# A SACCADE-RELATED NOISE REDUCTION IN EEG SIGNALS USING OUTER PRODUCT EXPANSION WITH REFERENCE SIGNAL

*Akitoshi Itai*, Arao Funase†‡, Andrzej Cichocki‡, and Hiroshi Yasukawa**

*Aichi Prefectural University, Nagakute, Aichi 480-1198, Japan
E-mail: a_itai@cis.aichi-pu.ac.jp, yasukawa@ist.aichi-pu.ac.jp
† Nagoya Institute of Technology, Showa-ku, Nagoya 466-8555, Japan
E-mail: funase.arao@ics.nitech.ac.jp
‡ Brain Science Institute RIKEN, 2-1, Hirosawa, Wako Saitama 351-0198 Japan
E-mail: cia@brain.riken.jp

## ABSTRACT

This paper develops the tensor product expansion with absolute error (TPE-AE) to remove an electrooculogram due to eye movement (EOG artifact) from an electroencephalogram (EEG). The saccade-related EEG signal produced by a saccadic eye movement is analyzed to clear the relationship between a brain function and human activity. EOG artifacts in EEGs yield significant problems for the EEG analysis. The denoising of EOG artifacts is important task to extract a saccade related EEG. The TPE-AE, which calculates two terms of outer product from EEGs, was applied to reduce EOG artifacts. However, this technique has some difficulties to remove only EOG artifacts from EEG. In this paper, we propose the novel TPE-AE with the reference signal. We show that the proposed method is effective to separate EOG artifacts and other noises.

## 1. INTRODUCTION

Attention is being placed on the saccade-related EEG to clear the brain function corresponding to a saccadic eye movement. A saccadic EEG is researched to achieve a Brain Computer Interface (BCI) based on human's will in EEGs[1, 2]. However, the artifact from a blinking and eye movement interferes with a correct analysis of saccadic EEG.

From the typical EEG analysis using the ensemble averaging, sharp changes of a potential related to a saccade and an EOG artifact are recorded before and after the saccade, respectively. This EOG artifact yields the difficulty of a saccadic EEG analysis. The ensemble averaging requires many EEGs measured by same trials to find characteristics of saccadic EEG. Moreover, it is not suitable to extract the change of a latent time. Therefore, the reduction of various noises from single trial data is important task to analyze a sacaddic EEG.

In order to extract a saccadic EEG, EEG data excluding eye blinks and movement noises should be used. However, the conventional denoising technique with a high pass filter reduces important components for EEG analysis since the recorded potential during a saccadic eye movement contains both the saccade related EEG and EOG artifact. Note that "EOG artifact" used here means the artifact due to eye movement.

Funase shows that a fast independent component analysis with reference signal (FICAR) can extract a saccadic EEG from single trial EEG data to realize a practical use of BCI[3, 4, 5]. The FICAR method focuses on the extraction of the saccadic EEG explained by the ensemble averaging by using a reference signal. Therefore, the feature extraction of other components associated with a saccade is not considered.

EOG artifacts yield significant problems for an EEG and its analysis. EOG artifact denoising is important task to analyze the relationship between a saccade and EEG. In order to find a saccadic EEG, a high-pass filter which rejects from 0 to 4Hz is often employed to avoid the effect of EOG. Generally speaking, however, this lower frequency band may include many EEG components corresponding to a recognition and consciousness.

The tensor product expansion with absolute error (TPE-AE), which calculates two outer products, is applied to reduce EOG artifacts from the EEG signal[6]. TPE-AE is useful to remove EOG components, however, it has some difficulty to separate an EOG from saccade-related EEG data due to a background noise from a spontaneous EEG activity. In this paper, we propose a novel TPE-AE that uses a reference signal to separate a spontaneous EEG and EOG artifacts.

