論文の内容の要旨

論文題目

Supervised Learning over Matrices with Dual Spectral Regularization and Its Application to Single Trial EEG Classification

（和訳　双対スペクトル正則化を用いた行列上の教師あり学習とその単一試行 EEG 判別への応用）

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要旨

This thesis consists of three main contributions. The first contribution is to theoretically analyze and provide alternative views on popular techniques in motor imagination based brain-computer interface (BCI) from a statistical learning point of view. In particular for the common spatial pattern (CSP) algorithm we present a discriminative view as a lower-bound to the likelihood of a regularized logistic regression model as well as a generative view as a non-stationary de-mixing model. The common spatio spectral pattern (CSSP) algorithm is greatly simplified by a symmetry assumption on the time-delayed covariance matrix. Moreover a practical method for spatio-spectral filter optimization called SPEC-CSP is proposed. The second contribution is to unify the feature extraction and classification steps in single trial EEG analysis under a discriminative framework. We propose a regularized logistic regression model that directly works on the pair-wise covariances between electrodes; the conventional two steps are unified into a single optimization problem. We demonstrate that the rank=2 parameterized variant of the logistic regression model performs comparable to the conventional CSP based approach and is extremely robust to outliers. The last contribution is to introduce the dual spectral norm regularization for supervised learning problems over matrices in general. Prediction problems over matrices arise naturally in many fields. The dual spectral regularization provides automatic factorization of linear models over matrices; in fact, the L1 nature of the regularization forces many singular-values of the coefficient matrix to be zero. The dual spectral regularization can be considered as a convex alternative to the non-convex rank constraint. Additionally this sparseness allows good interpretation of the solution. Moreover, we propose an efficient optimization algorithm based on the interior-point method. The convex duality plays a key role in the implementation. We apply the logistic regression model with the dual spectral regularization to the classification of P300 visually evoked response and the motor imagination based BCI. In the P300 experiment, the classifier performs comparable to the best known models and uses only few spatial/temporal factors. on the motor imagination datasets, the classification performance is significantly improved against L2-regularized logistic regression, rank=2 approximated logistic regression as well as CSP based classifier. Connections to LASSO, kernel methods with the second order polynomial kernel are discussed. All methods presented in this thesis are tested on 162 real motor imagination BCI datasets.