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CEPS: a cardiac electrophysiology exploration tool for new mathematical models and methods

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Summary

Cardiac activity is regulated by the propagation within the heart muscle of an electric action potential (AP), which follows a specific synchronized pattern in normal conditions. Defects in the tissue or metabolic changes can lead to pathological propagations and cardiac arrhythmias, which are a major cause of death around the world.

Electrophysiology simulation tools at tissue scale are required to better understand the normal and pathological function of the heart, and could also be used as design tools for new medical devices and therapies.

Statement of need

CEPS stands for Cardiac ElectroPhysiology Simulator. The goal of this software is to freely provide a set of models and advanced numerical methods as a base for research on new models and methods to solve cardiac problems. CEPS focuses on the electric function of the heart: mechanical models that simulate muscle contraction or blood flow are not part of the software.

Developed since 2012 in the Inria CARMEN team, CEPS is designed as an exploration tool: computational efficiency is not its primary aim, contrary to other electrophysiology software that are more suited to production such as openCARP (Plank et al., 2021), Propag (Potse, 2018) or CHASTE (Cooper et al., 2020). Nevertheless, CEPS runs on parallel architectures with a level of performance which is reasonable for academic studies of direct problems. A strong effort on the clarity of the implementation, documentation and software quality assurance has been conducted to ease the use of CEPS and to make contributing relatively accessible, even for students that are freshly trained in applied mathematics and/or programming.

Main features

CEPS is a C++ code, parallelized with MPI using domain decomposition. CEPS runs simulations on 1D, 2D and 3D simplical meshes (segments, triangles, tetrahedra). Several meshes of different dimension can be given at the same time and coupled. The solvers for partial differential equations are based on Lagrangian finite elements. The software should be compatible with any Linux distribution and macOS. Windows users can run CEPS in Windows Subsystem for Linux. CEPS is developed and tested via continuous integration on Ubuntu machines.

On top of the standard *monodomain*, *bidomain* and *bidomain-with-bath* models of electrophysiology, CEPS offers several features, that were the product of our research:

- *Current-lifted monodomain* model (Coudière & Rioux, 2012): a more accurate way to approximate the bidomain model than the monodomain model, with a similar computational cost as the monodomain model.
- *Bilayer monodomain model for atria* (Labarthe et al., 2014): a model that simulates both layers of the atria with a single surface mesh.
- *Volume fraction* (Davidović et al., 2021): a way to modulate the tissue conductivity from a single scalar field that describes the fraction of healthy tissue per unit volume.
- *Stimulation by a pacemaker* (Pannetier et al., 2025): cardiac tissue can be stimulated by a realistic current pattern, with full coupling to the bidomain model.
- *High-order exponential numerical schemes* (Coudière et al., 2020),(Coudière et al., 2018) suited for cardiac ionic models.
- *Automated convergence tests*: we provided an easy way to convert the resolution of a single problem which depends on time and/or space into a convergence study.

Usage

CEPS runs exclusively in a non-interactive way, because it is intended to be launched in batch mode on computing clusters, and easily integrated in scripts. This means that all the runs must be completely parametrized beforehand. Simulation parameters are passed through a single YAML file, which may refer to other input files such as meshes or data files for spatially varying coefficients. A comprehensive list of all possible inputs can be found in the online documentation. The documentation and downloaded files also include examples of YAML input files for each of the main problems that can be solved with CEPS.

Software quality

Among the 400+ unit and non-regression tests that are part of continuous integration, twelve of them are run to check that CEPS solves accurately the benchmark problems that were proposed in (Pathmanathan & Gray, 2014), and suggested by the FDA to validate cardiac electrophysiology software. We also documented CEPS results of the (Niederer et al., 2011) benchmark and other convergence results for cardiac solvers. Additionally, we use the SonarQube linter to maintain good software quality as we code.

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CEPS uses the fkYAML library to parse YAML files.

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