## 2. EEG RECORDINGS

The measuring target in this research is a potential before and after saccadic eye movements. The recording is performed in the shielded dark room in order to reduce an electromagnetic noise and a visual stimuli. Visual targets (LEDs) are set on the board located 30cm away from the nasion of the subject. One LED is placed in front of the subject, two LEDs are located on 25 and -25 degree from the center LED (Fig.1). One LED of three LEDs is illuminated randomly to avoid the prediction of the subject. The EEG during the saccadic eye movement that a subject moves his eye toward the illuminated LED placed on a right or left side is recorded iteratively.

EEG signals are collected from 19 electrodes, which are placed at the location based on the international 10-20 system as shown in Fig.2. To detect an eye movement and an eye blinking, two pairs of sensors are attached to the right-left side (HEOG) and top-bottom side (VEOG) of a right eye. All potentials are digitally sampled at 1000Hz, and collected for the off line signal processing. A high-pass filter (cut-off 0.53Hz) and a low-pass filter (cut-off 120Hz) is applied to the collected EEG data, while the EOG data is recorded through a high-pass filter (cut-off 0.1Hz) and a low-pass filter (cut-off 15Hz).

EEG signals during the eye movement are collected by visual target tasks. The number of EEG signals used here is 25 for each saccade direction since some of signals contain an artifact due to eye blinking and other body movement. 50

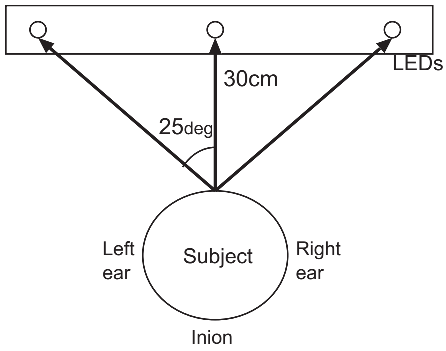



Figure 1: Placement of LEDs

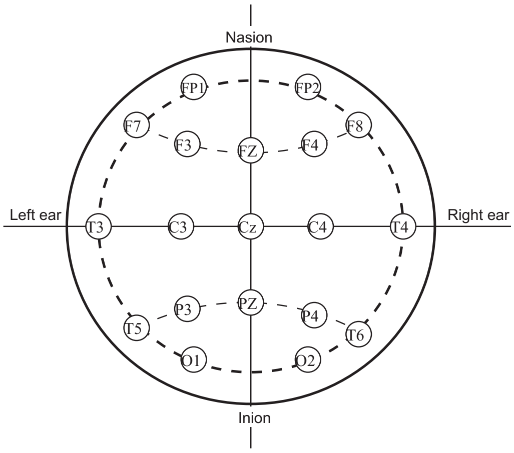



Figure 2: International 10-20 electrode system

EEG signals composed of 25 right and 25 left saccades are adopted to the denoising process.

## 3. TPE-AE

### 3.1 Typical TPE-AE

TPE-AE is the signal separation based on a tensor product expansion and L1 norm minimization[7, 8, 9, 10]. Assume that observed signals consist of two source signals, the one is observed in most signals (a background noise) while another is seen in just few signals (a local signal). In this case, the latter signal can be considered as outliers. TPE-AE estimates a background noise from observed signals as shown in Fig.3, while the major blind source separation, i.e. an independent component analysis, often estimates the $n$ sources from $n$ input signals.

L1 norm is employed in TPE-AE as a criterion to calculate the outer product [11, 12], since the absolute error have little influence of outliers. Let $h(l_1,l_2)$ be an input 2-D matrix which consists of observed signals. The outer product and its bias component of $h(l_1,l_2)$ is given by the L1-norm minimization as shown in (1).

$$J=\sum_{l_1=1}^{q_1}\sum_{l_2=1}^{q_2}|h(l_1,l_2)-(f_1(l_1)f_2(l_2)+f_3(l_2))| \tag{1}$$

where $J$ is an error function, $f_1(l_1)f_2(l_2)$ and $f_3(l_2)$ are one-dimensional vector outer product which approximates AC and DC components, respectively. $q_1$ and $q_2$ is the length of a signal and the number of signals, $f_1(l_1)$ and $f_2(l_2)$ is $l_1$th and $l_2$th element of a vector, respectively. $f_1(l_1), f_2(l_2)$ and $f_3(l_2)$, which yield minimum $J$, give us the background noise included in the observed signal $h(l_1,l_2)$.

