Nonlinear Modeling and Control of Artificial Muscles via Spectral Submanifolds

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Abstract

Advancements in robotics increasingly draw inspiration from the adaptability and versatility of biological systems. Artificial muscles, designed to mimic the force-generating functionality of biological muscles, play a crucial role in musculoskeletal robotics and prosthetics. Among various soft artificial muscles, Hydraulically Amplified Self-Healing Electrostatic (HASEL) actuators represent a promising solution that combines the benefits of soft fluidic and electrostatic actuation. They consist of oil-filled pouches partially covered with electrodes, that redistribute the oil upon activation through applied voltage and allow contraction. Modeling and controlling HASEL actuators poses significant difficulties due to their complex interplay between soft materials, electrostatic forces and frictional elements, which produce fundamental nonlinear dynamics and introduce memory effects and hysteretic behavior into the system. At the same time, capturing the essential dynamics is crucial for accurate system representation and effective control strategies, such as Model Predictive Control (MPC). The complexity of the problem prompts us to seek a reduced-order model directly from data. Among the numerous model reduction techniques, we employ the reduction to Spectral Submanifolds (SSMs). The theory of SSMs provides a mathematically justified method to capture the essential nonlinear dynamics on low-dimensional, attracting invariant manifolds in the phase space of the system. Nearby trajectories approach the SSMs and quickly synchronize with their internal dynamics, which then serve as accurate reduced models for the longer-term dynamics of the full system. The data-driven reconstruction of SSMs and their reduced dynamics have proven successful, not only in reconstructing the autonomous behavior, but also predicting the response under periodic and general external forcing. In particular, the setting of the adiabatic SSM under slow forcing lends itself well to control applications, wherein the internal time scale of the system dynamics is much faster than the targeted motion of the robot. We construct the SSM-based reduced order model of the HASEL actuator from a single observable, i.e. the vertical stroke, at different levels of voltage. With the inclusion of forcing into the model, we can then predict the robot's displacement given the commanded voltage or compute the voltage required for the robot to follow an envisioned trajectory.

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