Movement Noise Cancellation in PPG Signals

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***Abstract*—In this paper, we propose an algorithm to remove movement noise in photoplethysmography (PPG) signals. To that end, we use the multipath diversity of PPG signals measured at different locations and the wavelet transform to detect movement noise in the signals. In experiments, when PPG signals have movement noise for 30% of the time, the proposed algorithm can reduce that noise to 5.18%.**

I. Introduction

Recent developments in information and communications technologies have introduced new smart devices and their applications in biomedical fields [1]. One of the most popular biomedical signal measurements is photoplethysmography (PPG), which can monitor heart rates and cardiac cycles by optically detecting blood volume changes in the microvascular bed of tissues. PPG has become widely popular in wearable devices due to their portability, but the main drawback is vulnerability to movement noise.

During PPG measurement, a signal faces two types of noise: high frequency noise and movement noise [2]. High frequency noise is caused by electrical noise, such as thermal noise and electromagnetic interference in cables. Movement noise is caused by voluntary or involuntary movements of a subject and affects a wide frequency range. The noise in measurement distorts PPG signal shapes, and such distortion of PPG signals results in wrong diagnoses. Although high frequency noise can be filtered out using a low pass filter, movement noise cannot be cancelled by a low pass filter.

Most previous works studied the algorithms to cancel high frequency noise or additive white Gaussian noise [3]. In [4], the authors proposed an algorithm to reduce motion artifacts using adaptive filtering, but they considered only limited cases, such as vertical, horizontal, and bending motion of a finger. Hence, a movement noise cancellation scheme is necessary for more general cases.

II. Proposal Algorithm

In this paper, we propose an algorithm to mitigate the impact of mobility on PPG measurement by using multipath signals and the wavelet transform. First, we measure the PPG signal at different locations on the body, such as fingers and ears, and remove high frequency noise using a low pass filter, because a nominal pulsatile has frequencies lower than 4 Hz [5].

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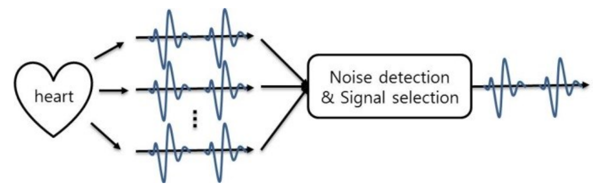

Fig. 1 Multipath diversity of PPG signals

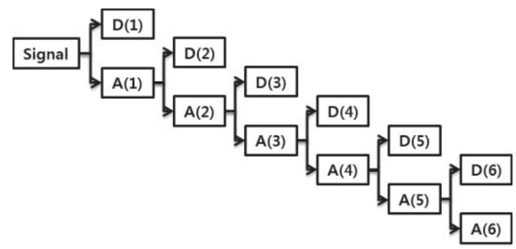

Fig. 2 Wavelet transform decomposition

To develop an algorithm robust to movement noise, we adopt a scheme combining and selecting multipath signals, which is popularly used in wireless communications [6]. This scheme utilizes the fact that the quality of signals independently experiencing fading can be improved at the receiver. First, we measure PPG signals at multiple locations, which might be independently influenced by movement, as shown in Fig. 1.

Even if the signals may originate from one source, the received signals may have different amplitudes and travelling times owing to the different paths taken. Hence, to resolve these problems, the algorithm adjusts the amplitudes and the time offsets, and determines a reference PPG signal, which is defined as a waveform of a single period, when a subject is in a comfortable state without movement. In addition, to detect movement noise in the signal of each channel, the wavelet transform is applied. To that end, the algorithm finds the mother wavelet, which is most similar to the reference signal, by examining cross-correlation between the reference signal and the mother wavelets.

With the selected mother wavelet, the signal is decomposed to a particular level N, as shown in Fig. 2, which depends on the sampling rate. If a sampling rate is 256 Hz, then level N is set to 6, so the lowest frequency band of the decomposed low pass filter becomes between 0 and 4 Hz [5], [7]. The decomposition procedure consists of two digital filters and two down samples by 2. The first filter is a high-pass filter, and the second filter is a low-pass filter. The down-sampled outputs of the high-pass and low-pass filters provide detail components (D(1)) and approximation components (A(1)), respectively [7]. Approximation A(1) is iteratively decomposed until the level reaches N, which means that approximation A(N) is computed. We detect a signal period

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by using approximation components, A(N) in level N, for which the frequency range is between 0 and 4 Hz, whereas we detect movement noise by using detail components D(N-3) in a level (N-3), for which the frequency range is between 32 and 64 Hz.

