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Understanding Compliance Properties of Soft Continuum Robots: from Analytical Model to Model-Based Control

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I. Problem Statement and Research Objectives

Continuum robots offer continuous deformation and are highly flexible, which is advantageous in applications involving compliant interactions [19, 9, 10]. Moreover, leveraging soft materials to construct elastomer-based continuum robots can further enhance robots' inherent compliance and flexibility, leading to safer robot-environment interactions [17] and enabling variable stiffness behaviour [26]. To utilise the intrinsic compliance of these soft continuum robots, addressing challenges in modelling and controlling their compliant behaviours are of paramount importance [14, 6].

A. Open Challenges for Compliance Modelling and Control

*1) **Compliance Modelling**:* The significance of understanding the configuration-dependent compliance has been underscored in both rigid-linked and continuum robots [2, 8, 1]. The fundamental difference between robot compliance in traditional rigid-linked robots compared with soft robots primarily lies in the generation of compliance. Rigid-linked robots regulate compliance through finite variable compliance joints [27] (see Fig. 1(a)). The compliance matrix in the Cartesian space is determined via the Jacobian projection [20, 3]. Instead, soft robots undergo continuous deformations without physical joints, with compliance distributed along their bodies (see Fig. 1(b)). Consequently, the challenge lies in comprehending how robot configurations affect passive compliance properties.

*2) **Compliance Regulation and Control**:* Typical methods for controlling the compliance of soft robots include integrating stiffening mechanisms [13] and employing antagonistic actuation principles [4]. However, the specialised structural design needed for these approaches limits their utility in space-constrained scenarios like minimally invasive surgery. Moreover, achieving on-demand compliance control along specified directions remains a challenge. Exploring the potential of utilising modelled compliance for achieving model-based compliance control without resorting to stiffening mechanisms is an intriguing area for exploration.

B. Research Objectives

Aiming at advancing compliance modelling and model-based control approaches for soft continuum robots, my research objectives include:

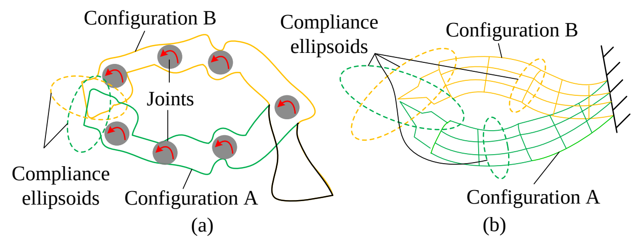

Fig. 1. Illustration of robot compliance for (a) rigid-linked and (b) soft continuum robots, under two different robot configurations.

- To propose a compliance modelling and analysis framework, which can reveal the configuration-dependent compliance properties and the compliance distribution along the continuum structures.
- To achieve model-based compliance regulation and control, without requiring additional stiffening mechanisms.

II. Contributed Research to Date

My research to date primarily contributes to a static compliance modelling and control framework (see Fig. 2) for pneumatic-driven soft continuum robots [22], to understanding their inherent compliance using analytical models, meanwhile, to achieve model-based compliance control, exclusively relying on regulating the actuation pressure.

A. Configuration-dependent Compliance Model

To model the compliance, soft robots can be characterised by discretising their structures into finite elements, using the piecewise constant curvature (PCC) model for instance [26]. The Cartesian compliance of soft robots can then be modelled using Jacobian mapping [26]. In addition, compliance can be modelled through finite differentiation [18, 5]. However, dimensions of the Jacobian matrix depend on the number of virtual joints, and the finite differentiation approach involves multiple forward kinematics calculations. Furthermore, while the distribution of compliance along the robot is crucial, it often remains unexplored. Moreover, material hyper-elasticity was usually not considered.

A Lie theory based-compliance modelling framework is proposed in my previous work [21, 24]. This framework can investigate the underlying compliance/stiffness characteristics

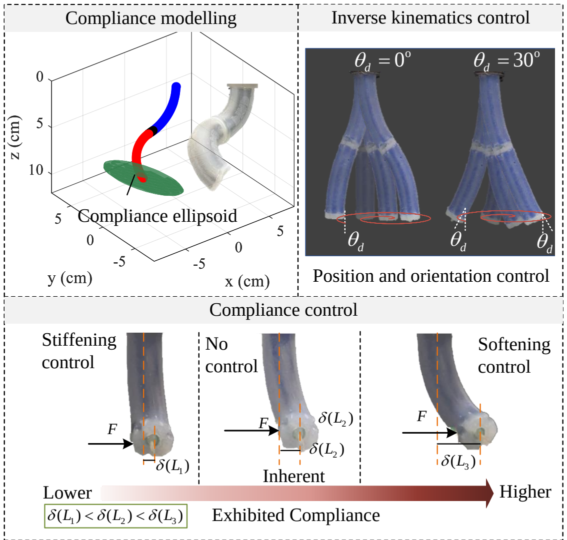

Fig. 2. Summary of the research to date: A static compliance modelling and model-based control framework.

for pneumatic-driven soft continuum robots and deliver a configuration-dependent stiffness/compliance analysis.

