

PhD Thesis in automatic control

Title: Port-Hamiltonian Modeling and Control of Systems actuated by dielectrophoresis

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Key words:

Dielectrophoresis, electrokinetics, Port-Hamiltonian systems, passivity based control, trajectory control

Context and aim:

The AS2M department of the FEMTO-ST institute is known for its research on the modeling and control of complex multi-physic systems particularly through energy-based approaches as the Port Hamiltonian framework [1, 2]. It is also recognized for its work on the manipulation of micro-object using electrokinetics phenomenon such as dielectrophoresis for cell sorting applications [3] or electrostatic forces for the actuation of HASEL [4]. Promising result have been obtained in the modeling and control of non-linear and distributed parameters systems actuated by electrostatic forces using the port Hamiltonian (PH) framework [5] demonstrating its relevance for this type of systems.

Dielectrophoresis (DEP) is a phenomenon of significant interest for biomedical applications, as it enables the manipulation of cells without the need for biological markers. Furthermore, the electric fields driving DEP can be leveraged to characterize cells via impedance spectroscopy or to apply targeted stimuli, such as electroporation. The dielectrophoretic force acting on cells is generated by the polarization of dielectric particles within a non-uniform electric field. It is a non-linear phenomenon proportional to the gradient of the electric field squared ($\nabla|E|^2$), where the field is typically generated by multiple electrodes with independently controlled voltages. With the advancement of organ-on-chip and lab-on-chip devices, achieving precise control over the electric fields and the induced electrokinetic phenomena has become of interest for a variety of applications (cell sorting, characterization, interaction...). This needed level of precision requires a framework capable of modeling multiphysical systems (encompassing electro-mechanical, thermal, and chemical interactions). From a control

perspective, those systems are particularly challenging due to its non linear dynamic, distributed inputs, position-dependent controlability, and an output that depends quadratically on the control variable.

The aim of this thesis is to use the port Hamiltonian framework to develop a model and a robust control for systems actuated by dielectrophoresis for applications linked to biological cells manipulation and characterization.

This work will be carried out in the MOCOPHYS team at the AS2M department at the FEMTO-ST institute.

Detailed Description:

Introduction

Dielectrophoresis (DEP) is an electrokinetic phenomenon in which neutral or polarizable particles experience forces generated by non-uniform electric fields [6]. DEP is widely used in microfluidics, lab-on-chip platforms [7, 8], and microrobotic systems [9]. Despite its broad applicability, existing DEP modeling and control methodologies remain limited, particularly when dealing with complex electrode geometries, nonlinear particle-field interactions, particle-particle interactions, and uncertain environmental conditions.

The Port-Hamiltonian System (PHS) framework offers an energy-based physical representation for modeling multi-physics systems [1], including finite both and infinite-dimensional systems [10, 11]. Its capacity to explicitly represent energy storage, dissipation, and its modularity based on interconnection makes it a strong candidate for developing models and controllers that enables robust control of DEP-based actuated systems.

The targeted system in this work is described in figure 1.

State of the art and current limitation

Current modeling of dielectrophoresis rely on strong assumptions. They usually assume a linear variation of the potential between electrodes, simplify the interaction between the electric field and the particle, and neglect particle-particle interactions, thereby limiting the simultaneous control of multiple objects [12].

From a control perspective, the system is particularly challenging due to its non linear dynamic, features distributed inputs, position-dependent controlability, and an output that depends quadratically on the control variable.

Current significant results in DEP-based control include:

- trajectory control of several beads with diameters around $100\mu\text{m}$ [13]
- position and orientation control of Tetris-shaped objects of size around $100\mu\text{m}$ [14]
- trajectory control of single biological cells of approximately $10\mu\text{m}$ in diameter, at speeds up to $60\mu\text{m/s}$ [9]

