Safe Control of Soft Robots: Bridging Physics and Learned Models
Rising Star Abstract

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Safe Control of Soft Robots: Bridging Physics and Learned Models

2025 IEEE-RAS International Conference on Soft Robotics (RoboSoft) Rising Stars

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TL;DR. The contributions presented in this abstract equip soft robots with the **motor intelligence** they need to function effectively in human-centric environments. We accomplish this by combining **advanced machine learning techniques** with **physical priors** and **stability guarantees**. By incorporating **physical structure into learned models**, we enable the use of well-established **model-based control** methods, ensuring **effective**, **stable**, and **computationally efficient control**. The contributions discussed in this abstract, both current and future, aim to **enhance the productivity and effectiveness of soft robotic manipulators** (e.g., achieving precise movements at high speeds) while **prioritizing safety, compliant behavior**, and the development of **transparent and inspectable computational intelligence**.

I. MOTIVATION

As we strive to integrate robotics into **human-centric environments**, guaranteeing safety becomes an absolute priority. While **safety** is traditionally ensured through computational control policies, this approach is vulnerable to perception errors and often results in overly cautious behavior that limits robot performance. Soft robotics presents a promising alternative by establishing **passive compliance** throughout the entire robot body with material softness. This **embodied intelligence** is inherently resistant to perception or control errors. Recent years have witnessed remarkable progress in soft robotics, with researchers developing new designs, smart materials, actuators, sensors, models, and control approaches. However, the **modeling and control of continuum soft robots** presents significant challenges due to their infinite degrees of freedom, complex nonlinear dynamics, and time-dependent behaviors such as hysteresis.

Currently, two dominant approaches exist for controlling soft robots. The first relies on model-based control using physics-based models derived from first principles under significant approximations. The second employs learned control policies, primarily through Reinforcement Learning (RL). **Both existing approaches face substantial limitations.** Existing model-based controllers cannot fully exploit the dynamics of soft robots as their underlying models inadequately capture complex dynamic behavior, particularly regarding how actuation and external interaction influence the robot's deformation. These models also require considerable expert knowledge to make appropriate design choices. Conversely, RL lacks interpretability and stability guarantees while being highly sample inefficient—a significant drawback given the time-dependent material properties and limited lifetime of current soft robots.

As visualized in Fig. 1, this abstract proposes that **integrating learned models with model-based controllers** presents a compelling alternative approach, **combining the strengths of both existing methods**: data-driven models that demand less expert knowledge and controllers with interpretable, provably stable behavior. **The central challenge lies in determining the essential characteristics and structures a learned model must exhibit to facilitate the application of established model-based control strategies**, such as PID-like feedback with feedforward control while ensuring the closed-loop robot system remains compliant and safe. This raises the key research question: **How can we effectively leverage learned models to achieve efficient, stable, and safe control of soft robots?**

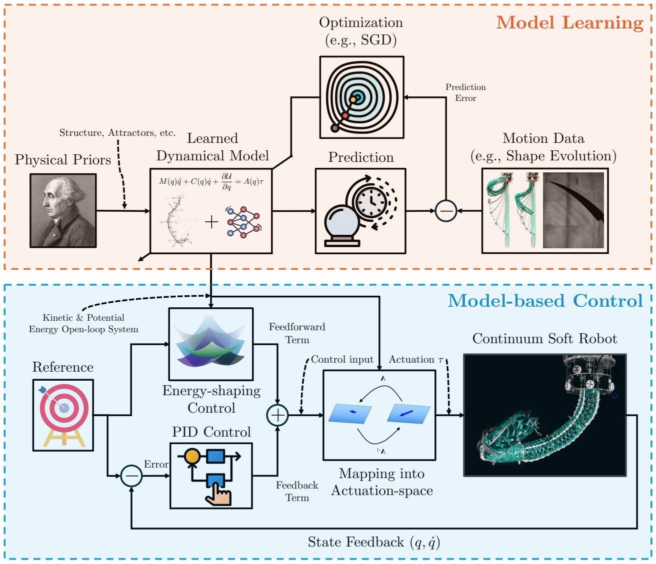

Fig. 1: Scheme of the **main contribution** - Model-based control of soft robots with learned models that exhibit a physical structure.

Our research addresses answers this research question through **several interconnected key contributions**, which we detail in the following section.

II. RESEARCH CONTRIBUTIONS

During our quest towards model-based control of soft robots with learned models, we contributed multiple interconnected key contributions to the domains of shape sensing, modeling, and control of soft robots.

Contribution I - Leveraging Kinematic Models for Soft Robot Shape Sensing. Proprioception via shape sensing is crucial for soft robots, particularly for feedback controllers that require state information. Existing methods rarely leverage prior knowledge, such as the robot's kinematic model. To fill this research gap, we developed two approaches for shape sensing using visual or magnetic sensor data, respectively - both integrating kinematic model knowledge. In one approach, we integrated visual SLAM with a projection onto the kinematic model to enable shape sensing from monocular camera images [2]. In another, we developed a method for proprioception using magnetic sensor measurements, parameterizing spatial relationships between magnets and sensors [1]. This approach reduced learning complexity and improved robustness by incorporating kinematic knowledge.

