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Adaptive Motion Artifacts Reduction Using 3-axis Accelerometer in E-textile ECG Measurement System

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Abstract The electro-conductive fabric (e-textile or e-fabric) as an electrode for ECG measurement is one of the best application for ubiquitous healthcare system. However, it is difficult to measure the bio-signal due to its sensitivity variation caused by impedance change, especially by motion of the subject. In this paper, adaptive motion artifacts reduction using motion information from 3-axis accelerometer is proposed and analyzed in quantitative manner.

Keywords ECG · Adaptive filter · E-textile · Motion artifacts · Accelerometer

Introduction

Wearable devices get much attention for ubiquitous healthcare environment on the ground of its mobility, flexibility and connectivity [1]. This environment requires novel systems and applications using information and communication technology (ICT) to measure bio-signals without any discomfort or time–space limitation [2].

The electro-conductive fabric, also called as e-textile or e-fabric, consists in comfortable texture which has an advantage for monitoring one's health status in the long-term rehabilitation or whole day nursing, because it is a wearing type rather than the adhesive type such as the conventional ECG electrode [3]. However, its very low impedance characteristic indicates that it is weak to thermal noise, motion artifacts and power line interference. Among them, researchers are interested in motion artifacts because its various frequency ranges and relatively large magnitude make the important bio-signal information distorted and even buried. It leads wrong diagnosis and improper follow-up [4], and gives a challenge to be overcome for best healthcare provision.

There are several researches on reducing motion artifacts by considering it as a simple sinusoidal noise in conventional ECG electrode. Friesen et al. [5] explained noise sensitivity in detecting QRS by finding out that motion of ECG electrode caused electrode-skin impedance changes inducing baseline changes with its duration of 100~500 ms. Ruha et al. [6] proposed real-time QRS detector system for measuring ambulatory HRV. In this case, motion artifacts were considered to be lower than 5 Hz sinusoidal wave and filtered using over-sampled (2 kHz) ECG signal for better timing-resolution.

Some researchers have studied in motion artifacts as a more complicated noise source. Tong et al. [4] proposed adaptive filter for electrode motion artifact caused by relation between the subject's skin and electrode. Liu and Pecht [7] also did it by considering motion artifacts as a skin stretch through LED and optical sensor.

In spite of more complex situation than the conventional electrode mentioned above, there are few considerations on motion artifacts, so far, in ECG signal by means of electro-conductive fabrics. In [8], motion artifacts are modeled by the relation between ECG from conventional electrode and ECG from e-textile with maximum frequency of 5 Hz.

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Then, Least Mean Square (LMS) adaptive filter algorithm shows the possibility and validity that motion from the e-textile ECG system can be reduced as did in conventional ECG electrode.

In this paper, we propose motion artifacts reduction using 3-axis accelerometer in e-textile ECG measurement system. In addition, transformation method of motion acceleration into the motion information for estimating motion artifacts and quantitative analysis focused on Signal-to-Noise-Ratio (SNR) increase and unit process time are described.

Mathematical background

Adaptive filter system

Conceptual diagram of the adaptive filter system is described in Fig. 1a. Let **x** be the signal input consisting in the signal source **v** and the unknown noise source **m** from the subject. Let the desired input **r** be correlated with **m** but uncorrelated with **v**. Suppose that **v**, **r** and **m** have zero mean in stationary random properties.

The system output **o** can be formulated by **v**, **m** and adaptive filter output **y** as follows.

$$\mathbf{o} = \mathbf{x} - \mathbf{y} = \mathbf{v} + \mathbf{m} - \mathbf{y} \tag{1}$$

By the perpendicularity between **v** and **m**, **y**, square-mean of Eq. 1 is

$$E\{\mathbf{o}^2\} = E\{\mathbf{v}^2\} + E\left\{(\mathbf{m} - \mathbf{y})^2\right\}. \tag{2}$$

As we want to minimize system output power $E\{\mathbf{o}^2\}$ for maximizing the output signal to noise ratio (SNR) [9], the relation between **y** and **m** must be

$$\mathbf{y} = \mathbf{m}. \tag{3}$$

Equation 3 can be achieved by adjustable impulse response approach, so called adaptive filter, dependent on the error signal from the filter's output for decreasing output noise power, even though characteristics of the noise source have unknown nature [9].

We think that motion information of the subject has relation to the motion artifacts in ECG measurement system, but the relation rule is unknown. This means that we cannot fix the coefficients (**w**) of the filter which can transform the motion information into the motion artifacts.