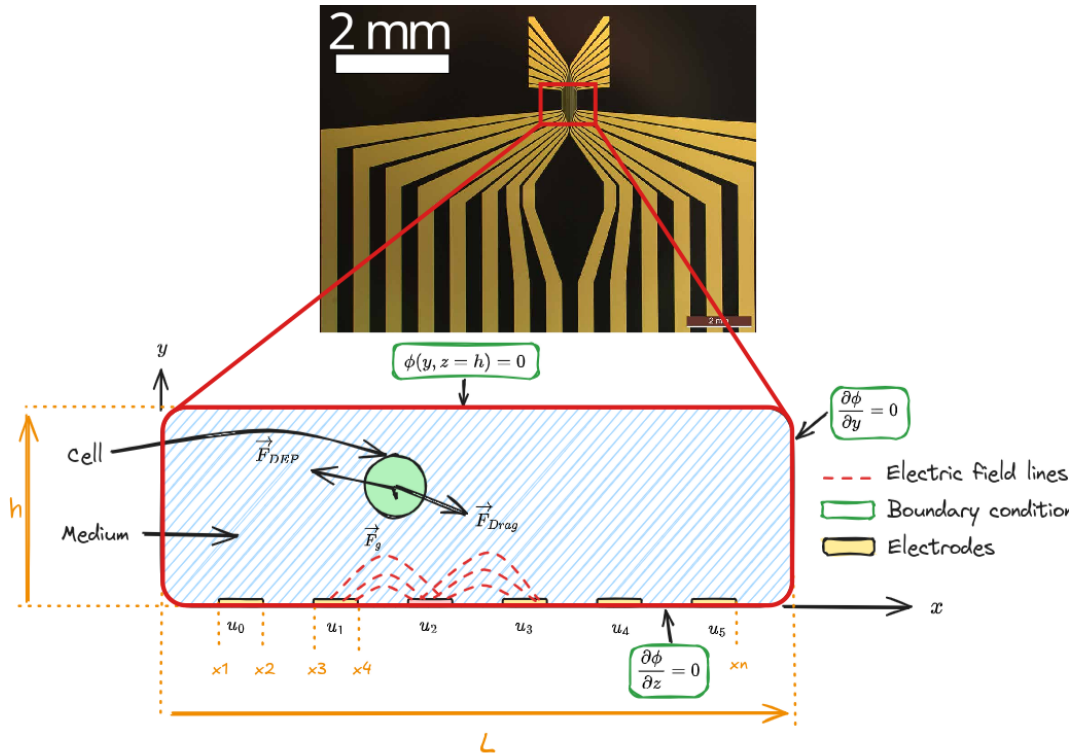


Figure 1: System actuated by dielectrophoresis. It is composed of a substrate with electrodes used to generate a nonuniform electric field inducing displacement of a cell through dielectrophoresis. The top image represents a microfluidic chip with electrodes made of gold (in yellow). The schematic below is a representation of the zoomed view of the working area.

These works use similar methodologies based on a semi-analytical model inverted using a stochastic optimization algorithm and combined with a PI controller. Their main limitations arise from the fact that dielectrophoresis is the only electrokinetic effect considered [15], the inertia of the object is neglected, and the approach is highly sensitive to variations in object size and initial position, while also lacking a reliable method to estimate the particle altitude. To the best of our knowledge, the only study addressing time-optimal control is that of Chang et al. [16], however it is limited to a one-dimensional model of a neutrally buoyant particle actuated by a single input.

From the port-Hamiltonian perspective, there is currently few work on the modeling [17] of the dynamic of polarizable particle under nonuniform electromagnetic field and none focusing on control of systems actuated by electric fields under the electroquasi-static assumption. However, magnetic-field-based actuation is well studied and structure-preserving formulations of Maxwell's equations have already been proposed [18, 19]. Given the strong sensitivity of DEP systems to disturbances and model uncertainties, robust control methods such as passivity-based control or μ -synthesis (which are already used in linear systems and are of growing interest for nonlinear systems [20, 21]) appear particularly relevant.

Summary of current limitations:

- only one electrokinetic effect is considered
- interaction between particles is neglected
- no reliable method to estimate the particle height
- lack of optimal or robust controller

An experimental platform described figure 2 already exists in the AS2M department, enabling rapid parameter identification and experimental validation of the proposed models and control strategies.

