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Real-time ocular artifacts removal of EEG data using a hybrid ICA-ANC approach

Aysa Jafarifarmand[a], Mohammad-Ali Badamchizadeh[a,*], Sohrab Khanmohammadi[a], Mohammad Ali Nazari[b], Behzad Mozaffari Tazehkand[a]

[a] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
[b] Cognitive Neuroscience Laboratory, Department of Psychology, University of Tabriz, Tabriz, Iran

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ABSTRACT

Removal of ocular artifacts (OA) in real-time is an essential component in electroencephalography (EEG) based brain computer interface (BCI) applications. However, many proposed artifact removal methods are not applicable in real-time applications due to their time-consuming process. In this paper we propose a hybrid approach based on a new combination of independent component analysis (ICA) and adaptive noise cancellation (ANC). A particularly new feature of the proposed approach is the utilization of the ICA decomposition to extract the artifact source signal to be used in ANC based on neural networks. The method performs using a few EEG signals without requiring any additional electrodes (e.g. electrooculography). We show that the proposed approach is capable of effectively reducing the ocular artifacts in a negligible time delay well applicable in real-time BCI. In order to achieve reliable results, the proposed approach is evaluated using data recorded during cue-based BCI. The efficacy of the proposed approach in both offline and online performances is compared to several state of the art methods. The results demonstrate that the proposed approach outperforms the compared methods in terms of removal of OA and recovery of the underlying EEG.

1. Introduction

REAL-TIME brain computer interface (BCI) enables the extremely disabled people to interact with the external world using just the brain power, bypassing the role of the muscles. Electroencephalography (EEG) is the most widely used non-invasive brain-imaging technique for real-time BCI applications, mainly due to its fine temporal resolution, ease of use, portability and low cost. Unfortunately, EEG signals are highly contaminated by artifacts of both biological and technical origins [1]. Biological artifacts originating from eye blink/movements (ocular artifacts, OA), heartbeat, and muscle activities interfere inevitably in EEG measurements, among them OA have high amplitude signals that obscure the information available in the EEG recordings. Therefore, removal of the OA is an essential component prior to the EEG signals analysis.

A variety of methods have been proposed for EEG artifact removal [2–11] among them two methods are the most widely used: 1) *Adaptive noise cancellation* (ANC) is a relatively fast approach [6,8]. EEG signals are corrected by subtracting the interference contribution that is estimated by identifying a model between artifact source and the corresponding interference signal. A common problem in using such a method is its requirement to separately measuring the artifact source signals coincide with the EEG measurements. The other concern associated with this approach is also that the directly measured artifact source signals (especially the ones close to the head i.e. ocular activities) may be contributed by EEG activities that may cause in loss of some cerebral information. 2) *Independent component analysis* (ICA) is another powerful algorithm introduced to separate and remove a wide variety of EEG artifacts [9–11]. ICA decomposes the measured EEG data into their underlying independent artifactual and cerebral components. The artifactual independent components (ICs) are then rejected and the artifact-free EEG is reconstructed using the residual ICs. Due to the large number of EEG channels required for precise separation of the components, ICA is not suited for portable applications and also is a computationally demanding and therefore time consuming approach. The detection of the artifactual ICs is also another time consuming step necessary in ICA based artifact removal. The other concern about the ICA based algorithms is

* Corresponding author.
E-mail address: mbadamchi@tabrizu.ac.ir (M.-A. Badamchizadeh).

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that the ICA models are applied for EEG analysis with underlying assumption that the cerebral and the artifactual sources are mixed linearly, which might not always be true especially for electrodes located away from the signal origin.

In addition to the acceptable elimination level of the artifacts while preserving the cerebral information, a suitable artifact removal method for a real-time BCI application should satisfy certain specifications containing

- Automatic performance, a practical BCI needs to perform fully automatic without any expert interaction,
- Utilizing suitable number and position of electrodes, attaching high number of EEG electrodes or the electrodes around the artifacts origins during long-term EEG recording in BCI applications causes in inconvenience for the subject, and
- Real-time processing, artifact removal process for a real-time BCI cannot introduce unacceptable time delays [12–14].

Mateo et al. have applied ANC using radial basis function (RBF) neural networks to reduce OA from EEG signals in [15]. Simultaneously measured ocular activities using electrooculography (EOG) has been utilized as artifact source signal. Mahajan et al. have used ICA to denoise eye blink artifact from EEG data in [16]. They have used modified multi-scale sample entropy along with kurtosis to identify the eye blink atrifactual independent components resulted by ICA decomposition. Multi-resolution wavelet analysis has then been applied to denoise these components instead of completely zeroing the ICs in order to better retaining of the neural activities. The algorithm is applicable for dense EEG systems and also is not capable for real-time BCI applications.

