Global Journal of Researches in Engineering: F
Electrical and Electronics Engineering
Volume 15 Issue 7 Version 1.0 Year 2015
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

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GJRE-F Classification : FOR Code 090699

ANESTIMATIONTECHNIQUEUSINGFFTFORHEARTRATEDERIVEDFROMPPGSIGNAL

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An Estimation Technique using FFT for Heart Rate Derived from PPG Signal

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Abstract- Heart rate (HR) observation by using photoplethysmography (PPG) signals during intense physical activity is a crucial task because of the fact that PPG signals are affected by the noise due to movement artifacts by the user's hand movements. This paper addresses the discriminating assessment of a novel encapsulation for wearable PPG sensor during the severe physical activity. In this work, we plan the HR estimation issue, and utilization of proposed algorithm to find high-determination power spectra of PPG signals, from which heart rates are evaluated by selecting and comparing the peaks. The proposed system was applied on PPG recordings obtained from 10 subjects who were quick runners at the top velocity of 15km/hour on a treadmill. Utilizing correlation and HR investigation with the assistance of peak detection, we assessed the simulation of the proposed framework against the existing works. The outcome demonstrated that the average absolute estimation error achieved using proposed method is lesser contrasted with ground truth heart rates obtained at the same time through the recording of electrocardiogram (ECG).

I. Introduction

The heart rate (HR) is a major physical sign amongst the many physical parameters that are identified with human health. Heart Rate (HR) of the patients is frequently need to be observed in the clinical environment by the doctor to provide appropriate diagnosis. Observing the HR is important for the patients as well as advantage for common man to know their health condition. In recent years, automatic detection of HR during exercise has enabled new type of health assessment and wearable tools used for such purpose will help in monitoring of health in real time. Heart Rate (HR) exhibits various characteristics in different physical activities. Recent technological advances have made it possible to build wearable products that can capture and process bio-signals generated by the human body. In terms of HR monitoring, two essential innovations are accessible for gadget producers: ECG and PPG. ECG is a standard signal that is utilized by healthcare providers for the assessment of health of an individual based on their cardiac activity. In the other hand PPG sensors use ECG signal as a reference for HR comparison.

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PPG signals are weak to motion artifacts, which is critical to heart rate checking during exercise. Numerous signal processing strategies have been proposed to remove movement artifacts (MA) from raw PPG signals. PPG signals can be obtained from fingertip, earlobe, wrist etc. Contrasting with fingertip and earlobe, wrist can bring about much more complex MA because of expansive adaptability of wrist and free interface between heartbeat oximeter and skin. However, recording PPG from wrist enormously encourages configuration of wearable gadgets and expands user experience. Thus, assessing HR from wrist type PPG signals turns into a mainstream highlight in smart-watch type gadgets. In this regard, developing high-performance HR observation and analysis algorithms for wrist-sort PPG signs is of great value.The current study focuses on HR analysis utilizing wrist-type PPG signals when the wearer performs severe physical exercises. A novel system is proposed which comprises of four key parts, specifically: preprocessing, denoising, heart rate estimation and the optimization of the heart rate estimation. The aim of the decomposition of signal is to remove MA in a raw PPG signal and sparsifies its range. Periodogram estimation plans to ascertain a high-resolution range of the PPG signal, which is strong to noise and is profitable over conventional nonparametric range estimation calculations and model-based sparse signal estimation algorithms. Heart rate estimation using peak detectionis a vital part of the proposed structure, which looks for the peak relating to HR. To further overcome solid obstruction from MA and supplement the peak determination approach, some decision systems are intended to check the selected spectral peak. The proposed technique is applied on PPG recordings of 10 subjects who were quick running at the top velocity at 15 km/hour on a treadmill. The results of the proposed method shows that its estimation performance is high compare to other works. The rest of this paper is organized as follows: Section II provides the related work in this field, Section III presents the proposed framework, Section IV describes recorded datasets, experiment settings, and experimental results and conclusions are given in the last section.

II. Literature Survey

Tamura et al [1] utilized the PPG innovative idea to develop small, wearable, heartbeat rate sensors.

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These gadgets comprising of infrared light-emanating diodes (LEDs) and photodetectors offer a basic, dependable, ease method for observing the beat rate noninvasively. In this survey, authors present the historical backdrop of PPG and late advancements in wearable heartbeat rate sensors with green LEDs and the use of wearable heartbeat rate screens.

