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Mathematical Modeling of ICA Algorithm for Fetal ECG Extraction

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ABSTRACT

ECG signal recording is one of the best techniques for signal monitoring of Fetus heart beat. It is used to monitor the health condition of fetus during pregnancy continuously. FECG signal is extracted from abdominal signal which includes mother ECG, FECG and noise signal. Recently Blind Source Separation by ICA has received better attention because of its potential applications in signal processing. In this paper we present the mathematical theory of ICA algorithm for fetal ECG extraction.

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INTRODUCTION

Fetal ECG signal estimation is a classical problem in medical engineering. The signal FECG contains the information about the electrical activity of fetal heart and reflects the health status of fetus. The extraction of FECG signal help children's heart disease specialist to evaluate the health status of the fetus during pregnancy. The fetal heart rate is monitored using Doppler ultra sound (Daniel Graupe, *et al,* 2005) during pregnancy. Unfortunately this technique is inaccurate and provides relatively low positive predictive value; it is reliable only when the fetus condition is clearly good or clearly bad. For different situations additional tests are required. The extensive use of Doppler ultra sound for fetal heart rate monitoring affects the fetus due to its high sensitivity. During pregnancy FHR is important to obtaining the significant information about the fetal condition (Fabian J, *et al,* 2008). The FECG signal measured from abdominal ECG signal by placing electrodes on mother's abdomen, but it is distorted by different types of noises, MECG (YusufSevim, *et al,* 2011). Independent Component Analysis (ICA) can be used to separate the fetal ECG from the mother's ECG signal, background interferences, electrical activity produced by muscles which is extremely low voltage.

1 Fetal ECG extraction:

Fetal Electrocardiogram provides better information about the health status of the fetus which can be extracted between 20^{th} to 40^{th} weeks of gestation period (Evaggelos C, *et al,* 2009). This information gives better knowledge about the fetus development, cardiac disorders such as fetal stress, fetal acidosis, cardiac arrhythmias etc... The invasive method of acquiring fetal ECG is inconvenient and risk to the patient. Because in the invasive method the recording electrodes have direct contact with the fetal skin. Another one method of acquiring FECG is non-invasive method. In this method the electrodes are placed in the mother's abdomen and record the FECG. It will be done at any stage of pregnancies. This method is very convenience and it has no effect on fetal growth and development.

The recorded signal contains different types of noises from different noise sources such as power-line interference, muscle contractions, baseline wander, instrumental noise, etc. (Sornalatha.M, *et al,* 2013). These noises make many problems while extracting the fetal ECG signal. So we need to remove the noises using different noise removal techniques.

There are several techniques used for the extraction of fetal ECG signal such as Principal Component Analysis, Singular value Decomposition, Independent Component Analysis. The main objective of this paper is to present the mathematical theory of ICA algorithm.

2 Independent Component Analysis:

Independent Component Analysis has an important role in the field of signal processing which aims to recover the source signal from the mixed signal.

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2.1 ICA Model:

ICA is a technique used to obtain independent sources (S) from their linear mixtures (x). The mixing matrix is denoted by A.

The ICA model for abdominal ECG signal is denoted as

$$X = AS + N \quad (1)$$

Where S is the source and X is the Observation matrix.

For the set of random variables,

$$x(t) = As(t) \quad (2)$$

The main aim of ICA is to find the demixing matrix W, this is given by

$$\hat{s}(t) = Wx(t) \quad (3)$$

Where W is the unmixing matrix

The demixing matrix helps to find out the sources S(t). At the same time, the measured sample is a linear combination of the original source ECG signals.

2.2 ICA Steps:

The ICA steps used for mathematical modeling are

Centering:

Determine the independent components by removing the mean variables. This process is called as centering the ECG signal.

Assume that $E(s) = 0$

Removing the mean does not change the mixing matrix A.

From equation (1)

$$x - E(x) = A[S - E(s)]$$

$$x - E(x) = AS \quad (4)$$

Whitening:

Whitening is the process by which the observation vector is linearly transformed (Ganesh R. Naik.*et.al,2011*).

Let X_w denotes the whitened vector, then satisfies the following equation

$$\varepsilon = E[X_w X_w^T] = I \quad (5)$$

Where $E[X_w X_w^T]$ is the covariance matrix of X_w

Assume that the source vector S is white, i.e. $E[SS^T] = I$

Eigen decomposition is used to perform whitening transformation (Meyer.C.D, *et.al,*). The co variance matrix of x is denoted as

$$\varepsilon = cov(x) = E[xx^T]$$

$$\varepsilon = E[ASS^T A^T] = AA^T \quad (6)$$

By Eigen value decomposition

$$\varepsilon = UDU^T$$

Where U is the Eigen vector of $E[xx^T]$

D is the diagonal matrix of Eigen values

The transformation used to whiten the observation vector is

$$X_w = UD^{-1/2}U^T x$$

Whitening process transforms the mixing matrix into,

$$X_w = UD^{-1/2}U^T AS$$
$$X_w = A_w S \quad (7)$$

Hence,

$$E[X_w X_w^T] = A_w[E\{SS^T\}A_w^T]$$
$$= A_w A_w^T$$
$$= I$$

Whitening used to reduce the number of parameters to be estimated. Instead of estimating n^2elements of matrix A, we need to estimate the matrix with $n(n-1)/2$ degrees of freedom. We can say that half of the ICA problem solved by whitening. It is a useful step to solve ICA problem. It is a simple and efficient process to reduce the computational complexity of ICA. In the next section an illustration of whitening process with simple source separation is presented.

3 Simple Illustrations of ICA:

One simple illustration of ICA is presented here to clarify the above discussed concepts. The presented results were taken by using Fast ICA algorithm.