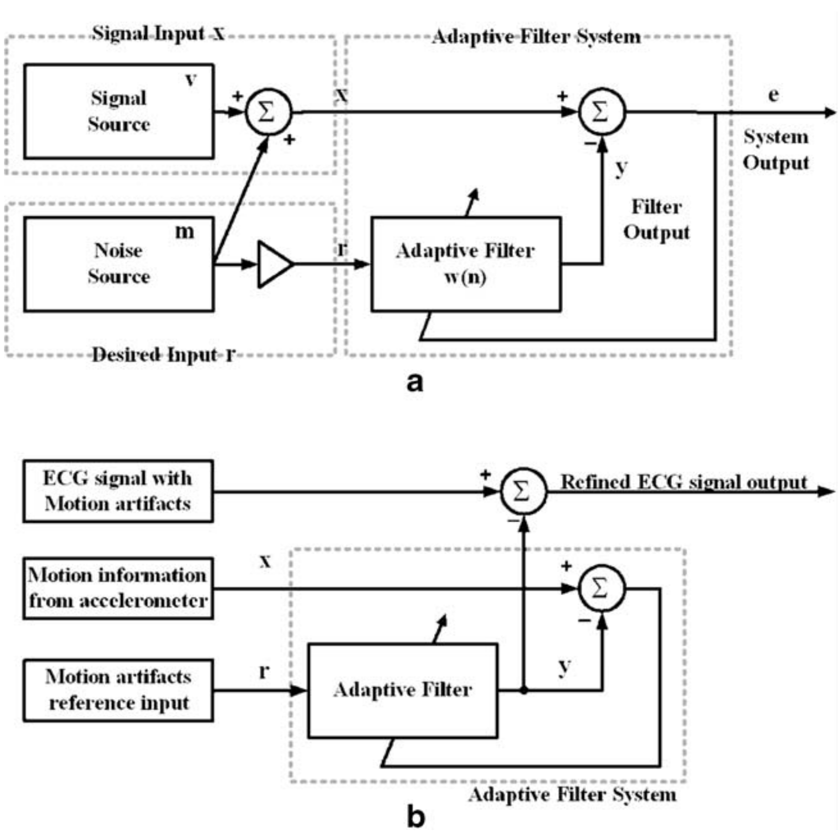

Fig. 1 Conceptual diagram of **a** adaptive filter system, **b** proposed motion artifacts reduction e-textile ECG measurement system

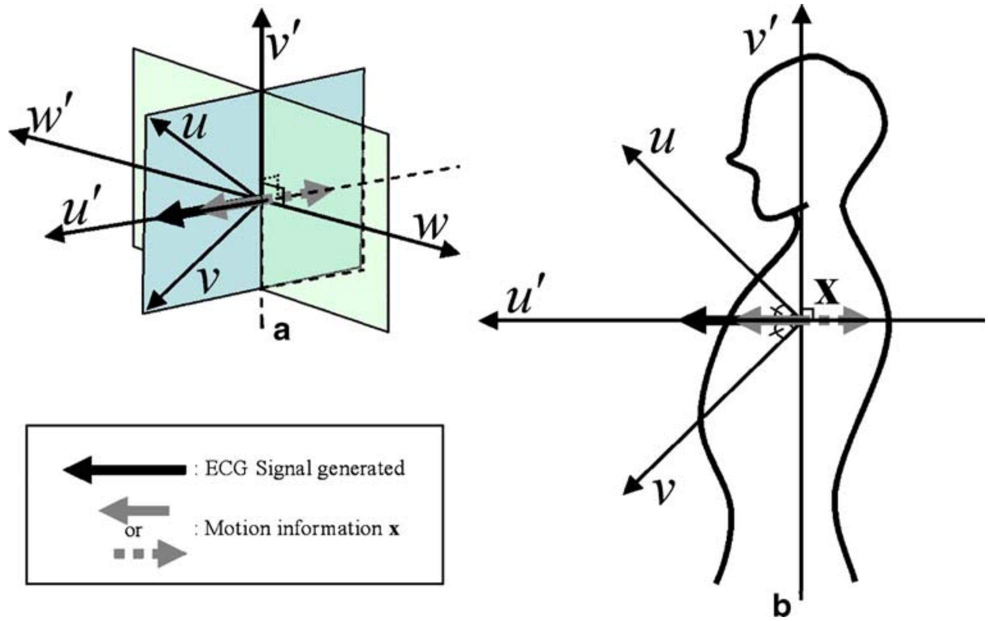

Fig. 2 Coordinates system: **a** orientation, **b** sectional view (u–v' plane) at the experiment

Therefore, we need adaptive filter method for motion artifacts reduction in e-textile ECG measurement system.