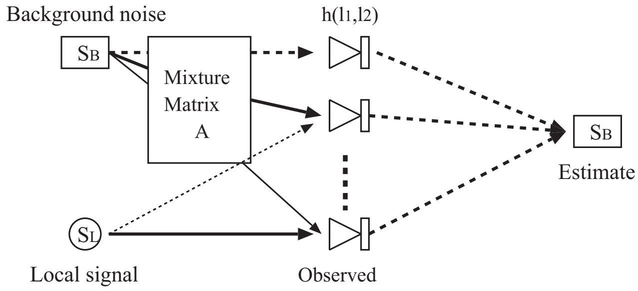



Figure 3: Model of noise reduction for TPE-AE

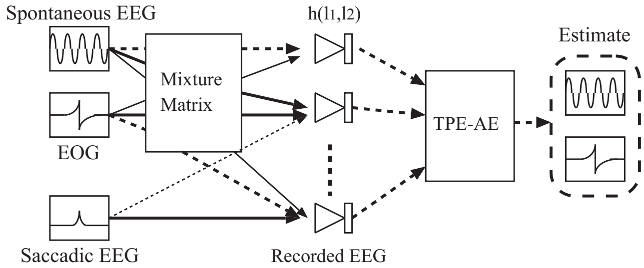



Figure 4: Model of noise reduction for saccadic EEG data

TPE-AE can estimates the background noise generated by one source, however, EEG signals during an eye movement include two undesired signals due to the EOG and a spontaneous EEG. We reduce the undesired signal in EEG data by estimating two terms of outer product (Fig.4). TPE-AE applying to EEG data does not require the estimation term for DC component since the EEG signal is corrected and processed through a high-pass filter. Therefore, (1) is rewritten as (2).

$$J=\sum_{R=1}^{r}\sum_{l_1=1}^{q_1}\sum_{l_2=1}^{q_2}|h(l_1,l_2)-f_{1R}(l_1)f_{2R}(l_2)| \tag{2}$$

where $R$ and $r$ indicates the index and number of an estimated term. A spontaneous EEG and EOG artifact are estimated by TPE-AE whose the number of expansion terms is 2 [6]. We call this technique typical TPE-AE. In order to avoid the notation confusion, the number of expansion terms for TPE-AE is written as ($r=1$ or 2).

The simple and reasonable method based on Monte Carlo Simulation (MCS) was applied to solve a minimization problem in (2). MCS produces better solutions by extensive trials using random numbers for an initial number and update. Feasibility and separability conditions of this method for a background noise estimation are confirmed [11].

### 3.2 Outer product expansion with reference signal

EEG signals during an eye movement include an EOG artifact and a spontaneous EEG. Two terms of outer product estimated by typical TPE-AE include both of a spontaneous

