Imaging of cerebrovascular accident through High Performance Computing

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Figure: Pierre Jolivet, Frédéric Hecht, Pierre-Henri Tournier, Frédéric Nataf, Victorita Dolean

Imaging of Cerebrovascular Accidents (CVA) through HPC
Cerebrovascular accidents (CVA)

120 000 people each year in France
Two types of cerebrovascular accidents:

- **ischemic** (80%)
- **hemorrhagic** (20%)

The therapy strongly depends on the diagnosis:

- ⇒ thin the blood
- ⇒ lower blood pressure

Imaging of Cerebrovascular Accidents (CVA) through HPC
Imaging of CVAs

In order to distinguish between ischemic and hemorrhagic CVA, CT scan or even better MRI are currently used. **Electromagnetic tomography systems** (∼ 1 GigaHertz) are investigated.

<table>
<thead>
<tr>
<th></th>
<th>CT scan</th>
<th>MRI</th>
<th>Microwave imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>excellent</td>
<td>excellent</td>
<td>good</td>
</tr>
<tr>
<td>Safety</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mobility</td>
<td>∼</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Cost</td>
<td>∼ 300 000 €</td>
<td>∼ 1 000 000 €</td>
<td>&lt; 100 000 €</td>
</tr>
<tr>
<td>Accessibility</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Monitoring</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
</tbody>
</table>

Importance of rapid stroke intervention: "*Time is Brain*
Monitoring: Clinicians wish to have an image every fifteen minutes
Microwave Imaging

EMTensor company, Vienna, Austria.

First prototype: cylindrical chamber with 5 rings of 32 antennas each.

New technologies: sensors miniaturization, high capacity mobile networks (4G-5G), massively parallel computations.
Since year 2005:

- CPU frequency stalls at 3 GHz due to the heat dissipation wall. **The only way to improve the performance of computer is to go parallel.**
- Power consumption is an issue:
  - Large machines (hundreds of thousands of cores) cost 10-15% of their price in energy every year.
  - Smartphone, tablets, laptops (quad - octo cores) have limited power supplies.
Need and Opportunities for massively parallel computing

Parallel computers are more and more available to scientists and engineers

- Apple, Linux and Windows laptops, 2/4 cores
- Desktop Computers, 6/12 cores
- Laboratory cluster, 300 cores
- University cluster, $\sim$ 2000 cores
- Cloud computing on Data Mining machines
- Supercomputers with more hundreds thousands of cores via academic (CNRS, GENCI, IDRIS, PRACE, ...) or commercial (BULL, HP, IBM, ...) providers

All fields of computer science are impacted.
Physical and Mathematical modeling

Let $\Omega$ be a dielectric material, linear, isotropic, non magnetic, dispersive and dissipative.

For each emitter $j$ from 1 to $5 \times 32$, the electric field $E_j$ satisfies Maxwell system of equations:

\[
\begin{cases}
\nabla \times (\nabla \times E_j) - \kappa E_j = 0, & \text{in } \Omega, \\
E_j \times n = 0, & \text{on } \Gamma_{\text{metal}}, \\
(\nabla \times E_j) \times n + i\beta n \times E_j \times n = g, & \text{on } \Gamma_j, \\
(\nabla \times E_j) \times n + i\beta n \times E_j \times n = 0, & \text{on } \Gamma_k \text{ with } k \neq j,
\end{cases}
\]

where $\kappa := \mu_0 \left( \omega^2 \varepsilon + i\omega \sigma \right)$ where $\mu_0 > 0$, $\omega$, $\beta$ are known physical parameters, $\varepsilon > 0$ and $\sigma > 0$.

Imaging the brain is recovering the field $\kappa \in \mathbb{C}$ that matches measurements.

Challenge: Imaging at least every 15 minutes – Real time HPC
Inverse problem

In order to image the brain, we recover the field $\kappa \in \mathbb{C}$ which minimizes the squared error between measurements and computed values:

$$J(\kappa) = \frac{1}{2} \sum_{i=1}^{160} \sum_{j \neq i} \left| S_{ij}(\kappa) - S_{ij}^{obs} \right|^2 dx,$$

where $S_{ij}(\kappa)$ depend on solutions $E_j(\kappa)$ to

$$\begin{cases} \nabla \times (\nabla \times E_j) - \kappa E_j = 0, & \text{in } \Omega, \\ E_j \times n = 0, & \text{on } \Gamma_{\text{metal}}, \\ (\nabla \times E_j) \times n + i\beta n \times E_j \times n = g, & \text{on } \Gamma_j, \\ (\nabla \times E_j) \times n + i\beta n \times E_j \times n = 0, & \text{on } \Gamma_k \text{ with } k \neq j, \end{cases}$$

This non linear minimization problem is solved in parallel with a BFGS algorithm. Many computations

Challenge: Imaging at least every 15 minutes – Real time HPC
Two in-house open source libraries (LGPL) linked to many third-party libraries:

- HPDDM (High Performance Domain Decomposition Methods) for massively parallel computing
- FreeFem++(-mpi) for the parallel simulation of equations from physics by the finite element method (FEM).
Parallel Software tools: HPDDM and FreeFem++

**HPDDM**
- Implements parallel algorithms: Domain Decomposition methods and Block solvers
- 2 billions unknowns in three dimension solved in 210 seconds on 8100 cores
- Interfaced with FreeFem++ and Feel++
- can be interfaced with a C++, C or Python code

**FreeFem++**
- versatile parallel simulation tools: fluid and solid mechanics, electromagnetism, quantum physics, ... 
- documentation in English (Franglish say), Japanese, Spanish and Chinese
- used for teaching (universities and "Grandes écoles"), research, prototyping in some big companies and in some small/medium companies as a production code
Imaging with massively parallel computations

High Performance Computers Turing (IDRIS, CNRS) and Curie (TGCC, CEA) via GENCI grants.
Several levels of parallelism:

- Sliced image reconstruction
- Cost function evaluation
- Domain Decomposition Methods

Figure: Wall clock time vs. # cores
Inverse problem
Imaging

Proof of concept
Time to image : 320 seconds $\simeq$ 5 minutes $<$ 15 minutes

Figure: Evolution of a CVA: exact sections of a 3D image and its reconstructed image, 10% noise
Feasibility of a mobile imaging of CVA
Conclusion

- Medical imaging modality based on new technologies:
  - many sensors
  - mobile fast communication
  - and many cores computers
  - parallel flexible tool for scientific simulations

- With IoT (Internet of Things) many other applications can be envisioned e.g. Precision agriculture

![Figure: Precision agriculture](image_url)

- Parallel computers are more and more readily available but software developments still lag behind
Thanks to (1/2)

Our employers

Our laboratories: IRIT (Toulouse), LJLL and Inria Team Alpines (Paris), JAD (Nice)
Thanks to (2/2)

Funding based on projects

- **ANR MEDIMAX 2013-2017**: led by Christian Pichot from Laboratoire d’Electronique, Antennes et Télécommunications (Nice). Collaboration between applied mathematics laboratories (LJLL and MAP5, Paris, JAD, Nice), electrical engineering teams (LEAT, Nice and informally EMTensor, Vienna)

- Computing hours (millions of) and technical support on large HPC supercomputers with hundreds of thousands of cores: Curie (CEA, BULL) and Turing (CNRS, IBM) via GENCI or PRACE calls
Imaging of cerebrovascular accident is feasible thanks to High Performance Computing

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