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Publication date
2021

Document Version
Final published version

Citation (APA)
Stölzle, M., & Della Santina, C. (2021). *Putting Back Actuation in Pneumatically Actuated Soft Robots: modeling and backstepping control*. Abstract from Benelux Workshop on Systems and Control 2021, Rotterdam, Netherlands.

Putting Back Actuation in Pneumatically Actuated Soft Robots: modeling and backstepping control

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1 Introduction

The control of continuum soft robots is very challenging because of the unlimited degrees of freedom and the considerable nonlinear characteristics such as multi-body dynamics and nonlinear potentials [1]. This complexity can be tamed by combining feedback controllers (which are inherently robust to model uncertainties), and simplified models of the soft robot's dynamics. For what concerns the latter, many approaches investigated the use of the Constant Curvature (CC) assumption and its extensions for static and dynamic control [2] for continuum soft robotic manipulators. While the actuator dynamics are neglectable for tendon-driven robots, the actuator dynamics of pneumatic actuators is slower and more nonlinear [1]. But existing model-based dynamic controllers for soft robots do not consider these actuator dynamics if not through simple heuristics. We propose a general approach based on backstepping to incorporate pneumatic actuator dynamics into model-based control for soft robots independent of the chosen model for the soft system.

2 Dynamic model and backstepping control

We consider a robot with n_S segments each of them with n_D configurations q and actuated with a set of n_C dedicated pneumatic chambers. We model the fluid as an ideal gas in first approximation and consider the process to be isotherm. We require access to a function $V_{C,i}(q)$ which maps the robot configuration $q \in \mathbb{R}^{n_S \times n_D}$ to the volume of fluid stored in the robot chamber i. This function can be derived either analytically for the specific system or off-line from data. We derive the acting forces and equations of motion of the pneumatic actuator using the conversation of energy principle.

We use the backstepping [3] control technique to derive the model-based controller taking into account the full system dynamics including the dynamics of the pneumatic actuator. We assume that we have access to a feedback controller $\gamma(\mathbf{q}, \dot{\mathbf{q}})$ such that the reduced system without actuator dynamics convergences to a desired trajectory $\bar{\mathbf{q}}$ and suppose that convergence can be proven using the Lyapunov function $H(\mathbf{q}, \dot{\mathbf{q}})$. We subsequently prove convergence for the full system using backstepping in two steps first for the velocity of the pistons $\dot{\mu}_p$ and subsequently for the required actuation force on the pistons $\mathbf{f}_p$.

3 Example: Tracking posture under PCC approximation

We show the effectiveness of our approach for the example of a soft continuum manipulator robot modelled using the Piecewise Constant Curvature (PCC) assumption. We use a trajectory tracking controller based on the PCC model [2] and derive the full system controller using backstepping as explained above and evaluate the actuation-aware controller against the same PCC controller unaware of the actuation dynamics. We expect our approach to perform very similarly in quasi-static conditions and much better for highly dynamic movements. [2] shows that for sinusoidal movements with high frequencies the tracking error is still significant especially at the extremas of the movement.
We verify our approach in a FEM simulation with integrated CFD to simulate the behaviour of the pneumatic fluid. We discretize each arm segments into several rigid links connected through a revolute joint.
We additionally perform experiments using a soft planar robotic arm inspired by an elephant trunk analogue to [2].

References

[1] T. George Thuruthel, Y. Ansari, E. Falotico, and C. Laschi, "Control strategies for soft robotic manipulators: A survey," *Soft robotics*, vol. 5, no. 2, pp. 149–163, 2018.

[2] C. Della Santina, R. K. Katzschmann, A. Bicchi, and D. Rus, "Model-based dynamic feedback control of a planar soft robot: trajectory tracking and interaction with the environment," *The International Journal of Robotics Research*, vol. 39, no. 4, pp. 490–513, 2020.

[3] P. V. Kokotovic, "The joy of feedback: nonlinear and adaptive," *IEEE Control Systems Magazine*, vol. 12, no. 3, pp. 7–17, 1992.