International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 9 (2017) pp. 2087-2090

Design of a Mobile Maternal ECG Measurement System with Fetal ECG Extraction Features

ChulhyungChoi[1*], [2]Md Saıfur Rahman, [3]Young-pil Kim & [4*]Sikyung Kim

[1, 2, 3, 4] Institution: Kongju National university, Department of Electrical, Electronic and Control Engineering #214 office, #8 engineering building,1223-24, Cheonan-daero, Seobuk-gu, Cheonan-si, Chungcheongnam-do, 31080, republic of Korea.

[1]ORCID: 0000-0003-1186-9812, [2]ORCID: 0000-0001-8345-0952

*[3]ORCID: 0000-0002-3232-4136 [4]ORCID: 0000-0002-2635-933 (*corresponding Author)*

Abstract

In this paper, an abdomen electrocardiogram (AECG), as opposed to a thoracic ECG, is employed to measure a mother's ECG (MECG). A fetal ECG (FECG) signal extraction algorithm from an AECG is proposed for a mobile FECG measurement platform based on BLE (Bluetooth low energy). The algorithm is implemented by using a replacement processor without the large statistical data processing required in an ICA (independent component analysis) process directly from a BLE platform. The proposed algorithm is implemented on the mobile platform with BLE wireless and ECG system hardware, to enable the measurement of the MECG. It is also implemented in the form of a compact module to help build secure attachments to download and store the collected ECG data without having to interrupt or move the logger, and later link the module to a computer for downloading and analyzing the data. A mobile ECG measurement prototype is manufactured and tested to measure the FECG. The prototype shows real-time FECG extraction capability with ECG experimental data from mother's abdomen.

Keywords: MECG, FECG, ICA, BLE, AECG, AF, SVD, EVD, SVM, MCU

INTRODUCTION

There have been numerous studies that extract the FECG from an MECG. The most common method uses AF (adaptive filtering), ICA, and SVM (support vector machine) . An adaptive filter is a system with a linear filter that has a transfer function controlled by variable parameters and a means to adjust those parameters according to an optimization algorithm.R. Sameni [1] proposed the AECG signal modelling scheme using the state space equations and Bayesian filter. However, this technique has a disadvantage in case that FECG cannot be extracted when the ECG signals of pregnant women and fetal are overlapped with each other in a sufficient time.

To solve this problem, R. Swarnalatha [2] proposed the FECG extracting scheme with a multistep adaptive filtering technique using thoracic ECG (Thoracic ECG). However, the disadvantage of this technique is that it requires one thoracic and one abdominal ECG signal .It also difficulty of processing the normally adaptive filter coefficients of other signals used to improve the reference signal and tuning processing that is not suitable for a mobile platform.

As another study, B.Widrow [3] proposed a linear adaptive filter However, this method unable to extract FECG when pregnant and fetal ECG signal is overlapping in time.

The ICA (Independent Component Analysis) technique is a method for separating multivariate signals and analyzing independent components of FECG. P. P. Kanjilal [4] proposed a fetal ECG extraction method based on SVD (Singular Valued Decomposed). The MECG component constructs an identity data matrix by SVD mode. Furthermore, with the isolation of the SVD corresponding to the maternal ECG can provide FECG. This technique does not require any thoracic ECG (Thoracic ECG) reference signal and has an efficient characteristic. Another study of ICA was performed by Lieven De Latauwer [5]. In addition, the ICA technique for extracting FECG from multi-channels was proposed by A. van Oosterom. [6]. K. V. K. Anant hanag [7] proposed a technique for extracting FECG using blind and semi-blind source separation, statistical measurement of the maximization signal, and basis functions. However, ICA has advantages of not using thoracic ECG (Thoracic ECG), but it has a lot of computational complexity and is not suitable for real-time application or lightweight and portable monitor implementation.

