Abstract

Pattern Recognition Methods in Brain-Computer Interfaces Based on Motor Imagery and Steady-State Visual Evoked Potentials Electroencephalogram

Computational and medical science experts have designed an interaction module between a human brain and an external device; such systems are known as brain-computer interfaces (BCIs). Research on BCI has spread its contribution in different fields, including both medical and non-medical sectors. In BCI systems, brain signals are recorded while the subject performs a specific mental task of controlling an external device. Pattern recognition methods capture and convert the useful information present in the brain signals into commands to control the device. The most commonly used modality for the acquisition of brain signals is electroencephalogram (EEG) due to its advantages like non-invasive method and high temporal resolution. The popular EEG patterns in BCI are P300, sensorimotor rhythms (SMRs), event-related potentials (ERP), and steady-state visual evoked potentials (SSVEPs).

Despite its high use in BCI systems, EEG has certain limitations. The raw EEG signal is highly contaminated by environmental noises and other body movement artifacts such as eye blinks, head movements, electrocardiogram (ECG), and electromyogram (EMG). Hence, the first step in EEG signal analysis is the preprocessing of the signal to reduce artifacts and noises.

In BCI's medical applications, SMRs and SSVEPs have been finding wide applications, including rehabilitation of stroke patients, prosthetic arm control by amputees, and wheelchair control using patient's intentions. The SMRs, get activated during motor imagery (MI) tasks, which is a mental task associated with the imagination of movement-related activities in the body. In SSVEP-BCI, SSVEPs are originated in the occipital lobe of the brain while a person gazes at a flickering light visual stimulus. The MI and SSVEP

EEG signals are processed using preprocessing and pattern recognition methods and thus converted into commands. The main goal of this study is to introduce advanced signal processing algorithms for preprocessing and pattern recognition of MI-EEG and SSVEP-EEG signals.

In the preprocessing stage, we target eliminating the interference of the biopotential signals originating from other body parts than the brain. Ocular artifacts (OAs) are interfering eye-related biopotential signals found in EEG due to eye muscle activities such as eyeblink and eyeball movement. Elimination of OAs is a primary step for the successful design of a BCI system. Numerous methods like Independent component Analysis (ICA), and Principal Component Analysis (PCA) are extensively used to remove OAs, but these methods involve multi-channel EEG signals for processing. Since BCI systems target using less number of channels for user comfortability, there is a need for an algorithm to remove OAs from single-channel EEG. In this thesis, we have proposed the use of dual-tree complex wavelet transform (DTCWT) with quantum-inspired adaptive wavelet threshold algorithm for the elimination of OAs from single-channel EEG signal. An experimental study is conducted to compare the proposed method's performance with traditional methods such as DWT-soft threshold, DWT-hard threshold, DTCWT-soft threshold, and DTCWT-hard threshold. We have estimated Relative Root Mean Square Error (RRMSE). Results show better performance in the reduction of ocular artifacts when using DTCWT with quantum-inspired adaptive threshold.

The signal processing of MI-EEG signals includes temporal, spectral, and spatial analysis of the EEG data to extract MI task-related information from the raw signal. In advanced methods, various combinations such as temporal-spectral, spectral-spatial, and time window optimization in spectral-spatial analysis have been explored to improve efficiency.

In temporal and spectral analysis models, feature extraction using statistical and power spectral density in frequency domain methods are used to create a feature vector. However, high feature dimensions of the extracted feature vector emerge the need for an appropriate feature selection algorithm that can improve the classification performance and computational speed of the classifier. To improve MI-BCI performance, we propose a novel method to regularize neighbourhood component analysis (NCA) for the MI data's feature selection. Firstly, features are extracted based on time, frequency, and phase analysis of EEG using dual-tree complex wavelet transform. Further, relevant features are selected using regularized-NCA (RNCA). Then, a support vector machine (SVM) classifier has been employed to perform the classification task. The effectiveness of the proposed method is compared with the widely used feature selection techniques such as Principal component analysis (PCA), ReliefF, and Genetic algorithm (GA) in terms of classification accuracy, kappa coefficient, and the number of features selected. The average classification accuracy and kappa value achieved using RNCA are 80.7% and 0.615, which are the most significant values compared to baseline feature selection methods. Also, the proposed algorithm dramatically reduces the number of features selected and results in increased computational speed. Obtained superior results indicate that the proposed RNCA based feature selection method has the potential to improve the classification performance of an MI-based BCI system.

