Nonlinear Modeling & Robust Control of Electro-active Polymer Actuators

Scientific context of the thesis

The port-Hamiltonian (pH) framework, originally introduced in [1], offers an energy-based approach for modeling dynamical systems. This is achieved by incorporating energy and co-energy variables together with an intrinsic geometric structure, namely the Dirac structure, which reflects maximality and ensures power preservation between conservative and dissipative phenomena. A finite-dimensional pH system reads:

$$\begin{aligned} \dot{x} &= (J(x) - R(x))\,\frac{\partial H}{\partial x} + g(x)u(t), \\ y(x) &= g(x)^T \frac{\partial H}{\partial x}, \end{aligned}$$

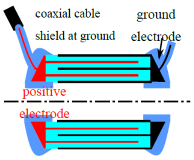
where $H(x)$ is the total stored energy, $J(x) = -J(x)^T$ represents the power-preserving interconnection among subsystems, $R(x) \geq 0$ captures dissipation, and $g(x)$ maps the external ports. The power balance $\dot{H} \leq u^T y$ implies the intrinsic passivity of the system. Because $H(x)$ is bounded from below, it is a suitable and natural Lyapunov candidate function, rendering pH systems particularly well-suited for nonlinear stability analysis and the design of physically interpretable controllers.

Two passivity-based control (PBC) strategies exploit the pH framework [2]: Control by Interconnection (CBI) that consists in shaping the closed-loop energy through a power-preserving coupling between plant and controller, while Interconnection and Damping Assignment PBC (IDA-PBC) assigns a target interconnection matrix J_d and damping R_d so that the closed-loop Hamiltonian H_d has its minimum at the desired equilibrium.

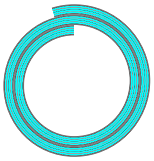
The extension to infinite-dimensional systems governed by partial differential equations (PDEs), introduced in [3], uses a Stokes-Dirac structure defined on spaces of differential forms over a spatial domain Ω with boundary $\partial\Omega$. This formulation has been widely studied for one-dimensional (1D) linear distributed parameter systems, leading to important advances in both analysis and controller design: for example in [4] for boundary control, and in [5] for in-domain distributed control. Nevertheless, the modelling and control of flexible structures undergoing large deformations and nonlinear material behavior, leading to inherently nonlinear PDEs, remain largely unexplored in the literature, with multiphysical coupling posing an additional challenge that has received even less attention.

The objective of this Ph.D. thesis is twofold: first, to develop a nonlinear infinite-dimensional port-Hamiltonian (pH) model for flexible structures undergoing large deformations with strongly nonlinear (electro-)mechanical behavior; and second, to synthesize robust controllers with clear physical interpretations to stabilize such structures at desired configurations and to follow desired trajectories.

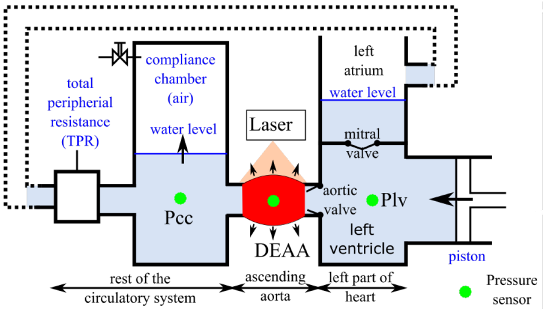
The proposed theoretical framework will be applied to the modeling and control of a cardiac assist device based on dielectric elastomer technology. Dielectric elastomer actuators (DEAs) have attracted considerable interest in biomedical robotics over the past two decades, owing to their large deformation capacity, fast response, high compliance, low power consumption, and biocompatibility. Fig. 1a and 1b illustrate the front and cross-sectional views of a DEA tube under investigation, which is intended to be integrated into the ascending aorta as a treatment for heart failure. Fig. 1c depicts a schematic of the interaction between the DEA tube and a mock-up fluid system replicating the cardiovascular environment. Nevertheless, DEAs have instability when the applied voltage exceeds certain limits. As the electric field induces membrane thinning via Maxwell stress, the resulting reduction in thickness further intensifies the field, leading to a positive feedback loop [7]. Recent studies have investigated the modeling and stabilization of this instability within finite-dimensional pH systems, under the restrictive assumption that the deformation field is spatially homogeneous [8]. However, this lumped-parameter hypothesis fails to capture the non-homogeneous deformations that DEAs exhibit in practice, and cannot accurately predict the true instability threshold. To overcome these limitations, and to lay the groundwork for future work accounting for fluid-structure interaction between the DEA and the surrounding flow, modeling DEAs as nonlinear infinite-dimensional pH systems is required. The DEA structure considered here is weakly electromechanically coupled and will be a 1D infinite-dimensional pH system. Its nonlinearity arises in both the interconnection operator $\mathcal{J}(x)$ and the gradient of the Hamiltonian, related to geometric nonlinearity, material nonlinearity, and electro-mechanical coupling. The input operator is distributed in space, while the input voltage remains finite-dimensional, which gives rise to instability under changes in deformation. The controller design for such DEAs naturally leads to the problem of in-domain distributed control of 1D infinite-dimensional pH systems. In-domain control of *linear* infinite-dimensional pH systems via CBI has been investigated in [5]. However, owing to the dissipation obstacle in electromechanical systems, extending IDA-PBC to the *nonlinear* infinite-dimensional setting remains a necessary step, which this thesis proposes to address.



(a) DEA tube: front view [6].



(b) DEA tube: cross section view [7].



(c) Schematic of a pulsatile flow loop replicating the physiological flow and pressure behaviour of the cardiovascular system, with a DEA tube implemented in the ascending aorta during the diastole phase, where 'DEAA' denotes the dielectric elastomer augmented aorta [6].

Figure 1

Ph.D. thesis activities and time planing

The PhD will be carried out in MOCOPHYS team at the AS2M department of FEMTO-ST institute (CNRS UMR 6174, Besançon, France), internationally recognized for micro-nano robotics, smart materials, and automatic control. The candidate will have access to DEA experiment setup, real-time control hardware (dSPACE), and high-voltage equipment.

The primary goals of this thesis include:

1. Develop a nonlinear, multi-physical, infinite dimensional pH model of DEAs. Perform structure-preserving spatial discretization and numerical simulation.
2. Design robust passivity control for 1D nonlinear infinite-dimensional pH systems.
3. Validate the proposed model identification and test the designed controllers against the electromechanical instability.

Administrative information

ANR funding ensures a full 3-year doctoral contract, with support for international conferences, and research visits. The candidate will be under the supervision of Prof. Yann Le Gorrec, and Dr. Ning Liu. The Ph.D. thesis will start in September 2026 or by arrangement.

Candidate profile

Required:

- MSc in Control Engineering, Mechanical Engineering, Applied Mathematics, or equivalent.
- Solid background in dynamical systems theory, numeric simulation, Lyapunov stability, and mathematical analysis.
- Scientific programming skills (MATLAB or Python).
- Good written and oral English.

Appreciated:

- Knowledge of continuum mechanics, or PDEs analysis.
- Familiarity with passivity-based control or energy-based methods.
- Experience with dSPACE, smart materials, soft actuators, or experimental platforms.

How to apply

List of documents to be provided:

- Detailed CV (including publications, if any).
- A concise cover letter describing your interest in the topic, written without LLM assistance.
- An academic transcript and ranking of (Bachelor's and Master's)
- Recommendation letters.

For more information and application, please contact: ning.liu@femto-st.fr.
Deadline : 2026/06/15 - early applications strongly encouraged [a].

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[a] 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 process: processing by the Defence 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.

References

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