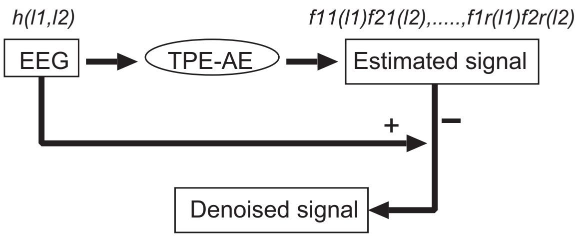



Figure 5: Denoising flow for typical TPE-AE

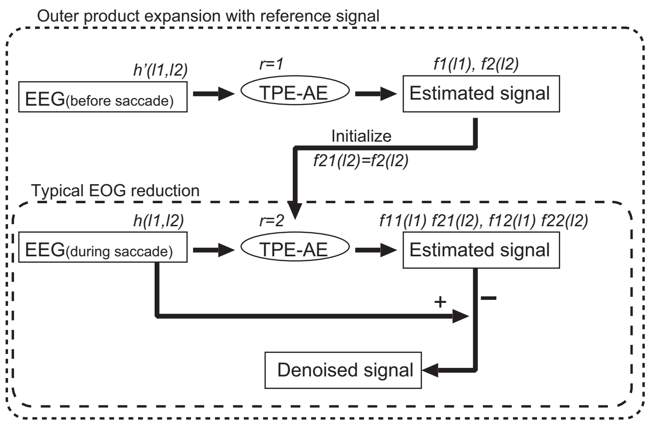



Figure 6: Denoising flow for proposed method

EEG and EOG. As we shown in the conventional research[6], a spontaneous EEG represents the similar trend at almost all positions, while EOG artifact indicates three patterns of EEG change. Therefore, the EEG adopted to this research includes two dominant background noises whose mixing coefficient is significantly different. In order to separate these components correctly, we propose a novel outer product expansion which uses the mixture matrix of a spontaneous EEG calculated from previous EEG data.

A spontaneous EEG is recorded on electrodes placed at an entire head. Assume that the strength of spontaneous EEG in each measurement electrode changes slowly. The strength of spontaneous EEG during saccade and just before the saccade forms a similar mixture matrix. If the mixture matrix of EEG just before saccade is assigned as an initial value of TPE-AE, the spontaneous EEG appears on the initialized term. Therefore, the spontaneous EEG and EOG artifact is separated into two outer products, respectively. The input vector $h(l_1, l_2)$ is the EEG observed at 19 electrodes over the period of 2 seconds whose middle time corresponds to the starting time of saccade. $h'(l_1, l_2)$ is the EEG recorded 2 seconds before $h(l_1, l_2)$ (Fig.7).

The denoising flow is given as following steps and Fig.6.

**STEP:**

1. Estimate a mixture matrix $f_2$ by using TPE-AE ($r = 1$) from the reference signal $h'(l_1, l_2)$
2. The mixture matrix ($f_{21}$) of first outer product is initialized by the estimated $f_2$ in STEP 1
3. Calculate the two terms of outer product by using TPE-AE ($r = 2$) from EEG $h(l_1, l_2)$

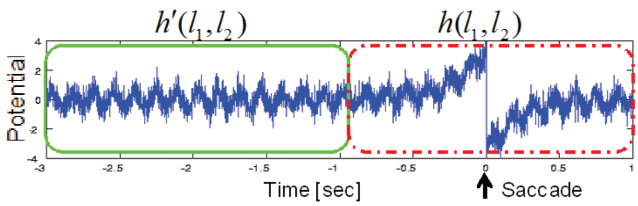



Figure 7: Input data for proposed method (Artificial signal)

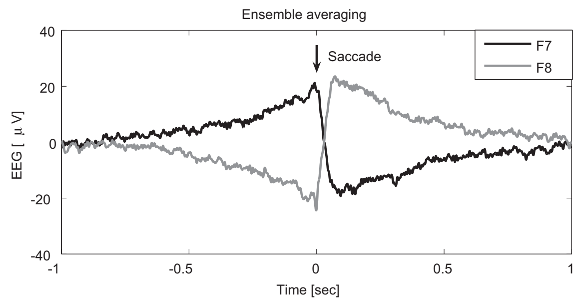



Figure 8: EEG of ensemble averaging in right saccade

4. Subtract the outer products from EEG

STEP 1 gives us a mixture matrix of a spontaneous EEG before the saccade. The first term ($f_{11}f_{21}$) and the second term ($f_{12}f_{22}$) obtained by STEP 3 represents an EOG component and a spontaneous EEG, respectively. We call this proposed method an outer product expansion with reference signal.