Yousefi et al [2] proposed a novel real-time adaptive calculation for the accurate movement tolerant extraction of HR and oxygen saturation (SpO2) from wearable PPG biosensors. The proposed algorithm overcomes the motion artifacts arising from different sources including tissue impact and venous blood changes during body movements and gives commotion free PPG waveforms. A two-stage normalized least mean square adaptive noise canceler is designed and validated using a novel synthetic reference signal at each stage.

Ram et al [3] proposed a basic and effective methodology based on adaptive step-measure least mean squares (AS-LMS) adaptive channel for minimizing MA in undermined PPG signals. The proposed technique is an expansion to our earlier work to use it efficiently for reducing of MA in PPG signals. The novelty of the method lies in the fact that a synthetic noise reference signal for an adaptive filtering process, representing MA noise, is generated internally from the MA-corrupted PPG signal itself instead of using any additional hardware such as accelerometer or source-detector pair for acquiring noise reference signal.

Chia-Ching Chou et al [4] presented a compelling PPG gaining and signal handling framework taking into account square wave modulation. Through modulating the achieved signal on different frequency square waves, it is effective to get PPG signals with high SNR by utilizing basic transporter wave generators and diminishing the harmonic load and force. The proposed framework incorporates a wonderful and wearable three way PPG front-end sensor for procuring PPG signals, a FPGA-based DSP for signal modulation.

Ucar et al [5] presented a technique for the diagnosis of obstructive sleep apnea syndrome based on respiratory scoring process. To examine the patient's condition, four signals are required according to this method. For analysis and diagnosis PPG (during normal sleep) signal are considered in this work. Changes occurring in PPG signal during respiratory events were examined.

Lin and Kunpeng [6] presented a new method to calculate the pulse wave quality index using a quality evaluation function. By using the pulse quality index, the reliability of PPG feature point selection can be calculated.

Verma et al [7] proposed a framework for the heart rate variability (HRV) spectra from the PPG and ECG signals. In this work, first of all the signals were interpolated to a common sampling frequency then to remove the lower frequencies, IIR filter has been used. Next step to remove the high band frequencies by using undecimated wavelet transform. To detect the peak, the filtered signal is squared and peaks are extracted from the signal. Once peaks are detected HRV signal was determined using cubic spline interpolation to create a signal at a very low sampling rate of 1-4 Hz.

Fukushima et al [8] proposed the algorithm to estimate HR for the wrist-type PPG sensor. The accuracy of heart rate estimation is affected by motion artifacts. This study uses accelerometer built in the wrist-type sensor to improve the accuracy of heart rate estimation. Two main components are presented in this work. One is removing artifacts with the power spectrum's difference between PPG and acceleration obtained by frequency analysis. The other is the reliability of heart rate estimation, defined by the acceleration.

III. Proposed System

This section describes our proposed approach to estimating the heart rate. We have considered the input signal and then it is getting divided into time series and again that time series is getting decomposed into oscillatory components and noise. Let $P^u \triangleq [P^u{}_1, \dots, P^u{}_m]^T$ represent the raw PPG signals of length m aquired.

According to the proposed method the first step is to perform preprocessing on the signal which is for removing the partial noise and performing the bandpass filtering. Next step is denoising of the signal, in this first of all the filtered signal is converted into multidimensional signal which is used for creating trajectory matrix, then this matrix is decomposed in singular values to get the eigen vectors.

Once the signal is decomposed, next step is estimation of heart rate using first and second order frequency difference. Finally, we perform the optimization of the detected heart rate based on peak frequency and their harmonics. The proposed method is described below:

a) Preprocessing

This is the first stage of proposed framework. At this stage the P^u signal is processed and filter in order to remove the motion artifacts. According to this framework, in a given time window, the recorded raw PPG signal and the acceleration sign are first band-pass shifted with the cut-off recurrence of 0.4 Hz and 7 Hz. This pre-processing evacuates bunches of noise and MA outside of the recurrence band of interest. This can facilitate sparsifies the range coefficients when utilizing the frequency strategy. Let P represent the filtered or preprocessed signal. The preprocessing step can be defined as

