The 3rd Russian-Chinese School on Mathematical Modeling and Parallel Computing:

SIAT-Sechenov Competition on Numerical Modeling of Bioimpedance Analysis

Sechenov University, Moscow, Russia   SIAT, Shenzhen, China

Rules of the competition

1. **Dates:** October 25, 2021 – November 26, 2021

2. **Objective of the competition:** developing students' problem-solving capabilities by searching appropriate software or related solutions through independent research; experiencing design of a full technological chain, from medical image to sensitivity analysis.

3. **Participants:** 4-5 groups of students (10-15 students from SIAT and 10-15 students from Sechenov University, 5-6 students per group), tutors from both sides, judges.

4. **Competition Schedule:**

Phase 1. Medical image segmentation (October 25 – November 4)

Phase 2. Mesh generation (November 5 – November 10)

Phase 3. FEM discretization (November 11 – November 15)

Phase 4. Parallel solution of linear systems (November 16 – November 22)

Phase 5. Analysis of results (November 23 – November 26)

5. **Deliveries:** Each phase is completed by requested deliveries which are assessed by the judges awarding scores.

 Awards are given according to the total score accumulating scores of each phase:

 - The First Prize is given to 1 group,

 - The Second Prize is given to 1 group,

 - The Third Prize is given to 1 group,

 - The Honorable Mention is given to the other groups.

The First and the Second Prizes imply participation in the student exchange program for 2022 between SIAT and Sechenov University for all members of the winning group. The First Prize grants 9-days visit: arrival Saturday morning, departure Sunday evening. The Second Prize grants 7-days visit: arrival Monday morning, departure Sunday evening. The Third Prize is a diploma. Each member of each group will receive a certificate of a participant of the competition.

Problem setting

The final objective is computation of the sensitivity function for a tetra-polar (i.e. with four electrodes) scheme of bioimpedance measurements. The sensitivity function distinguishes parts of the human body whose pathological changes of resistivity may be detected by chosen positions of electrodes.

Two pairs of electrodes are attached to the body surface in chosen locations. One pair is used to inject current (current-carrying electrodes, CC), another pair is used to measure the impedance (pick-up electrodes, PU). The following mathematical equations are used to compute the electric current in the body [1]:

$$\mathrm{div}(\mathbf{C}\nabla U) = 0 \quad \text{in} \quad \Omega, \tag{1}$$

$$(\vec{J}, \vec{n}) = \pm I_0/S_{\pm} \quad \text{on} \quad \Gamma_{\pm}, \tag{2}$$

$$(\vec{J}, \vec{n}) = 0 \quad \text{on} \quad \partial\Omega \backslash \Gamma_{\pm}, \tag{3}$$

$$\vec{J} = \mathbf{C}\nabla U. \tag{4}$$

In these equations Ω is the computational domain, $\partial\Omega$ is its boundary, $\Gamma_{\pm}$ are the electrode contact surfaces, $\vec{n}$ is the outward unit normal vector, U is the electric potential, $\mathbf{C}$ is the conductivity tensor allowing to describe anisotropic materials, $\vec{J}$ is the current density, I_0 is the electric current, $S_{\pm}$ are the areas of the electrode contacts. Each contact is represented by a disk with $1cm$ diameter. Equation (1) determines the distribution of electric field in the domain with heterogeneous conductivity $\mathbf{C} = \sigma\mathbf{I}$, see table 1. Additional conductivity properties for other tissues may be obtained from online database [2]. Equation (2) sets the constant current density on the contact surfaces for one electrode pair, $I_0 = 1mA$. Equation (3) defines the no-flow condition on the boundary.