Specifically, the framework is, for the first time, capable of configuration-dependent compliance modelling and analysis at different static robot configurations derived from various forward kinematics models (e.g., the PCC model and the Cosserat rod model). This framework considers nonlinear responses resulting from large longitudinal deformations (e.g., when elongating or bending). In addition, my approach demonstrates that the robot compliance can be derived by various integration schemes based on the obtained static configurations of soft robots, without using Jacobian projections [26] or finite differentiation [15, 18]. Moreover, the proposed modelling framework can thoroughly reveal the compliance distribution along the soft robot, and for the first time, it achieves a detailed configuration-dependent compliance/stiffness modelling and analysis for extensible fluidic-driven continuum robots.

B. Model-based Compliance Control

Stiffening mechanisms include granular or layer jamming [7, 28], use of low melting point alloys [16], and a combination of tendon-driven and air pressurisation [26, 25]. The pioneering work of stiffness control for continuum robots was outlined in [12]. Building on a PCC assumption, a Cartesian stiffness control approach was proposed for a multi-segment, tendon-driven soft robot [26]. Likewise, a tendon-tensioning method was proposed to control the stiffness of a dual-segment, tendon-driven soft robot based on depth vision [11].

To actively regulate the exhibited robot compliance, I propose a compliance controller by regulating robot configurations based on the modelled compliance in [24]. The robot configuration is controlled via the inverse kinematics. To this end, I propose a model-based, multi-mode position and orientation controller for hyper-elastic soft continuum robots [23]. The method is based on the static Cosserat rod model including a pressure-dependent dynamic modulus. The kinematic model and control strategy are then expressed as non-linear least-squares optimisation problems. Hence, various inverse kinematics control modes can be achieved for a multi-segment robot, e.g., tip position and orientation control of the overall robot or tip position control of each segment.

Building on the modelled compliance [24] and inverse kinematics control approach [23], I further devise a model-based compliance controller. My approach enables the regulation of the exhibited robot's compliance in the Cartesian space, allowing for achieving both higher (softening control) or lower (stiffening control) compliance compared to the inherent properties of the pneumatic-driven robot. Experiments illustrate that the exhibited robot's compliance can be regulated up to 49.5% higher or 34.2% lower compared to inherent robot's compliance, using the proposed compliance controller. Notably, my work for the first time realises the compliance control for the pneumatic-driven soft robot without the need for employing stiffening mechanisms [13, 16, 7] or hybrid actuation principles [25, 26].

III. Future Research Directions

My current research offers an analytical framework to describe, analyse and control the compliance of pneumatic-driven soft continuum robots. Building on the framework, I plan to focus on three main directions for future work.

Interaction force control. There are demanding challenges to achieve on-demand force control in desired directions, e.g., minimally invasive surgery [6] or prescribed robot-environment interaction [26]. In Section II-B, the interaction compliance is regulated by controlling desired deflected robot configurations. As the modelled compliance essentially relates displacements and interaction forces. I will explore to achieve on-demand force control based on the proposed compliance control approach, in particular, when the soft robot interacts with both rigid and soft environments.

Proprioceptive sensing and closed-loop control. Current model-based, open-loop inverse and compliance control approaches are advantageous when e.g, applying soft robots on applications where deploying proprioceptive sensing and obtaining feedback information are challenging. However, open-loop control techniques may face limitations in robustness when confronted with unknown disturbances or unmodelled uncertainties. Once the feedback information becomes accessible, my model-based control framework can be extended to a closed-loop manner.

A unified statics and dynamics framework. The proposed framework focuses on fluidic-driven continuum robots operate in static or quasi-static scenarios. Nevertheless, compliant materials usually exhibit non-negligible viscoelasticity, hysteresis, with their mechanical properties further influenced by actuation principles. Integrating these complex behaviors into the framework and applying it to compliant continuum robots with diverse morphologies (such as vine robots) could not only advance the understanding of their mechanics but also potentially improve their practicality and versatility.

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