Contribution II - Advanced Physics-based Actuation Models for Soft Robots. We developed advanced physics-based actuation models for robots, including auxetic metamaterial-actuated robots like Handed Shearing Auxetics (HSA) [4], [6] and piston-driven pneumatic soft robots [7]. These models support provably stable nonlinear controllers, emphasizing their control-oriented design. This work also

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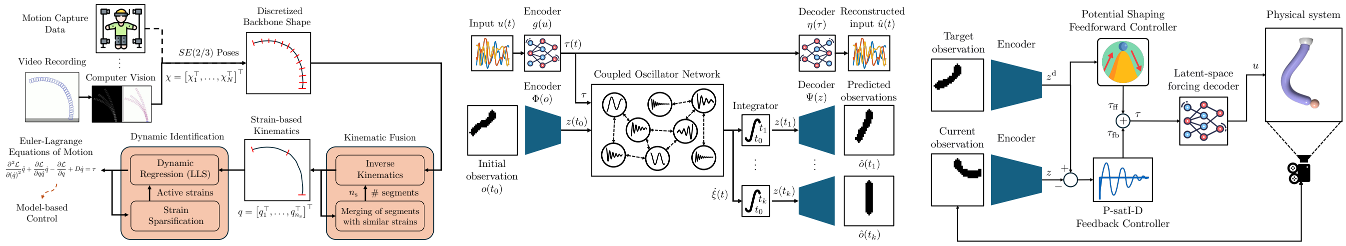

(a) Learning Low-Dimensional Strain Models [8] (b) Oscillatory Latent Dynamics [5] (c) Model-based Control in Latent-space [5]

Fig. 2: **Panel (a):** Methodology for learning strain models based on the shape evolution of soft robots, including (i) the *Kinematic Fusio*n algorithm to identify low-dimensional kinematic parametrizations based on the Piecewise Constant Strain (PCS) model, and (ii) the *Dynamic Identification* algorithm to regress dynamic parameters and reduce DOFs by excluding negligible strains [8]. **Panel (b):** Framework for learning soft robot dynamics directly from pixels, ensuring global asymptotic and input-to-state stability, using an autoencoder paired with coupled oscillators for learning latent dynamics [5]. **Panel (c):** An example of leveraging physically structured models with well-defined kinetic and potential energies for closed-form latent-space control by combining potential energy shaping feedforward and disturbance rejection via integral-saturated PID feedback terms.

highlights the limitations of physics-based models regarding their expressiveness in fully capturing the dynamical behavior of soft robots and the needed expert knowledge to design them, motivating the exploration of more expressive neural network-based alternatives.

Contribution III - Integrating Physical Structure and Stability Guarantees into Learned Models. Fourthly, we identified techniques for learning soft robot models with physical structures and stability guarantees. Two notable approaches are presented: an algorithm, visualized in Fig 2(a), that identifies low-dimensional, physics-based strain models using samples of the robot backbone's shape evolution [8] and Coupled Oscillator Networks (CONs) for learning Input-to-State Stable (ISS) latent dynamics of physical systems from high-dimensional observations such as images shown in Fig. 2(b).

Contribution IV - Exploiting Learned Models for Closed-form Model-based Control. We aim to develop closed-form model-based controllers for the learned models introduced in Contribution III, building on trailblazing prior work that designed feedback+feedforward controllers for continuum soft robots using physics-based models. For example, an integral-saturated PID+energy-shaping controller for HSA robots was presented in [6]. Unlike earlier learned models, which lacked the physical structure needed for energy-shaping control, the strain-based and CON-based models in Contribution III include well-defined potential and kinetic energy terms. This feature enables the use of energy-shaping feedforward controllers, which gives rise to effective and stable control behavior directly in strain-space [8] or in a learned latent space [6], as shown in Fig. 2(c).

III. Future Directions

This abstract so far outlined our past research on using modern AI approaches to learn dynamical models for soft robots that preserve physical structure and enable efficient and provably stable closed-loop control. Despite significant progress, several key challenges remain for safe and effective soft robot control: (1) controllers must explicitly address safety risks, (2) high-level motion policies must ensure stable and compliant behavior, and (3) computationally tractable methods are needed for co-designing the robot's body and brain. These challenges are discussed in detail below.

Safety-aware Control. Soft robots' embodied intelligence offers passive compliance, but its effects on the overall safety of the (closed-loop) system remain unquantified. To address this, we aim to develop a quantitative safety metric that accounts for both the robot's physical structure and control system. Using this metric, we will design controllers—such as ones based on Control Barrier Functions (CBFs)—that explicitly consider injury risk, ensuring the robot's actions stay within safe limits.

Integrating Stability Guarantees into Compliant Motion Policies. Building on our previous work on compliant impedance controllers for soft robots [3], we aim to ensure stability and compliance not just at the low-level controller but also in the motion policies that define task-space references. By leveraging stable motion primitives parameterized with dynamical systems, we aim to develop methods for learning motion policies that guarantee stability and compliance in soft robots, informed by demonstrations.

Tractable Co-design of Embodied and Computational Intelligence. Co-designing the body and brain of soft robots can optimize performance while reducing control effort, but computational demands limit existing methods. Most approaches use a cascaded optimization loop: an outer loop focuses on structural design (e.g., via evolutionary algorithms), while an inner loop trains control policies (e.g., using reinforcement learning). These inner loops are computationally expensive, limiting the exploration of the design space. To overcome this, we aim to create metrics that assess controllability, observability, and safety in a computationally efficient manner, enabling more effective co-design algorithms.

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