Internship on numerical methods for optimizing the locomotion of flagellated micro-swimmers

Keywords	Mathematical modeling, Numerical simulations, Fluid-structure interactions, Flagellated micro-swimmers, Optimization and Control.
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Hosting team	EPC Calisto, Inria Sophia Antipolis-Méditerranée

Context

Swimming bacteria, spermatozoa, or plankton are natural examples of self-propelled, active particles. These living microorganisms have the ability to deform or alter internal features according to their environment in order to achieve a specific goal. Finding inspiration from such adaptive behaviors is key for the design of artificial devices used in medicine[5]. Micro-robots are particularly appealing because they can reach selected locations, opening the way to an increased efficiency in targeted drug delivery and appearing as a minimally-invasive alternative to traditional surgery. Thus, this is expected to be of significant help to clinicians for diseases requiring to access difficult-to-reach regions of the body (cancer, thrombosis, eye surgery).

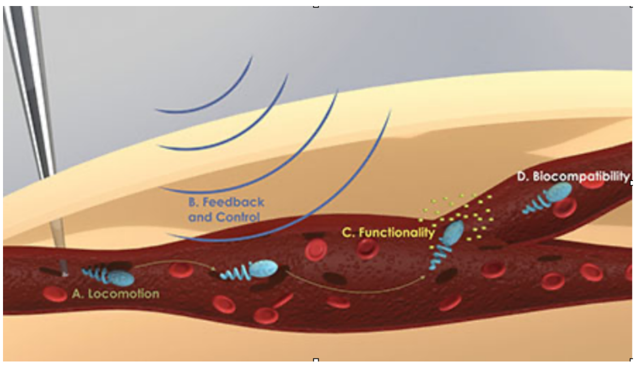

Figure 1: Sketch of micro-robots moving into a body.

Objectives

The internship focuses on bio-inspired micro-robots composed of a magnetic head and an elastic tail which are immersed in a laminar flow. Hereafter, we call this robot a Magnetozoon (see Fig 2). These robots Magnetozoon imitate the propulsion of spermatozoa by propagating a travelling wave along their flagellum. Their movement is controlled by an external magnetic field which produces a torque on the robot's head resulting in the deformation of the tail. The beating tail then pushes the surrounding fluid and makes it move. The advantage of such a deformable swimmer is its aptness to carry out a large set of swimming strategies, which could be selected according to the geometry or the rheology of the biological media where the swimmer evolves (blood, eye retina, or other body tissues). The main challenge is to design external magnetic fields that allow them to navigate efficiently in complex realistic environments.

The objectives of the internship is to model and simulate the Magnetozoon displacement under a prescribed magnetic field in the 3D confined spaces. The equations of motion derive from the coupling of Navier-Stokes equations or the Carreau-Yasuda laws governing the fluid flow, the hyper-elastic equations describing the swimmer's deformation and the magnetic torque representing the action of the external magnetic field on the swimmer's head. The fluid is assumed to be laminar (it means that it could move slowly).

The resulting system of PDE will be solved by the finite element methods (FEM) extending the Feel++ open source software[2,3]. Two strategies will be developed. The first approach is to use the ALE method. It consists in meshing the fluid and the solid, and the mesh is deformed following the solid deformation. Another approach is to develop Cut Finite Element (CUTFEM) type methods. This approach consists in moving the solid on a fixed fluid grid. In both approaches, parallel computing is required. Contact between boundaries and the swimmer i.e., lubrication effects should be studied. The simulations will be tested in various types of confined environments and could be calibrated with experiments. Optimizations using Statistical learning could be investigated[1]. Contact between boundaries and the swimmer i.e., lubrication effects should be studied.

Student is encouraged to write a publication at the end of the training period. The internship is directly associated with a PhD thesis within the NEMO's ANR project.

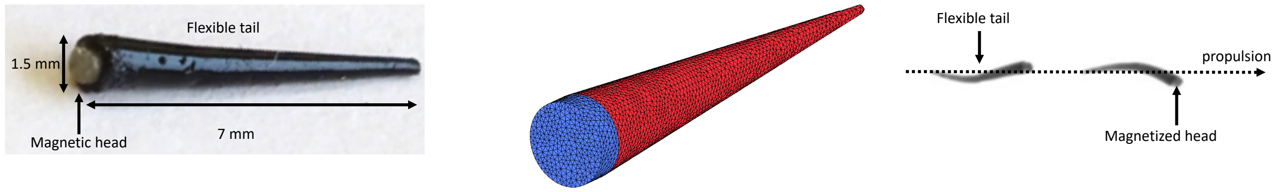

Figure 2: Scaled robot used in experiments called *Magnetozoon* and its digital twin. Swimmer evolving in an unconfined environment when actuated by a classical sinusoidal field[4]. A symmetric beating tail produces a straight displacement.

Candidate : He/she should have a background in applied mathematics (PDEs, Numerical methods, Numerical simulations, statistical learning, optimization). Students are encouraged to write a publication at the end of the training period. We strongly encourage student motivated to continue on a PhD thesis.

Practical aspects : The internship will take place at INRIA, Sophia-Antipolis within the team CALISTO. The student will also collaborate with the team of Christophe Prud'Homme at the mathematical laboratory of Strasbourg university. It covers a period of 6-7 months, from March-April to August-September. The exact date of departure is quite flexible and can be adapted to the constraints of the student. This work could result in a grant for a PhD thesis founding by NEMO's ANR project.

Application : Send a cover letter, a resume and a recommendation letter to laetitia.giraldi@inria.fr and christophe.prudhomme@unistra.fr.

References :

[1] Y.E. Alaoui-Faris, J.B. Pomet, S. Régnier, L. Giraldi. (2020) *Phys. Rev. E* **101** 042604
[2] L. Berti, L. Giraldi, C. Prud'Homme. (2019) *ESAIM: Proc. Surv.* **67** 46–60
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