Cemracs Project Proposal
Modeling and Simulation for the motion of deformable bodies in low-Reynolds flows. Applications to Magnetic Elastic Microswimmers and Cells under Flow in a Zebra Fish

Organizers :
- Laetitia Giraldi (laetitia.giraldi@inria.fr),
- Christophe Prud'Homme (christophe.prudhomme@cemosis.fr).
- Jacky Goetz INSERM (jacky.goetz@inserm.fr)
- Sébastien Harlepp (harlepp@ipcms.unistra.fr)
- Mourad Ismail (mourad.ismail@univ-grenoble-alpes.fr)

Modeling and Simulation of Deformable Bodies Motion in Low-Reynolds Flows

This project is concerned by the motion of deformable bodies in low-Reynolds flows and their interaction with the environment.
We consider two application domains in which the modeling and the simulation setting depart slightly from each other but they share nevertheless a lot of commonalities in particular in terms of modeling, numerical methods and implementation. Indeed we shall use in both cases the same computational framework in Feel++ (http://www.feelpp.org) which readily provides an advanced high performance toolbox for large scale fluid structure interaction. Note that in both cases the models are three dimensional.

Magnetic Elastic Microswimmer

This part of the project will focus on studying the motion of micro devices immersed into a fluid. At this length scale, locomotion presents a different set of challenges compared with those encountered by macroscopic robots. Most microorganisms live in fluid environments where they experience a viscous force that is many orders of magnitude stronger than inertial forces. This is known as the low Reynolds number regime characterized by instantaneous and time-reversible flows that are described by the time-independent Stokes equations.

A recent promising technique resides in using an external magnetic field to act on a magnetized micro-object by creating an external force or torque (see [3]). The robot experiences a deformation and then moves without requirement for chemical fuel or motor. The project focuses on a model which consists in a head magnetized and a flexible filament (see [1]).

The first objective is to simulate the motion of a 3D magneto-elastic micro-robot immersed into Stokes fluid, first far away from the boundary and in a second step, study the influence of the closeness of a boundary on the motion of the swimmer. The simulations will be done by using a finite element embedded library called Feel ++[1] (see [2]) and compare the results deriving with another approach that exploits an approximation of the hydrodynamic forces called the Resistive Force Theory (see [4]).

Within the collaboration with Institut des Systèmes Intelligents et de Robotique at UPMC (Paris), the simulation would be compare with real experiments.

The project allows the student to study mathematical model for fluid structure interaction, numerical methods, their implementation and the execution the simulation on supercomputer.

Bibliography

[1] F. Alouges, A. DeSimone, L. Giraldi, M. Zoppello. *Can magnetic multilayers propel micro-swimmers mimicking sperm cells?* **Soft Robotics**, 2015.

[2] C Prud'Homme, V Chabannes, V Doyeux, M Ismail, A Samake, G Pena. *Feel++: A computational framework for galerkin methods and advanced numerical methods,* **ESAIM: Proceedings** 38, 429-455, 2012.

[3] T. Xu, G. Hwang, N. Andreff, S. Régnier. *Planar path following of 3-D steering scaled-up helical microswimmers.* **IEEE Transactions on Robotics**, 2015.

[4] J. Gray and J. Hancock, *The propulsion of sea-urchin spermatozoa,* **J. Exp. Biol.**, 1955.

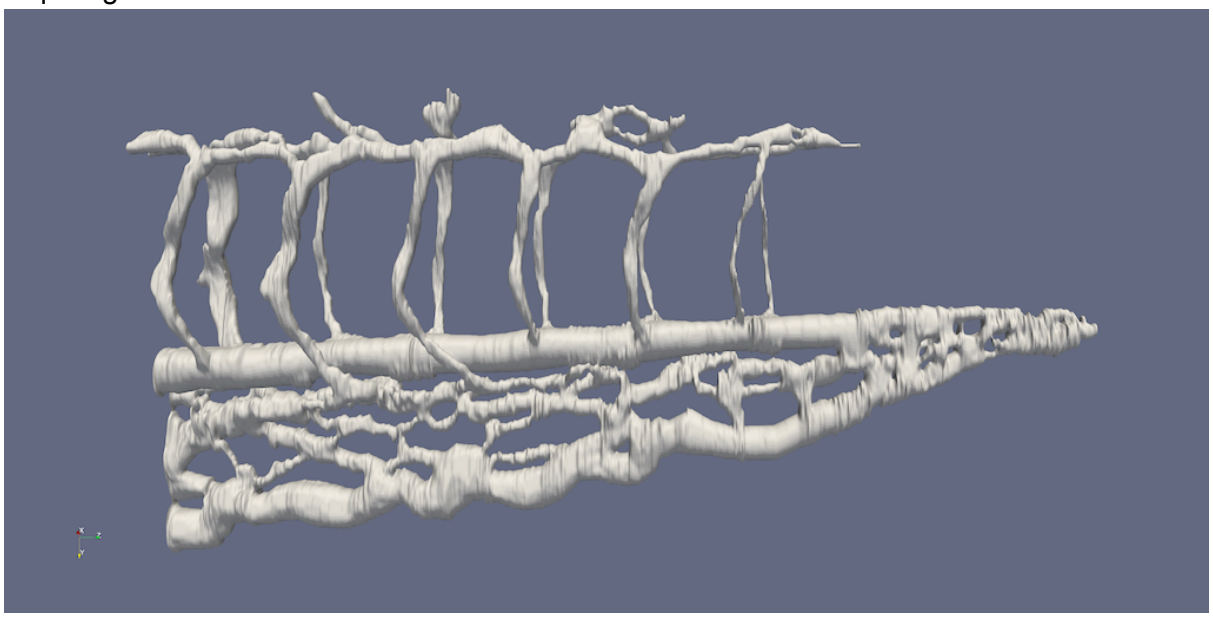
1 http://www.feelpp.org

Cells under Flow in the Zebra Fish

This second part of the project deals with building the numerical tools to model and simulate red blood cells and tumor cells in the vessels at the tail of a zebra fish.

