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Adaptive Motion Artifact Reducing Algorithm for Wrist Photoplethysmography Application

Jingwei Zhao, Guijin Wang, and Chenbo Shi

Department of Electronic Engineering, Tsinghua University, Beijing 100084, China.

ABSTRACT

Photoplethysmography(PPG) technology is widely used in wearable heart pulse rate monitoring. It might reveal the potential risks of heart condition and cardiopulmonary function by detecting the cardiac rhythms in physical exercise. However the quality of wrist photoelectric signal is very sensitive to motion artifact since the thicker tissues and the fewer amount of capillaries. Therefore, motion artifact is the major factor that impede the heart rate measurement in the high intensity exercising. One accelerometer and three channels of light with different wavelengths are used in this research to analyze the coupled form of motion artifact. A novel approach is proposed to separate the pulse signal from motion artifact by exploiting their mixing ratio in different optical paths. There are four major steps of our method: preprocessing, motion artifact estimation, adaptive filtering and heart rate calculation. Five healthy young men are participated in the experiment. The speeder in the treadmill is configured as 12km/h, and all subjects would run for 3-10 minutes by swinging the arms naturally. The final result is compared with chest strap. The average of mean square error (MSE) is less than 3 beats per minute (BPM/min). Proposed method performed well in intense physical exercise and shows the great robustness to individuals with different running style and posture.

Keywords: Adaptive filter, heart rate, motion artifact, PPG, wavelet filter, PCA

1. INTRODUCTION

Photoplethysmography(PPG) technology is broadly used to monitor the variation of heart rate during exercises, real time heart rate monitoring provides a guidance of safely training. However, PPG signal is easily corrupted by motion artifact (MA), especially in strenuous exercises. To date, plenty of algorithms have been proposed to extract heart pulse signal from back ground motion artifact[1235] . Wavelet-based algorithms[3] are highly effective for real time processing, but performed poorly when MA and pulse signal are in same frequency area. Extraction of heart pulse from MA could also be regarded as a blind source separation problem,[6] so independent component analysis(ICA) is introduced to solve the problem. Adaptive filter[1],[2] such like normalized least mean squares(NLMS), recursive least squares(RLS), Kalman filter,[7] is another effective approach to reduce MA from corrupted PPG signal. Most of MA reducing algorithms mentioned above are applied to finger PPG application that could hardly meet the requirements of wrist application. PPG pulse signal collected around wrist is more sensitive to motion artifact than finger application due to the thicker tissues and the fewer amount of capillaries. Therefore, a higher standard is imperative for MA cancelling algorithm to process feeble PPG signal. A novel approach is proposed to separate the pulse signal from motion artifact by exploiting their mixing ratio in different optical paths. There are four major steps of proposed method: Motion Artifact Estimation, Motion Artifact Extraction, Adaptive Filter, Heart Rate Estimation. In Motion Artifact Estimation stage, the major frequency bands of subjects′ movement are computed by three axes′ acceleration signals. Afterwards, signal fluctuations in these frequency bands of optical paths are extracted to represent motion artifact. RLS with adjustable forgetting factor is designed in this stage as adaptive filter. In the end, heart rate is computed in Fourier domain.

Further author information: (Send correspondence to Guijin Wang)Guijin Wang: E-mail: Wangguijin@tsinghua.edu.cn

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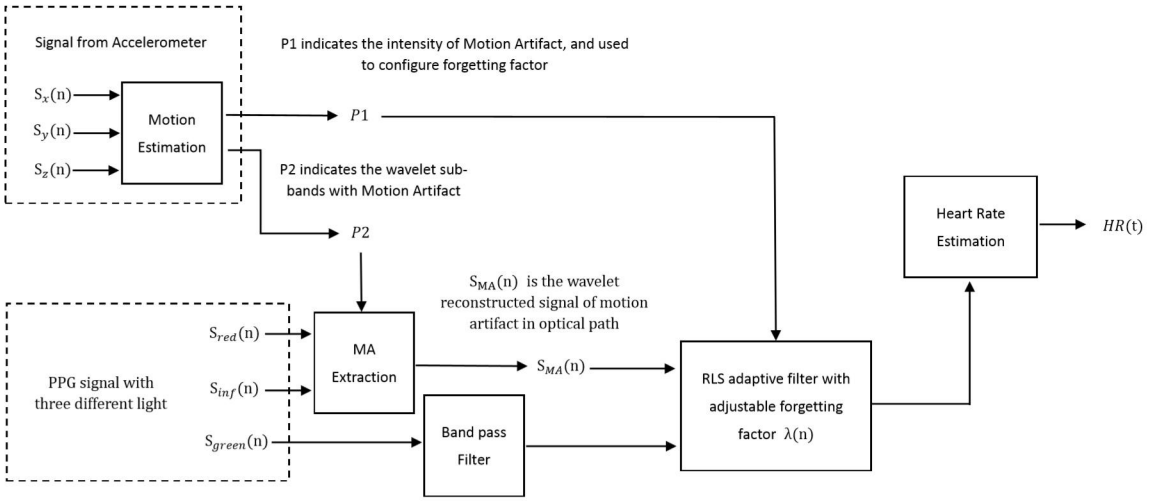