To measure the noise level of each channel, we define the signal-plus-noise-to-signal ratio (SNS) as

$$\mathrm{SNS} = \frac{\textit{Power of signal and noise}}{\textit{Power of reference signal}}.$$

The algorithm compares the SNSs of measured signals and selects the lowest SNS signal. The algorithm is summarized in Fig. 3.

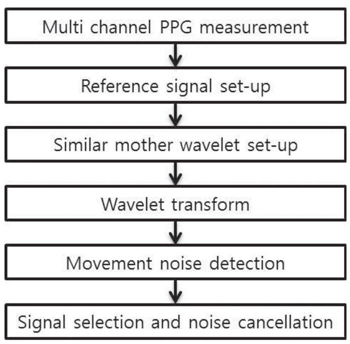

Fig. 3 Proposed algorithm

III. Simulation Result

For simulations, we measured PPG signals at two different places (a finger and a toe) on eight adults using Ubpulse T1 from LAXTHA Inc. at a sampling rate of 256 Hz. We conducted a 70-second measurement four times per person. The subjects sitting in a comfortable chair moved their fingers or their toes randomly during a certain time period.

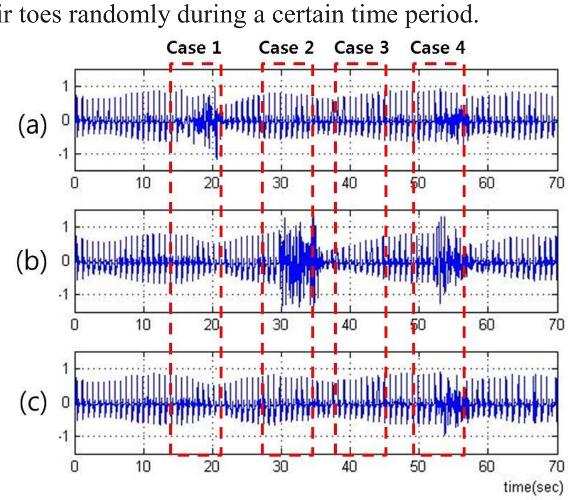

Fig. 4 Noise cancellation result: (a) a PPG signal measured on channel 1; (b) a PPG signal measured on channel 2; (c) a PPG signal on output

Figure 4 shows the original PPG signals of a subject measured in a session. The signals on channels 1 and 2 were measured at two different locations, and the output signal represents the signal performed by our algorithm. When only one channel signal has movement noise, such as cases 1 and 2 in Fig. 4, the algorithm can remove movement noise. In contrast, the algorithm is unable to cancel the movement noise when two channels simultaneously have movement noise.

We verify the performance of the proposed algorithm in various movement noise environments, as seen in Table 1. The inserted noise implies the period of time when subjects moved, and the detected noise represents the period of time during which the algorithm recognized PPG signals as deteriorated due to movement. The noise at output is the time portion of the PPG signals with movement after cancellation.

The results show that the wavelet transform can accurately detect a noisy period in the signals, and that the movement noise can be reduced using the proposed algorithm. For example, when each channel included movement noise for 30% of the experiment time, the algorithm detected the noise as 29.78% and 29.77% (99.3% and 99.2% accuracy, respectively) and reduces the noise to 5.18%.

Table 1 Performance comparison according to noise rates (%)

Case	Noise at Channel 1		Noise at Channel 2		Noise at output
	Inserted	Detected	Inserted	Detected	
1	20	19.4	15	14.9	4.29
2	20	19.12	10	11.2	7.33
3	30	29.78	30	29.77	5.18

IV. Conclusion

We proposed a movement noise cancellation algorithm for PPG signals using multipath diversity and the wavelet transform. PPG signals were measured at multiple different places on different subjects. After measuring the PPG signals, the wavelet transform determined if the measured signals included movement in a certain period of time, and the best signal was selected. By experiments, we showed that movement noise could be reduced to 5.18% when movement noise was inserted randomly and independently into PPG signals during 30% of the experiment time.

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