The INSERM U1109 team, under the direction of Jacky Goetz, started in 2014, has shown the influence of hemodynamics on the localization of preferential stopping sites of tumor cells in the arteriovenous system. . To do this, they used the Zebra fish embryo model and developed original techniques to dissect the hemodynamic flow within the embryo. The team obtained the support of various organizations which allowed to accelerate the experimental research leading to a first joint publication. In order to deepen the experimental observations, it is now essential to build in-silico models in order to better target the mechanisms involved (hemodynamics, biochemistry of interactions, ...). Jacky Goetz's team is in charge of providing the data of the experiments. -vivo / in-vitro.

The team of Pr Christophe Prud'homme, director of Cemosis (Center of Modeling and Simulation of Strasbourg - http://www.cemosis.fr), hosted by the IRMA UMR 7501 has been working for several years in the field of blood flow through two flagship projects: Vivabrain and Eye2brain. On the one hand, we are particularly interested in blood flow in arterial and venous vessels and we have developed a platform for blood vessel reconstruction, called AngioTK, for numerical simulations from MRI images (see below). reconstruction steps involved in AngioTK). On the other hand, we are interested in blood rheology and the simulation of deformable particle flows and in particular vesicles and red blood cells in collaboration with the team of Dr. Mourad Ismail of Liphy (Interdisciplinary Laboratory of Physics of Physiology). University Grenoble Alpes). In this context, we have developed approaches based on the coupling of finite element and level set methods and have shown that we precisely reproduce the dynamics of vesicles and red blood cells (RBCs) in flows up to dilutions of the order of 30% of GR, results that we validated with some in-vitro experiments. We have recently made progress to move to dilutions of the order of 45% requiring new methods to take into account the contact the GR and the GR and the wall.



The image above shows a reconstruction with AngioTK of the vessels at the tail of the fish using images from Jacky Goetz team.

We have recently had a common publication published in developmental cell on a simplified/idealistic geometry reproducing the main feature of the geometry and the flow.
We would like now to pursue by completing the following lacking points:

1. the modeling and simulation of tumor cells in low Reynolds flows. An original formulation will be developed, studied and eventually implemented tested
2. the modeling and simulation of fluid wall interaction in a reconstructed geometry (see above) of a zebra fish. It involves in particular *(i)* the modeling of tissue constraint on the vessels, *(ii)* the modeling of the rest of the hemodynamics system using e.g. a 0D models that will be fitted with in-vivo data. The reconstruction process may be also developed during the cemracs to improve the quality of the reconstructed mesh.

Bibliography

[1] Hemodynamic forces tune the arrest, adhesion and extravasation of circulating tumor cells. Gautier Follain 1-4 , Naël Osmani 1-4 , Sofia Azevedo 1-4 , Guillaume Allio 1-4 , Luc Mercier 1-4 , Matthia A. Karreman 5 , Gergely Solecki 6 , Nina Fekonja 1-4 , Claudia Hille 7 , Vincent Chabannes 8 , Guillaume Dollé 8 , Thibaut Metivet 8 , Christophe Prudhomme 8 , Bernhard Ruthensteiner 9 , André Kemmling 10 , Susanne Siemonsen 11 , Tanja Schneider 11 , Jens Fiehler 11 , Markus Glatzel 12 , Frank Winkler 6 , Yannick Schwab 5 , Klaus Pantel 7 , Sébastien Harlepp 2,13-14 , Jacky G. Goetz 1-4*
http://www.cell.com/developmental-cell/abstract/S1534-5807(18)30147-3

[2] Thibaut Metivet, Vincent Chabannes, Vincent Doyeux, Mourad Ismail, Christophe Prud'Homme. 3D simulation of two-fluid flows using a finite element/level-set method in 3D. Application to two drop benchmarks. 2016. 〈hal-01345573v2〉

[3] Nicolas Passat, Stéphanie Salmon, Jean-Paul Armspach, Benoît Naegel, Christophe Prud'Homme, et al.. From real MRA to virtual MRA: Towards an open-source framework. Medical Image Computing and Computer-Assisted Intervention (MICCAI), 2016, Athène, France. Springer, 9902, pp.335-343, 2016, Lecture Notes in Computer Science. 〈10.1007/978-3-319-46726-9_39〉. 〈hal-01472890〉

[4] Vincent Chabannes, Christophe Prud'Homme, Marcela Szopos, Ranine Tarabay. High order finite element simulations for fluid dynamics validated by experimental data from the fda benchmark nozzle model. 5th International Conference on Computational and Mathematical Biomedical Engineering - CMBE2017, Apr 2017, Pittsburgh, PA, United States. 〈hal-01429685v2〉

[5] Vincent Doyeux. Modelisation et simulation de systemes multi-fluides. Application aux ecoulements sanguins. Physique Numérique [physics.comp-ph]. Université de Grenoble, 2014. Français

[6] Vincent Doyeux, Yann Guyot, Vincent Chabannes, Christophe Prud'Homme, Mourad Ismail. Simulation of two-fluid flows using a Finite Element/level set method. Application to bubbles and vesicle dynamics Journal of Computational and Applied Mathematics, Elsevier, 2013, Fifth International Conference on Advanced COmputational Methods in ENgineering (ACOMEN 2011), 246, pp.251-259. 〈10.1016/j.cam.2012.05.004〉