Figure 1. Flow chart of proposed approach.

2. METHOD

2.1 Background

The frequency spectrum of pulsatile PPG signal is generally concentrated on 0.5Hz to 4Hz, denoted as f_{pulse}. While the frequency spectrum of MA (f_{MA}) is more complicated than f_{pulse} due to the various coupling accesses of MA. Although f_{MA} dominates a broad region in frequency domain, the out-band (<0.5Hz, >4Hz) frequency components of f_{MA} could be filtered by a band-pass filter. The knotty problem in this case is that the in-band (>0.5Hz, <4Hz) components of f_{MA} could hardly be distinguished from f_{pulse} by conventional approaches. In addition, the in-band frequency spectrum of MA might not be unimodal all the time due to multi-mode features of MA. Acceleration signal is a common reference applied in present studies to represent MA directly. However it′s not the optimal representation since there is no conclusive evidence to clarify the exact relationship between acceleration signal and motion artifact that detected at optical path. Therefore, three LEDs with different wavelengthes are selected in our study to represent MA instead of acceleration signal. Plenty of studies[4] before reveal the fact that the reflection depth under the superficial skin is inversely proportional to the emitter wavelength. Pulse signal is detected from blood vessels under deeper skin layers in wrist PPG application, so the intensity variation of reflective light at superficial skin tissues is the primary cause of generating MA. According to mentioned reasons, green LED with 550nm wavelength is used to maximize the content of pulse signal. On the other hand, optical jitter due to MA occurred at superficial tissues is collected by red (660nm) and infrared (940nm) LEDs.

2.2 Overview of Proposed Approach

The flow chart of proposed approach is illustrated at Fig.1. Three LEDs with different wavelengthes (550nm, 660nm, 940nm) and accelerometer with 3-axes are applied at proposed approach for MA reduction. Three optical emitters and one collecting sensor are used to continuously monitor the light absorption at different layers under skin surface. The spectrum of acceleration signal would be analyzed separately on each axis at wavelet domain. Motion artifact might be introduced by arm movements at three directions independently, so the frequency spectrum of motion artifact on optical pathes offered by three directions might be multi-modal in frequency domain. Given that, the frequency sub-bands with massive motion artifact would be calculated by acceleration signal. Afterwards, the optical motion artifact S_{MA} offered by movements would be extracted from red and infrared channels. Specifically, reconstructed red and infrared signals by particular wavelet sub-bands are input to principle component analysis(PCA) algorithm for computing S_{MA}. Since PPG signal collected from green light (S_{green}) contains the maximum volume of pulse wave, S_{green} and S_{MA} would be processed by RLS algorithm in consequence to reduce the influence of MA. The forgetting factor λn of RLS algorithm is fine

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adjusted by the intensity of exercising, which is computed by total energy of acceleration output. As a result, the RLS filter would be shut off when subjects stay quiet, on the contrast, λn would be reduced during severe exercise, then the RLS filter would be more sensitive to current PPG data. The estimation of heart rate would be computed in Fourier domain by exploiting the output signal from RLS algorithm.

