An ARMA model based motion artifact reduction algorithm in fNIRS data through a Kalman filtering approach

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ABSTRACT

Functional Near infrared spectroscopy (fNIRS) is a newly noninvasive way to measure oxy hemoglobin and deoxy hemoglobin concentration changes of human brain. Relatively safe and affordable than other functional imaging techniques such as fMRI, it is widely used for some special applications such as infant examinations and pilot's brain monitoring. In such applications, fNIRS data sometimes suffer from undesirable movements of subject's head which called motion artifact and lead to a signal corruption. Motion artifact in fNIRS data may result in fallacy of concluding or diagnosis. In this work we try to reduce these artifacts by a novel Kalman filtering algorithm that is based on an autoregressive moving average (ARMA) model for fNIRS system. Our proposed method does not require to any additional hardware and sensor and also it does not need to whole data together that once were of ineluctable necessities in older algorithms such as adaptive filter and Wiener filtering. Results show that our approach is successful in cleaning contaminated fNIRS data.

Keywords: Brain, Gaussian noise, linear model, state estimation

1. INTRODUCTION

Functional near infrared spectroscopy (fNIRS) is an analytic way that uses electromagnetic radiation in infrared range (about 650-950 nm). The skin of head, bones, and tissues around the brain make a transparent light window in the NIR range[1]. In general, light in this range is emitted to a substance and then by investigating the scattered light, the characteristics of the substance are determined. By using changes of detected light, concentrations of absorbents (chromophores) such as oxy Hb and deoxy Hb can be calculated. Relation between light intensity and concentration of chromophore is stated by Beer- Lambert law[1]. So far NIRS has been used in several areas of study such as quality control, pharmacy, and medical diagnoses [2, 3]. In the past, fNIRS was used to monitor cerebral oxygenation saturation, and then it applied to local oxygenation measuring [4]. Recently NIRS data are widely under a variety of signal processing methods to examine a variety of experiments. Now, signal processing approaches on these signals are growing fast. Furthermore, recently for analyzing faster and even related NIRS data, some mathematical algorithms based on analytical methods which used in fMRI, have also been proposed [5-7]. Because of safety and facility considerations, fNIRS is widely used in infant examinations. In such studies both oxy Hb and deoxy Hb are used. However, in some studies, robust results are extracted by oxy Hb examinations [8-10]. In contrast to other present imaging techniques such as CT, PET, X ray, nuclear medicine and fMRI, this technique is affordable, safe, noninvasive and does not contain intrusive monitoring setting that totally make it suitable for many operations in particular the monitoring of ongoing activity under routine working conditions and in the field [10-12]. Beside infant examinations, one of the other appealing uses of NIR can be the monitoring of a pilot's brain during flight.

When dealing with infants, there may be some ineluctable undesirable head movements which called motion artifacts. Undesirable movements of subject (or object) during data acquisition is a distorting factor for fNIRS data. An important aspect in fNIRS data processing is to reduce motion artifacts. Motion artifacts are simultaneously observed in several channels because of abrupt changes during signal recording and are almost completely distinguished from normal slow and soft hemodynamic response. Displacement of electrodes can change incident and collected light angles, and consequently increases reflection effect of skin surface. Head movement can increase blood flow in scalp or rarely increase blood pressure in stimulated brain regions. Because of gravitational influence on blood, orienting of head also may affect the signal [11].

There are several solutions in the developmental range to reduce motion artifact. Headgear design and stimulation quality can play an important role. During data analysis, motion artifact impacts can be reduced. Another approach is to

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examine infants when they are sleep or in the full rest state [12, 13]. In this way, motion artifact is reduced or completely eliminated [14].

In the previous decade, some methods proposed to overcome motion artifact problem in fNIRS signals. Adaptive filtering approach was an approach in this area [15]. An adaptive filter is a finite impulse response filter that includes an adaptation algorithm which senses environment changes by additional hardware and sensors. Requiring to extra devices is considered as a great shortcoming in some applications.

Another approach was based on Wiener filtering [11]. Wiener filter is an optimal filtering method in term of mean square error. However it uses statistics of signals to estimate filter coefficients. The main point is that it requires the whole stationary data to calculate coefficients and therefore this method cannot be applied to real time situations.

In a different approach, wavelet transform has been applied to reduce motion artifact in fNIRS signals. Spikes of artifacts result in large coefficients in wavelet domain. If these large coefficients arbitrarily eliminated, it may lead to missing some useful information. So, statistical tests have been used to select the coefficients to obviate [16]. Nevertheless, this method requires all data together.