$$P = f_{bp}(P^u, f_l, f_u) \quad (1)$$

Where f_l and f_u represent the lower and upper cutoff frequencies of the bandpass filter f_{bp}

b) Denoising

The preprocessed motion artifact removed signal is passed for the denoising stage. Preprocessed signal P is one dimensional, to perform the signal denoising, we convert the signal to multidimensional. This conversion process is defined as

$$P_d = (P_{i-1}, \ldots . . P_{i+m-2}), 1 \leq i \leq K \quad (2)$$

$$K = N - m + 1$$

Where P_d multidimensional signal, N is length of the signal, m is window length

This signal P_d can be written into a trajectory matrix. In this step a time series $P \triangleq [P_1 \ldots P_M]^T$ is mapped into $M_1 \times M_2$ matrix($M_2 = M - M_1 + 1, M_1 < M/2$, called $M1$-trajectory matrix.

$$D \triangleq \begin{bmatrix} P_1 & P_2 & \cdots & P_{M_2} \\ P_2 & P_3 & \cdots & P_{M_2+1} \\ \vdots & \vdots & \ddots & \vdots \\ P_{M_1} & P_{M_1+1} & \cdots & P_M \end{bmatrix} \quad (3)$$

In the *signal decomposition step*, the M_1-trajectory matrix is decomposed by decomposition method as follows,

$$D = \sum_{i=1}^{d} D_i, d \triangleq min\{M_1, M_2\} \quad (4)$$

Where $D_i = \sigma_i u_i V_i^T$ and σ_i, u_i ,v_i are the ith singular value, the corresponding left-singular vector and the corresponding right-singular vector, respectively.

This gives us a decomposed signal which contains the eigen values.

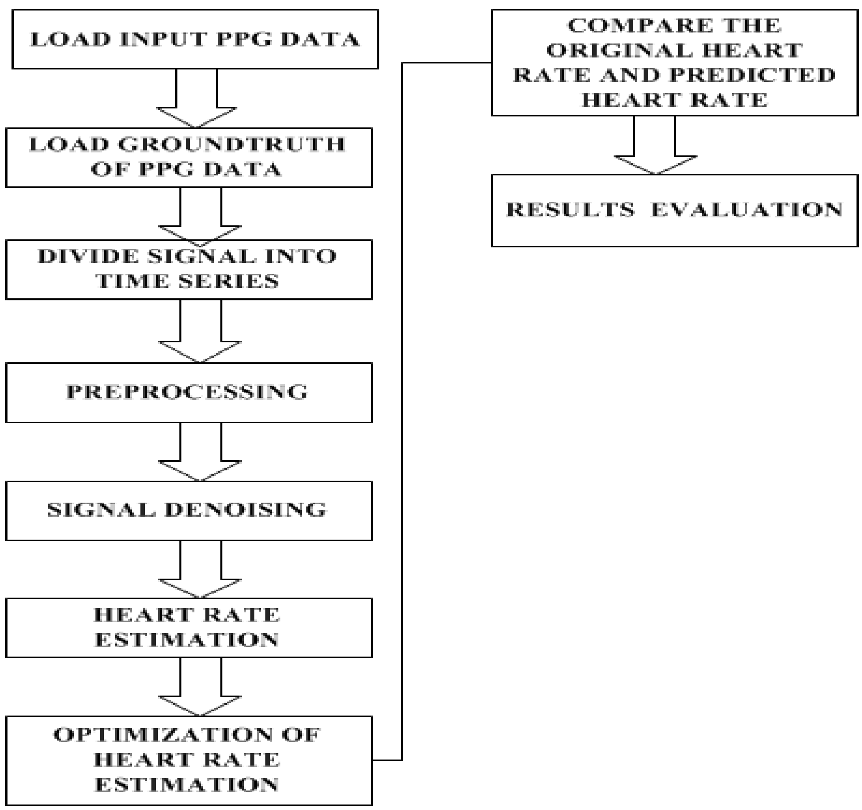

Figure 1 : Flow chart of the proposed framework

c) Reconstruction

Once the decomposed signal D is achieved, the next step is to perform reconstruction of the signal. In this step the d rank-one matrix D_i is assigned into G groups namely the set of indices $\{1, \ldots, d\}$ is portioned into G disjoint subsets $\{I_1, \ldots, I_G\}(G \leq d)$ and

$$Y = \sum_{p=1}^{G} D_{I_p} \quad (5)$$

With $\sum_{t \in I_p} D_t$ .The rank-one matrices in each group D_{I_p} generally satisfy some common characteristics (such as their corresponding oscillatory components after reconstruction have the same frequency or exhibit harmonic relation).