2.3 Motion Artifact Estimation

Acceleration signal is analyzed in this stage to estimate the frequency spectrum of motion artifact, and two parameters(P1, P2) are computed for the following processing. P1 indicates the intensity of exercising, and it is calculated by normalizing the total energy of acceleration signal:

$$P1 = \frac{1}{E_{max}} \sqrt{S_x^2 + S_y^2 + S_z^2} \tag{1}$$

where E_{max} is the maximum total energy of acceleration signal, and $P1 \in (0, 1]$. P1 is used to fine tune the forgetting factor of adaptive filter. The following MA reducing algorithm would not work if P1 approximates to zero,it could prevent clean input PPG data from being corrupted by over-processing. Signal from each axis is decomposed by 7 levels with wavelet packet(WP) algorithm respectively. The effective band-width of heart pulse(0.7Hz to 4.3Hz) is segmented into 10 wavelet packet sub-bands. In each sub-band, one axis with maximum acceleration energy would be selected to represent the dominating axis. The maximum acceleration energy of dominating axis in each sub-band is showed in Fig.2. Given that, P2 is composed by serial numbers of wavelet sub-bands that contain top 70% of maximum acceleration energy. P2 is used to guide following MA extraction algorithm that coefficients in which wavelet sub-bands should be reconstructed for calculating the motion artifact coupled in optical path.

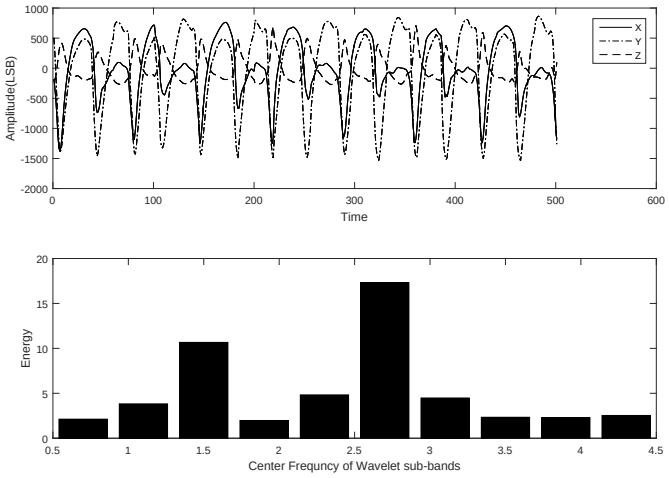


Figure 2. Acceleration Signals and Acceleration Energy in Each Wavelet Packet Sub-bands.

2.4 Motion Artifact Extraction

Optical motion artifact is extracted from PPG signals of red and infrared channels. Red and infrared lights could hardly reach the blood vessels under superficial tissue at wrist due to their wavelengthes, therefore, these two channels′ signals have abundant optical motion artifact reflected at surface tissues. Infrared light with 940nm wavelength is used to detect the reflective optical interference at superficial layer of skin, and red light with 660nm wavelength would carry more optical MA information at deeper layers under skin. However, both of these two channels might be corrupted by different kinds of noises due to the huge different wavelengthes between them, even if the interference sources are always dominated by motion artifacts primarily. Given that, PCA is used

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here to calculate the principle component of the optical reflective interference at surface tissues. PPG signal at each optical path would be decomposed into several sub-bands by WP algorithm, only the coefficients in the sub-bands which P2 indicates would be participated in the reconstruction. S_{MA} is computed by processing two channels of reconstructed optical signals with PCA algorithm.

2.5 Adaptive Filter

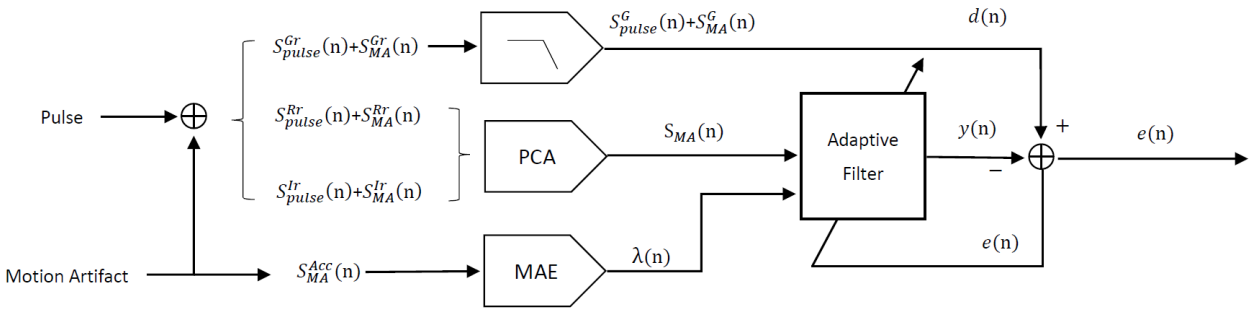


Figure 3. Flow chart of RLS filter, where MAE stands for Motion Artifact Estimation.