3.1 Separation Of two Signals:

A simple ICA source separation of abdominal ECG signal is explained in this section. In this illustration abdominal signal is generated using MATLAB. This signal is shown in fig.1.

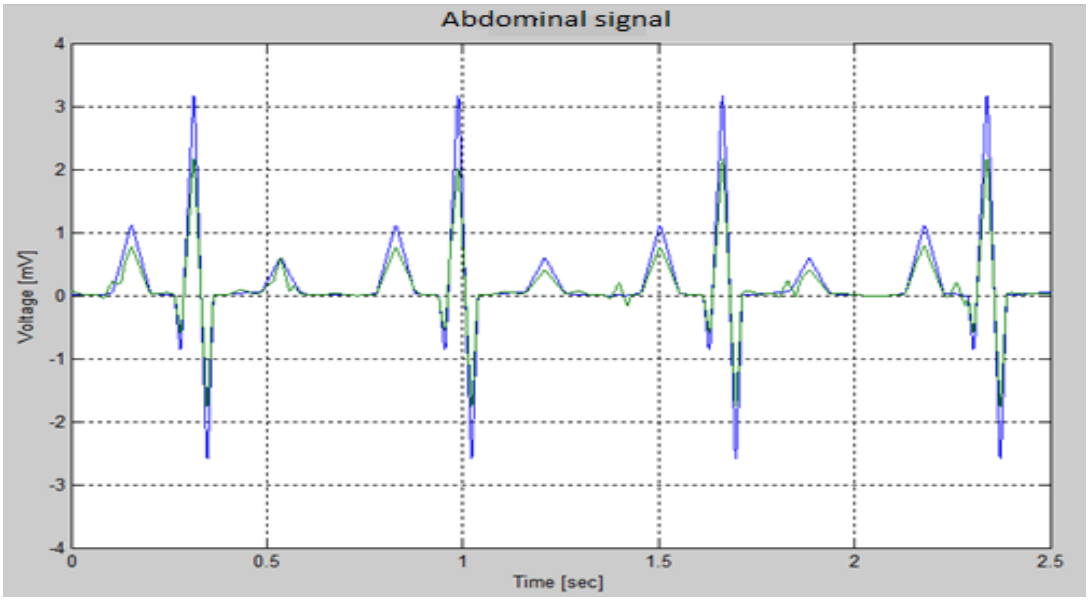

Fig. 1: Abdominal ECG signal

The abdominal signal mixed with two independent components such as mother ECG and fetal ECG signal. From this mixed signal chosen the mixing matrix A, Where

$$A = \begin{pmatrix} 0.0934 & 0.4561 \\ 0.3074 & 0.1017 \end{pmatrix}$$

Centering:

Centering process is performed to "center" the observation matrix X by subtracting its mean value to zero. From this point, all the observation vectors will be assumed to be centered. The unmixing matrix has been estimated using centered data.

Whitening:

The covariance matrix of X is given by

$$\varepsilon = cov(X) = AA^T$$

$$\varepsilon = \begin{pmatrix} 0.2181 & 0.0751 \\ 0.0751 & 0.1048 \end{pmatrix}$$

Using Eigen value decomposition and Jacobian rotation we get the unmixing matrix W as

$$W = \begin{pmatrix} 0.1539 & 0.2039 \\ 0.0904 & 0.1873 \end{pmatrix}$$

Estimated output of ICA:

The estimated output $\hat{S} = WX$

$$\hat{S} = \begin{pmatrix} 0.0703 & 0.0332 \\ 0.0521 & 0.0231 \end{pmatrix}$$

The estimated output signals of ICA from the generated abdominal signal (fig.1) are shown in fig.2.

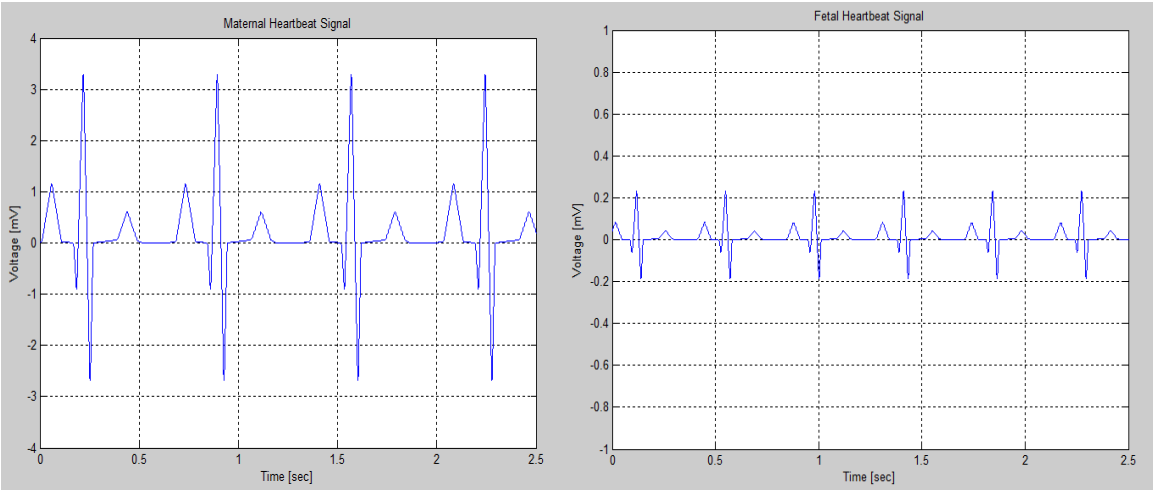

Fig. 2: Estimated maternal and fetal heart beat signals

Conclusion:

This paper presented the fundamentals of ICA model for the extraction of fetal ECG signal. As part of this discussion; two important steps of centering and whitening were examined. ICA processing has been discussed graphically as well as computationally.

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