Table 1: Reference conductivity σ of human body tissues (Sm/m) at electric frequency 50 kHz

Bones	0.05203
Fat	0.02425
Heart	0.19543
Liver	0.07204
Lung	0.26197
Muscle	0.35182

In order to perform the sensitivity analysis, we introduce the reciprocal lead field $\vec{J}'_{\mathrm{reci}}$ which is equal to current density vector field generated by a unit current excitation using the two PU electrodes. Field $\vec{J}'_{\mathrm{reci}}$ is computed from $\vec{J}'_{\mathrm{reci}} = \vec{J}_{\mathrm{reci}}/I_0$, where $\vec{J}_{\mathrm{reci}}$ is computed from (1)-(4), with electrode surfaces $\Gamma_{\pm}$ corresponding to PU electrodes and $I_0 = 1mA$. The distribution of the sensitivity field is computed as

$$S = \vec{J}'_{\mathrm{cc}} \cdot \vec{J}'_{\mathrm{reci}}, \tag{5}$$

where $\vec{J}_{\mathrm{cc}}$ satisfies (1)-(4) with $I_0 = 1mA$ and electrode surfaces $\Gamma_{\pm}$ corresponding to the CC electrodes, $\vec{J}'_{\mathrm{cc}} = \vec{J}_{\mathrm{cc}}/I_0$.

The boundary value problem (1)-(4) is solved approximately by a P_1 finite element method on a tetrahedral mesh which recovers basic organs and tissues of the human torso. The sensitivity function (5) is computed from the finite element approximation of the electric potential U.

The position of electrodes should provide the best sensitivity to right lung hydration monitoring: one pair of electrodes (CC_1, PU_1) is located on the frontal surface of the chest near the top of the right lung, another pair of electrodes (CC_2, PU_2) is on the loins on the back near the bottom of the right lung.

Phase 1. Medical image segmentation

Input data: Computed Tomography (CT) image in DICOM format (unique image for each group)

Output data: Segmented image in MetaImage format with description of labels

The goal of the image segmentation is to prepare an anatomical model from a medical image. Students can find appropriate software or related solutions through independent research (any algorithm is applicable: threshold-based, user-guided active contours, or deep learning algorithm, or any other, or their combination).

Evaluation: maximum score 15.

Students should provide the corresponding label dataset of the segmented tissues or organs (bones and lungs are obligatory), the remaining part of the torso should be distinguished from bones and lungs and exterior space. Therefore, at least 4 labels should be set, and in case of correct segmentation, the 4-label segmentation gives 10 points. Additional credits will be given for additional segmentation of the heart ($+1$), the liver ($+1$), and muscles ($+1$), since they have impact on the simulation results. Correct segmentation of additional organs/tissues is awarded by 1 or 2 points. The assessment of segmentation correctness is based on one of standard metrics, such as Jaccard Index, DICE, etc. However, due to lack of the ground truth segmentation for all organs, these metrics will be calculated only for a limited set of organs (e.g. lungs, liver).

A list of labels with their meaningful description should be provided. This list will be used to assign conductivity properties to different tissues.

Phase 2. Mesh generation

Input data: Segmented image in MetaImage format

Output data: Unstructured consistent tetrahedral mesh in Paraview (open source software) format

Any two cells of a consistent mesh either have no intersection, or they share an entire face, or entire edge, or one common vertex. Each mesh cell should be labeled with one material, corresponding to a material represented in the segmentation.

Evaluation: maximum score 10.

The mesh should be provided in Paraview format so that the Judges can evaluate the grid correctness: its topological correctness (consistent mesh, no degenerate and tangled elements $+3$), good shape quality of the cells ($+1$), anatomical correctness (smoothness of organs $+1$) and correspondence to the segmented image. No more than 1 million nodes $+1$. Recovery of all segmented organs/tissues $+1$. Anatomically correct meshes with moderate number of nodes (less than 0.3 million nodes) with heart, lungs, liver, muscles $+1$. Accounting of positions of electrodes for future simulation $+2$.

Phase 3. FEM discretization

Input data: Unstructured tetrahedral mesh in Paraview or any other text format, with description of cell labels

Output data: Sparse linear systems in CSR (compressed sparse row) text format

The CSR text format is:

```
N
IA_1 .. IA_N+1
JA_1 .. JA_NNZ
```

```
A_1 .. A_NNZ
b_1 .. b_N
```

The first line contains the order of the matrix, the next line contains array IA with N+1 elements. The number of matrix nonzero elements NNZ is equal to IA[N+1] - IA[1]. The following lines contain arrays JA and A each with NNZ elements. The final line contain the right hand side b with N elements.

