A Wearable Electrocardiogram Monitoring System Robust to Motion Artifacts

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Abstract **- This study proposes a wearable system that can measure electrocardiogram (ECG) signals reliably in an environment with high motion artifacts. This system employs a motion artifact extraction method based on a triple-axis accelerometer attached to each electrode independently to remove motion artifacts from ECG signals with high performance. Recursive Least Square (RLS) and Least Mean Square (LMS) algorithms remove extracted noise from the source signals, thereby obtaining a mean square error (MSE) of 0.0166 when using RLS and 0.0160 when using LMS. This means that the performance improved respectively by approximately 5.1% and 8.6% compared to that of the recently developed ECG monitoring system.**

Keywords **— Adaptive filtering Electrocardiogram (ECG), Mean Squared Error (MSE), Motion artifact,**

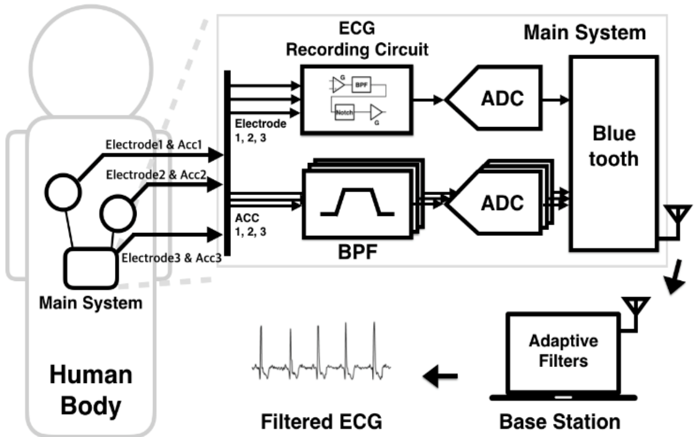

Fig. 1. The proposed wearable ECG monitoring system that is robust to motion noise.

I. INTRODUCTION & BACKGROUND

Electrocardiogram (ECG) monitoring is one of the most important and simplest methods that can determine and prevent cardiac illness. But aside from the simplicity of the method, the ECG must be monitored frequently and may require up to 4 weeks of monitoring for careful checkups. That is, patients have to attach such measurement devices to their body for a long time in their daily lives. Thus, a small wearable ECG monitoring system needs to be developed to resolve the inconvenience of such measurements.

Such wearable devices suffer from continual exposure to human movements, which can significantly disturb the accuracy of ECG measurements. For example, ECG results are invalid when the subject is monitored while performing excessive movements such as running or jogging. One fundamental reason that motion artifact occurs is the changes in the electrode–tissue impedance (ETI) between the electrode and the human body caused by movement. Thus, a wearable ECG monitoring system that is robust to motion artifact requires the precise observation of electrode movement and a technique to remove motion artifact from ECG signals based on observations.

Studies on the removal of motion artifact for wearable ECG monitoring devices are at primitive stages. Many attempts to reduce the motion artifact based on various algorithms were made. The following shows some motion artifact reduction methods and prior works that utilizes them.

For ECG diagnosis, good low-frequency response is required for low distortion of the ST segment. A low frequency cutoff of 0.5Hz is recommended by the heart association for exact diagnosis of the ECG signal. Therefore, digital filters which do not result in distortion of the low frequency components in the ECG signal is therefore important. One of the advantages of FIR filters is that they have linear phase responses and are always stable, compared to IIR filters utilizing feedback. Therefore, FIR filters are commonly used when performing biomedical processing of the ECG signals. Furthermore, complex but more effective filters are used.

Adaptive filters are one of the most commonly used filters to reduce motion artifact. It is a time-variant filter which is capable of adjusting its own parameters automatically. The parameters are adjusted from the information that the reference signal gives and processed by the algorithm which makes it able to track signals that are non-stationary. The adaptive filter can also be used as system identification and prediction along with adaptive noise cancellation. Adaptive

