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EEG signal co-channel interference suppression based on image dimensionality reduction and permutation entropy

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ABSTRACT

It is well known that electroencephalogram (EEG) signals collected from scalps are highly contaminated by various types of artifacts and background noise. The perturbations induced by artifacts and random noise are particularly difficult to correct because of their high amplitude, wide spectral distribution, and variable topographical distribution. Therefore, de-noising of EEG is a very challenging pre-processing step prior to qualitative or quantitative EEG signal analysis. To address this issue, some de-noising approaches have been proposed for noise suppression. However, most of these methods are only available for multi-electrode EEG signal processing, besides, the co-channel interference are always left unprocessed. Aiming at the obstacles encountered by the conventional approaches in single electrode EEG signal co-channel interference suppression, a method based on time-frequency image dimensionality reduction is proposed in this paper. The innovative idea of the proposed method is that it is applicable for single electrode EEG signal enhancement and the background noise can be suppressed in entire time-frequency space. The proposed method is experimentally validated by a group of real EEG data. The experimental results indicate that the proposed method is effective in EEG single electrode co-channel interference suppression.

1. Introduction

Brain-computer interfaces (BCIs) provide humans with a new communication approach between their brains and external devices [1–3], especially for the disabled people. By translating brain electrical activities typically measured by electroencephalogram (EEG) into computer commands, the communicative and environmental control abilities for severely disabled people can be reconstructed [4–9]. Recently, steady-state visual evoked potentials (SSVEPs)-based BCIs, which show advantages of little user training and high information transfer rate (ITR), have received increasing attentions [10,11].

In SSVEP-based BCIs, users gaze at one of multiple visual flickers tagged by frequencies, then SSVEP is elicited at the same frequency as the target stimulus and also its harmonics over occipital scalp areas [12,13]. Therefore, the basic idea of SSVEP-based BCI is to detect the desired commands through identifying the SSVEP target frequency in EEG. Although original SSVEP responses present relatively stable spectrums over time, they are likely to be contaminated by various sources of artifacts and other background noises. Some of these artifacts are externally generated, such as power line noise and instrumentation noise. Additionally, there is noise that is generated by physiological sources, external to the brain, such as eye movements, muscle activity and heart pulse. Due to the heavy artifacts and background noise, the EEG signal will be corrupted and the accuracy of the recognition of the SSVEP frequency will be influenced. Therefore, de-noising is a very important and challenging pre-processing stage for development of SSVEP-based BCI with high performance.

In recent years, EEG signal de-noising has received increasing attentions. Different de-noising methods have been proposed and tested to extract noise free SSVEP responses, such as wavelets [14–20], independent component analysis (ICA) [21–27], and adaptive filters [28–31]. To reduce the instrumentation complexity, many ambulatory systems operate using single-electrode EEG signal only [32]. In the case of single source, it is of significance importance to extract as much useful information as possible by corrupting artefact suppression or removal techniques. Therefore, the ICA methods based on multi-electrode EEG signals are not applicable in this circumstance. Besides, the adaptive filtering, due to its requirements of additional electrodes for reference purpose, is also ineffective for single-electrode EEG signal processing. Furthermore, since artifacts and other background noises span within a wide frequency range, the wavelet

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methods based on bandpass filtering can just suppress the noise outside the filtering frequency band while the co-channel interferences are left unprocessed. Especially for the multi-target SSVEP-based BCIs, the SSVEP target frequencies in EEG signals always vary within a relative large frequency range to represent different commands, therefore, the traditional bandpass filtering with fixed passband cannot effectively and adaptively extract the SSVEP response.

To tackle the difficult problems occurred in the traditional single-electrode EEG signal processing methods, a method which can adaptively wipe off the interference in the whole frequency band is necessary. Motivated by the concept of noise suppression based on image dimensionality reduction [33], this paper proposes a novel SSVEP response extraction method by T-F image dimensionality reduction. As time-frequency distribution (TFD) image can reveal intrinsic feature of non-stationary EEG signals, and the degrees of freedom or possible independent pixel values in the T-F image refer to image dimensionality. Thus we intend to use the dimensionality reduction method based on singular value decomposition (SVD) to suppress the background noise in raw T-F image. In the proposed method, SVD is used to transform the original T-F image, defined in a high dimensional space, to another space with fewer dimensions by subtracting the redundant or irrelevant pixel values related to background noise, without loss of valuable information of periodic SSVEP response. The minimum permutation entropy criterion is employed to optimize the selection of intrinsic dimension of the T-F matrix. The proposed method is experimentally validated by a group of real EEG data. The results indicate that the proposed method is effective in EEG co-channel interference suppression and outperforms the traditional methods.

The outline of this paper is as follows. The following section presents the proposed image dimensionality reduction based T-F image noise suppression method in detail. In 'Experimental validation' section, the effectiveness of the proposed method is experimentally validated. Finally, conclusions are drawn in the last section.

