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Motion Artifact Reduction in Photoplethysmography Using Independent Component Analysis

Byung S. Kim and Sun K. Yoo*

***Abstract*—Removing the motion artifacts from measured photoplethysmography (PPG) signals is one of the important issues to be tackled for the accurate measurement of arterial oxygen saturation during movement. In this paper, the motion artifacts were reduced by exploiting the quasi-periodicity of the PPG signal and the independence between the PPG and the motion artifact signals. The combination of independent component analysis and block interleaving with low-pass filtering can reduce the motion artifacts under the condition of general dual-wavelength measurement. Experiments with synthetic and real data were performed to demonstrate the efficacy of the proposed algorithm.**

***Index Terms*—Block interleaving, ICA, motion artifact, photoplethysmography.**

I. INTRODUCTION

Photoplethysmography (PPG) is an electro-optic technique to measure the pulse wave of blood vessels. In pulse oximeter, the measuring apparatus for PPG [1], motion artifacts can limit the accuracy of the measured PPG signal during movement. Particularly, the motion artifacts cannot be easily managed because of the frequency overlapping between PPG and the motion artifact signals [2]. Since general frequency domain filtering methods can be unsuccessful, some methods have been researched to manage the motion artifacts from measured PPG signals [1], [2]. However, further research is still required to improve the performance of motion artifact rejection.

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B. S. Kim is with Graduate School of Biomedical Engineering, Yonsei university, Seoul 120–752, Korea.

*S. K. Yoo is with the Department of Medical Engineering, Center for Emergency Medical Informatics, Human Identification Research Center, Yonsei University College of Medicine, Seoul 120–752, Korea (e-mail: sunkyoo@yumc.yonsei.ac.kr).

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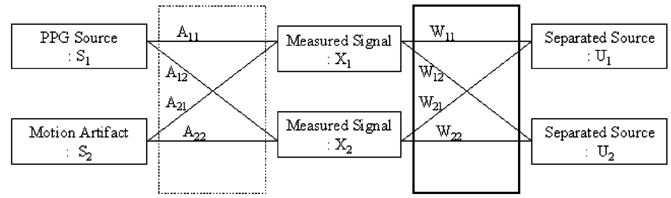

Fig. 1. ICA model for motion artifact separation.

In this paper, the new motion artifact reduction method was proposed under the constraint of dual-wavelength measurement. We combined independent component analysis (ICA) and a signal enhancement preprocessor to separate the PPG signal from the motion artifact-contaminated measured signals. Experiments with synthetic and real data were performed to demonstrate the efficacy of the proposed algorithm.

II. MOTION ARTIFACT REDUCTION

The motion artifact reduction method, consisting of the preprocessor and the ICA, is newly designed based on the quasi-periodicity of PPG signal and the independence between the PPG and the motion artifact signals. The preprocessor enhances the PPG component from measured signal and then the ICA separates the PPG signal from preprocessed signal. The preprocessor consists of period detection, block interleaving, low-pass filtering, and block de-interleaving. In particular, the ICA model with two independent sources is considered to complement the popular dual-wavelength optical probe.

A. ICA Model for Motion Artifact Separation

The PPG and motion artifact signal sources can be assumed to be independent of each other, since the heart pulsation for the PPG signal has little correlation with the physical movement for the motion artifact signal. As shown in Fig. 1, two measured signals $(\mathbf{X})$, can be modeled as the linear mixture of motion artifact and PPG signal sources $(\mathbf{S})$ with an unknown mixing matrix $(\mathbf{A})$, if they are independent

$$\mathbf{X} = \mathbf{AS}. \tag{1}$$

The unknown $\mathbf{A}$ and the unknown $\mathbf{S}$ can be estimated from the measured $\mathbf{X}$ (motion artifact contaminated signals) by ICA. The separated sources $\mathbf{U}\ (= \mathbf{S})$, the PPG signal and the motion artifact signal, can be obtained by estimated $\mathbf{W}\ (= \mathbf{A}^{-1})$. The $\mathbf{W}$ can be estimated by a fast ICA algorithm [3], [4]. In other words, the PPG source separation achieves the motion artifact reduction.

However, the actual number of independent sources contained in the measured $\mathbf{X}$ can be more than two. The motion artifact signal is postulated as the complex combination of multiple sources [2]. In addition to the motion artifacts, other noise can be added to $\mathbf{X}$ [1]. In order to separate PPG from multiple sources using the ICA model for two independent sources, the preprocessor should be employed to suppress noise in measured $\mathbf{X}$, which in turn enhances the PPG signal comparing with other noise sources, before applying the ICA model.