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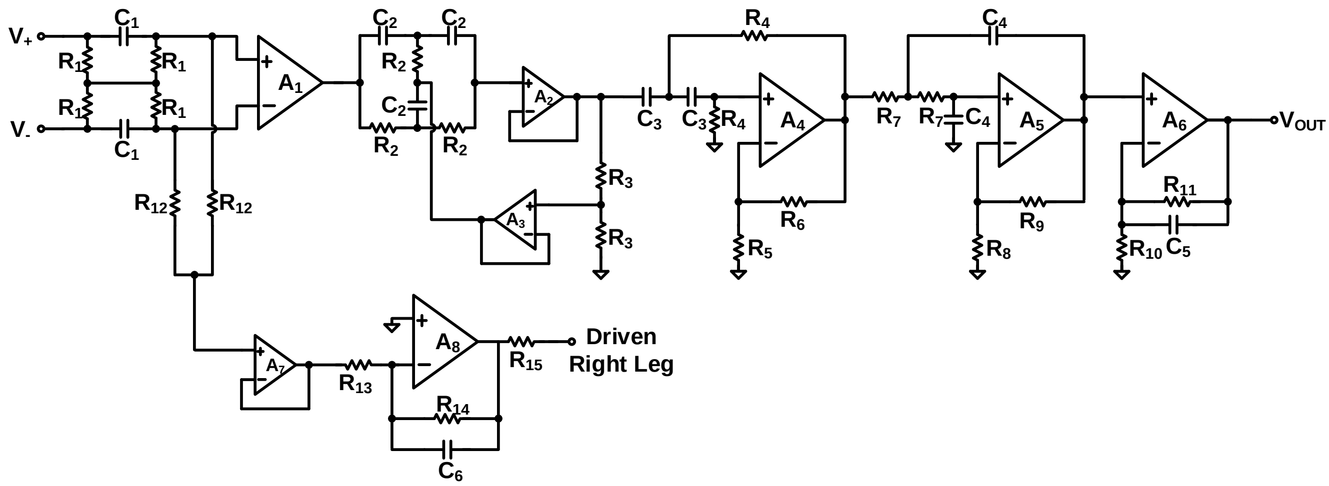

Fig. 2. Circuit diagram of the ECG recording circuit

filters have two input signals. First, the primary input which contains the desired signal and noise. Second, the reference input which is correlated with the noise. The reference signal is processed by the digital filter producing an output which is similar to the replica of the noise. The digital filter is changed adaptively by the chosen algorithm. When the noise replica is subtracted from the input signal, the desired signal is acquired. In [1], for noise cancellation an adaptive recurrent filter which uses impulses correlated with the beginning of each P-QRS-T wave as the input reference. The method adjusted the filter coefficients at each wave in order to obtain the desired impulse response by minimizing the mean square error between the main and reference signals. The results removed the motion artifact along with the baseline artifact showing outputs of the heart rate measurement. However, since the reference impulse requires exact coincident with the signal wave, the resulting signal shape may be distorted, which results in lacking diagnostic display quality. In [2], cascaded adaptive filter utilizing least mean square was used. It adapted two-stage adaptive filtering which is capable of changing the step-size adaptively to the noise which results in precise noise cancellation without the distortion of the ECG components. However, the results showed that the low-frequency components were not removed enough for proper diagnosis. In [3], an adaptive filter utilizing normalized least mean square was used. The method utilizes an accelerometer and gyroscope sensors for adaptive removal of the motion artifact from the ECG signal. However, the motion artifact was not removed completely which requires additional sensors for more correct reference for the adaptive removal.

Another popular technique is the Wavelet Transforming. Wavelet Transforming decomposes the ECG signal into several time-domain signals each different frequency bands. At the lowest frequency band, the approximation coefficients are set to zero and reconstructs the ECG signal by synthesizing the coefficients. The performance is varied heavily by different wavelets. Haar wavelet, Daubechies wavelet and Symlet wavelet are some of the most commonly used wavelets. The removal of motion artifacts using each wavelets were compared by prior works. The Daubechies wavelet is mostly chosen by a majority of works. In [4], discrete wavelet transform was used. The DWT was applied in order to suppress the EMG and motion artifact signals using soft and hard threshold and zeroing the approximation coefficients. However, the noise including the motion artifact was not removed completely. In [5], discrete wavelet transform was also used, but with a different wavelet. Various thresholds were applied to get better motion artifact removal. However, this method failed to remove the artifacts having spectral overlap with the ECG signal itself, which is a critical problem in diagnosis. In [6], stationary wavelet transform was used to estimate the motion artifact by removing the QRS wave and apply thresholds at different SWT decomposition levels which are then subtracted from the original signal. However, this method is invalid when both low and high frequency motion artifacts is applied. In [7], stationary wavelet transform was used with the same wavelet as [6]. It removes the QRS, P and T waves from the original ECG which is affected by the motion artifact using threshold based on the energy of the QRS wave and median values of the local maxima and minima. However, the method cannot detect the QRS peak completely, making the reduction of motion artifact less.

