Integration of data and model in cardiac electrophysiology

Mehdi Juhoor, Marc Fuentes

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Introduction

Carmen team aims to build complete realistic models of the electrical activity of the heart. The study of such models is a multistep process, which can be summarized by 3 main steps:

- preprocessing phase to obtain meshes and parameters from imaging and experimental data
- use a numerical simulator to solve cardiac electrophysiological models
- postprocessing phase to visualize, analyze and confront results to reality

Acquisition → Registration → Segmentation → Meshing → Numerical Simulation → Analysis & Visualization

Motivation

On the one hand, building complex anatomical meshes raises **major issues**:

- time-consuming
- error-prone
- specific expertise needed
- require multiple softwares

On the other hand, the computing time for numerical simulation is proportional to the complexity of the model and the size of the domain.
Main goal: **streamline** all the workflow from preprocessing to postprocessing in the MUSIC environment.

MUlti-modality platform for Specific Imaging in Cardiology

MUSIC is a joint *Liryc* and *Inria* platform used to visualize and process cardiac imaging and electrical data.

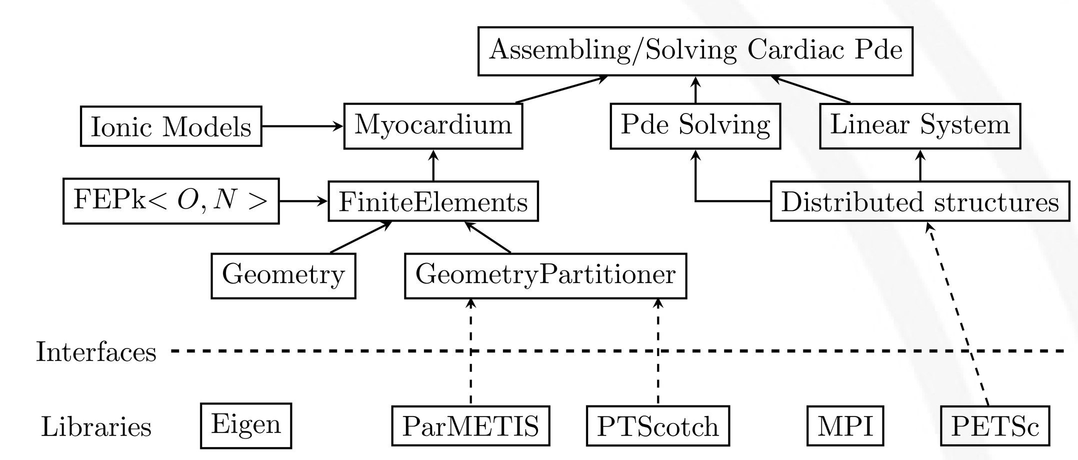
- toolboxes organized in workspaces for image and surface mesh processing
- pipeline architecture, a step-by-step approach for a given problem

Our aim: **expand** the possibilities of MUSIC by adding toolboxes and implementing specialized pipelines.

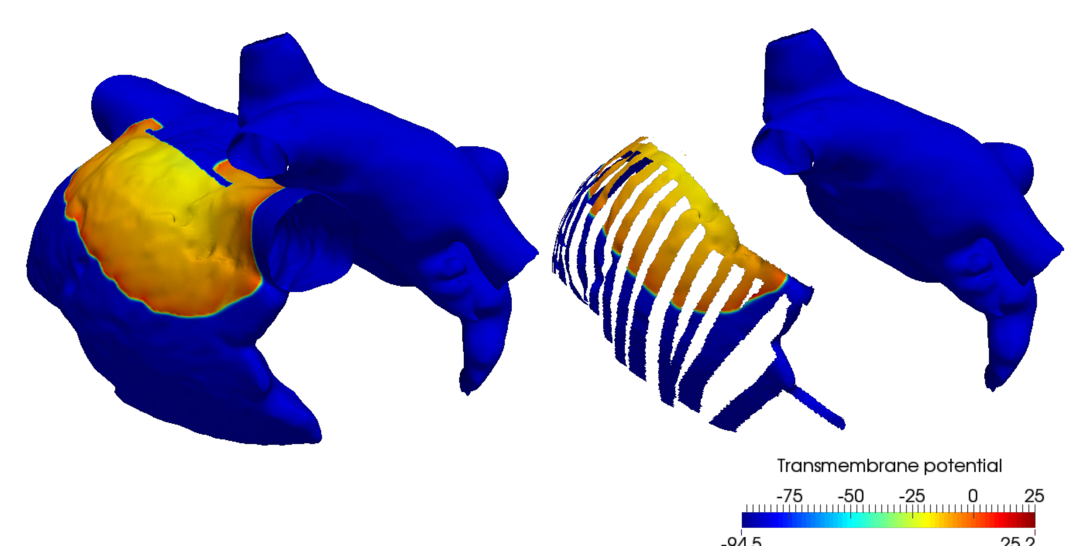
About CEPS Software

The Cardiac ElectroPhysiology Simulator aims to integrate a broad range of multiscale models, and to make use of computing capacity of clusters. It features:

- finite elements P1/P2
- simple or bilayer monodomain model
- multidimensional meshes (1D/2D/3D)
- supported I/O formats: VTK, Medit and Tetgen
- hard-coded ionic models: TTNP, CRN, MS, BR
- multistep time integration schemes : Rush-Larsen , SBDF
- parameters file with simple syntax
- distributed memory parallelism : `MPI` and PETSc
- programmed in `C++11` with templates and dynamical polymorphism



Overview of the module organization in CEPS



Wavefront using bilayer atria model.