Normalized Least Mean Square (NLMS) algorithm

Least Mean Square (LMS) algorithm is based on the steepest descent approach [10]. Let filter coefficients (**w**) have the relation at time (k+1) as follows:

$$\mathbf{w}_{k+1} = \mathbf{w}_k + \mu(-\nabla). \tag{4}$$

Approximation of ∇ can be expressed as

$$\begin{aligned}\nabla &= 2\mathbf{x}_k\mathbf{x}_k^T\mathbf{w}_k - 2\mathbf{x}_k\mathbf{r}_k \\ &= 2\mathbf{x}_k(\mathbf{y}_k - \mathbf{r}_k) = -2\mathbf{x}_k\mathbf{e}_k.\end{aligned} \tag{5}$$

Therefore,

$$\mathbf{w}_{k+1} = \mathbf{w}_k + 2\mu\,\mathbf{x}_k\mathbf{e}_k. \tag{6}$$

Generally, μ or 2μ is called as step size. It is known that the LMS algorithm is only stable if the step size is limited [10], this lead to the normalized step size, as follows.

$$\mu_{\mathrm{NLMS}} = \frac{2\alpha}{\mathbf{x}_k^T\ \mathbf{x}_k + \sigma}. \tag{7}$$

The μ of Eq. 6 is substituted by Eq. 7, which means normalization by the energy of the input signal [10]. In Eq. 7, normalized step size, 2α, is usually 1 and σ (offset) is used for avoiding divide-by-near-zero if the input signal amplitude becomes very small. Therefore, Eq. 6 is represented as Normalized LMS (NLMS) in Eq. 8.

$$\mathbf{w}_{k+1} = \mathbf{w}_k + \frac{2\alpha}{\mathbf{x}_k^H\ \mathbf{x}_k + \sigma}\mathbf{x}_k\mathbf{e}_k. \tag{8}$$

Motion information model

Let u, v and w be orthogonal axes of the motion acceleration coordinates and u', v', w' are axes of the global Cartesian coordinates. For a convenience, let us suppose that chest of the subject is corresponding to the $v'w'$-plane, then ECG is generated at normal direction on the chest plane and motion artifacts increase/decrease ECG magnitude at same/opposite direction. Under the condition, we assume that motion artifacts can be obtained by adaptive filter system from the motion information which is proportional to the u'-axis component of the motion acceleration obtained by accelerometer. Other suppositions are described in Fig. 2.

The motion acceleration $\mathbf{a}=(a_1, a_2, a_3)$ on acceleration coordinates can be transformed to $\mathbf{a'} = \left(a_1', a_2', a_3'\right)$ on global coordinates by coordinates rotation matrix with clock-wise rotation angle, $\frac{3}{4}\pi = \frac{1}{2}\pi + \frac{1}{4}\pi$ and we can simplify the relation by focusing on (u, v) to ($-u$', v') transformation from the suppositions. That is,

$$\begin{aligned}\begin{pmatrix}-a_1' \\ a_2'\end{pmatrix} &= \begin{pmatrix}\cos\left(\frac{1}{2}\pi+\frac{1}{4}\pi\right) & \sin\left(\frac{1}{2}\pi+\frac{1}{4}\pi\right) \\ -\sin\left(\frac{1}{2}\pi+\frac{1}{4}\pi\right) & \cos\left(\frac{1}{2}\pi+\frac{1}{4}\pi\right)\end{pmatrix}\begin{pmatrix}a_1 \\ a_2\end{pmatrix} \\ &= \begin{pmatrix}-\sin\left(\frac{1}{4}\pi\right) & \cos\left(\frac{1}{4}\pi\right) \\ -\cos\left(\frac{1}{4}\pi\right) & -\sin\left(\frac{1}{4}\pi\right)\end{pmatrix}\begin{pmatrix}a_1 \\ a_2\end{pmatrix} = \begin{pmatrix}-a_1\sin\left(\frac{1}{4}\pi\right) + a_2\cos\left(\frac{1}{4}\pi\right) \\ -a_1\cos\left(\frac{1}{4}\pi\right) - a_2\sin\left(\frac{1}{4}\pi\right)\end{pmatrix}.\end{aligned} \tag{9}$$

Therefore, motion information **x** as the signal input in the adaptive filter system can be expressed with a_1' and the proportional factor α as follows.

$$\begin{aligned}\mathbf{x} &\propto \left(a_1\sin\left(\frac{1}{4}\pi\right) - a_2\cos\left(\frac{1}{4}\pi\right)\right),\ \mathbf{x} \\ &= \alpha(a_1 - a_2).\end{aligned} \tag{10}$$