In [8], independent component analysis was used. This method separates the independent components from multiple ECG signals and finds the highest correlation with the original signal in order to remove the notion artifacts and also other noises as well. However, it requires multiple data for processing and there is no guaranteed that one of the data set is a clean ECG signal that is not distorted by any noise sources.

Moving average filter smooths data by replacing each data with the average of each neighboring data. It can also be considered as a high pass FIR filter. It is a very simple method for low frequency noise reduction. However, due to the QRS wave of the ECG signal having such large amplitudes that affect the average, signal distortion may occur. Another filter that is based on the same principle is the moving median filter. The median within a moving window is replaced with the average. In [9], peak detection and moving average method was used. The QRS peaks are first detected, followed by the repairs of the off-balanced waves. The low frequency motion artifact of removed by using the midpoints of the Q S peaks, and the high frequency motion artifact are removed by the average of S Q waves. However, this changes the ECG signal shape and does not remove the low frequency in-band component completely.

Average filtering was chosen as the digital method for the reduction of motion artifact in this work. Among the works that uses adaptive filtering, studies using accelerometers for the reference signal have been published in [10] [11]. A system for the removal of motion artifact from ECG signals using single and dual-axis accelerometers has been conducted in [10]. A similar system that implements a triple-axis accelerometer has been conducted in [11]. However, since these did not consider each electrode's movements, which can cause motion artifact due to the use of only a single accelerometer, they have limited ability to measure ECG precisely. The proposed wearable ECG monitoring system has an independent triple-axis accelerometer attached to each electrode, thereby measuring each electrode's movements accurately to extract the motion artifact. Removing the extracted noise data from the source signals using Recursive Least Square and Least Mean Square algorithms, which employ an adaptive filtering technique, means that ECG signals can be measured successfully even in environments where motion artifact is high such as during exercise.

II. ECG MONITORING SYSTEM

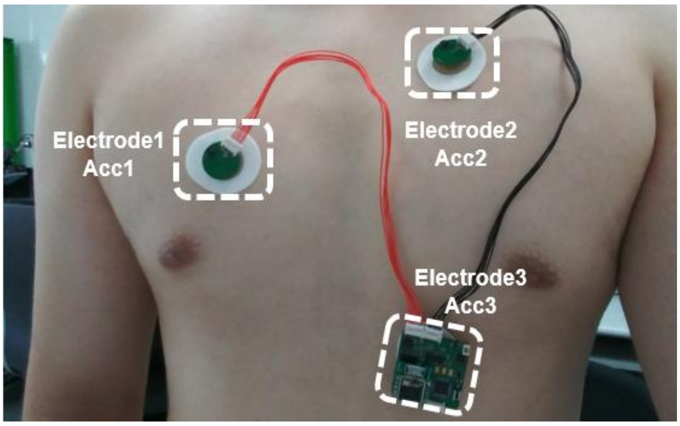

Fig. 3. Wearing example of the proposed system

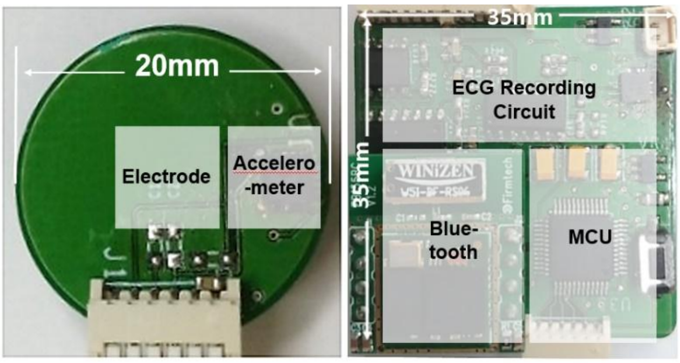

Fig. 4. Fabricated circuit board

TABLE I. MSE Comparison of ECG Recording Methods

	[10]	[11]	This work	
Method	Dual-axis, Single accelerometer	Triple-axis, Single accelerometer	Triple-axis, Triple accelerometer	
Algorithm	RLS	LMS	RLS	LMS
MSE	0.0749	0.0175	0.0166	0.0160

Fig. 1 shows the wearable ECG monitoring system proposed in this study. As shown in Fig. 1, this system consists of two units: the main system that reads the ECG signals from the human body using three electrodes and transfers the read signals wirelessly after their conversion to digital data, and a base station that displays the recovered ECG signals after adaptively filtering the transferred data wirelessly.