In this study, we propose a novel method that does not have these limitations, an approach based on Kalman filtering. In this approach there is no need to additional hardware and stationary data as well. We use a linear model, autoregressive moving average (ARMA) model, for motionless fNIRS signal. Then the model is transformed into state space representation. As we know, there are countless state space representations for an assumed linear model; however, to achieve to desired results, a proper transform should be selected. Eventually, Kalman filter will estimate motionless signal from the information of state space matrices. To evaluate accuracy of our proposed method, we applied the algorithm to some simulated data. A simulated signal is in fact, a clear fNIRS signal that is added by a known variance white Gaussian noise. Then we tried to estimate the variance of noise by our algorithm. The results of simulated data as well as real data show the accuracy and competence of the method.

2. METHODS

2.1 NIRS data

The fNIRS data that used in this work were recorded by a three channel fNIRS headset through subject's head at Drexel University (3508 Market Street, Philadelphia, PA 1904, Drexel University). fNIRS data were collected using a continuous wave fNIRS system. The fNIRS system is composed of three subsystems: 1) fNIRS sensors that consist of one light source and three photo detectors. The light source is a multi-wavelength light emitting diode (LED) manufactured by Epitex Inc. type L4*730/4*850 – 40Q96-I. The LED comes in a STEM TO- 5 package at 730 nm and 850 nm wavelengths with an output power of 5 to 15 mW. The photo detectors are manufactured by Burr-Brown Corporation type OPT101 and come in an 8-pin DIP package. 2) A control box for operating the LEDs and photo detectors. 3) A desktop computer running the COBI (Cognitive Optical Brain Imaging) Studio software developed in the laboratory for data acquisition and real-time data visualization. Three channels are used to record fNIRS signals. Source-detector distances for the channels are 2.8, 2.8, and 1 cm. Normally, each channel records two signals of the oxy-Hb and deoxy-Hb concentrations. Sampling frequency is about 2 Hz. The device is like to that used by Barati *et al* [17]. Six healthy, right handed individuals (3 males) with no history of neurological, psychological, or psychiatric disorders who were analgesic-free were recruited from the Drexel University community. All participants signed the informed consent approved by the Institutional Review Board (IRB) at Drexel University. An example of such signals is shown in Figure 1.

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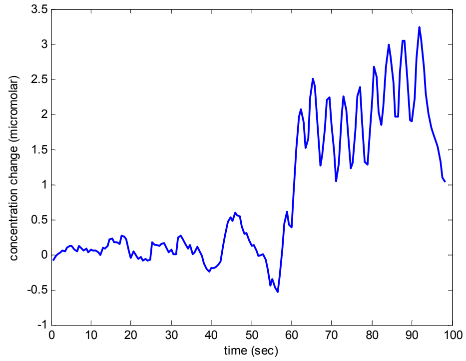

Figure 1. A typical fNIRS signal.

As Figure 1 shows, the first part of the signal taking about one minute time shows motionless signal. The rest of the signal is accompanied by regular head movement of subject for about 40 seconds. As the figure shows, motion artifact impact on signal can easily be distinguished from natural homodynamic responses.

2.2 Linear model

Initially, the motionless signal is modeled as an ARMA model. The optimum order of system is calculated by Akaike Information Criterion (AIC) as (4, 4). Afterwards, the ARMA coefficients should be calculated. For that, we do not calculate by our own, but by using "armax" function of MATLAB software. MATLAB assumes ARMA as follows.

$$A(q)y(n) = C(q)e(n) \tag{1}$$

In which, operator q is in fact delay tap, and

$$A(q) = 1 + a_1 q^{-1} + a_2 q^{-2} + a_3 q^{-3} + a_4 q^{-4} \tag{2}$$
$$C(q) = 1 + c_1 q^{-1} + c_2 q^{-2} + c_3 q^{-3} + a_4 q^{-4}$$

$y(n)$ is the extracted linear model, $e(n)$ is white Gaussian noise, a_i and c_i , $i = 1, \dots, 4$ are ARMA coefficients. The approach through which, software estimates the parameters of the model, is a recursive algorithm in which prediction error is minimized. The cost function is covariance matrice and the sampling interval is 1. The values of loss function and final prediction error (FPE) for some of signals are brought in Table 1.

Table 1. Values of loss function and fpe in establishing ARMA model.

Signal index	Loss function	FPE
1	0.001915	0.002271
2	0.005289	0.006199
3	0.000513	0.000601
4	0.002298	0.002693
5	0.001220	0.001430

2.3 State space representation

At the next step, this linear model ought to be transformed into state space representation. In general, a state space representation is as follows.

$$\boldsymbol{x_k} = A\boldsymbol{x_{k-1}} + B\boldsymbol{w_k} \tag{3}$$
$$\boldsymbol{z_k} = H\boldsymbol{x_k} + \boldsymbol{v_k} \tag{4}$$

Where

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$$\boldsymbol{x_k} = \begin{bmatrix} x_k \\ x_{k-1} \\ . \\ . \\ . \\ x_{k-N+1} \end{bmatrix}_{N\times 1} \tag{5}$$

And $\boldsymbol{x_k}$ is motionless signal vector, $\boldsymbol{z_k}$ is measured signal vector that is motion corrupted in fact. k is time (or sample) point. w_k and v_k are noise of system and noise of measurement respectively that their variances should be calculated.

