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MS-EMD based Signal Processing Method for Reduction of Motion Artifacts from PPG Signals

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Abstract

Pulse oximeter (PO) is used in critical care units to display the estimations of arterial oxygen saturation (SpO_2) and pulse rate (PR). Error free estimation of PR and SpO_2 by using PO is always a research challenging task. Using non-invasive procedure, PPG signal can be acquired from PO. Due to voluntary or involuntary movements of patient/subject, the PPG signal has every possibility of being corrupted by motion artifacts (MAs), which results in unreliable & inaccurate estimations of SpO_2. It is observed that weighted average based methods employed by present day POs face certain limitations due to which, those POs have to compromise with erroneous SpO_2 estimations. In this paper, we present a signal processing method based on Multi-scale Empirical Mode Decomposition (MS-EMD), which combines wavelet processing and empirical mode decomposition. PPG data acquired with intentionally created MAs is considered for experimental analysis. Performance of the proposed MS-EMD based method is also compared with Multi-scale Principle Component Analysis (MS-PCA) and Multi-scale Independent Component Analysis (MS-ICA) based signal processing methods. SpO_2 estimations are observed to be quite good in terms of their reliability and accuracy.

Keywords: Pulse oximeter, PPG, MA noise, MS-EMD, MS-PCA, MS-ICA, SpO_2.

INTRODUCTION

Pulse oximeter (PO) is very much helpful for medical diagnosis and enables the process of non-invasive & continuous monitoring of arterial blood oxygen saturation levels (SpO_2) and pulse rate (PR). In PO of critical care units, the transmittance type Photoplethysmographic (PPG) sensor unit, operated at red and IR wavelengths, is used for acquiring the PPG data [1]-[2]. Reliability & Accuracy of SpO_2 estimations are important characteristics of the PO, which is usually affected by the voluntary or involuntary movements of the subject attached with PPG sensor head. Main cause of error for inaccurate measurements of SpO_2 will be due to motion artifacts (MA) in the acquired PPG signal. Present day POs use weighted average based signal processing techniques to reduce MAs in case of MA episodes and then estimate SpO_2 from MA reduced PPG. Several signal processing techniques are proposed for effective removal of MA noise from PPGs.

Conventional methods like weighted moving average techniques and other methods proposed for MA reduction fail to eliminate MA noise [2]. Researchers found that MA noise component is an in-band noise with substantial spectral overlap. Quality of reference signals, correlation of signals and false peak detection during some window frames are the key features to be considered in case of adaptive filtering methods [3]-[5]. Signal processing methods based on Wavelet transforms [6] and smoothed pseudo Wigner-Ville distribution [7] could extract clean PPGs, but these methods have scale ambiguities and introduce phase distortion. Period estimation becomes difficult in case of ICA based MA reduction methods [8]. Researchers also focused on application of advanced signal processing methods based on cycle-by-cycle Fourier series (CFSA) [9], higher-order-statistics (HoS) [10] for MA reduction from corrupted PPGs. These methods fared well in MA reduction preserving all the morphological characteristics, but proved to be complex. Empirical mode decomposition (EMD) based method [11] works well with a limitation of soft thresholding. Motion tolerant adaptive filter [12] and Ensemble EMD based method [13] proposed for wearable gadgets to detect intense motions during physical exercises extracted artifact free PPGs but have limited performance due to inaccurate peak detection.

This paper presents a signal processing method based on Multi-scale Empirical Mode Decomposition (MS-EMD). The method is a combination of wavelet processing with empirical mode decomposition for effective reduction of MAs from acquired PPG signals.

PROPOSED METHODOLOGY

A. Multi-scale EMD

The MS-EMD processing algorithm has two main stages, namely decomposition and reconstruction. The decomposition stage requires embedding of wavelet processing and EMD. As part of wavelet processing, the acquired PPG is decomposed into detailed and approximate coefficients at each scale. The processing steps are given as follows.

Step 1: Perform wavelet decomposition on each column of a formed data matrix of PPG signal. Let $A_{L_1}, D_{1_1}, D_{2_1}, ..., D_{L_1}$ $A_{L_2}, D_{1_2}, D_{2_2}, ..., D_{L_2}$,.. and $A_{L_N}, D_{1_N}, D_{2_N}, ..., D_{L_N}$ are the approximate and detailed coefficients, computed on each column matrix decomposition.