The monodomain model

The monodomain model describes the evolution of the transmembrane potential V_m in myocardial tissue Ω .

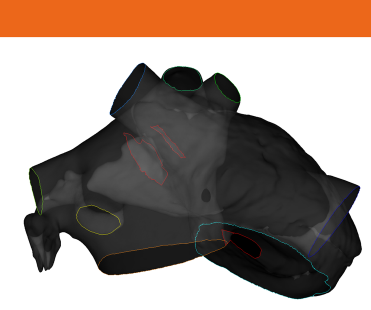
$$\chi(C_m\partial_t V_m + I_{ion}(V_m, w)) = \text{div}\,(\sigma\nabla V_m) + I_{app} \quad \text{on } \Omega$$
$$\partial_t w + g(V_m, w) = 0 \quad \text{on } \Omega$$
$$(\sigma\nabla V_m)\cdot n = 0 \quad \text{on } \partial\Omega$$

Toolbox examples

Utility tools on meshes

Regroups common operations on meshes

- append, clean, merge
- conformity and manifoldness
- hole detection
- quality metrics

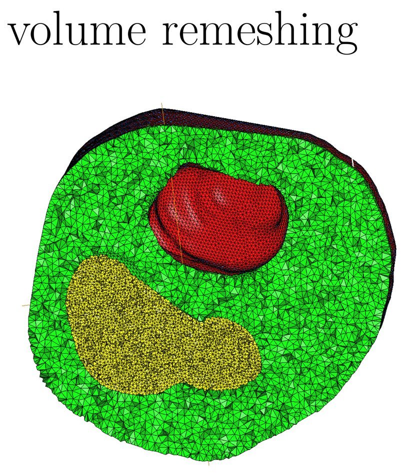


Rings on atria surface mesh.

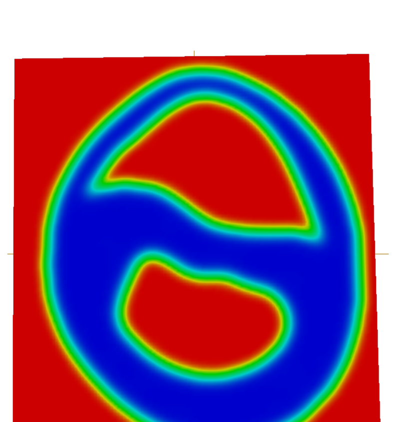
Volume and surface meshing

Specialized libraries to generate high quality meshes.

- Tetgen: volumic meshing from piecewise linear complex. Able to specify holes inside the volume
- MMG suite: implicit domain meshing, surface and volume remeshing



Tetgen generated mesh with different volume constraints.

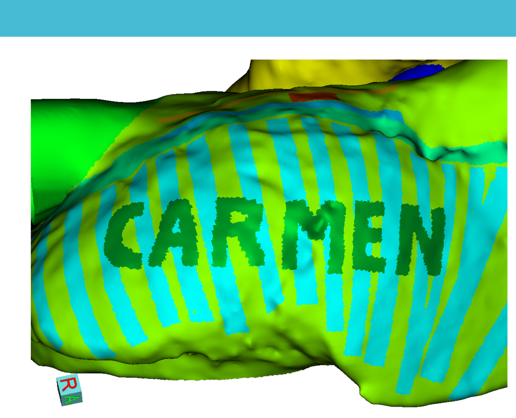


Level-set function as input to MMG3D.

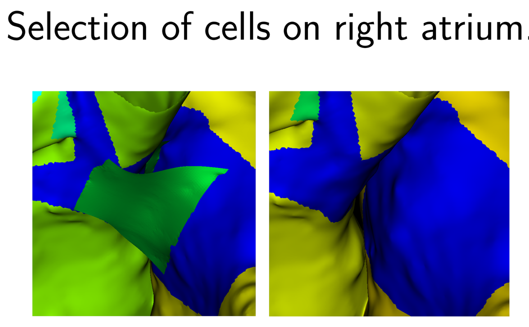
Region selection

Gathers multiple tools to **enrich and modify** a geometry

- selection tools: paint, region, and shape selection
- removal of cells and points
- modify labels and attributes



Selection of cells on right atrium.



Removal of Bachmann bundle.

Pipeline example: inverse problem

Imaging:

- CT-scan or MRI
- segmentation step, creates masks:
  - torso
  - lungs
  - rib-cage
  - pericardium
- mask filtering

→ **Meshing:**

- associate masks with regions
- volumic meshing using multiple constraints
- verify conformity and quality

→ **Simulation:**

- generate input file with simulation parameters
- launch numerical simulation process on cluster

→ **Postprocessing:**

- import results
- visualization and analysis

Future works

CEPS

- P3 finite elements
- bidomain model
- *shared memory* parallelism (`OpenMP` or `Intel TBB`) for ionic models
- look-up tables to accelerate evalutions of ionic models

MUSIC

- reconstruction of fiber direction
- improve existing toolboxes
- extend visualization interface
- generate customized pipelines
- visualize simulation results