In this study, the proposed algorithm does not directly process the calculations and statistical data analysis on a BLE platform. Furthermore, this study realizes a BLE wireless platform is able to measure the FECG and MECG. The following list summarizes the traits of the proposed mobile fetus ECG:

- An energy-efficient technique that allows battery life of up to 2~3 years (changeable battery);
- Compact module (53mm x 63mm);
- Communication distance of 30m~50m;
- An algorithm that extracts the FECG based on the substitution ICA processor;
- Provides data on the fetus and the mother during pregnancy;

- Doctors are able to efficiently manage and observe the fetus' and mother's health.

HARDWARE SPECIFICATION

Mobile ECG measurement system for the mother

The ECG measurement system developed in this study is composed of a wireless electrocardiograph module and a smartphone application. The overall component and operational process is explained in Figure 1.

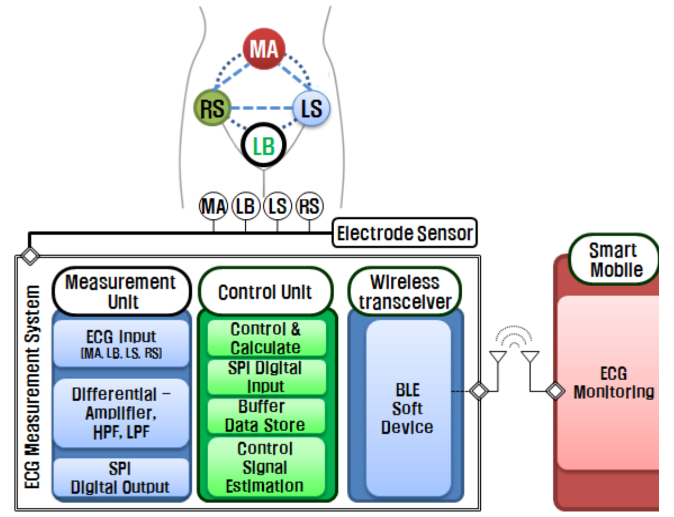

Figure 1. Electrocardiogram monitoring system (4-lead system)

BLE-based wireless transceiver

The digital ECG data signal from the MCU(Micro Controller Unit) is sent to the wireless transmitting and receiving unit to collect the predetermined packet unit. In this paper, the wireless transceiver chip nRF51822 is employed which has a physical layer of the BLE and transmits data in packet units. The 2.4GHz antenna is designed as a form of microstrip. The transmission distance is 30m indoors, and smartphones support this BLE. Therefore, it does not need a separate LNA (low noise amplifier) for transmitting.

Digital filter

The measured ECG signal has several noises. Therefore, a low-pass filter (sampling rate 1000Hz and cut-off frequency 30Hz) is designed to remove high-frequency noise and obtain a clean waveform. In addition, a high-pass filter is also used to remove power source noise around 60Hz.

PROPOSED ALGORITHM

Mathematical Expression

Pre-processing of ECG data is required to apply the measured MECG onto a mobile platform. To meet this requirement, this paper employs PCA (principal component analysis) techniques. The PCA extracts a feature of a unique component with the existing data, and projects the data at a principle axis with a feature that reduces the dimension. The newly measured ECG signal is treated as a linear combination of the signals via the existing ECG signal in any mixing matrix. At this point, a whitening ECG is constructed by linear transformation of the covariance matrix on $V(t) = [V_1(t),\ldots, V_P(t)]$, the ECG signal vector. A whitening transformation is a linear transformation that converts a vector of random variables with a known covariance matrix into a set of new variables whose covariance is the identity matrix, meaning that they are uncorrelated. In this paper, the eigenvalue decomposition (EVD) algorithm is utilized; however, the EVD can be implemented using SVD (singular value decomposition). After taking the EVD of the covariance matrix V(t), the result is as follows:

$$R_V(0)=E\,(V(t)*V(t)^T)=QDQ^T$$

Q is the orthogonal matrix $E\,(V(t)*V(t)^T)$ and D is a diagonal matrix of eigenvalues.

In other words, the diagonal matrix $D=diag\,(\lambda_1, \lambda_2, \lambda_3,\ldots, \lambda_n)$ is a p * p matrix. The whitening procedure makes a signal vector after the vector of the measured ECG signals following linear transformation.