Step 2: Wavelet sub band matrix is formed with individual approximate and detailed coefficients. $D_1 = \lfloor D_{1_1}; D_{1_2}; ....; D_{1_N} \rfloor$ $D_2 = \lfloor D_{2_1}; D_{2_2}; ...; D_{2_N} \rfloor$ $D_L = \lfloor D_{L_1}; D_{L_2}; ...D_{L_N} \rfloor$ $A_L = \lfloor A_{L_1}; A_{L_2}; ...A_{L_N} \rfloor$

Step 3: Compute energy contribution (EC) of approximate and detail coefficient for each wavelet sub-band matrix

$$EC_{A_L} = T[C_{A_L}] / \left[T[C_{A_L}] + \sum_{j=1}^{L} T[C_{D_j}] \right] \quad (1)$$

$$EC_{D_j} = T[C_{D_j}] / \left[T[C_{A_L}] + \sum_{j=1}^{L} T[C_{D_j}] \right] \quad (2)$$

where 'T' denotes the trace (sum of all diagonal elements) of the matrix indicated in the braces. The matrices are the covariance matrices (C) of approximate and detail coefficients. C_{A_L} is the covariance matrix of A_L sub-band matrix. Similarly C_{D_j} is the covariance matrix of D_j, where *j* is *1, 2, 3, . . . , L*

The EC is used here to estimate the energy contribution of each wavelet sub-band components, so that we can estimate, which frequency sub-band is contributing more towards the total energy of the overall signal, and thereby identifying strong periodic component in the given signal.

Step 5: Modify the wavelet sub band matrix based on the above parameter mentioned in eq. (1) & (2). i.e. preserving strong periodic component and zeroing the remaining components which forms the basis for den-noising.

Step 6: For all scales, reconstruct the signal using modified detail and approximate coefficients.

Step 7: Apply the EMD processing steps (as described in next section) on wavelet reconstructed signal to get EOFs.

B. EMD Processing Steps

Step 1: Find all the local maxima and the minima of the MA corrupted PPG signal.

Step 2: Connect the maxima forming a curve as the upper envelope, $u_{max}(t)$, repeat the procedure to the minima forming the lower envelope $u_{min}(t)$.

Step 3: Identify the mean, $m(t) = [u_{max}(t)+u_{min}(t)]/2$.

Step 4: Subtract *m(t)* from the original PPG signal, $h(t) = x(t) - m(t)$, and regard *h(t)* as the new signal to repeat the steps 1 to 4 until *h(t)* meet the IMF's conditions, then $c_1 = h(t)$.

Step 5: Separate IMF to get the quasi-residue function, $r(t) = x(t) - c_1$.

Step 6: Repeat the loop on *r(t)* until *r(t)* has only one extremum or it become monotonous function, in this process $c_2, c_3, ..., c_n$ can be obtained.

Step 7: Compute the spectrum of each IMF based on the frequency range defined for desired and noisy portions. Where the frequency spectrum of MA corrupted PPG signal consists of various frequency components viz., the pulsatile portion (0.5-4 Hz), respiratory activity (0.2-0.35 Hz) and MA noise component (0.1 Hz or more) information.

Step 8: MA recovered PPG is obtained by identifying the range of MA noise frequency, eliminating IMF corresponding to MA and then adding the remaining IMF's falling in the particular range of desired portion.

RESULTS AND DISCUSSION

A prototype of PPG data acquisition system was developed and interfaced to the PC. The developed PPG data acquisition system is shown in Fig. 1. Red and IR PPGs are acquired at a sampling rate of 200 Hz using an data acquisition system module, NI-DAQ Pad-6015.

