finger. In this PPG signal, there are less inflection points and therefore there comes a difficulty in detecting the various changes in the signal due to blood flow [9]. For this reason, the first and the second derivatives of the PPG signal are taken which gives more inflection points as compared to the original PPG signal. Therefore these are more useful in the detection of changes in the signal due to the blood flow. The first derivative of the PPG signal is useful for the detection of parameters such as the systolic and diastolic points, the peak to peak time, the crest time and the stiffness index, which help in the accurate classification of cardiovascular diseases [9]. The second derivative of the PPG signal is useful for the visualization and detection of useful features which are not seen in the original PPG signal. It has some useful inflection points which form the 'a, b, c, d and e' waves and the different ratios of these points prove useful as a measure of different physiological parameters and indicators [9]. Figure below shows the PPG signal and its first and second derivative signals with the variations in the inflection points.

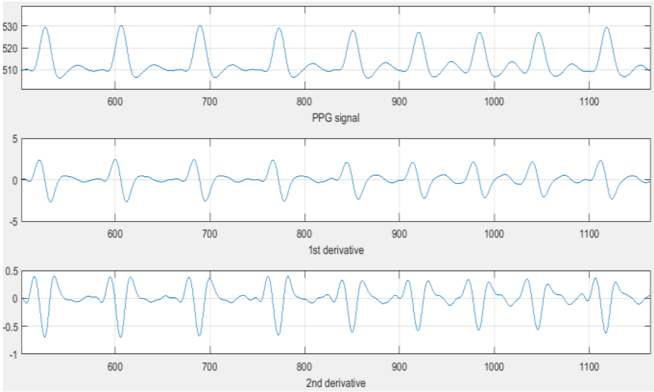

Fig. 11. PPG signal, its first derivative and second derivative

The spectral analysis of the PPG signal was done using the Lomb-Scargle method which provides the visualization of the different frequency components of the PPG signal. The main frequency components include the very low frequency, low frequency and the high frequency. The very low frequency component is due to the activity of both sympathetic and parasympathetic nervous system. The low frequency is due to the circulation or the sympathetic system [2]. The high frequency component is due to the respiration or the mechanical activity. The figure below shows the different peaks of very low frequency at 0.01 to 0.04 Hz, low frequency at 0.04 to 0.15 Hz and the high frequency component at 0.15 to 0.40 Hz.

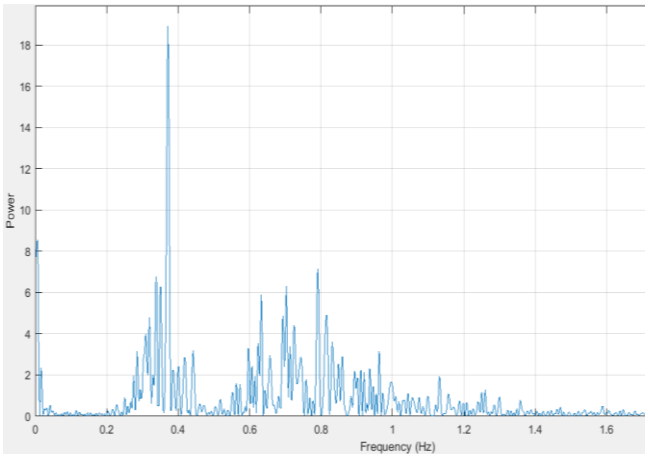

Fig. 12. Power spectral density of the PPG signal

The Lomb-Scargle PSD estimate is useful for the PPG signal as it is not uniformly spaced. The estimate is evaluated over the different frequencies of the signal.

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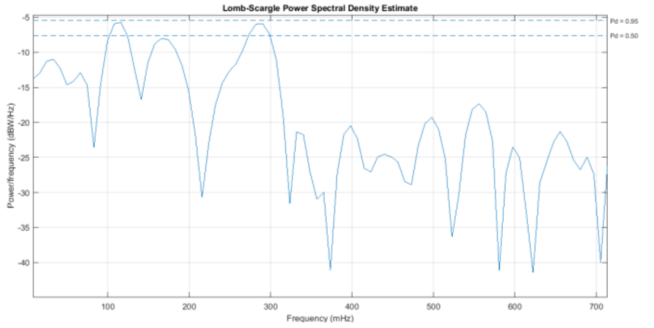

Fig. 13. Lomb-Scargle Power spectral density (PSD) estimate

The estimate gives the probabilities of 95% and 50% at the frequencies around 0.1 to 0.3 Hz. which are present the PPG signal.