In the *Averaging based Reconstruction Step*, each D_{I_p} is used to reconstruct a time series $\widetilde{P}_p$ with the length M by a so called diagonal averaging procedure.

Thus the original signal p is composed into g time series, i.e.

$$P_{AR} = \sum_{p=1}^{G} \widetilde{P_p}. \quad (6)$$

P_{AR} = averaging based reconstructed signal

IV. Heart Rate Estimation

After reconstruction of the signal, reconstructed signal P_{AR} is achieved. By utilizing the spectrum method heart rate of this signal can be achieved. This signal is in periodic time series so for a periodic time series $S = [S(1), S(2), \dots, S(M)]$with the fundamental frequency $freq_0$, its first-order difference, defined as $S' \triangleq [S(2) - S(1), S(3) - S(2), \dots, S(M) - S(M-1)]$, maintains the fundamental frequency and the harmonic frequencies. The second-order difference of h, i.e. the first-order difference ofS', also maintains the fundamental frequency and the harmonic frequencies. As long as k is not large, the spectrum of the $k-th$ difference of the periodic time series always significantly exhibits the fundamental frequency and its harmonic frequencies. In contrast, this is not observed from a non-periodic time series. Note that an artifact free PPG signal is approximately periodic in short time, while motion artifact is generally non-periodic (except to the situation when only hand swing occurs). Therefore, we calculate the $k-th$ difference of the cleaned PPG signal. In our experiments we calculated the second-order difference. The resulting time series of difference is denoted by p_{diff}. After this step, the spectrum peak corresponding to the HR and harmonic spectrum peaks are more prominent in the spectrum.

V. Optimiz ation of Heart Rate Estimation

The above section discusses about the heart rate estimation by calculating the first and second order difference of the periodic time series signal but this method sometimes can wrongly track the spectral heart rate associated with MA or spectral fluctuations. Thus, an optimization stage is necessary. This optimization to estimate the heart rate is discussed in this section.

Corresponding to the estimated HR the frequency is denoted by $freq_{old}$ in the previous time window. We set a search range for the fundamental frequency in the signal s which is $R_0 = [freq_{old} - \Delta, \dots, freq_{old} + \Delta]$. Another search range is$R_1 = [2(freq_{old} - \Delta - 1) + 1, \dots, 2(freq_{old} + \Delta - 1) + 1]$. In the spectrum, we select at most two highest peaks in each search range. Denote the frequency bin indexes of the two peaks in $R0$ by $freq_0^1$and $freq_0^2$, the frequency bin indexes of the two peaks in R1 by $freq_1^1$ and $freq_1^2$

If there exists a peak-pair $(freq_i^0, freq_j^1)(i \in \{1,2\}, j \in \{1,2\})$ which holds a harmonic relation, then $freq_i^0$ corresponds to the heart rate. If there is no such peak-pair (presence of strong motion artifacts), we select $\widehat{freq} \leftarrow \arg \min_{freq} \{|freq - freq_{old}|\}$

Where $freq \in \{freq_1^0, freq_2^0, \frac{freq_1^1 - 1}{2} + 1, \frac{freq_2^1 - 1}{2} + 1$

and$\widehat{freq}$ corresponds to the heart rate

VI. Results and Discussion

a) Dataset

To show the performance of our proposed algorithm we had considered the PPG signal, we have taken the wrist-type PPG signals from 10 male subjects having age in the range of 18 to 33 years. For each user data has been recorded while performing physical exercise on the treadmill. The treadmill exercise is executed with different speed consideration wherein initially subject walked at the speed of 2 km/hour for 1 minute, then at 4 km/hour for 1 minute, and then ran at the speed of 10 km/hour for 1 minute, next fast ran at the speed of 15 - 17km/hour for 1 to 1.5 minutes, and then again ran at the speed of 10 km/hour for 1 minute, and finally walked at the speed of 4 km/hour for 1 minute. While performing the exercise each subject has been asked to use the hand with the wrist-band to pull clothes, wipe sweat on forehead, and push buttons on the treadmill, in addition to freely swing. This is done to incorporate for the motion artifacts. These PPG signals are having three-axis acceleration. These signals are recorded from user's wrist by using a PPG system with LED as light source having wavelength of 609 nm. For simulating these recorded PPG signals we have sampled all the data at 125 Hz. The ground-truth of the each PPG signal is recorded at the same time.