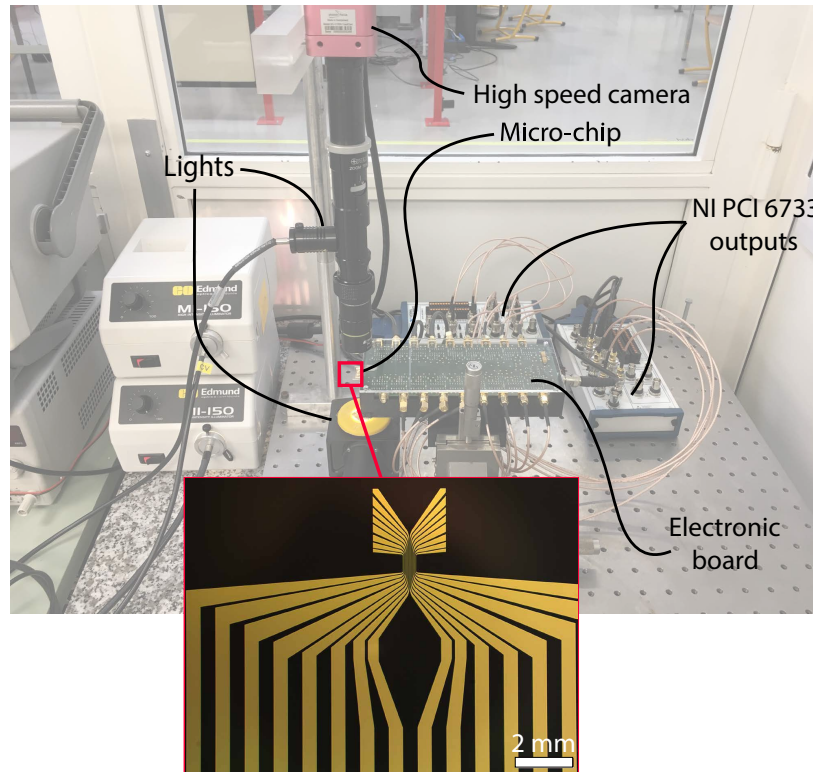


Figure 2: Current experimental setup of the AS2M department used to perform dielectrophoretic actuation. Allow the control of 16 voltages and visual feedback.

Expected contribution and planning of the thesis

The use of the port-Hamiltonian framework for modeling and control a system actuated by dielectrophoresis can address several of the limitations identified in the previous section.

- The modularity of the approach enables the integration of existing work, for example on particle–particle interactions, which have already been studied from an energetic perspective;
- The port-Hamiltonian representation explicitly tracks the energy within the system, which can be used to estimate the particle altitude through an observer;

- The intrinsic structure of the framework supports the use of passivity-based control, enabling robust and physically grounded control strategies.

Overall, these advances in modeling and control are expected to enhance contactless manipulation using electric fields while demonstrating through simulations and experiments the relevance of the port-Hamiltonian framework for this class of systems.

The expected planning of this work is :

- First year, we will focus on precisely identifying and defining the class of non-linear system under consideration. A lumped model of the system will then be developed and experimentally validated.
- The second year will be dedicated to improve the model (higher or infinite dimension) and develop an observer and a passivity based controller to perform closed loop control. We will propose a method to perform trajectory control considering uncertainties on parameters
- During the third year, the application of new robust control strategies (such as extension of μ -synthesis to PHS) will be investigated together with experimental validation. We will propose an experimental implementation and validation of the proposed model and controller considering uncertainties on parameters or real uncertainties.

Administrative information

This PhD funding ensure a 3 years doctoral contract and additional funds are planned for international conferences. The candidate will be under the supervision of Prof. Yann Le Gorrec, Prof. Yongxin Wu and Dr. Alexis Lefevre. The thesis will start in September or by arrangement.

Candidate profile

Required:

- Excellent MSc/Engineer in Automatic Control, Applied mathematics, Robotics
- Fluent in speaking and reading English
- Scientific programming skills

Appreciated:

- Good knowledge about Maxwell equations and electrokinetic phenomenon
- Interest for experiments

How to apply

Provide the following documents:

- Detailed CV and cover letter describing your interest in the topic
- Academic transcript and ranking of Master's
- Recommendation letter

For additional information, contact Alexis Lefèvre (alexis.lefevre@femto-st.fr).

Deadline

Rolling, early applications strongly encouraged.

Additional information

The laboratory operates under a "Zone à Régime Restrictif (ZRR)" a French restricted access security regime. All incoming PhD students are required to obtain security clearance before starting. Applicants are strongly advised to anticipate this pro-

cess: processing by the Defense Security Officer (Fonctionnaire Sécurité Défense, FSD) currently takes up to 2 months. As of 1 January 2025, any application without a response after 3 months will be automatically refused. The required documents must be submitted with the assistance of the laboratory host supervisor.

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