2.4 Estimating the variance of noise of system

In this stage we are going to estimate variance of w_k, the noise of system. For this purpose, the ARMA model can be rewritten as following.

$$y(k) = -a_1 y(k-1) - \cdots - a_4 y(k-4) + e(k) + c_1 e(k-1) + \cdots + c_4 e(k-4) \tag{6}$$

Now, we retain the term of noise in one side and the rest terms in the other side as shown below.

$$e(k) = y(k) + a_1 y(k-1) + \cdots + a_4 y(k-4) - c_1 e(k-1) - \cdots - c_4 e(k-4) \tag{7}$$

Equation (7) gives the value of noise in a recursive way. If we assume that initial values of noise are zero, next values of $e(k)$ will be recursively estimated by (7). After that, the desired variance can be easily calculated.

2.3.2 Estimating the variance of measurement noise (motion artifact)

Now, we are going to estimate variance of measurement noise v_k, that in our approach is considered as motion artifact. An estimation of v_k can be as follows.

$$\boldsymbol{\hat{v}_{k+1}} = \boldsymbol{z_{k+1}} - H\boldsymbol{x_k} \tag{8}$$

Then the variance can easily be calculated.

2.3.3 Estimating the state of system

By now, we have prepared required materials for applying Kalman filtering estimator. Estimated signal and motion corrupted signal will be plotted in a same figure so that the evaluation of method will be visually provided.

3. RESULTS

3.1 Algorithm assessment (using simulated data)

The results of applying algorithm to some of simulated data are brought in Table 2.

Table 2. Results of simulated data.

Covariance of Gaussian noise	0.08	0.08	0.10	0.11	0.12	0.10	0.08	0.1	0.07
Estimate covariance	0.14	0.17	0.19	0.23	0.22	0.19	0.19	0.19	0.13

RMSE of difference between known variance values and estimated values is 0.09.

Figure 2 shows an estimated signal (dashed line) as well as the original signal (solid line) after implementing the proposed method.

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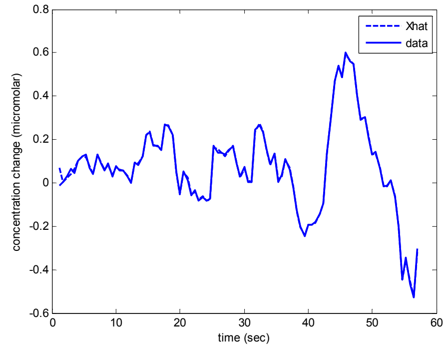

Figure 2. An estimated fNIRS signal contaminated by simulated noise (dashed line) and the original one (solid line).

3.2 Results of real data

Now, the algorithm is applied to real NIRS data including real (actual) motion artifacts. An example of applying the proposed method to fNIRS signals is demonstrated in Figure 3.

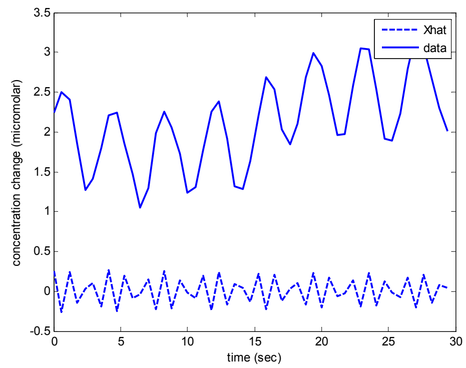

Figure 3. Result of real data (contaminated signal in solid line and the cleaned one as dashed line).

4. DISCUSSION

Use Because of some excellent advantages such as affordability, safety, not restricting the subject in specific conditions and positions, and capability of online applications, fNIRS sometimes is exposed to undesired and also at times unavoidable movements of head of subject that aim to vitiate the quality of signal and confuse the results. In the past, some methods have been proposed to reduce motion artifacts. In this paper we proposed an ARMA based Kalman filtering method, to reduce the effect of motion artifacts in fNIRS data. Unlike to older methods, our method does not need to additional hardware or sensors and can be applied in online applications. It also does not need to all data together nor a priori knowledge of system. We applied the proposed to both simulated data in which fNIRS motionless data had been added by white Gaussian noise, and the real (actual) data. The results show that the proposed algorithm is successful in reducing motion artifacts of fNIRS data. We will investigate the priority of the proposed method over a similar approach proposed by Izeetoglu et al. in term of signal to noise ratio.

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