b) Simulation Parameters

In our proposed system we set its execution parameters as input PPG signal grid parameter = 2048, the regularization parameter = 0.1. For filtering the PPG signal the window distance is considered uniform distance and Gaussian distance, the size of the window is taken 15. To calculate the HR the number of cardiac cycles Q and time duration T (seconds) then heart rate is given by 60Q/T beats per minute (BPM).

c) Performance Measurement Parameters

For the recorded PPG signal to measure the performance of our proposed system in terms of BPM we have measured the average absolute error. The original heart rate of the user can be achieved using the ground truth, now in order to show our proposed system measurement accuracy we have achieved the HR for the each user. The accuracy of the system is represented in the terms of average absolute error and percentage error. The HR estimated from the groundtruth is denoted by BPM_{true} and the calculated heart rate using our system is demoted as BPM_{est}

To calculate the average absolute error

$$Error1 = \frac{1}{W}\sum_{i=1}^{W}|BPM_{est}(i) - BPM_{true}(i)|$$

where W is the total number of time windows.

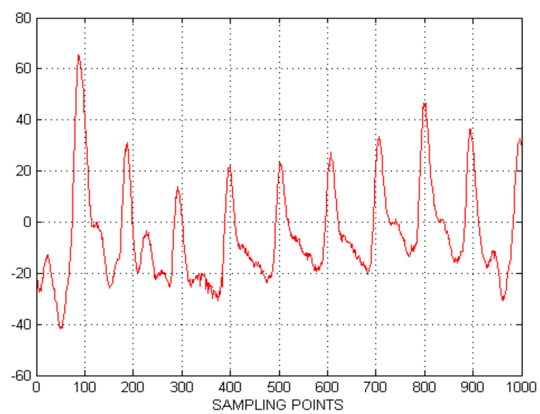

Fig 2(a) Raw PPG Signal

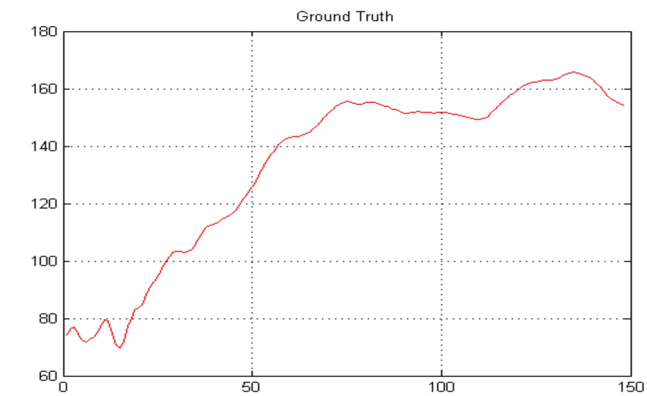

Fig 2(b) Ground Truth of the PPG Signal

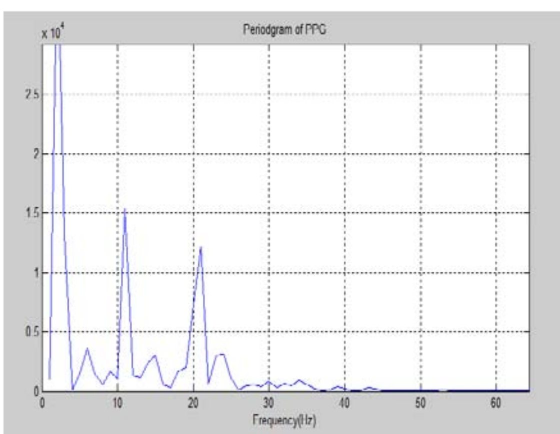

Fig 2(c) Periodogram of PPG Signal

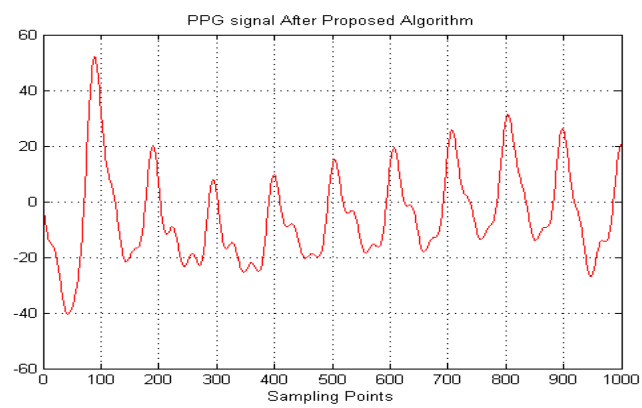

Fig 2(d)PPG signal After Proposed Algorithm

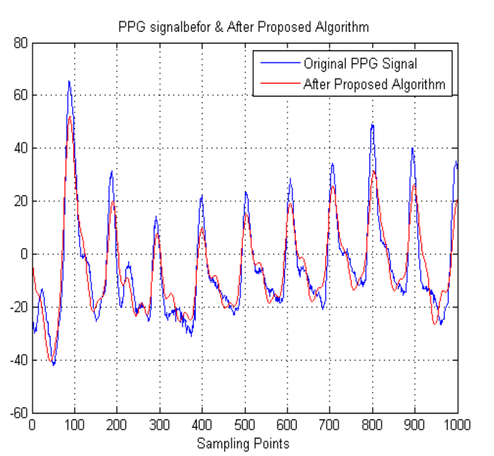

Fig 2(e) Combined Representation of the signal

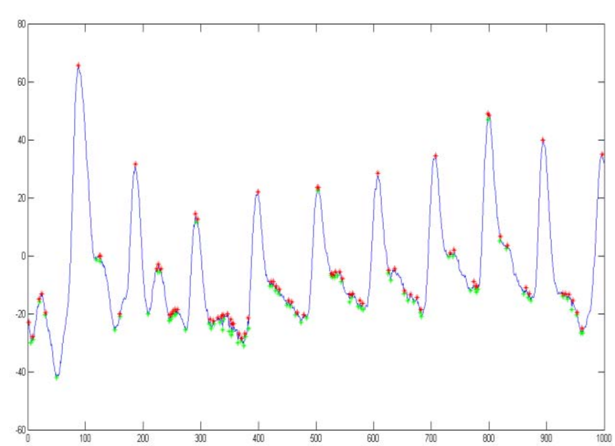

Fig 2 (f) Peak Detected

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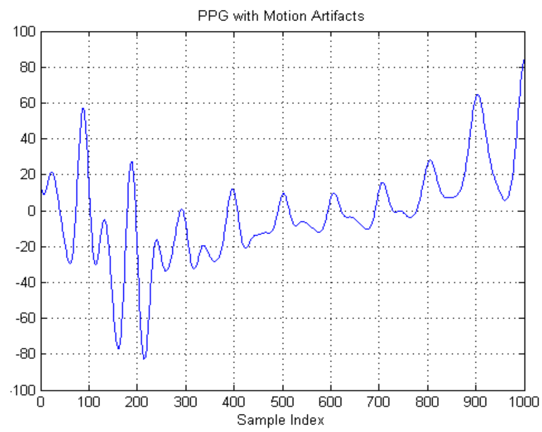

Fig 2 (g) PPG with Motion artifacts

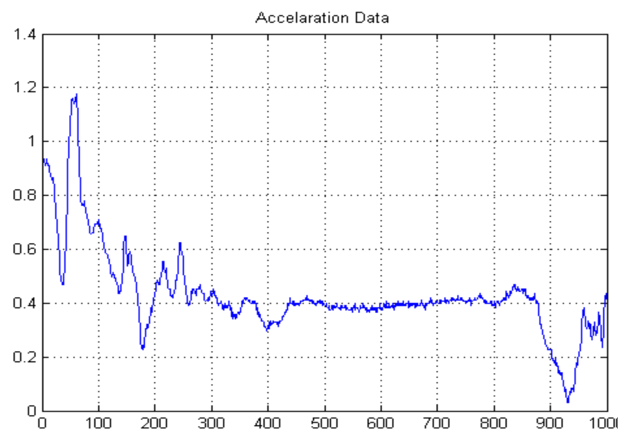

Fig 2 (h) PPG Accelaration

In the above given figure fig2 (a) is the representation of the Raw PPG signal. Fig2 (b) is the ground truth of the original PPG signal. Groundtruth is the actual heart rate of the user. Fig2(c) is the Periodogram of the PPG signal. Fig 2(d) is the signal achieved after passing through proposed algorithm which gives peaks associated with Heart rate. . Fig 2(e) is the combined representation of the original signal and after passing through the proposed algorithm for the peak detection. Fig2 (f) shows the detected peaks in the PPG signal