As it claimed before, PPG signal sampled from green optical path carries the maximum amount of heart pulse information whose frequency spectrum is in the range of 0.5Hz to 4Hz. However, filtering all the out-band frequency opponents would reduce the processing performance significantly. Since pulse signal is not a standard sinusoidal signal, it has lots of ultra-harmonics in the high frequency region in Fourier domain. In another aspect, these ultra-harmonics are also embodied by the higher-order statistics. For instance, pulse signal always has positive skewness and kurtosis that distinguished with motion artifact. Band width of the band-pass filter is configured to be 0.5Hz to 25Hz for preserve these ultra-harmonics and morphological features from being distorted. These protected morphological features are crucial to distinguish pulse signal from MA by adaptive filter in following process. The flow chart of RLS adaptive filter designed in the research is showed in Fig.3. The RLS filer is developed with the structure of interference cancellation, where the filtered PPG signal from green channel is regarded to be the expected response($d_{(n)}$) and the extracted MA from red and infrared channels is considered as input signal, the residual error $e_{(n)}$ between filter output and $d_{(n)}$ is the processed result of adaptive filtering. $\lambda_{(n)}$ is the forgetting factor of RLS filter that fine adjusted by the parameter P1 which indicates the intensity of subject′s exercise. RLS algorithm would optimize filter coefficients recursively to minimize the least square errors between filter output and expected response $d_{(n)}$. The iterative formula is showed at Eq.2.

$$\vec{\omega}_{(n)} = \vec{\omega}_{(n-1)} + \vec{k}_{(n)} e_{(n)} \tag{2}$$

Where $\vec{\omega}_{(n)}$ is the filter coefficients vector at time point n, and $\vec{k}_{(n)}$ stands for gain vector that computed by input vector $\vec{x}_{(n)}$ and forgetting factor $\lambda_{(n)}$:

$$\vec{k}_{(n)} = \frac{\lambda^{-1}_{(n)} P_{(n-1)} \vec{x}_n}{1 + \lambda^{-1}_{(n)} \vec{x}^H_n P_{(n-1)} \vec{x}_n}; \tag{3}$$

where

$$P_n = \sum_{i=1}^{n} \lambda^{n-i}_n \vec{x}_i \vec{x^H_i} \tag{4}$$

The final RLS filter output $e_{(n)}$ is computed by Eq.5:

$$e_{(n)} = d_{(n)} - \vec{\omega}^H_{(n)} \vec{x}_{(n)} \tag{5}$$

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3. HEART RATE ESTIMATION

The output of RLS filter $e_{(n)}$ is denoted as the de-coupled PPG signal by MA reduction algorithm, the heart rate would be computed at frequency domain. However, RLS filter only processes the additive MA alone, it assumes that the energy of pulse signal is not shrank due to the interference of MA. In fact, the content of received pulse signal is reduced significantly by the corruption of MA. Therefore, the distorted waveform of pulse signal is compensated in this stage. The envelope of $e_{(n)}$ is used to weight every single point to enhance the amplitudes of distorted waveforms. The final signal output S_{fin} is showed in Fig.4

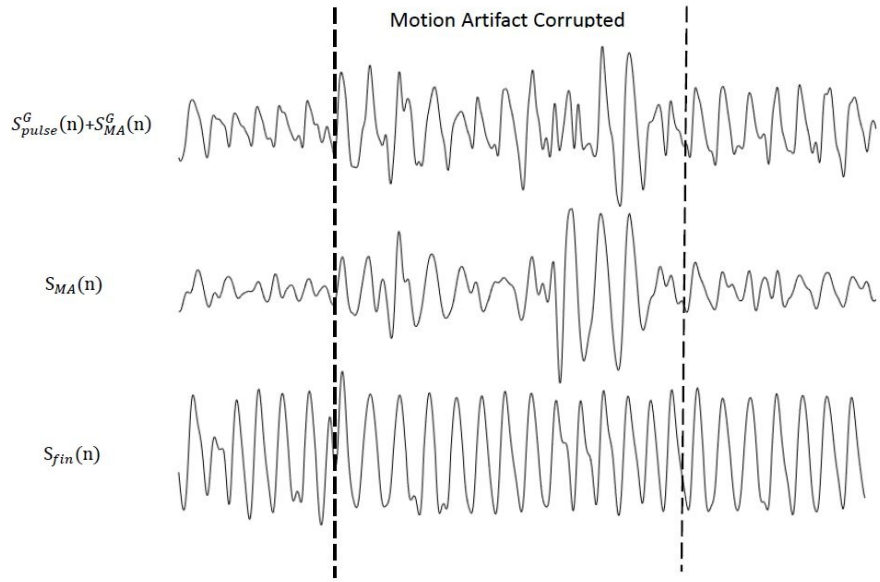


Figure 4. Final output of proposed approach.

