SABRE: Seizing Advances in Bci from high Resolution Eeg imaging in runtime

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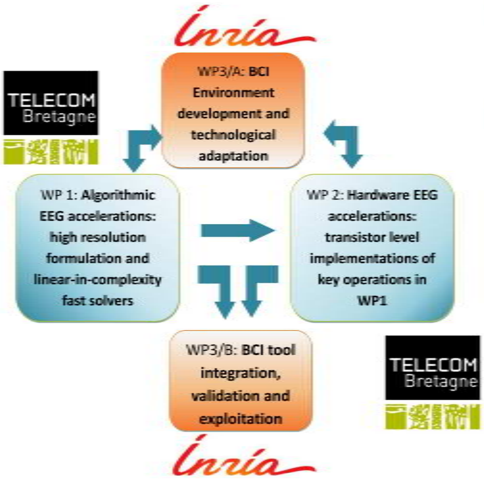
General Description

Aim of the project:

Translating computational expensive Epilepsy imaging algorithms in runtime with mutually-inspired techniques in software and hardware acceleration and final integration in the INRIA BCI open source package OpenVibe.



Background

Forward Brain Propagation Models

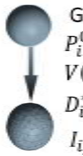
- Adjoint Double Layer Operator :

$$D^{*}\varphi=\int_{\partial\Omega}\partial_n G(r-r')\varphi(r')\partial_s r'$$

- Integral Equation Adjoint Double Layer Formulation

$$\frac{\sigma_j+\sigma_{j+1}}{2(\sigma_{j+1}-\sigma_j)}V_j(r)-\sum_{i=1}^{N}(\sigma_{j+1}-\sigma_j)D^{*}(V_i(r))=\partial_n v_j(r)$$

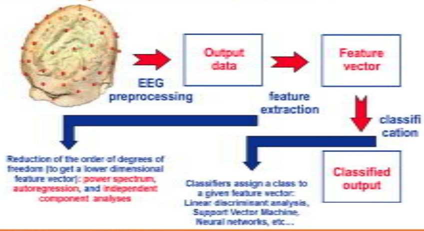
Standard Discretization and Testing



Galerkin approach:
$P_i^0 \in H^{-1/2}$ functions for basis and testing :
$V(r) \approx \sum_{j=1}^{N} \alpha_j P_j^0$
$D_{ij}^* = \langle P_i^0, D^* P_j^0 \rangle$ and
$I_{ij} = \frac{\sigma_k+\sigma_{k+1}}{2(\sigma_{k+1}-\sigma_k)}\langle P_i^0, P_j^0 \rangle$

The system equation then writes: $[Z][A] = [\Phi]_j$
with $[Z]_{ij} = -D_{ij}^*$ *and* $[Z]_{ii} = I_{ij} - D_{ij}^*$
$[\Phi]_j = \langle P_i^0, \partial_n v_{s,j} \rangle$ and $[A]_j = \alpha_j$

Brain Computer Interface Chain



Achieved Results
Mixed EEG Formulations

Definition Domain of the Integral Operators

$$D*: H^{\frac{-1}{2}}(\Gamma) \rightarrow H^{\frac{-1}{2}}(\Gamma)$$

→ Testing should be done in the dual space of the range of the operator

→ In particular D* is not tested in a correct way : $P_i^0 \in H^{-1/2}$ functions are too irregular

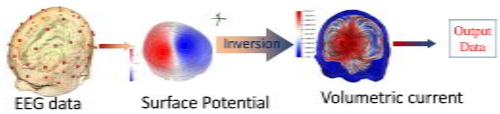
→ Use $\tilde{P}_i^1 \in H^{1/2}$,Buffa Christiansen, functions defined on the dual mesh

→ New mixed formulations

$D_{ij}^* = \langle \tilde{P}_i^1, D^* P_j^0 \rangle$ and $I_{ij} = \frac{\sigma_k+\sigma_{k+1}}{2(\sigma_{k+1}-\sigma_k)}\langle \tilde{P}_i^1, P_j^0 \rangle$

$[Z][A] = [\Phi]_j$ with $[\Phi]_j = \langle \tilde{P}_i^1, \partial_n v_{s,j} \rangle$

The Inverse EEG Problem



Challenges: EEG problem is an ill-posed problem :

1) a lack of accuracy in the forward solution will increase the current reconstruction
2) a substantial computational cost given that the forward problem has to be solved multiple times
3) Building Z: storage complexity $O(N^2)$ and solving the forward problem $O(N^3)$