In the spatial analysis of MI-EEG signals, the most commonly used method is common spatial patterns (CSP). Advancements in conventional CSP method are explored since conventional CSP method obtains suboptimal classification accuracy because it uses a fixed wider frequency band for spatial feature extraction. Advanced CSP variants aim to optimize the frequency bands within CSP. Specifically, EEG data is filtered into multiple narrow frequency bands using filters, and then spatial features are extracted using CSP.

However, frequency band optimization within CSP increases the dimensions of the feature space. Also, CSP's performance is dependent on the type of filter technique used. To tackle these issues, we designed a DTCWT based filter bank to filter the EEG into sub-bands instead of traditional filtering methods, which improved the spatial feature extraction efficiency. After filtering EEG into different sub-bands, we extracted spatial features from each sub-band using CSP and optimized them by the proposed supervised learning framework based on NCA. Subsequently, SVM is trained to perform classification. An experimental study, conducted on two datasets (BCI Competition IV (Dataset 2b) and BCI competition III (Dataset IIIa)), validated the MI classification effectiveness of the proposed method in comparison with standard algorithms such as CSP, Filter bank CSP (CSP), and Discriminative FBCSP (DFBCSP). The average classification accuracy obtained by the proposed method for BCI Competition IV (Dataset 2b) and BCI Competition III (Dataset IIIa) are 84.02±12.2 and 89.1±7.50, respectively, and found significant than that achieved by standard methods. Achieved superior results suggest that the proposed algorithm can improve the performance of MI-based Brain-computer interface devices.

Besides frequency band optimization in spatial analysis, time window optimization can further enhance the MI signal classification performance because there occur inconsistent time latencies in MI EEG for different subjects in response to MI tasks. For time window optimization, EEG is segmented into multiple time windows. Thus, the final feature space has spatial-spectral features extracted from each segmented EEG time series. However, the dimensionality of the feature space increases with the addition of time windows. The features space becomes a higher-order tensor EEG data. Most previous models optimized the tensor EEG by converting the tensor into a larger matrix using unfolding and concatenating approaches. However, this method disturbs the internal structure of the tensor data and results in suboptimal classification accuracy. To solve this issue, this study proposes a novel multi-view feature selection method based on regularized neighbourhood component analysis to optimize time windows and frequency bands simultaneously. In the experiment, we extracted spatial features using common spatial patterns (CSP) from MI-related EEG data at multiple time windows and frequency bands and optimized them using the proposed feature selection method. A support vector machine is trained to classify optimized CSP features to identify MI tasks. The proposed method achieved classification accuracies on three public BCI datasets (BCI competition IV dataset 2a, BCI competition III dataset IIIa, and BCI competition IV dataset 2b), which are 82.1%, 91.7%, and 84.5%, respectively. Obtained results are superior to those obtained using standard competing algorithms. Hence, the proposed multi-view learning approach for simultaneous optimization of time windows and frequency bands of MI signals shows the potential to enhance a practical MI BCI device's performance.

The signal processing of SSVEP-EEG includes feature extraction and classification steps. One of the challenges in SSVEP signal processing is to detect the user's idle state, i.e., when the subject does not gaze at any of the stimuli. Existing methods detect idle state as one of the target classes and results in suboptimal Information Transfer Rate (ITR). These are considered false positives. To alleviate this issue, we propose a class labeling method where a classifier is trained against the non-target class. In the experiment, features are extracted using Canonical Correlation Analysis (CCA), and class labeling is performed using the proposed method. Afterward, Linear Discriminant Analysis (LDA) has been employed for classification. The results of the proposed method were compared with standard methods such as CCA and Fast Fourier Transform (FFT), we implemented all the methods for the same experimental setup. The proposed method was found to be highly accurate, and it successfully overcame the issues found in previous methods.

Keywords:

Brain-computer interface; Dual-tree complex wavelet transform; Motor imagery; Neighbourhood component analysis; Steady state visual evoked potentials.