ME – MTech(Res) Thesis Defense

Data-Driven Modeling and Control of Soft Continuum Robots: A Comparative Study

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ABSTRACT

Soft continuum robots exhibit nonlinear, high-dimensional, and coupled dynamics, which make first-principles modeling and control particularly challenging. In this work, a systematic comparative study of data-driven modeling and control architectures for soft robotic systems is presented. The primary objective is to evaluate the effectiveness of different system identification paradigms in enabling accurate closed-loop control for trajectory tracking tasks.

Five distinct data-driven approaches are investigated for learning the underlying system dynamics: Dynamic Mode Decomposition with control (DMDc), Extended Dynamic Mode Decomposition with control (EDMDc) within the Koopman operator framework, Reservoir Computing (RC) as a machine learning-based hypothesis class, and Subspace Spectral Manifold Reduction (SSMR) as a manifold-based system identification technique. These methods represent diverse perspectives, ranging from linear regression-based approximations to nonlinear lifting techniques and nonlinear reduced-order manifold representations. Unlike these methods that primarily minimize prediction error, the Bayesian Koopman approach optimizes the model with respect to closed-loop control performance by minimizing trajectory tracking error, thereby producing models that are inherently better suited for feedback control.

Following system identification, model predictive control (MPC) strategies are designed for closed-loop reference trajectory tracking. Linear MPC formulations are employed for the DMDc and EDMDc models due to their linear structure in the lifted space, while nonlinear MPC is developed for the RC and SSMR models to account for their inherent nonlinear representations. The control objective is to track user-defined 3-DoF and 6-DoF trajectories at the end-effector of the soft robot under realistic operating conditions.

The proposed approaches are validated through both simulation and experimental studies. In simulation, a soft elastomer diamond robot modeled within the SOFA environment is used. The robot consists of five nodes, each described by six states (three positional and three velocity components), with four base nodes independently actuated and the fifth node acting as the end-effector. For experimental validation, a cable-driven soft continuum manipulator with two segments is developed, actuated using six stepper motors. Motion capture data from a Qualisys system is utilized to obtain position and orientation measurements of the intermediate and terminal sections, enabling real-time data-driven modeling and control under disturbances.

The study provides a comprehensive comparison of modeling accuracy, computational efficiency, and control performance across the considered approaches. The results offer insights into the trade-offs between model expressiveness and control tractability, contributing toward the development of reliable data-driven control frameworks for soft robotic systems.

ABOUT THE SPEAKER

Saras Vibhuti is currently pursuing his M.Tech. (Research) in the Department of Mechanical Engineering at the Indian Institute of Science, Bengaluru, under the guidance of Prof. Jishnu Keshavan. He obtained his B.Tech. degree in Mechanical Engineering from NIT Shillong in 2019. He has 27 months of work experience spanning process engineering (SKF India), mechanical maintenance (Vedanta Resources), and vibration testing (Bharat Electronics).