Achieved Results
Linear-in-complexity algorithmic accelerations

Algorithmic Acceleration

Z is full rank → identify sub-blocks of sparse matrix using octrees

- Octrees give a hierarchical decomposition of the mesh
- Get hierarchical decomposition of Z and interactions list
- Decompose the matrices as :

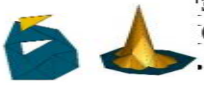
$$S = S_n + S_f \quad D = D_n + D_f \quad D^* = D_n^* + D_f^*$$

n = near interactions
Usual way of computation
Sparse matrix
Complexity O(N)

f = far interacting
Numerical integration
Use sparse matrix multiplication

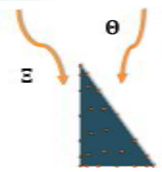
$$S\varphi=\int_{\partial\Omega}G(r-r')\varphi(r')\partial_s r'$$
$$D\varphi=\int_{\partial\Omega}\partial_n G(r-r')\varphi(r')\partial_s r'$$

- Use Gaussian integration rules



$[\Xi]_{ij} = w_i A_j$ complexity O(N)
$[\Theta]_{ij} = w_i \tilde{P}_1(r) A_j$ complexity O(N)

- Hierarchical decomposition of G:



$$[W]_{ij} = \begin{cases} \frac{e^{ik|r_i-r_j|}}{|r_i-r_j|} \ (1) & \text{for} \int G dr_i \\ 0 \ (2) & \end{cases}$$

$$[\Lambda]_{ij} = \begin{cases} \hat{n}_{r_i} \cdot \nabla \frac{e^{ik|r_i-r_j|}}{|r_i-r_j|} \ (1) & \text{for} \int \nabla G dr_i \\ 0 \ (2) & \end{cases}$$

(1) if the integration points r_i and r_j do not belong to the same smallest partition, (2) otherwise.

→ $S = S_n + \Xi^T W \Xi$, $D^* = D_n^* + \Xi^T \Omega \Xi$ and $D = D^{*T}$
→ $\tilde{D}^* = \tilde{D}^*_n + \Theta^T W \Xi$ for the mixed discretization

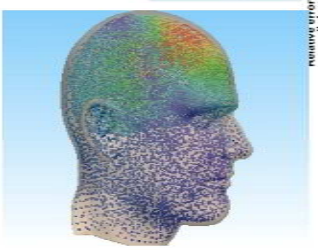
- Adaptive Cross Algorithm (ACA) for the submatrices,
→ Complexity O(N log(N))

Achieved Results
Validations and performance assessments

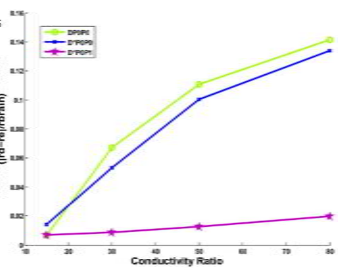
Realistic accelerated source reconstruction

EEG data at 256 electrodes + Head geometry description

Forward Model + Acceleration + Inverse Algorithm

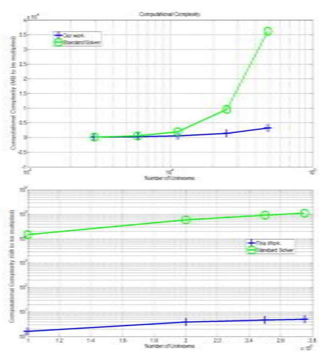


Highly accurate mixed formulations



- Similar advantages have been observed for the new mixed discretizations when their noise resistance is comparatively assessed

Efficiency of the Acceleration

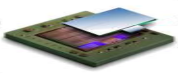


On-going and future work

BCI Integration

- Development of specific OpenVibe tools to handle the high number of channels (256) of the available EEG device
- On going experiments to validate the interfacing of the Accelerated EEG brain imaging tools with OpenVibe

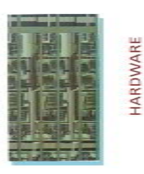
Hardware Acceleration



Perform computationally critical operations on a full-custom hardware

- Intel Core I7-5960X: 112GM/s

Circuit integration:



- Xilinx Virtex 7 980 T : 2667GM/s
  24h -> 1h
- Ad-hoc full-custom circuit (BiCMOS 250nm): 20000GM/s
  24h -> 8min