In order to have robust characteristics to motion artifact, an independent triple-axis accelerometer is attached to each of the three electrodes, thereby measuring the electrode movement directly to have a close correlation with both the three ECG signals and with the motion artifact that is included in the signals at the same time. The measured ECG signals and movement signals of each electrode are transferred to the main system, which is implemented in Electrode 3 in Fig. 1.

Fig. 2 shows the ECG recording circuit diagram. It has a bandwidth of 0.5–100 Hz, and amplifies the cardiac signal in the main system, then transfers the data to the base station wirelessly through the module. The low pass and high pass filter parameters is adjusted to satisfy the requirements of the ECG bandwidth mentioned above. A notch filter is also attached to reduce the 60Hz noise. For better common mode noise rejection, a driven right leg circuit is used. Finally, the base station removes motion artifact from the measured ECG signals and the results are as shown in the display. The adaptive filtering technique is applied using RLS and LMS algorithms to eliminate motion artifact with high performance.

Fig. 3 and Fig. 4 shows the proposed wearable ECG monitoring system and a worn example system. The size of Electrode 3 in the main system is 35 × 35 mm and the sizes of accelerometer-attached Electrodes 1 and 2 are each 20 mm

The ECG took measurements while doing sit ups using the implemented system and this paper compared the results with those using the existing method in the same conditions as shown in Fig.5; the figure shows the recovery of the distorted ECG signals to some extent in all used methods but the accuracy was not determinable.

Thus, this paper uses MSE to compare the performance objectively and Table 1 summarizes the results. Compared to the method proposed in [10], the proposed system has an improved performance by approximately 77.8% compared to using the RLS algorithm and 78.6% compared to using the LMS algorithm.

Compared to the result using the method proposed in [11], which is the most recently published, the performance improved by approximately 5.1% and 8.6% compared to when using RLS and LMS, respectively.

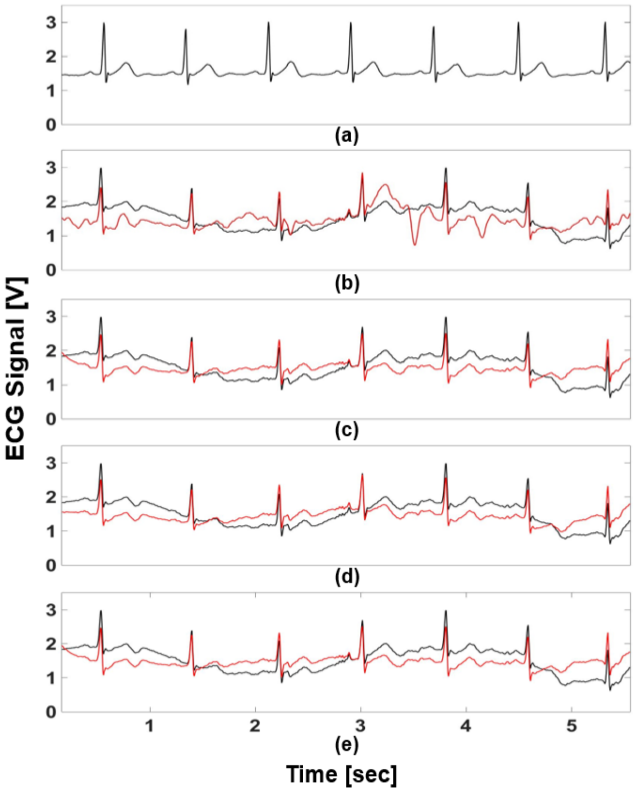

Fig. 5. (a) ECG signal graph in a static state, (b) ECG signal graph mixed with the motion artifact during sit ups and using the method proposed in [10], (c) using the method proposed in [11], (d) ECG graph when applying the RLS algorithm proposed in this study, and (e) when applying the LMS algorithm.

III. CONCLUSIONS

This study proposes a wearable ECG monitoring system that recovers ECG signals distorted by motion artifact through an accelerometer attached to the electrodes and adaptive filtering. Using this system, ECG signals were successfully measured in a high-motion- artifact environment, and the motion artifact removal performance was improved by >8% compared to using a recently developed ECG monitoring system. In addition, this paper expects that the proposed technique can easily be applied to other wearable bio-medical systems.

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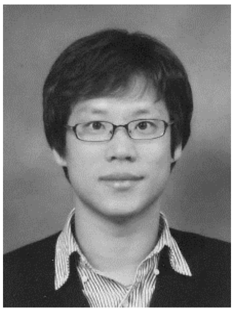

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