Controllable Spatio-Temporal Smoothness Constraints for EEG Source Localization

Damon Hyde1 and Simon Warfield1,1 Children’s Hospital Boston and Harvard Medical School

Surgical Interventions In Epilepsy:

Epilepsy is a chronic neurological disorder which affects over 2.5 million Americans and has an estimated total health care cost of close to $132 billion annually. The disease is caused by disturbances in the normal electrochemical functioning of the brain. This can be due to developmental anomalies, brain injury, or even in some cases, genetic factors. Approximately 75% of epilepsy patients have been shown to have some form of neuroimaging abnormality. These abnormalities are critical in localizing the seizure focus. However, the current clinic standard for localization electrocorticography, which involves placement of electrodes directly on the exposed cortex.

Seizure Focus Localization:

Surgical success is largely dependent upon the accurate identification of the seizure focus. However, the current clinic standard for localization, electrocorticography, has several disadvantages:

1. Highly invasive: Placement and removal of electrodes requires the use of a craniotomy. This is a highly invasive procedure which may involve significant risk to the patient.
2. Limited Sensing: Because of the risks involved, electrocorticography is performed only on those patients considered the best surgical candidates.

MRI Acquisition and Segmentation:

Current clinical MRI is intended primarily for examanalytical. Typically, several systems use only 20-30 electrodes, placed manually based on head measurements. The limited measurements do not provide sufficiently dense sampling of the scalp to yield good spatio-temporal information. Emerging EEG systems are based around headcap type systems incorporating increased number of electrodes. By using a head-cap with more electrodes (As many as several hundred electrodes) can be used. Photometry techniques are used to identify the relative location of each individual electrode. For use with patient-specific biowave, the source plane should be further conformed to the patient’s MRI scan.

Patient Specific Modeling:

To model electrical propagation within the head, we generate patient-specific models of the electrical conductivity. Fine differences models are constructed on a hemispheric mesh defined at the resolution of the MRI acquisition. Additional finite element models are generated using ScanIP and its integrated Biomedical3D pipeline. While many anisotropic models are obtained from fMRI scans.

The lead-field basis approach is used to construct the source model. It can also be used to measure the presence of current sources between the brain.

Time series EEG data averaged over 128 inter-cortical spikes showing change in scalp voltage distribution.

Bayesian Source Estimation:

Given a linear prior \( P(x|y) \) for \( x \), with \( y \) a zero-mean white Gaussian with covariance \( 1/2 \) the maximum posterior solution will be:

\[
\hat{x}(t) = \arg \min_{x} \{ \mathbf{W}^T \mathbf{x} - y(t)^2 \} + \frac{1}{2} \mathbf{x}^T \mathbf{V}^{-1} \mathbf{x}
\]

For multiple time points, the prior becomes \( \mathbf{W} \) and the minimization:

\[
\hat{x}(t) = \arg \min_{x} \{ \mathbf{W}^T \mathbf{x} - y(t)^2 \} + \frac{1}{2} \mathbf{x}^T \mathbf{V}^{-1} \mathbf{x}
\]

Is chosen, with \( \mathbf{x} \) containing only spatial derivatives, and \( \mathbf{y} \) containing only temporal derivatives, then the discretized version:

\[
\hat{x}(t) = \arg \min_{x} \{ \mathbf{W}^T \mathbf{x} - y(t)^2 \} + \frac{1}{2} \mathbf{x}^T \mathbf{V}^{-1} \mathbf{x}
\]

Can have the linear operator rewritten as:

\[
\mathbf{W}^T \mathbf{S} + \mathbf{W} \mathbf{S}^T \mathbf{W}
\]

To be rewritten as:

\[
\mathbf{W}^T \mathbf{S} + \mathbf{W} \mathbf{S}^T \mathbf{W}
\]

This significantly reduces the overhead required to work with the matrix \( \mathbf{W} \), and makes it feasible to obtain lowest level square solutions using approaches such as the conjugate gradient method.

Choice of Regularization:

For regularization, we choose the function:

\[
\Omega(\mathbf{r}) = \mathbf{r}^T \mathbf{V} \mathbf{r}
\]

This function applies a spatially weighted Heuristic-type equation in both the spatial and temporal dimensions. This has the effect of enforcing local smoothness within the solutions. In discretized form, the two matrices are:

\[
\mathbf{W}^T \mathbf{S} + \mathbf{W} \mathbf{S}^T \mathbf{W}
\]

With \( \mathbf{W} \) being a diagonal matrix with elements equal to the norms of the associated columns of the leadfield matrix. The approach originated as the weighted minimum norm approach, and is also used in the common LORETA solution algorithm.

The temporal matrix is similarly written as:

\[
\mathbf{W} \Omega_\mathbf{L} \mathbf{J}_\mathbf{F}
\]

Here, the temporal weighting function \( \omega(t) \) is encoded in the matrix \( \Omega_\mathbf{L} \): \( \Omega_\mathbf{L} = \mathbf{w}(t)^T \), \( \mathbf{J}_\mathbf{F} = \mathbf{w}(t)^T \mathbf{w}(t) \).

The assumption here is that the measurement noise is uniform across all time points. Therefore, weighting by the inverse of the signal norm will appropriately adjust the regularization applied to each timepoint according to the time-varying signal to noise ratio.

Controllable Correlation:

Our choice of regularization function was done specifically to allow an increased degree of control over the covariance induced in the model. In a basis space, the Laplacian operator, used in techniques such as LORETA, implies high correlation between widely separated voxels. However, in an infinite space, the correlation between any two points will be a function of the parametric gamma and the distance between them.

\[
C(r) = \frac{1}{1 + \gamma r^2}
\]

Gamma can be used as a controlling “correlation distance” within the volume.

Constraints for EEG Source Localization

Controllable Spatio-Temporal Smoothness

Controllable Correlation

Conclusions

Coupled Bayesian Source Localization is Computationally Feasible

The combination of temporal with higher spatial resolution results in solutions which complicate changes in time. These can potentially be used to examine the propagation of seizure activity to more accurately identify the true seizure focus.

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