B. Preprocessor for PPG Signal Enhancement

In order to remove noise without the deterioration of the PPG signal, we exploited the quasi-periodicity of the PPG signal. The PPG signal

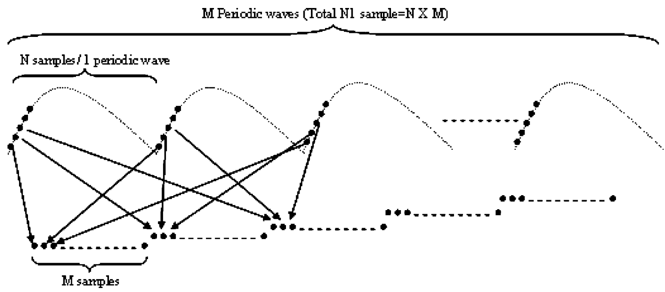

Fig. 2. Block interleaving.

associated with heart pulsation is inherently quasi-periodic [5]. However, in measured $\mathbf{X}$, most noise is not periodic, and even periodic noise may not be synchronized with heart pulsation. Hence, if the period of the PPG signal is appropriately estimated, the noise can be suppressed without affecting the PPG signal.

The preprocessor consists of period detection, block interleaving, low-pass filtering, and block de-interleaving. The period of the PPG signal can be estimated by auto-correlation [6]. Then, the block interleaving shuffles the measured signal samples into rearranged sample sequence, which has a different order based on the estimated period of the PPG signal. As shown in Fig. 2, a block consists of M periodic waves with N samples. The block interleaver is implemented by selecting the starting point from the continuous input samples, writing the bits into a matrix $(\mathrm{N} \times \mathrm{M})$ row by row, and then reading them column by column. The block interleaving process can group input samples into frequency-related samples. As shown in Fig. 2, M interleaved sample points can comprise the DC line (low-frequency) if waves are periodic, and samples are synchronized with the period. Hence, the low frequency components and the high frequency components in block interleaved samples are associated with the synchronized samples (periodic PPG signal) and the nonsynchronized samples (noise), respectively. Because of the frequency rearrangement property of the block interleaving, the noise associated with high frequency components can be simply reduced by low-pass filtering without deterioration of the PPG signal. The low-pass filtering is conducted by three sample moving average filter [6]. Indirectly, the optimum number of M can be determined by means of numerical experimentaion. When we adjusted the M of the known signal (typical PPG signal obtained from normal human) with the added noise of 3-dB signal–to-noise ratio (SNR), it was observed that the quality of the separated signal converged after M increased to more than 10. The M of 10 can be chosen as one of the possible tradeoff values between the quality and the delay. Finally, the block de-interleaving, which reverses the interleaving operation, recovers the interleaved sampled order for the application of ICA.

III. Results

As shown in Fig. 3, the performance comparison between the proposed ICA with the preprocessing method (PICA) and the ICA only method (ICA) was evaluated by the use of two synthesized reference signals, $5\sin(2\Pi n/300)$ and $2\sin(2\Pi n/300)$, with different levels of synthesized motion artifact signals (0–13.5 dB SNR). The period of 300 (1.66 Hz) of the reference signals approximately matched the heart rate of 100 beats/min associated with a 500-Hz sampling frequency. Three different sinc functions (rectangular pulses in the time domain) with different levels and center frequencies were inter-mixed in the frequency domain to synthesize three different motion artifact signals having different accentuated frequencies. Subscripts 1, 2, and 3 correspond to accentuated frequencies of 0, 2.5, and 5 Hz, respectively. In both the ICA and PICA methods, the mean-square error (MSE)—between the known reference signal and the separated PPG signal—increases as the power of the motion artifact increases, and as the amount of frequency overlapping between the reference and the motion artifact signals increases (the MSE performances for an accentuated frequency of 5 Hz, ICA3 and PICA3, are significantly better than those for 0 Hz and 2.5 Hz). However, PICA shows a markedly smaller MSE than the ICA, as the SNR decreases (the level of motion artifacts increases). Moreover, PICA is less sensitive to the frequency overlapping than is ICA for all three accentuated frequencies.

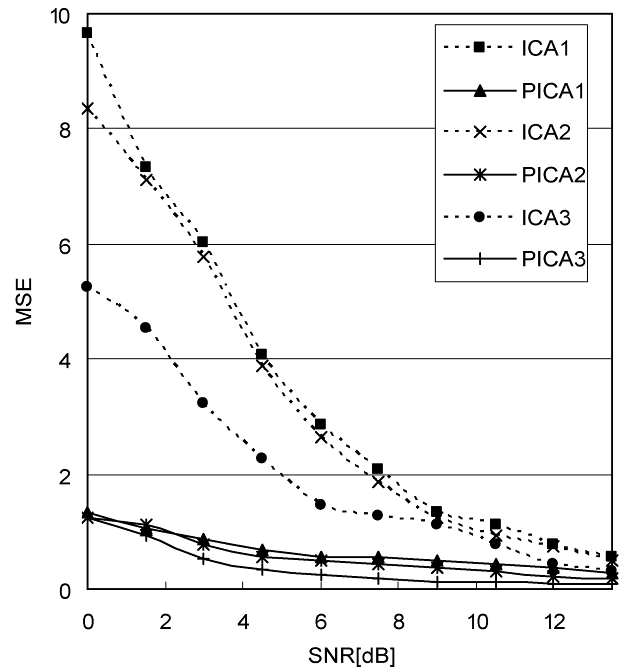

Fig. 3. The performance comparison between the proposed ICA with preprocessing (PICA) method and the ICA-only method (ICA) using a synthesized reference with a period of 1.66 Hz and three motion artifact signals. Subscripts 1, 2, and 3 correspond to accentuated frequencies of 0, 2.5, and 5 Hz for the synthesized motion artifact signals, respectively.