Peng et al. proposed an approach combining discrete wavelet transformation (DWT) and ANC that removes only OA from EEG signals [6]. The method applies DWT to a single contributed EEG signal in order to construct the OA source signal utilized in ANC removal procedure. Using only one EEG channel without requiring the EOG recordings, the method is suited for portable environments. However, the performance accuracy is sensitive to the selection of wavelet basis and thresholding function that may cause in losing the useful information or keeping the artifact interference. The algorithm is also not suited to real-time BCI applications. Continuing the work, Zhao et al. have improved the process speed by utilization of adaptive predictor filtering to recover true EEG by predicting EEG signal amplitudes in OA zones in [17]. The short-term prediction constraint however restricts the real-time performance. The performance of the method is also heavily dependent on the proper selection of the parameters.

Breuer et al. have also proposed an algorithm based on constrained ICA (CICA) for real-time cardiac and ocular artifact rejection in magneto-encephalography (MEG) in [18] and [19]. The algorithm utilizes the knowledge derived from the simultaneously measured artifact source signal (i.e. electrocardiogram, ECG or EOG) to optimize the cost function of infomax ICA. The algorithm is capable of real-time reduction of cardiac/ocular artifact, however, it requires large number of EEG channels for precise decomposition and also additional ECG/EOG electrodes.

In this paper, we propose a new fully automated hybrid approach, well suited for real-time applications applying very small number of EEG electrodes, in order to remove OA from EEG signals. The method is based on combination of ICA and ANC techniques. In the proposed method, we apply ICA decomposition to only a few EEG signals close to the artifact origin. ANC based on a fully automated neural network is then conducted using the resulted independent component (IC), the most relevant to the artifact, as the reference input bypassing the requirement to direct EOG recording.

The particular feature of the proposed method is applying ICA decomposition just for extraction of the artifact source component to be utilized in ANC. Accordingly, the combination of the artifactual components is assumed to be linear just in the close distances. This also allows us to benefit the advantage of NNs in adaptively adjusting the parameters in order to well follow the changes. Moreover utilizing only a small number of EEG channels, in addition to convenience, results in speeding up the ICA decomposition toward introducing no restriction for an adaptive real-time procedure. Consequently, presenting an appropriate work-flow, the approach well removes OA in real-time appropriate in BCI application.

2. Methods and materials

2.1. EEG recording

All EEG data used in this paper are recorded (from healthy adult subjects) using a Mitsar® amplifier and WinEEG® software. Explaining the procedure and the purpose of our study, all the subjects gave their informed consent to participate in the experiment. EEG signals are recorded using EEG cap by 19 electrodes including A1 and A2 located based on the international standardized 10–20 system. The signals are recorded using monopolar channels referenced to linked ear lobes, with the ground electrode placed on AFz. Electrode impedance is also maintained below 10 kΩ. The recordings additionally contain the simultaneous measurement of vertical EOG for testing purposes too.

The data are collected from 10 participants (age between 20 and 40 years). Toward ensuring the accuracy of the results, the recordings are done in two separate sessions for each subject. Recording procedure is designed based on the cue-based BCI paradigm applied in BCI Competition 2008 [20]. The paradigm consisted of four different motor imagery (MI) tasks, namely the imagination of movement of the left hand, right hand, both feet, and tongue. Recordings are done while the subjects are sitting in a comfortable armchair in front of a computer screen. At the beginning of each session, a recording of approximately a minute of blinking is performed to be utilized for initial training of the algorithm for OA removal. The procedure is then continued by classic cue-based BCI recording according to the arrow appears on the computer monitor. All the data are recorded continuously in order to be applicable for the real-time process.

All EEG and EOG signals are recorded at sampling rate of 250 Hz and filtered using a digital band-pass filter between 0.5 and 45 Hz in real-time to especially suppress the line noise and also noise originating from the mains and preserve the data applicable for BCI application [12,14].

2.2. Positioning of ocular artifact source EEG electrodes

With respect to a practical BCI application, it is necessary to utilize the least possible number of EEG electrodes, which are also well positioned toward the subject's convenience. Besides, the selected EEG channels should be well applicable to extract the pure artifact source signal as possible. A tradeoff between the number of the EEG electrodes and ICA decomposition quality should therefore be considered. For this purpose, the alternatives are selected among the EEG electrodes with the most artifactual and the least cerebral activity contribution as possible. The more an EEG electrode is close to the artifact origin, the more it is affected by the artifactual potential. This effect is also well accepted to be linear due to the close distance. Furthermore, EEG channels farther from the motor area contain less neural contribution that may reduce the number of underlying independent components. Such choices consequently increase the ICA ability in a pure separation of the