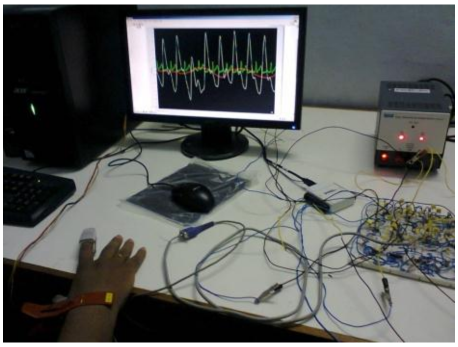

Figure 1. PPG data acquisition system

To analyze the performance of proposed signal processing method, more frequently encountered MAs (horizontal, vertical and bending movements of subject's index finger) were created intentionally during the PPG data acquisition process from patient/subject. Acquired red and IR PPGs contaminated with the MA during vertical movement of subject's finger are shown in Fig. 2.

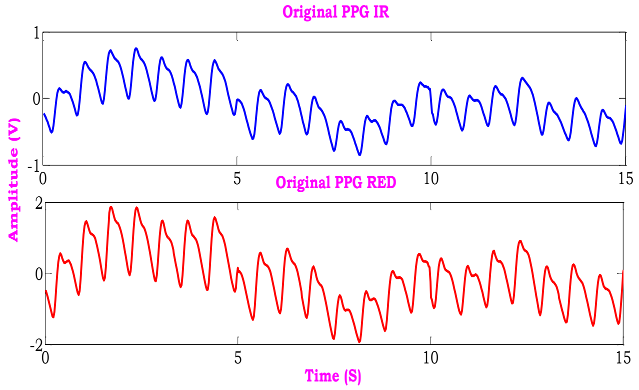

Figure 2. Acquired red & IR PPGs contaminated with MA

A. *PPG Normalisation*

The PPGs are normalised in order to get a reference section for comparative analysis. For PPG data normalization, data of 10 cycles is considered and mean & variance is evaluated for those cycles. Mean is subtracted from the considered 10 PPG cycles and then divided the same with the variance to obtain reference section. The normailzed PPGs of red and IR are shown in Fig. 3.

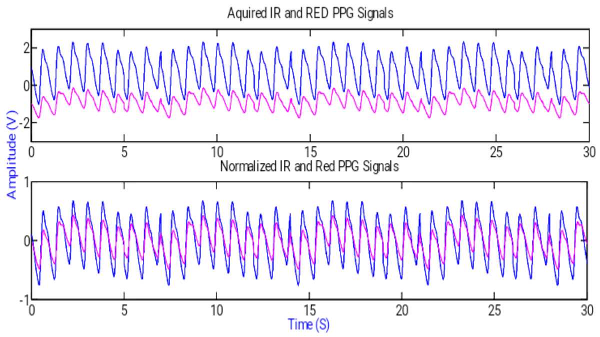

Figure 3. Acquired and normalized red & IR PPGs

The normalised signals are then processed with proposed method.

B. *PPG De-noising results*

Fig. 4 portrays the experimental results of IR PPG signal afflicted with bending motion of finger. The figure also shows results of processing done with other multi-scale techniques MS-PCA and MS-ICA based MA reduction methods. MA recovered sections of processed PPGs in Fig. 4(d), clearly indicate the effective and efficient reduction of MA noise using proposed method. Good part is the recovered sections have restored the essential morphological features of PPG. Similarly, results of processing are presented in Fig. 5 for red PPG.

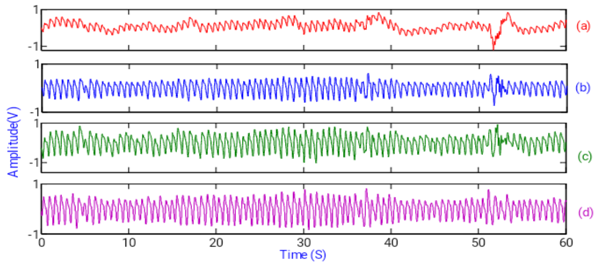

Figure 3. IR PPG with "Bending movement of finger": (a) MA corrupted PPG (b) MA reduced PPG using MS-PCA (c) MA reduced PPG using MS-ICA (d) MA reduced PPG using MS-EMD