The pulse rate variability (PRV) gives an estimate of the heart rate variability (HRV) which arises due to the time variation in the heart beats and has irregular samples due to the physiological variations and the varying heart rate. The PRV is obtained from the PPG signal and the amplitude of each systolic peaks is computed. The varying intervals cause non- uniformity in the PRV signal. The PRV is useful for detecting different heart rate conditions.

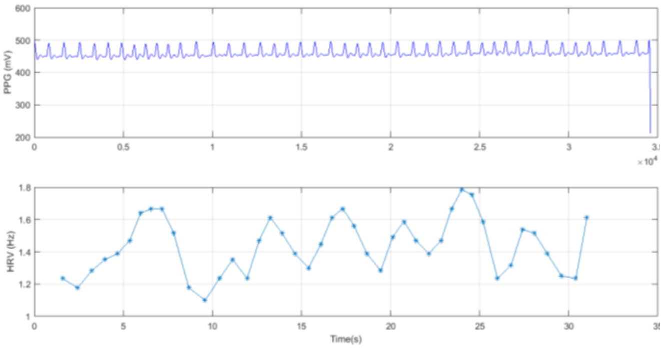

Fig. 14. Pulse rate variability as a measure of HRV.

V. DEVELOPMENT OF REMOTE TRANSMISSION SYSTEM

A. Hardware components:

The heart rate and the peak intervals calculated using the MATLAB software is obtained in the command window of MATLAB. This heart rate information needs to be displayed so that the parameters can be visualized and interpreted easily. For this, the values from MATLAB are then transmitted to the Arduino Nano board through the USB cable connected to the PC. These values obtained in the Arduino board are then transmitted to the mobile phone through the Bluetooth. This is done with the help of the Bluetooth module HC-05 data transmission hardware. The Bluetooth connection needs to be established between the HC-05 Bluetooth module and the mobile phone Bluetooth. For this, the mobile phone application needs to be started and scanning needs to be done to get the Bluetooth device information and then it can be connected. Once the connection is setup the value of the heart rate is received by the user in the mobile phone.

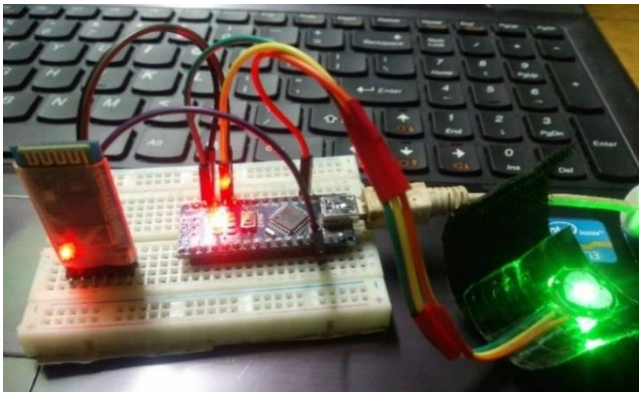

Fig. 15. Hardware components used for data acquisition and transmission

B. Application developed:

An application (app) has been developed using the MIT App Inventor platform. This Application is used for receiving the information and has been specifically designed for this purpose. The values received by the Application in the mobile phone can be further transmitted to a remote place. This is done with the help of the GSM communication network inbuilt in the mobile phone. For this, the particular cell phone number to which the information has to be transmitted needs to be entered into the application. Then a text message containing the information is generated and is sent to that particular number remotely. Depending upon the information received the condition of the person whose PPG values were acquired, can be monitored and interpreted by a remote physician.