4. EXPERIMENT

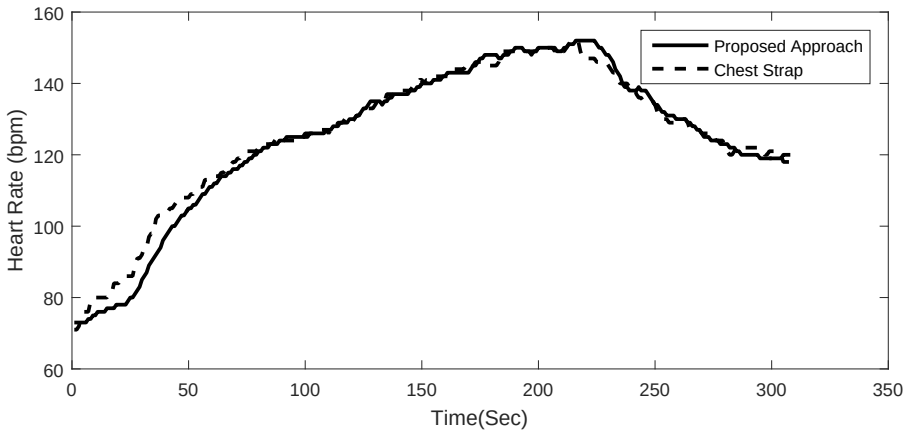


Figure 5. Test result compared with chest strap.

The sample rate of our ADC is 100Hz with 22-bits resolution. 5 healthy young men participate the experiment that have 30 minutes running exercise on treadmill at speed of 12km/h. Subjects would swing their arms naturally

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by wearing the PPG collector. All the competed heart rate value would be compared with heart rate trap. One of the tests is showed in Fig.5, and the final test results including all five subjects are illustrated in Fig.6. The mean squared error (MSE) is 2.96 bpm in a broad rage of heart rate from 70 bpm to 180 bpm.

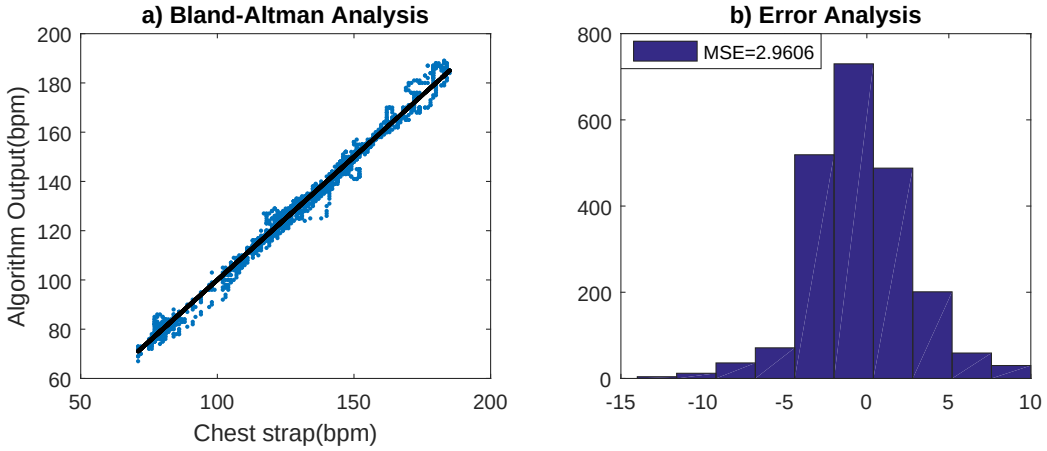


Figure 6. Test result compared with chest strap.

5. ACKNOWLEDGEMENT

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6. CONCLUTION

Proposed approach could extract accurate heart rate during strenuous exercises, such like 12km/h running on the treadmill. All the test data are collected by wrist PPG application with naturally arm swinging. Even if the low perfusion index of PPG signal in wrist application is a big challenge, proposed approach could also recover pulse signal from severe background motion artifact.

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