UNIVERSITÀ DI PISA

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Dottorato di Ricerca in Ingegneria dell'Informazione

Doctoral Course

"Physics-based modelling for information engineers: a practical guide"

Prof. Chiara Magliaro, Eng. Ermes Botte

Department of Information Engineering – University of Pisa, Italy
chiara.magliaro@unipi.it, ermes.botte@ing.unipi.it

Short Abstract:

Multi-physics and physics-based modelling represent important tools to support quantitative analyses and parametric design for different engineering problems, including the structural evaluation of complex mechanical parts, the functional assessment of power supply systems, transducers and smart materials (*e.g.*, piezoresistive, magnetostrictive), the implementation of electromagnetic field sources and the optimization of culture conditions in engineered cellular systems.

The course aims at introducing the students to physics- and multi-physics-based modelling in the field of information engineering using the finite element method (FEM), with a particular focus on biomedical applications.
The first part of the course will provide them with the basics for developing, solving and handling results of FEM models in the COMSOL Multiphysics environment. Specifically, simple dynamical systems involving (bio)physical phenomena concerning transport and reaction of chemical species, heat transfer and solid mechanics will be presented. Then, the second part of the course will be devoted to hands-on sessions on the software, identifying applications relevant to the PhD activities of the students.

Course Contents in brief:

- Brief introduction to physics- and multi-physics-based modelling using FEM
- COMSOL Multiphysics: an easy-to-use interface for FEM modelling in information engineering
- Less is more: geometrical and physical symmetries and definition of the space dimension
- Design of easy and complex geometries and meshing (predefined and customized)
- Study design: solver choice, steady-state and time-dependent models, parametric sweep
- Data handling: result post-processing and visualization

- Using and combining specific modules (“Fluid flow”, “Transport and reaction of chemical species”, “Heat transfer” and “Structural mechanics”) for modelling simple multi-physics systems
- Identification and implementation of specific models relevant to the PhD field of the students

Total # of hours of lecture: 24 (6 CFU)

References:

[1] Berger E, Magliaro C, Paczia N, *et al*. (2018). *Millifluidic culture improves midbrain organoid vitality and differentiation*. Lab on a chip. doi.org/10.1039/C8LC00206A.

[2] Magliaro C, Rinaldo A and Ahluwalia A (2019). *Allometric Scaling of physiologically-relevant organoids*. Scientific Reports. doi.org/10.1101/559682

[3] Botte E, Biagini F, Magliaro C, *et al*. (2021). *Scaling of joint mass and metabolism fluctuations in in silico cell-laden spheroids*. Proceedings of the National Academy of Sciences (PNAS). Doi.org/10.1073/PNAS.2025211118.

[4] Biagini F, Botte E, Calvigioni M, *et al*. (2023). *A millifluidic chamber for controlled shear stress testing: application to microbial cultures*. Annals of Biomedical Engineering. doi.org/10.1007/s10439-023-03361-4.

CV of the Teachers

Chiara Magliaro is a Biomedical Engineer. She got her PhD with honours in 2016. For the high quality of her work, she also got the certification for the European Doctorate (Doctor Europaeus), and the award for the best Italian PhD Thesis (premio Massimo Grattarola). She won for two years the Fondazione Umberto Veronesi Post-Doctoral Fellowship, in 2018 and 2019. She is the coordinator of the European Innovation Council Pathfinder Project NAP (GA 10109310), which aims at developing an innovative, personalised models of the human brain for studying sleep pathophysiology. Currently, she is a tenure-track Researcher at the Department of Information Engineering (DII).

Main research focuses:

- Development of imaging protocols and methods for tissue processing, single neuron segmentation and 3D morphometric extraction from confocal/two-photon datasets representing densely packed neurons in their native arrangement within the brain and cellular models of the brain. The quantitative morphological analysis of the micro-structure could be useful to better understand the structure-function relationship within the brain.
- Multi-physics and physics-based modelling of nutrient transport and diffusion in engineered *in vitro* constructs. The real-time monitoring of cellular behaviour in *in vitro* constructs at different complexity (from traditional monolayers, up to cell-laden spheroids and organoids) is crucial for defining quantitative metrics and determining the physiological relevance of engineered constructs.

Ermes Botte graduated in Biomedical Engineering with honours in 2019 and achieved the professional qualification as Industrial Engineer in 2020. In 2023, he got his PhD in Information Engineering with honours. Currently, Ermes is a post-doctoral fellow at the Department of Information Engineering (DII) and lecturer of "Transport phenomena in biological systems" for the bachelor's degree course in Biomedical Engineering at the University of Pisa.

Main research interests:

- Studying metabolic scaling phenomena in artificially generated cellular systems (from single cells up to complex architectures of 3D cell aggregates, such as spheroids and organoids) through computational models and experimental measurements of transport and consumption of oxygen and nutrients. Predicting and accurately monitoring cellular metabolism and the associated scaling behaviour *in vitro* support the definition of biomimetic design constraints for the development of tissue engineering models with enhanced translational power.
- Modelling and experimental characterization of functional and behavioural variability of cells *in vitro*, *i.e.*, their fluctuations in terms of metabolism and motility. As physiological systems are known to be noisy, quantifying the inherent variability of cell cultures can provide a robust criterion to assess their human relevance and a reliable marker to discriminate between healthy and diseased states.
- Development of *in silico* tools enabling the estimation of nano-sized particle deposition and distribution in biological tissues and organs, supporting the assessment of nanomaterial-related hazard in the field of nanotoxicology.

Final Exam: Application of FEM modelling to the PhD topic of the student. Development, solution and result post-processing of a multi-physics model in the COMSOL environment. Oral discussion of the model and result interpretation (to be planned with the teachers by 3 months after the end of the course).

Room and Schedule:

<u>Room</u>
Meeting room of the Dipartimento di Ingegneria dell'Informazione, Via G. Caruso 16, Pisa – Ground Floor.

<u>Schedule</u> (4 – 21 March)

March 4th, Tuesday – 4h (9 – 13). Introduction to physics-based modelling and FEM. Overview of the COMSOL Multiphysics environment. Space dimension of a FEM model. Design of basic and advanced geometries using the built-in CAD toolkit. Import options of geometries designed using external CAD platforms. Assignment of material properties. Domain and boundary conditions. Meshing: physics-driven and user-defined.

March 5th, Wednesday – 4h (14 – 18). Steady-state and time-dependent simulations. Characteristic time(s) of the problem and the Deborah number. Numeric solvers in COMSOL Multiphysics. Parametric simulations. The "Structural mechanics" module: recap of governing equations and basic examples.

March 6th, Thursday – 4h (14 – 18). The “Fluid flow” module: recap of governing equations and basic examples. The “Transport and reaction of chemical species” module: recap of governing equations and basic examples.

March 7th, Friday – 4h (14 – 18). The “Heat transfer” module: recap of governing equations and basic examples. Multiphysics simulations: built-in and user-defined couplings. General hints on moving meshes, thermal stresses, fluid-structure interactions, reacting flows and non-isothermal flows.

March 14th, Friday – 4h (9 – 13). Implementation of relevant models identified together with students (part 1).

March 21st, Friday – 4h (9 – 13). Identification of relevant models identified together with students (part 2).