Titre de la thèse/Thesis title : Port-Hamiltonian Modeling and Control of Systems actuated by dielectrophoresis

Laboratoire d'accueil / Host Laboratory : AS2M / FEMTO-ST

Spécialité du doctorat préparé/Speciality : Automatique

Mots-clefs / Keywords : Dielectrophoresis, electrokinetics, Port-Hamiltonian systems, passivity based control, trajectory control

Descriptif détaillé de la thèse / Job description

Link to the subject : http://www.femto-st.fr/fr/offres-emploi-stage-these/doctorants#job-6047

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]. It is also recognized for its work on the manipulation of micro-object using electrokinetics phenomenon such as dielectrophoresis for cell sorting applications [2] or electrostatic forces for the actuation of HASEL [3]. 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 [4] 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 (∇|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.

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 parti-cle–particle interactions, thereby limiting the simultaneous control of multiple objects [10].

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 100µm [11]
- position and orientation control of Tetris-shaped objects of size around 100µm [12]
- trajectory control of single biological cells of approximately 10µm in diameter, at speeds up to 60µm/s [7]

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 [13], 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. [14], 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 [15] of the dynamic of polarizable particle under nonuniform electromagnetic filed 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 [16]. Given the strong sensitivity of DEP systems to disturbances and model uncertainties, robust control methods such as passivity-based control

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

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.

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Profil demandé / Applicant profile

Requiered:
• 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

Financement : MESRI Etablissement

Dossier à envoyer pour le **1/06/2026**
Début du contrat : 1er Octobre 2026
Salaire mensuel brut : 2300€

Direction de la thèse:/ **Thesis Supervisor**
Yongxin Wu

Encadrement de la thèse : **co-directeur(s) et co-encadrant(s)**
Yann Le Gorrec (co-directeur)
Alexis Lefevre (co-directeur)

Applicants are invited to submit their application to the PhD supervisors.
Application must contain the following documents:
- CV
- Cover letter
- At least 1 reference letter