Materials and methods

System configuration

ECG signals are acquired by BIOPAC® MP 150 with ECG amplifier module (ECG100C, set its gain to 1,000 times) using lead II configuration. A round-type conventional Ag/AgCl electrode for reference ECG signal and the electro-conductive fabric for e-textile ECG signal are used in the experiment. Motion acceleration is acquired by 3-axis piezoresistive silicon acceleration sensor module (ACH-04-08-05, MSI Inc., USA). The sampling frequencies for data acquisition are 1,000 Hz and recorded to 500 Hz for the system input with Intel® Core™ 2 CPU 6420 (2.14 GHz each) and 2 GB RAM. 10 subjects are participated and data are collected to 20 cases (10 subjects*2 activities) during more than 60 s (up to 300 s).

Activity control

In the experiment, subject movement is restricted to 2 types:

- Type 1: sitting down a chair and standing (small v'-axis movement)
- Type 2: squatting and standing (big v'-axis movement)

Signal manipulation

Input ECG signals are normalized by z-score normalization to make its mean value zero, as shown bellow:

$$\text{Normalized signal} = \frac{(\text{signal} - E\{\text{signal}\})}{\sigma_{\text{signal}}}. \tag{11}$$

Where, $E\{\mathbf{x}\}$ is the mean value of signal $\mathbf{x}$ and $\sigma_{\mathbf{x}}$ is the standard deviation of signal $\mathbf{x}$, which is assumed to have a Gaussian distribution.

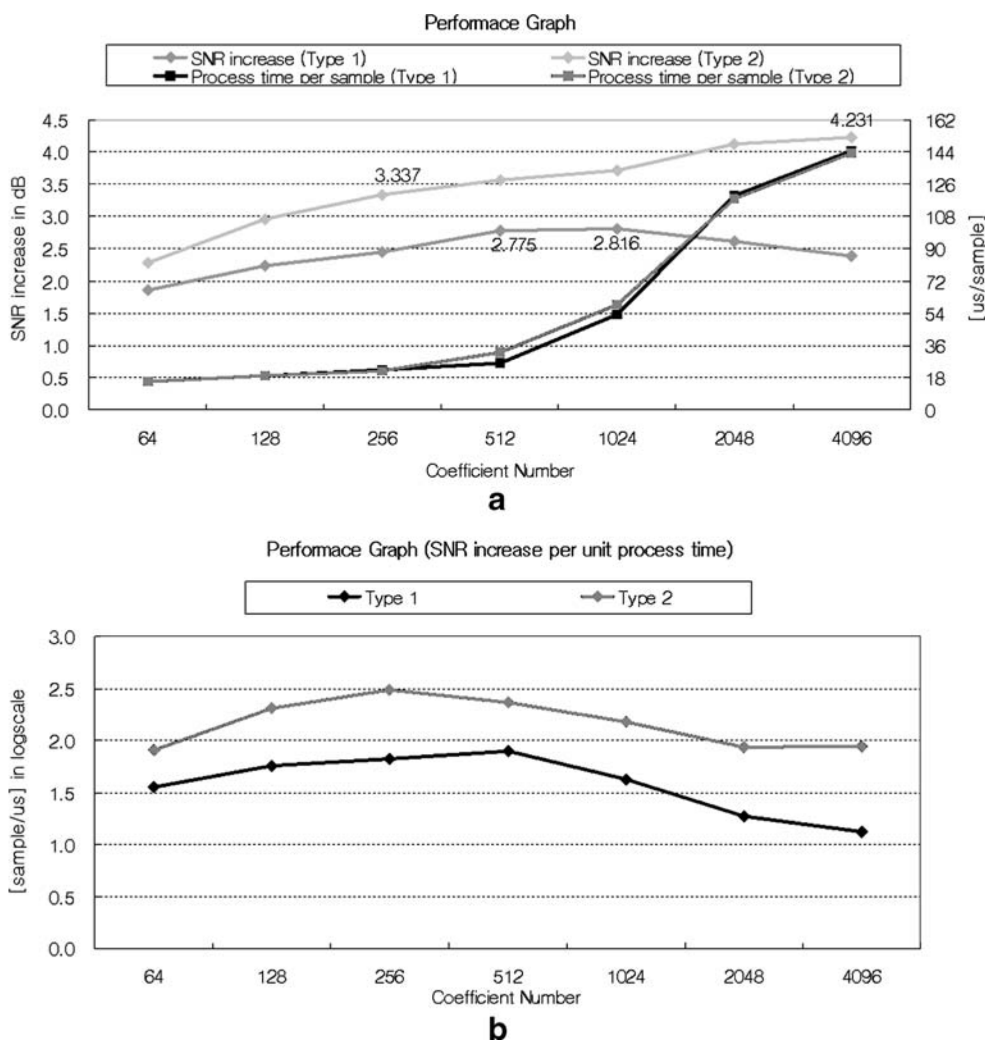

Fig. 3 Experimental results with **a** individual results, **b** SNR increase per unit process time