## 4. EXPERIMENTAL RESULT

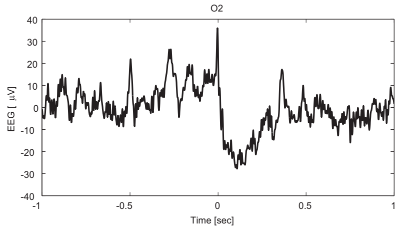
### 4.1 Typical EEG data in saccade

The typical EEG data with right-eye movement recorded on the left and right occipital lobe (F7 and F8 in international 10-20 system) is shown in Fig.8. This figure draws the ensemble averaging calculated from 25 trials. The horizontal axis is the time whose 0 [sec] indicates the starting time of an eye movement to right. The vertical axis indicates the measured potential. The EEG signal on F7 and F8 is sharply increased and decreased after an eye movement, respectively. This change is the effect of the dominant undesired signal related to EOG artifacts.

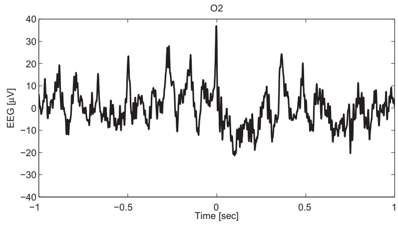
### 4.2 Example of denoising for single trial EEG

Results of denoising for single trial EEG is described here. Fig.9 indicates the EEG on O2 and its denoised signal when the subject moves his eyes toward a right side. Fig.9(b),(c) and (d),(e) are denoised signals by using the typical TPE-AE and proposed method, respectively. The horizontal axes of these graphs indicate the time, where 0 [sec] represents the starting time of eye movement.

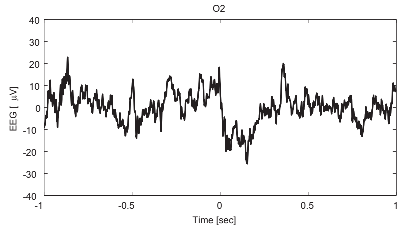
There is the sharp decrease of a potential recorded from 0 to 0.1 [sec] in Fig.9(a). From Fig.9(b),(c), the potential change from an EOG artifact is reduced by subtracting either the first term or second term. On the other hand, this change remains in Fig.9(d) while this change is rejected in Fig.9(e). This means that the both two terms of outer product estimated by typical TPE-AE includes an EOG artifact. However, EOG is reduced by only subtracting the second term by



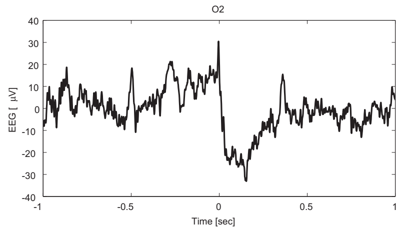

(a):EEG



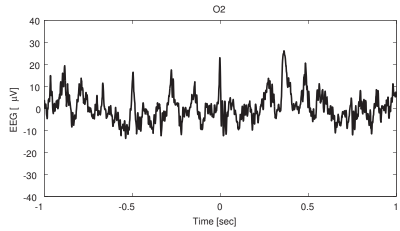

(b):Denoised signal by typical TPE-AE: EEG $-f_{11}(l_1)f_{21}(l_2)$




(c):Denoised signal by typical TPE-AE: EEG $-f_{12}(l_1)f_{22}(l_2)$




(d):Denoised signal by proposed method: EEG $-f_{11}(l_1)f_{21}(l_2)$




(e):Denoised signal by proposed method: EEG $-f_{12}(l_1)f_{22}(l_2)$

Figure 9: EEG and denoisd EEGs for right saccade (1st saccade)

Table 1: Differences of the averaged amplitude spectrum between EEG and denoised EEG [dB]

(a): For right saccade

| | | EOG (0∼4Hz) | Spontaneous (8∼13Hz) |
|---|---|---|---|
| Conventional | EEG$-f_{11}(l_1)f_{21}(l_2)$ | 2.8 | 1.8 |
| | EEG$-f_{12}(l_1)f_{22}(l_2)$ | 3.1 | 1.7 |
| Proposed | EEG$-f_{11}(l_1)f_{21}(l_2)$ | 2.2 | 2.5 |
| | EEG$-f_{12}(l_1)f_{22}(l_2)$ | 4.2 | 0.9 |