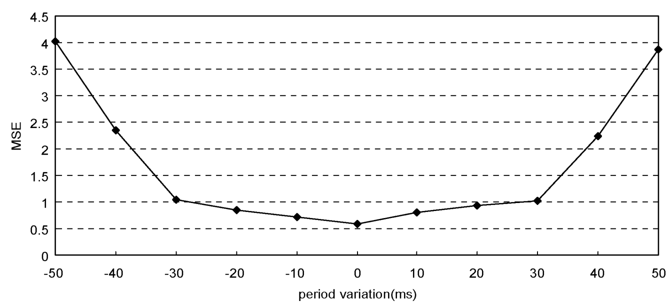

Fig. 4. MSE with respect to the amount of period mismatch.

The performance degradation due to inaccurate estimation of the periodicity was tested as shown in Fig. 4. When we adjusted the amount of period mismatch of the synthesized reference signals with known period artificially, significant quality degradation of the separated PPG signal was observed after the amount of period mismatch reached 30 ms.

Experiments using real data were conducted using dual-wavelength illumination (890 nm for infrared illumination, and 660 nm for red illumination) with a sampling frequency of 500 Hz. Four different types of motion artifacts were produced by the following artificial movements: 1) pressurizing the probe clip; 2) bending the finger; 3) waving the

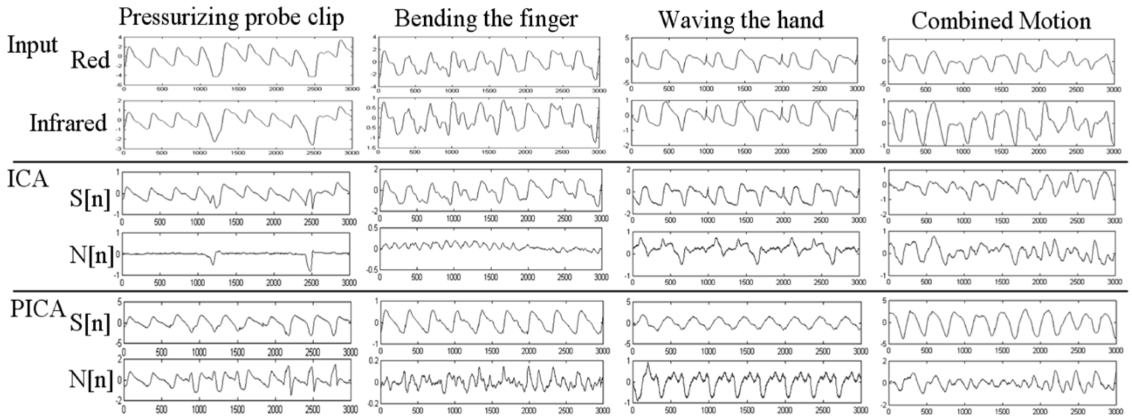

Fig. 5. The proposed method (PICA) was visually compared with the ICA-only method (ICA) with respect to four different types of motion artifacts.

hand; 4) the combined motions of 1), 2), and 3). The PICA was visually compared with ICA, as shown in Fig. 5. The PICA can separate the motion-artifact reduced PPG signals (s[n]) and the motion-artifact signals (N[n]) better than ICA for all four test cases.

IV. Discussion

Some factors should be carefully considered for the successful application of the proposed method. First, the number of independent sources in the ICA model is important, since it can affect the process of the pursuit of statistical independence from multivariate statistical data [4]. Nevertheless, the number of independent sources can be restricted by the number of input channels available in measuring apparatus. One of the possible alternatives that would increase the number of independent sources is to adopt triple-wavelength illumination rather than the dual-wavelength illumination. However, the performance gain associated with the use of an additional independent source is not significant, since the preprocessing (interleaving with low-pass filtering) can effectively reduce multiple noise sources associated with the number of independent sources. In addition, the use of dual-wavelength illumination is of practical significance due to its popularity [1]. Secondly, inaccurate estimation of the periodicity due to the imperfection of the period estimator can directly influence the block interleaving (refer to Fig. 4). The slight amount of inaccurate period estimation of PPG signal and of heart rate variability during continuous measurement can be tolerable, but specific procedures should be considered to cope with the undesirable situation where the periodicity estimator has failed. Thirdly, the number of periodic waves (M) is associated with the processing delay and the tolerability to period variation. As M increases, the tolerability to period variation increases positively due to the accumulated effect of multiple waves, but the delay increases negatively due to the block interleaving. Finally, the proposed method is less sensitive to the SNR of the measured signal (refer to Fig. 3) than is the existing ICA, and it is also less sensitive to the selection of starting point, because the frequency rearrangement property associated with the block interleaving is irrespective of the initial selection of starting point.

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