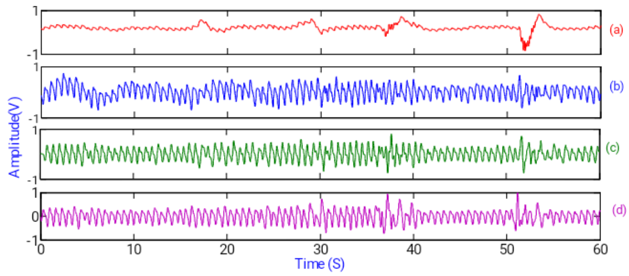

Figure 4. Red PPG with "Bending movement of finger": (a) MA corrupted PPG (b) MA reduced PPG using MS-PCA (c) MA reduced PPG using MS-ICA (d) MA reduced PPG using MS-EMD

C. *Stastical Analysis*

The performance of the proposed method is also studied using statistical analysis in terms of mean ± SD of peak-to-peak values of the recovered PPG cycles after processing the acquired PPG signals with MS-PCA and MS-ICA based filtering methods and proposed MS-EMD based method. Table I shows statistical measurements. It can be clearly seen that the peak-to-peak values of MA recovered PPGs obtained using MS-EMD based method are very close to the reference sections of the PPG

D. *SpO_2 estimation*

For the estimation of arterial blood oxygen saturation (SpO_2) readings [14], clearly separable AC and DC components are essential. The DC components of the red (DC_{Red}) and Infrared (DC_{IR}) PPG signals are extracted. Similarly, the peak to peak values of the pulsatile components at the heart rate AC_{Red} and AC_{IR} of the red and IR PPG signals respectively are measured.

SpO_2 is calculated using the eqn. (3) below

$$SpO_2\,\% = (110 - 25\boldsymbol{R})\,\% \qquad (3)$$

Table I. Superiority of proposed method in restoring peak-to-peak values of PPG

PPG section	**Horizontal movement**	**Vertical movement**	**Bending movement**
Reference	0.371 ± 0.025	0.428 ± 0.045	0.357 ± 0.022
Corrupted	0.426 ± 0.087	0.514 ± 0.107	0.459 ± 0.067
Recovered using MS-PCA based method	0.395 ± 0.036	0.462 ± 0.061	0.384 ± 0.142
Recovered using MS-ICA based method	0.395 ± 0.036	0.462 ± 0.061	0.384 ± 0.142
Recovered using MS-EMD based method	0.376 ± 0.036	0.431 ± 0.059	0.362 ± 0.131

Table II. Computed values of r and SpO_2 of PPG for different movements

PPG section	**Horizontal movement**		**Vertical movement**		**Bending movement**	
	R	**SpO_2**	**R**	**SpO_2**	**R**	**SpO_2**
Reference	0.68 ± 0.048	93%	0.720 ± 0.059	92%	0.56 ± 0.13	96%
Recovered using MS-PCA based method	0.70 ± 0.048	92.5%	0.76 ±0.076	91%	0.60 ±0.06	95%
Recovered using MS-ICA based method	0.70 ± 0.047	92.5%	0.76 ±0.075	91%	0.61 ±0.07	94.75%
Recovered using MS-EMD based method	0.69 ± 0.041	92.75%	0.722 ± 0.042	91.9.%	0.578 ± 0.09	95.5%

Where, $\boldsymbol{R}$ referred to as "ratio of ratios" is evaluated using the eqn. (4)

$$\boldsymbol{R} = \frac{(AC_{Red}/DC_{Red})}{(AC_{IR}/DC_{IR})} \quad (4)$$

The SpO_2 estimations for various sections of recorded PPG signals are portrayed in Table II. It can be clearly observed that the PPG signals processed by the proposed MS-EMD based method resulted in reliable SpO_2 estimations and are very close to that of the estimations computed from reference sections of the recorded PPGs for different motions considered.

CONCLUSION

In this work, we presented Multi-scale Empirical Mode Decomposition (MS-EMD) based signal processing method for MA reduction of PPG signals. The proposed method is a combination of wavelet processing with EMD. The advantage of proposed method was clearly demonstrated thorough simulation analysis carried out for the acquired PPG signals with different types of MA. The MS-EMD based method is compared with that of MS-PCA and MS-ICA based methods. In addition, statistical measurements are computed for the processed PPGs. SpO_2 estimations, computed from the MA reduced PPGs after processing through the MS-EMD based method, shown a reliable arterial blood oxygen saturation measurements.

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