(b): For left saccade

| | | EOG (0∼4Hz) | Spontaneous (8∼13Hz) |
|---|---|---|---|
| Conventional | EEG$-f_{11}(l_1)f_{21}(l_2)$ | 3.1 | 1.6 |
| | EEG$-f_{12}(l_1)f_{22}(l_2)$ | 3.1 | 1.7 |
| Proposed | EEG$-f_{11}(l_1)f_{21}(l_2)$ | 2.4 | 2.4 |
| | EEG$-f_{12}(l_1)f_{22}(l_2)$ | 3.0 | 1.0 |

using the proposed method.

### 4.3 Evaluation in frequency domain

In order to evaluate a denoising performance, attenuations of an EOG artifact and spontaneous EEG are employed here. The attenuation is the decrease of EOG and spontaneous components. The amount of decrease is defined as the difference between an averaged amplitude spectrum of raw EEG and its denoised EEG. EOG and spontaneous components correspond to from 0 to 4Hz and from 8 to 13Hz, respectively.

The attenuation is calculated by the following procedure.

I. 25 amplitude spectra of signals i.e. raw EEG, denoised EEG by using typical TPE-AE and proposed method, are calculated by using the fast Fourier transform.

II. 25 amplitude spectra are averaged.

III. Differences between the averaged amplitude spectrum of raw EEG and its denoised EEG are extracted for each position.

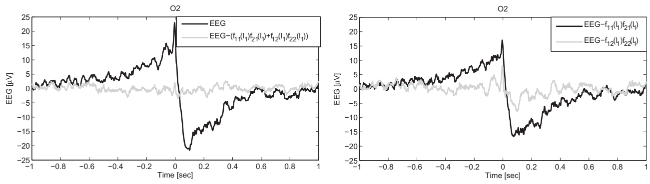
IV. Averaged differences of 19 positions calculated in III. are averaged.

Table 1 (a) and (b) shows the attenuation corresponding to an eye movement toward right and left side, respectively. Attenuations that are given by subtracting a first/second term from EEG are represented to verify the separability.

From Table 1 (a), EOG components are decreased an average of 2.8/3.1 decibel by subtracting first/second term with the typical TPE-AE, 2.2/4.2 decibel by the proposed method. Spontaneous components are reduced 1.8/1.7 decibel by the typical TPE-AE, 2.5/0.9 decibel by the proposed method. These results indicate that EOG and a spontaneous components appear on the first and second term by using the proposed method, respectively. On the other hand, two components are represented to both of first/second terms by using typical TPE-AE. Table 1 (b) denotes a similar result of Table 1 (a).

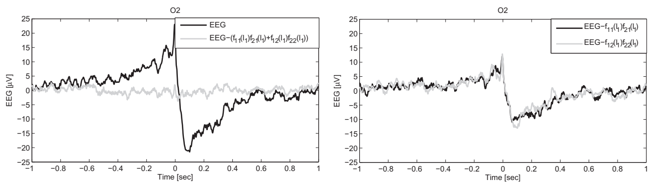
### 4.4 Evaluation in time domain

The ensemble averaging of denoised data for typical TPE-AE and proposed method is shown in Fig.10 and Fig.11, respectively. Fig.10,11(a) plot the EEG and denoised EEG. Results of subtracting the first and second term are shown in Fig.10,11(b). From Fig.10,11(a), the EOG artifact recorded from 0 to 0.1 [sec] is reduced by removing two terms of outer product. Fig.10(b) shows that the ensemble averaging of denoising which subtracts the second term from raw EEG does not indicate the rapid decrease due to an EOG artifact. From Fig.11(b), it is difficult to separate an EOG from a spontaneous EEG since a similar trend, which is a decrease




(a):EEG and EEG$-(f_{11}f_{21}+f_{12}f_{22})$ (b):EEG$-f_{11}f_{21}$ and EEG$-f_{12}f_{22}$

Figure 10: Ensemble averaging of denoised EEGs: Proposed method




(a):EEG and EEG$-(f_{11}f_{21}+f_{12}f_{22})$ (b):EEG$-f_{11}f_{21}$ and EEG$-f_{12}f_{22}$

Figure 11: Ensemble averaging of denoised EEGs: Conventional method

of potential after saccade. These results show that proposed method estimates an EOG artifact on the second term.