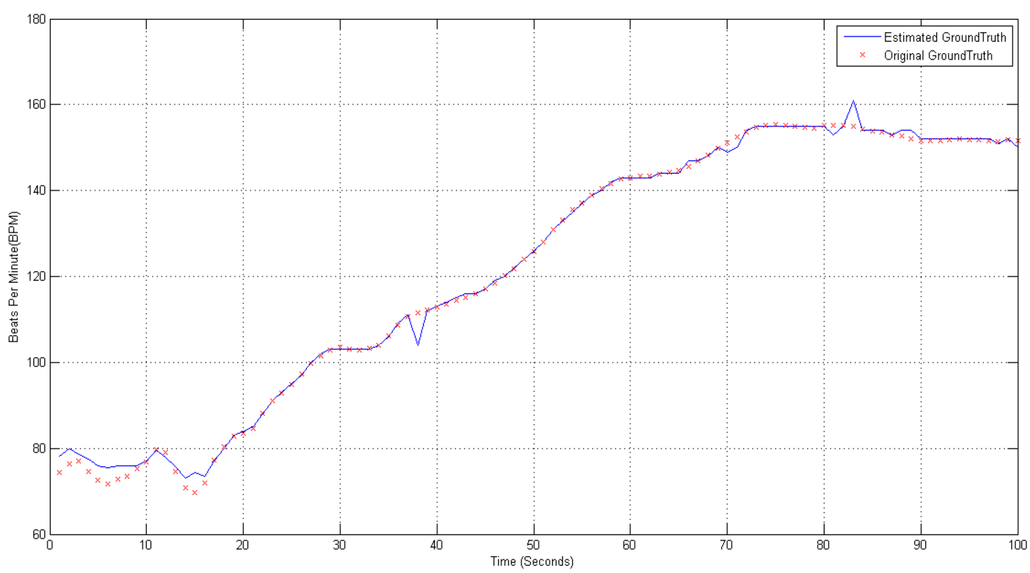

Figure 3 : Estimation result on recordings of user 5.

Fig. 3 shows the result on recordings of user 5 as an example when processed using our proposed algorithm. The estimated HR was very close to the ground truth, and every small change in the ground truth was estimated with high fidelity.To better see the benefit of proposed algorithm to partially remove MAs, we carried out an experiment using a raw PPG segment and a simultaneous ECG segment (see Fig. 2(a) and (g), respectively).

In contrast, after proposed algorithm, the spectrum of the cleansed PPG signal [see Fig. 2(d)] clearly presents the spectral peak associated with the HR, as shown in Fig. 2(f). This result shows that proposed algorithm can remove MAs in PPG and make more significant the spectral peak associated with HR.

	USER 1	USER 2	USER 3	USER 4	USER 5	USER 6	USER 7	USER 8	USER 9	USER 10
ERROR1(BPM) ES	3.09	1.37	2.51	3.58	7.19	2.21	1.60	1.22	1.11	1.79
ERROR1(BPM) PS	1.790	2.04	1.58	1.33	1.16	1.06	1.03	1.15	1.12	1.23

Comparing to other works on heart rate monitoring during running, our proposed algorithm showed competitive or superior performance.

VII. Conclusion

In this work, we proposed a general framework for HR estimation using wrist-type PPG signals when the user is performing intensive physical exercise. The novelty of the method lies in removing the noise efficiently, generated during intensive physical exercise and optimization of the heart rate estimation. The proposed method consists of four divisions: preprocessing of the signal, denoising of the signal, heart rate estimation and optimization of heart rate estimation. Experimental results on recordings from 10 subjects showed that the proposed algorithm has high estimation accuracy. The proposed algorithm removes motion artifact due to body movements during intensive exercise and provides noise-free PPG waveforms for further feature extraction.

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