The desired motion input **r** for adaptation is set to the difference between e-textile signal and Ag/AgCl signal followed by low-pass filter as in [8]. Normalized LMS (NLMS) algorithm is used for this adaptive filter system with 1 step size and 50 offset, coded with MATLAB® R14. The adaptive filter output **y** estimates the motion artifacts as the motion information gets more correlated with **r** and estimated motion artifacts **y** are subtracted by e-textile ECG signal for reducing motion artifacts in e-textile ECG measurement system. Figure 1b describes the proposed process as the block diagram.

Result and discussion

Figure 3 shows the experimental results in 2 factors according to 2 activity types. The one is (1) process time per sample (or denoted as 'unit process time') and the other is (2) Signal-to-Noise-Ratio (SNR) changes between 'after motion artifacts reduction' and 'before motion artifacts reduction'. In this case, SNR changes are denoted as 'SNR increase' and calculated as follows.

$$\begin{aligned}\text{SNR increase} &= \text{SNR}_{\text{after}} - \text{SNR}_{\text{before}} \\ &= 20\log\left(\frac{E\left\{(\text{ECG}_{\text{ref}} - \text{ECG}_{\text{i}})^2\right\}}{E\left\{(\text{ECG}_{\text{ref}} - \text{ECG}_{\text{o}})^2\right\}}\right).\end{aligned} \tag{12}$$

Where,

$$\text{SNR}_{\text{before}} = 20\log\left(\frac{E\left\{\text{ECG}_{\text{ref}}^2\right\}}{E\left\{(\text{ECG}_{\text{ref}} - \text{ECG}_{\text{i}})^2\right\}}\right)$$

$$\text{SNR}_{\text{after}} = 20\log\left(\frac{E\left\{\text{ECG}_{\text{ref}}^2\right\}}{E\left\{(\text{ECG}_{\text{ref}} - \text{ECG}_{\mathbf{o}})^2\right\}}\right)$$

$\text{ECG}_{\mathbf{i}}$ e-textile ECG signal before motion artifacts reduction

$\text{ECG}_{\mathbf{o}}$ e-textile ECG signal after motion artifacts reduction

Reasonably, both 2 factors have increasing tendency in order that the coefficient number gets suitable amount for estimating motion artifacts, which is shown in Fig. 3a. In this figure, we can find that type 1 activity requires less coefficient number than type 2, and it confirms that big movement (type 2) is more complex and requires more information for estimating motion artifacts. This means that we can achieve the system improvement by adaptive filter using coefficient number in SNR point of view. However, large coefficient number requires more time to process. It is because that coefficient number implies on the weighted consideration for the current values by the amount of past information and adaptive filter system uses those previous values for the system improvement. This process makes additional calculation for the signal filtering.

Therefore, it is proper to think that optimal choice of coefficient number is required for both (1) and (2). We can find this optimality as the SNR increase per unit process time (Fig. 3b) by each coefficient number of (2) divided by each logarithm value of (1). The optimality, which is identical to the maximum point on the graph, is found at 256 (in type 2) or 512 (in type 1) coefficients in the results. We can choose the coefficient number for system optimality or maximum improvement in the e-textile ECG measurement system.

In the experiment, we used motion artifacts model **r** as the difference between Ag/AgCl signal and e-textile signal followed by LPF for defining frequency range of the motion artifacts and preserving a certain amount of correlation (*R*) between observed motion artifacts and modeled motion artifacts. *R*-squared value between them had a range from 0.18 to 0.86, but this value was not proportional to SNR increase.

Conclusion

In this paper, we describe that motion artifacts is estimated and reduced in e-textile ECG measurement system by adaptive filter method using motion acceleration from 3-axis accelerometer for enhancement of the signal-to-noise-ratio in two types of activity in quantitative manner. For various applications, we also propose that selection of the coefficient number is required for the cost function, such as maximum SNR or optimality between SNR and unit process time.

In this paper, we used partial information of the ECG from Ag/AgCl for modeling motion artifacts as a desired input in adaptive filter. This must be removed for complete e-textile ECG measurement system establishment in future work. It will be a good approach to find another modeling method in various applications [9], such as plane-wave signal in radar system and multiple-reference used in fetal ECG experiment.

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