Catheter simulation using physically inspired neural networks (PINNs)

E Kerrien et PF Villard

1 Motivations

A catheter is a very long, thin and flexible tube that the physician navigates within the vascular system so as to establish a route from the groin to the brain. The route will later be used to deliver micro-devices to the pathological site and treat conditions such as strokes. During navigation, the catheter may undergo large deformations. Simulating a navigating catheter thus requires nonlinear mechanical modeling, posing challenges in terms of geometric precision, numerical stability, and computational speed for resolution. These limitations are the primary obstacles to designing a medical simulator capable of planning a catheterization intervention that is genuinely predictive of operative difficulties. The goal of this internship is to explore to what extent physically inspired neural networks (PINNs) can help overcome these challenges.

2 Objectives and tasks

Typically, a catheter is an object that can be mechanically modeled as a rod, expressing that its cross-section is much smaller than its length. Among the various proposed mechanical models, the Cosserat model makes the fewest simplifying assumptions. Therefore, it allows for the consideration of the most effects, especially those activated during large deformations of the rod (see [1] for a very concise overview). The system of differential equations associated with this model can be solved interactively by discretizing the rod into successive segments [2]. While these techniques are numerically stable, they suffer from imprecision that quickly diminishes the predictive nature of the simulation. More accurate solutions have been provided by continuous modeling combined with differential equation solving techniques, such as the shooting method [3], [4] or collocation on a Chebyshev basis [5], [1]. However, these solutions still face computational times incompatible with an interactive context and sometimes experience sudden numerical instabilities. Additionally, parameterizing the rotation part of the mechanical frame is a highly delicate problem [4], [5].

As neural networks are universal approximators, recent and remarkable progress in their training has sparked a frenzy of research aimed at leveraging them to solve differential systems. It quickly became apparent, however, that the learned solutions did not adhere to a priori constraints of the problem, that are paramount to satisfy in physics-related problems. Numerous works have therefore sought various ways to integrate these constraints into the training process [6]. Among them, Physically Inspired Neural Networks (PINNs) [7] often yield promising results by incorporating the physical equations into the cost function to compel the network to converge towards a satisfying solution.

The neural network approach has been applied to the resolution of a discretized Cosserat model [8] but, to our knowledge, not to its continuous formulation. The goal of the internship is to explore this avenue. We will restrict ourselves to the static case without contact (equations independent of time and without any force coupled to the catheter's geometry). The following steps can be followed:

1. If necessary, familiarize oneself with PINNs.
2. Conduct a state-of-the-art review on PINNs along two axes: 1) resolving the Cosserat model, and 2) parameterizing and optimizing rotations.
3. Propose, implement, and test a method where the neural network provides the model parameters for any given curvilinear abscissa as input. This method requires one neural computation for each point of the catheter.
4. Propose, implement, and test a method where the Cosserat model is discretized on a Chebyshev basis. Here, the network's output will be a set of components on the Chebyshev basis (as in [1]) allowing for the entirety of the model to be obtained via a single neural computation.

3 Context

This internship will take place within the Tangram team at the Inria Center of the University of Lorraine in Nancy, France. It is part of the PreSPIN project funded by ANR. This project aims to design simulation tools for the planning and treatment of ischemic strokes. Specifically, the internship focuses on simulating the navigation of a catheter in blood vessels. This aspect is the subject of Radhouane Jilani's doctoral thesis, and the intern will collaborate closely with him.

Several simulation tools for continuous Cosserat model have been developed as part of this thesis (in Python). They can be used to generate training data for neural networks.

3.1 Required Skills

We are seeking candidates in their final year of a Master's program (or equivalent) with excellent skills and knowledge in computational mechanics or computer graphics for physical simulation. However, candidates with a strong academic background in related disciplines such as computer vision and/or applied mathematics are also encouraged to apply.

An open-minded approach to related scientific fields, an interest in clinical research and medical applications, good communication skills, and a strong desire to learn and participate in a scientific project dynamic are expected from the candidate.

Software development will be primarily carried out in Python, and a solid practical experience in this language is required.

4 To Apply

Send your CV, cover letter, and transcripts (from current and previous year) via email to Erwan Kerrien (erwan.kerrien@inria.fr) and Pierre-Frédéric Villard (pierrefrederic.villard@loria.fr).

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