Since:

$$Z=WV=D^{-1/2}Q^T V(t),$$

covariance matrixes of the vector $V_{(t)}$ are as follows:

$$\begin{aligned} R_Z(0) &= E\,(Z(t)*Z(t)^T) \\ &= E\,(D^{-1/2}Q^T V_{(t)}\ \ D^{-1/2}QV_{(t)}{}^T) \\ &= D^{-1/2}Q^T\ E\,(V_{(t)}*\ V_{(t)}{}^T)\ \ D^{-1/2}Q \\ &= D^{-1/2}Q^T\ QDQ^T\ \ D^{-1/2}Q \\ &= I \end{aligned}$$

The covariance matrix through the pre-processing operations can be the identity matrix. That is, it is the object of the pre-processing to eliminate the correlation vector of the ECG. The $Z_1(t)$, $Z_2(t)$, $Z_3(t)$ has a poor SNR(Signal to Noise Ratio) which is obtained by the pre-processing operation. In this paper, we use a method that maximizes the kurtosis (fourth-order cumulant), as applied in other ICA algorithms. The peak value of Z(t) is measured from input $Z=WV=D^{-1/2}Q^T V(t)$, and defined by Z(k):

$$y_{(t)} = \frac{Z(k)^T}{||Z(k)||} Z(t)$$

$$FECG\,(t)=V(t)-y(t)$$

In order to increase the processing speed, Z(t) has to be calculated in advance. Figure 2 shows a block diagram of the FECG extraction algorithm proposed in this research.

Block diagram

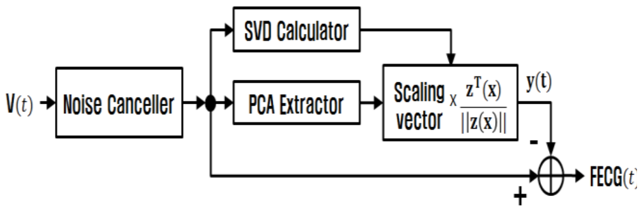

Figure 2 Block diagram of the FECG extraction algorithm

SIMULATIONS AND MEASUREMENT

Hardware efficiency

To implement our algorithm, we developed some seamless firmware and hardware modules and an Android Smartphone application. A 53mm x 63 mm board was prepared by adding test pins. The program environment was capable of debugging with JTAG(Joint Test Action Group**)**, generic smartphone and serial communications through the UART(Universal Asynchronous Receiver Transmitter). A standard ECG electrode method was employed. The shielded cable was connected through the electrode sensors. The shielded cable reduced noise and connected with a circuit to measure the ECG.

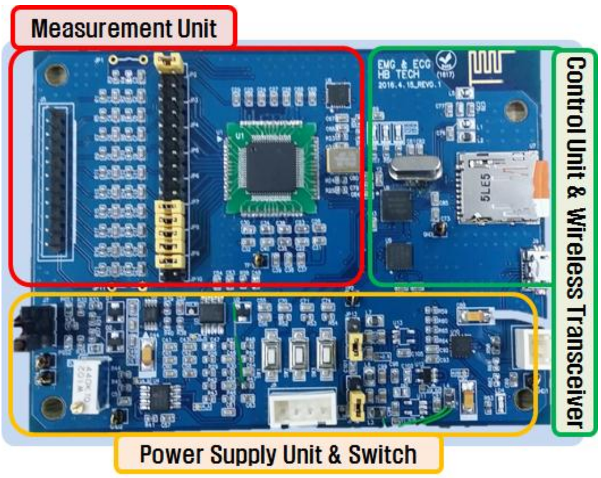

Figure 3 The wireless ECG module used in the experiment

Signal observation after data transmission via BLE

Figure 4 illustrates the operation of the overall ECG system that received the amplified ECG signal. The oscilloscope waveform on the left shows the unamplified ECG signal and the mobile device on the right shows the amplified ECG signal.