As previously noted, the TPE-AE which calculates two outer products can extract dominant background noises in input signals. It is difficult to estimate the EOG related undesired signal by using typical TPE-AE since a spontaneous EEG is extracted. Undesired EOG artifact and a spontaneous EEG are separated successfully by using a reference signal for an outer product expansion. These results mean that the proposed method is effective to reduce EOG artifacts related to the eye movement.

## 5. CONCLUSION

This paper presents the novel technique for reducing the EOG artifacts corresponding to the saccadic eye movement. We confirmed that an outer product expansion, which estimates two outer products by using reference signal, is effective to reduce EOG artifacts and spontaneous EEG. Remaining problems are to decrease a calculation cost and to extract the saccade-related EEG from denoised signals.

### Acknowledgment

This work was supported by Grant-in-Aid for Young Scientists Start-up (21800044).

## REFERENCES

[1] A.Funase, T.Yagi, Y.Kuno, and Y.Uchikawa, ”A study on electro-encephalo-gram (EEG) in eye movement,” *Studies in Applied Electromagnetics and Mechanics*, Vol.28, pp.709–712, 2000.

[2] G.D.Dawson, ”A summation technique for the detection of small evoked potentials,” *Electroencephalography and Clinical Neuro.*, 6(1), pp.65–84, 1954.

[3] A.Funase, A.K.Barros, S.Okuma, T.Yagi, and A.Cichocki, ”Reserach of saccade-related EEG: Comparison of ensemble averaging method and independent component analysis,” in *Proc. of ICA2003*, pp.867–872, 2003.

[4] A.Hyvarinen and E.Oja, ”Independent component analysis: algorithms and applications,” *Neural Netw.*, Vol.13, pp.411–430, 2000.

[5] A.Cichocki and S.Amari, *Adaptive blind signal and image processing*, 1/552, Wiley: New York, 2002.

[6] A.Itai, A.Funase, A.Cichocki, and H.Yasukawa, ”EOG-related noise rejection in EEG signal with eye movement task by tensor product expansion with absolute error,” in *Proc. of EUSIPCO2010*, pp.706-710, 2010.

[7] D.O’Leary and S.Peleg, ”Digital image compression by outer product expansion,” *IEEE Trans. on Commun.*, Vol.COM-31, No.3, pp.441–444, 1983.

[8] T.Saito, T.Komatsu, H.Harashima, and H.Miyagawa, ”Still picture coding by multi-dimensional outer product expansion,” (in Japanese) *IEICE Trans.*, Vol.J68-B, No.4, pp.547–548, 1985.

[9] N.Toda, and S.Usui, ”A method for structural identification of nonlinear system via tensor product expansion for symmetric function,” (in Japanese) *IEICE Trans.*, Vol.J73-A, No.1, pp.51–58, 1990.

[10] J.Murakami, T.Gouriki, and Y.Tadokoro, ”Detection of discontinuous frame from image sequence by 3d tensor product expansion method,” in *Proc. of Joint Technical Conf. Circuits/Systems*, Vol.2, pp.638–642, 1993.

[11] A.Itai, H.Yasukawa, I.Takumi, and M.Hata, ”Global noise estimation based on tensor product expansion with absolute error,” *IEICE Trans.*, Vol.E90-A, No.4, pp.778–783, 2007.

[12] A.Itai, and H.Yasukawa, ”Background signal estimation from multi-sensor signals based on outer product and non-linear filters,” in *Proc. of EUSIPCO2008*, poster, 2008.