PhD Proposal

EEG Source Reconstruction for Brain-Computer Interfaces

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INTRODUCTION

Brain-computer interface (BCI) research deals with establishing a direct communication pathway between the human brain and an external device. Many studies demonstrate the feasibility of the concept and the research is rapidly approaching a level of first-generation medical practice. Driven by advances in acquisition technology and signal processing, it is expected an increased impact in nonmedical applications as well, particularly in the gaming, automotive and robotics industries. BCIs already have achieved successes justifying the claim that controlling certain functions by neural interfaces will have a significant impact in the future operation of computers, wheelchairs, prostheses and robotic systems, besides the potential benefits to those with severe motor disabilities, such as brainstem stroke, amyotrophic lateral sclerosis or severe cerebral palsy.

BCIs can be broadly classified in non-invasive and invasive systems, depending on the placement of the electrodes used to measure the neuron activity on the scalp or directly into the cortex, respectively. The signal processing methods used to extract features and interpret user's intent depend on the recording modality, including electroencephalography (EEG), electrocorticography (ECoG), local field potentials (LFPs) and single-neuron action potential recordings (single units). Among all, the EEG-based BCI is perhaps the most studied interface by taking advantage of the available knowledge of EEG research and novel machine learning techniques. However, their applicability to the full set of functions needed in the unrestricted interaction of a subject with the environment is still limited. The main reason lies in the diffuse and unspecified correlation of the macroscopic brain activity with the subject's behaviour.

EEG signals result from the activity of large number of neurons whose activity is synchronous, containing time-domain signals phase-locked to events, such as the P300 and motor potentials. These field potentials also contain frequency-domain signals such as the mu-rhythm associated with motor imagery. The major challenges facing the development of BCIs are the difficulties of the automatic recognition procedure and the low signal-to-noise ratio (SNR). Besides measurement noise, the low SNR results from brain processes that do not correlate with the relevant mental activity and from smearing effects of the electric field by different conduction layers in the head. Designing a BCI based on less noisy brain sources, instead of their surface projections, seems a promising direction.

This PhD proposal focuses on source-based BCIs as an alternative design approach for advanced non-invasive BCIs. In this context, estimating the number, locations and waveforms of inner brain sources, referred as the EEG source reconstruction, represents the crucial task. The aim of EEG source reconstruction is to find the brain areas responsible for EEG waves of interest and it consists of solving forward and inverse problems. The forward problem is solved by starting from a given electrical source and calculating the potentials at the electrodes. These evaluations are necessary to solve the inverse problem which is defined as finding brain sources which are responsible for the measured potentials at the EEG electrodes. The research activities will be conducted in the context of the IEETA Computational Neuro-Engineering Research Group dedicated to the development of non-invasive BCIs for control and biometry [1-3].

OBJECTIVES

The main objective of this work is to make a contribution to the on-going research associated with the development of novel EEG-based source estimation methodologies. A second motivation is to extract principles that might be used for novel engineering implementations of BCIs. In line with this, the proposed work is directed along the following main lines:

1. **Studying the generators of EEG and head models to solve the forward problem.** On the one hand, this work will focus on multi-dipole models that assume the brain source activity can be represented by a few equivalent current dipoles. On the other hand, the head geometries should comprise both approximate spherical models and realistic shaped models. The main difference lies in the solution of the forward problem: analytical solutions exist for simplified geometries (*e.g.*, three-shell spherical head model representing brain, skull and scalp). However, realistically shaped head models obtained from 3D medical images require numerical methods, such as the boundary element method (BEM), the finite element method (FEM) and the finite difference method (FDM).
2. **Implementing novel mathematical solutions for the inverse problem.** The inverse problem aims to estimate the neural sources (number, location and time series) inside the brain that best explain the potential differences on the scalp. First, the widespread projection of source activities across the scalp surface implies that the inverse problem is ill-posed, requiring additional constraints and assumptions to be solvable. Second, given the wide variety of EEG inverse solutions found in the literature, the selection of the appropriate method is a difficult task that should reflect the specific application purpose. Research on this topic should cover and surpass the state of the art by placing the emphasis on Beamforming and Particle Filter approaches. Both emerged as unifying frameworks for EEG source reconstruction, comprising well established methods and offering promising new solutions. The main foci of interest are the source localization of fixed and moving sources with different levels of correlation.
3. **Comparing the performance from simulated and experimental data.** In spite of recent advances, numerous challenges still remain for an objective assessment of the relative performance of inverse algorithms and the statistical significance of different solutions computed from simulated and experimental data. Statistical testing will be conducted to assess the significance of several effects (*e.g.*, number of sources, dependencies and SNR) on robustness and other evaluation scores in different scenarios. At the same time, additional research efforts are needed to expose the implications of the inverse solution for designing and implementing novel BCIs.

REFERENCES

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