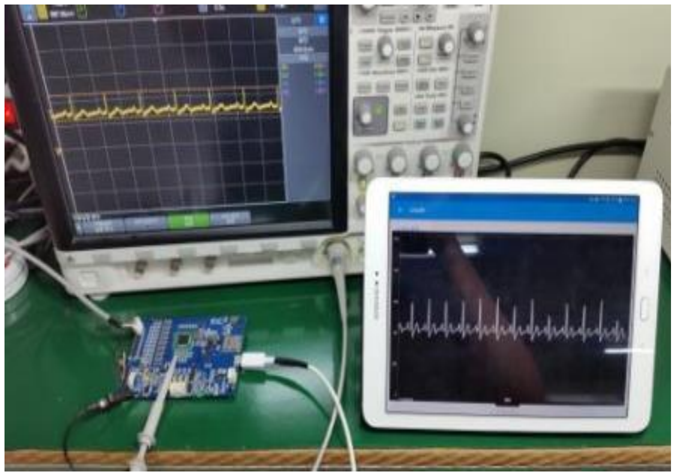

Figure 4 Photograph of the developed ECG monitoring system with BLE

In order to evaluate the proposed algorithm, we used ECG data from a number of pregnant women.

After implementation of proposed algorithm

Figure 5(a) shows the measurement data of the ECG of the mother, figure 5(b) shows the template ECG (TECG) obtained by the proposed technique from the data of Figure 5(a). Finally, Figure 5(c) successfully demonstrates FECG extraction by removing the template in the original ECG signal in Figure 5(a). The figure shows the MECG as 1.2 [mVpp] and the FECG as 0.4 [mVpp]. MECG and FECG take .68s and .4s for each cycle.

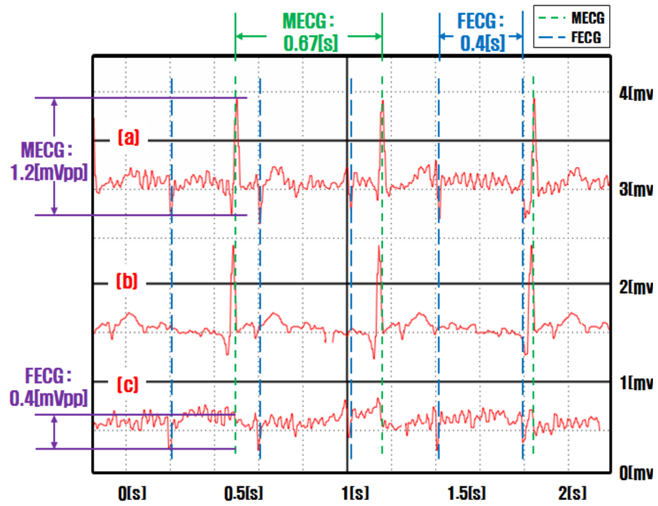

Figure 5 Maternal and fetal ECG, (a) Original AECG signal, (b) TECG, (c) Extracted FECG signal

CONCLUSION

Our research proposes a method that extracts FECG and MECG data using a wireless device. We also propose an energy-efficient compact algorithm for cost-effective FECG extraction. A BLE-based wireless FECG extraction system was designed and implemented. This system was able to accurately and reliably acquire, transmit, store, and display real-time FECG signals from the MECG. The major feature of the system was that it consumed significantly less power than traditional wireless medical devices. Based on the proposed substitution ICA processor and PCA and SVD techniques, it processed the MECG data and extracted the FECG information onto a smartphone platform. The experimental results demonstrated that FECG extraction could be obtained from the MECG signal.

LIMITATIONS

In our proposed algorithm, sometimes data loss when we try to send data via BLE. Now we can handle small amount of data because of memory space problem. To make smooth signal we need to improve our electrode.

FUTURE WORK

In the future, research towards analyzing and studying the algorithm in more detail is anticipated. Furthermore, the fetal and maternal data are expected to be expanded so that a more informative system can be constructed and hence maximize the proposed device's helpfulness.We try to improve our electrode and update our algorithm to minimize computational complexcity. We will add extra memory space to process more data.

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