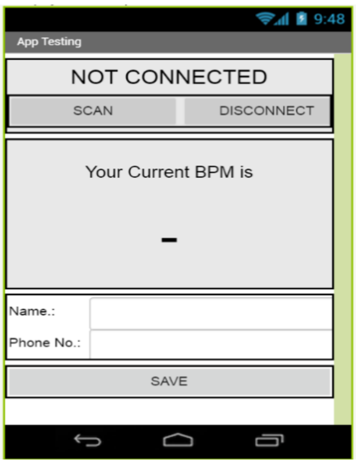

Fig. 16. Application developed on MIT App Inventor

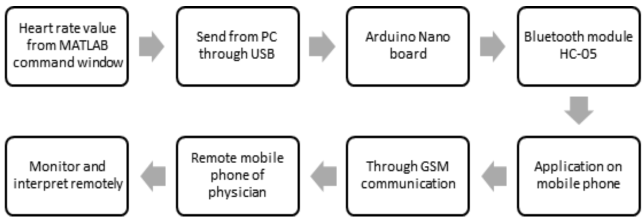

Fig. 17. Flow of the remote transmission system

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VI. RESULTS

The PPG signal was collected from persons belonging to different age groups for a period of 15 seconds. The signals thus acquired were used to obtain the resting heart rate value in bpm and the peak intervals between the values to get the averaged values for those persons. The normal heart rate of a person is in the range of 60 to 100 beats per minute. It can be seen that for younger people of age 20 or below, the heart rate value is more as compared to those above 20 and then it reduces with age for the people in the age group of 20-70. The heart rate value starts to increase again for the people above 70 years due to the reduction in the arterial elasticity with age. The table below shows the measured heart rate and the average value of the peak intervals for different persons.

Table 1. Heart rate and other PPG signal parameter values

Subject	Gender	Age	Measured Heart Rate (BPM)	Average Peak intervals (Tpeak)
Subject 1	F	24	72	0.8306
Subject 2	M	21	72	0.8194
Subject 3	F	52	76	0.7706
Subject 4	M	59	76	0.7756
Subject 5	F	85	80	0.7221
Subject 6	M	63	76	0.8418
Subject 7	M	64	84	0.7030
Subject 8	F	62	80	0.7373
Subject 9	F	46	74	0.8241
Subject 10	F	20	88	0.6586

The difference between the systolic peak and the diastolic peak 'T', is used to calculate the stiffness index of the arteries with the help of the formula SI= h/T, where h is the subject's height and T is the duration between systolic and diastolic peak. The pulse transit time and the pulse wave velocity are the parameters obtained with the help of two separate pulse rate sensors, one situated at the finger and one at the wrist. The time taken by the PPG wave to travel from the heart to the finger is little more as compared to that to the wrist. Therefore the finger PPG signal waveform lags and the wrist PPG signal waveform leads, as the finger is little far from the heart as compared to the wrist. The distance between the sensors measurement position in the hand from the finger to the wrist and the time difference between the two signals known as the pulse transit time (PTT), can be used to calculate the pulse wave velocity (PWV) of the signal. This PWV parameter can be useful for the estimation of the blood pressure of a person non-invasively and non-obtrusively, only with the help of two PPG pulse rate sensors situated at two different points of the hand. The PPG signal thus obtained and processed can be used for detection of the heart rate of a person with less error as well as useful for many other heart rate parameter estimation such as PTT, PRV and can prove helpful to the physician to monitor and examine the various physiological conditions of the person wearing the device.

VII. CONCLUSION

The system developed using the low cost Arduino Nano board and the pulse rate sensors is capable of detecting the heart rate of a person. This has been done by attaching the sensors to the Arduino and then programming the Arduino to convert the analog sensor signal into the digital form, without involving the use of any other equipment. The useful PPG signal is thus obtained by limiting the voltage levels of the signal in the Arduino program for the removal of the DC component present due to the power source. The PPG signal acquired is useful for peak detection to calculate the heart rate and average peak intervals, for extracting the features of the signal, for spectral analysis and PSD estimation and for calculation of PRV as a measure of the HRV.

The Bluetooth used for transmission also consumes low power and the mobile phone GSM helps in the transmission of the HR to a remote location through the specially designed Application. This reduces the need for the data evaluation and transmission boards readily available, by utilizing the Arduino Nano, pulse rate sensors and the Bluetooth module quite easily available for the system development purpose.

The different filtering techniques for smoothing the PPG signal were used in MATLAB in which the combination of the Savitzky-Golay filter with the zero-phase filter gives the best smoothing results as compared to the other filters applied.

This overall system thus provides a low cost solution as compared to the different systems involving embedded chips which are specially made for the purpose with inbuilt sensors and are quite costly. Those boards being more costly are not convenient to use for low cost fitness tracking systems. It also provides a reliable solution for transmission of HR value through the Bluetooth to the mobile phone app as well as the transmission of the message through the GSM supported mobile phone to a remote location.

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Retrieval Number: J98290881019/19©BEIESP
DOI: 10.35940/ijitee.J9829.0881019
Journal Website: www.ijitee.org

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