2. The proposed method

2.1. Theoretical backgrounds of EEG T-F image dimensionality reduction

In matrix decomposition based image denoising approaches, the image dimensionality is used to describe the degree of freedom or possible independent pixel values in the image. In this sense, the image dimensionality can be regarded as a descriptor of the image rank which is defined as the number of independent image rows or columns. Obviously, high or low image rank corresponding to high or low image dimensionality. Motivated by the idea of dimensionality reduction based image noise suppression, an EEG signal T-F image noise suppression method is proposed for SSVEP response extraction.

In the proposed EEG signal noise suppression method, the noise contaminated T-F image is decomposed into a set of sub-images. By blocking some noise-related sub-images, the reconstructed image by the remaining sub-images will has smaller rank, i.e. lower dimensionality, than the original one, and the noise suppressed T-F image is obtained. Since the singular value decomposition (SVD) method as a very powerful matrix decomposition and dimension reduction tool, is used to perform dimensionality reduction in the proposed method. A SVD of an $M \times N$ matrix A, representing the T-FD of the EEG signal x, is given by

$$A = U \sum V^T \tag{1}$$

where $U(M \times M)$ and $V(N \times N)$are orthogonal matrices, and $\sum$ is an $M \times N$ diagonal matrix with singular values as below,

$$\sum = diag(\delta_{11}, \delta_{22}, \ldots, \delta_{kk}, \cdots) \text{ and } \delta_{11} > \delta_{22} > \cdots > 0 \tag{2}$$

The columns of U and V will be denoted respectively as u_k,v_k, and are called left and right singular vectors of A. The singular values, δ_{kk} are real and positive valued. The rank, in other words the dimensionality of A, is directly related to the matrix $\sum$. The singular values (δ_{kk}) denotes the importance of individual singular vectors in the composition of the T-F matrix. In this sense, singular vectors corresponding to the larger singular values are considered more informative and representative in the composed T-F image. The rank of A, we denote as r, is the number of non-zero values in matrix $\sum$. The T-F image can be rewritten taking considering the SVD factorization as,

$$A = \sum_{k=1}^{r} u_k \delta_k v_k^T \tag{3}$$

Eq. (3) indicates that the EEG signal T-F image can be decomposed in terms of a summation of sub-images as,

$$A = \sum_{k=1}^{r} A_k \tag{4}$$

As different sub-images A_k are orthogonal so, $<A_i, A_j> = 0$, it indicates that different sub-images are independent and belong to different dimensionality. Besides, the representativeness of different sub-images (A_k) are characterized by its singular values. Therefore, we can effectively suppress the noise in EEG signal T-F image by truncating the rank of the noise contaminated image and obtain the low-rank approximation of the image.

2.2. EEG signal representation and reconstruction

The T-FD, a joint representation of a signal in both time and frequency domains, has been proved to be powerful tool for the demonstration of nonstationary features embedded in a signal. To obtain the TFD of an EEG signal $x(t)$, several techniques are available, such as the continuous wavelet transform (CWT), and Wigner-Ville distribution (WVD) the short-time Fourier transform (STFT). The efficacy of CWT heavily depends on the appropriate selection of shape factor and scale, thus it is not convenient in application. The WVD, due to the presence of cross-terms between different components, its application is limited. However, the STFT algorithm is easy to implement, and the STFT spectrogram gives the energy distribution and reveals intrinsic non-stationary feature of the original signal $x(t)$. At the same time, STFT is reversible, thus makes the reconstruction of signal components from the noise suppressed T-F image possible. Therefore, this paper uses STFT to obtain the T-F image of the noise contaminated EEG signal. The STFT of a EEG signal $x(t)$, with window function $w_s(t)$, can be formulated as

$$TF(\tau, f) = \langle x, w_{s,\tau,f} \rangle = \int_{-\infty}^{+\infty} x(t) w_s(t-\tau) e^{-ift} \mathrm{d}t \tag{5}$$

Since the STFT technique is constrained by the Heisenberg uncertainty principle, that is, the localization in time domain and the resolution in frequency domain cannot be obtained simultaneously, either of them can only be enhanced at the cost of the other one [34]. Therefore, it is very difficult to obtain the accurate target frequencies directly from T-F image. It is necessary to transform the SSVEP response pattern in noise suppressed time-frequency domain back to time domain for further commands identification. The inverse STFT (ISTFT) can be mathematically presented as

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} TF(\tau, f) w_s(t-\tau) e^{ift} \mathrm{d}f \mathrm{d}\tau \tag{6}$$

Therefore, in the proposed method, STFT is used to form a T-F image matrix for SVD based background noise suppression and artifacts cancellation in entire frequency-band. And then, the ISTFT is employed to transform the SSVEP response pattern to time domain for commands identification.