Electromagnetic inverse problems in biomedical engineering

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Overview

1. Introduction
2. Localization of magnetic markers in the alimentary tract
3. The influence of forward model conductivities on EEG/MEG source reconstruction
4. Optimization of magnetic sensor arrays for magnetocardiography
5. Validation of source reconstruction procedures
Magnetocardiography (MCG)

- Measurement of magnetic field produced by the heart
- Reconstruction of electric sources causing the field
Magnetocardiography (MCG) provides non-invasively information about the electrical activity of the heart.
Introduction

• New room temperature optical magnetometers allow customized and flexible sensor arrangements

• Arising question: how do we arrange the sensors optimally?

• Goal function: condition number (CN) of the lead field (LF) matrix
BEM model

Torso

Lungs

Ventricular blood masses
Source space

13 current dipoles, distributed around the left ventricle of the heart
The objective function

- LF matrix contains information on geometry of the source space, the boundary element model and the sensor array
- A minimal CN implies an optimal sensor arrangement for a given setup
Discretization of the search space

- Optimization: iterative search for a sensor setup with minimal CN
- But LF computation is slow, therefore pre-computation for a fixed grid of positions & orientations is needed
Constraint Framework for Continuous Optimizers

• Discrete search volume
  → snap into grid before each CN evaluation

• Minimum distance (MD) of sensors, here 2 cm
  → while mean(MD violation) > tolerance
  1. pick a sensor with max #clashes
  2. move all clashing sensors away radially
  3. snap into grid

• Pro: one representative sensor out of the clashing sensors is kept
Restoring the minimum distance

Representative

Untouched

Physical search

volume

2 cm
Particle Swarm Optimization (PSO)

- A set of candidate solutions (= particles) is randomly initialized
- Each particle has a position and velocity in high-dim. search space
- Each particle has informant particles, whose state it can access
- Iteration = move particles + update velocities + fix constraint
- After constraint fix, the velocities are corrected
PSO algorithm
PSO velocity correction

Particle = current solution

Velocity

Shift due to constraint

New Velocity

$\frac{1}{2}$ the shift length

High-dim. search space
Tabu Search (TS)

- Discrete search: combinatorial selection of $s$ out of $r$ sensors with minimal CN
- The minimum distance constraint is satisfied for all sensor selections
- In each iteration step: find a better selection of $s$ sensors (with lower CN) in the neighborhood of the current solution by exchanging $n$ sensors (during the search $n$ was decreased from $s/2$ to 1)
PSO vs. TS

- TS prevents reevaluations of sensor configurations by memorizing them
- TS is robust against local minima
- But: no use of spatial closeness or gradient, limited to combinations of predefined sensor positions/orientations
- Dense grids (i.e. a higher number of sensors on the same area) may be more difficult to optimize than sparse ones because of the combinatorial complexity
Numerical Results

- PSO and TS are implemented in C++ in SimBio: TS (green) and PSO (blue) optimized setups are very similar.
Reduction of CN

- Both optimizations significantly reduce CN
Conclusion

• Comparable results indicate that optimization of vectorial sensor setups may be significantly improved
• Reconstruction robustness may be improved and the number of sensors may be reduced while retaining information in terms of CN
• The new quasi-continuous PSO optimization incorporates the gradient and spatial closeness information while being robust against local minima in the goal function
• A fine 3D search volume, projection method based and lower error bound based sensor setup optimizations are planned

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   1. Simulations
   2. Phantom measurements
   3. Animal measurements
Simulations

4-layer sphere model:
- Radii: 92, 86, 80, 78mm;
- Conductivities: 0.33, 0.0042:0.042, 1.79, 0.33 S/m
- Nodes: 161,086
- 134 electrodes

Simulations

Dipole localization error

Forward: J.C. de Munck
Inverse: FEM

Simulations

Dipole orientation error

Forward: J.C. de Munck
Inverse: FEM

Simulations

Dipole magnitude error

Phantom measurements
Phantom measurements

Liehr, Haueisen et al. Annals of Biomedical Engineering, 2005
Phantom measurements
Phantom measurements

Wetterling, Haueisen et al. IEEE TBME, in revision, 2008
Animal measurements

• Combined ECoG and MEG measurements in rabbits
• median nerve / tibial nerve
  – current 0.2 - 0.5 mA
  – Interstimulus interval 503 ms
  – 2048 averages
  – latency
    • 15 - 20 ms (median nerve)
    • 20 - 24 ms (tibial nerve)
Animal measurements

Combined electric measurements (ECoG) with Compumedics Neuroscan Synamps
Animal measurements

Median nerve

Tibial nerve

Electric measurements
Animal measurements

Median nerve

Tibial nerve

Magnetic measurements
Animal measurements

Median nerve

Time point: 17 ms (P1)
Increment: 5 fT

Tibial nerve

Time point: 21 ms (P1)
Increment: 5 µV

Magnetic measurements
Animal measurements

Source localization setup

- 16 MEG pick up coils
- 16 electrodes
- One compartment model
Animal measurements

Comparison median and tibial nerve

dip 1 - median nerve: 44.8/46.6/50.5 mm; dip 2 - tibial nerve: 46.2/48.2/50.3); calculated dipole distance 2.1 mm
Influence of anisotropy

median and tibial nerve

isotropic

with anisotropy

isotropic
Validation results

- Validation in a spherical model successful
- Validation with two stimulus modalities successful
- Validation BEM and FEM successful
- Influence of anisotropy within the procedural limits for median and tibial nerve stimulation
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