Modeling and optimization of soft micro-robots swimmers

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Context

Miniature robots able to travel and act inside the human body, for targeted drug delivery or minimally invasive diagnostics, could transform medicine, but designing and optimizing them remains extremely difficult. Predicting their motion requires solving the coupled elasticity-Stokes problem governing the interaction between the deformable robot and the surrounding fluid; high-fidelity finite-element models of this problem, such as those implemented in [2] using `Feel++` library (Figure 1), capture the physics accurately but are far too costly to be optimized directly. This internship explores how much this physics can be degraded, while retaining a sound understanding of the underlying phenomena, using a low-fidelity models with a differentiable framework in which a deformable body is discretized into a small number of generalized coordinates ([1]).

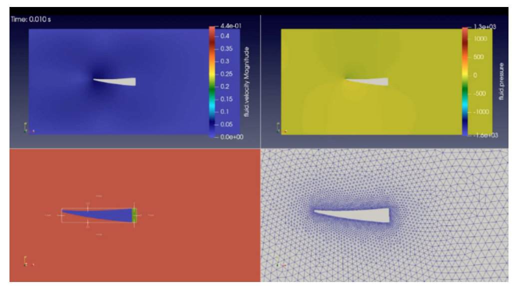

Figure 1: High-fidelity `Feel++` finite-element simulation of a deformable body coupled to a Stokes flow: fluid velocity magnitude (top left) and pressure (top right), the elastic body (bottom left), and the computational mesh (bottom right).

Objectives

The goal of the internship is to determine how closely a low-fidelity model can approach the predictions of the high-fidelity finite-element model of the coupled elasticity-Stokes problem solved with `Feel++` [2], and, in the long run, to optimize the low-fidelity model so as to recover the extrema (optimal shape/actuation) predicted by the high-fidelity one. The specific objectives are:

i. build a low-fidelity model of a soft micro-robot (using for instance the Soft Mobility toolbox [1]), in which the body is discretized into a chosen number of degrees of freedom;

ii. study how the predicted dynamics changes with this discretization, and identify from which resolution the low-fidelity model reproduces the high-fidelity `Feel++` simulations [2], whose code will be made available to the student;

iii. optimize the low-fidelity model, using both Bayesian optimization and direct (gradient-based) methods, to identify the configurations that extremize the robot's performance (e.g. speed, efficiency);

iv. compare these low-fidelity optima to those obtained with the high-fidelity model, to assess to what extent the degraded model recovers the true, high-fidelity optimal behavior.

This project is intended to train the student in advanced modeling, differentiable simulation, and optimization techniques, while contributing to bridge low- and high-fidelity descriptions of soft micro-robots. Motivated students will be encouraged to pursue their work on this topic with a PhD thesis.

References

[1] Eloy, C. (2026). Soft Mobility Theory. arXiv:2605.23869.
[2] Van Landeghem, C., Berti, L., Chabannes, V., Chouippe, A., Giraldi, L., Hoarau, Y., & Prud'Homme, C. (2024). Mathematical and computational framework for moving and colliding rigid bodies in a Newtonian fluid. Annals of Mathematical Sciences and Applications, 9(1), 59-89.