The finite element method with P1 linear basis functions should be used for discretization of equations (1)–(4) on the mesh generated at Phase 2. The conductivity coefficients in each mesh element should be defined by the element label and the list of label descriptions.

The boundary conditions are prescribed to the boundary faces with specific labels from the label description file. Two pairs of linear systems should be generated: one for current-carrying pair of electrodes, and one for pick-up pair of electrodes. Both systems will share the same matrix and will differ only in their right hand sides.

Evaluation: maximum score 5.

If the system is inconsistent, it gets 0 score, no extra points are given. The code is delivered to judges and they compare the time cost per degree of freedom. The fastest time gets 5 points, the slowest one gets 3 points, the others get 4 points.

Phase 4. Parallel solution of linear systems

Input data: Sparse linear systems in CSR text format

Output data: Two solution vectors in plain text format (N lines with one value per line).

Evaluation: maximum score 10.

If the residual is not zero (machine epsilon), it deserves 0 score, no extra points will be given. Any method of successful solution (even non-parallel) is awarded by 5 points. Parallel solution by OpenMP +1, MPI +1, hybrid solution (OpenMP&MPI +3). The code is delivered to judges and they compare parallel efficiency and time per degree of freedom. The best parallel efficiency gets +1. The best time per degree of freedom gets +1.

Remark. Finite element solution of (1)–(4) is not unique: addition to a solution vector of a constant vector results in a valid solution as well. The linear solver should be able to find at least one solution for the linear system. The sensitivity function (5) depends only on the gradient of U, and the kernel of FEM matrices will not alter it.

In case of the iterative solution, an appropriate preconditioner may reduce the computational time.

Phase 5. Analysis of results

Input data: Solution vectors and unstructured tetrahedral mesh

Output data: Visualization of the mesh and the solution

The following open source package is recommended for visualization:

- ParaView (`https://www.paraview.org/`)

Evaluation: maximum score 10.

Demonstration of correct solution isosurfaces gives 5 points. Demonstration of correct current lines +2. Demonstration of correct sensitivity field (scalar product of current densities) +3. The sensitivity function (5) in each mesh cell may be computed in different ways. One option is to use your favorite FEM package to compute gradients of the potential, another option is to use ParaView filters to compute gradients and scalar products.

Regions with high positive sensitivity will show the most sensitive parts of the body for specific tetrapolar electrode scheme. For example, Figure 1 shows high sensitivity zone in red and negative sensitivity zone in blue for the conventional wrist-to-ankle 4-electrode scheme: two electrode pairs on right arm and right leg.

Figure 1: Sensitivity analysis of the conventional 4-electrode scheme: red zone indicate high positive sensitivity, blue zone indicate negative sensitivity. The skeletal bones are added to the image to improve perception.

For more information about post-processing we refer to [1]. An online numerical simulator of bioimpedance measurements [3] is available for reference sensitivity fields.

Final evaluation

The final evaluation coincides with evaluation of Phase 5. Each group should give a 15-minute presentation to showcase their work and final results to the Judges.

References

[1] Danilov A., Rudnev S., Vassilevski Yu. (2018) Numerical Basics of Bioimpedance Measurements. In: Simini F., Bertemes-Filho P. (eds) Bioimpedance in Biomedical Applications and Research. Springer, Cham. https://doi.org/10.1007/978-3-319-74388-2_8

[2] Hasgall P.A., Di Gennaro F., Baumgartner C., Neufeld E., Lloyd B., Gosselin M.C., Payne D., Klingenböck A., Kuster N., IT'IS Database for thermal and electromagnetic parameters of biological tissues, Version 4.0, May 15, 2018, DOI: 10.13099/VIP21000-04-0. https://itis.swiss/database

[3] Online simulator for bioimpedance measurements — https://dodo.inm.ras.ru/bia/