BOSTON UNIVERSITY

COLLEGE OF ENGINEERING

Thesis Proposal

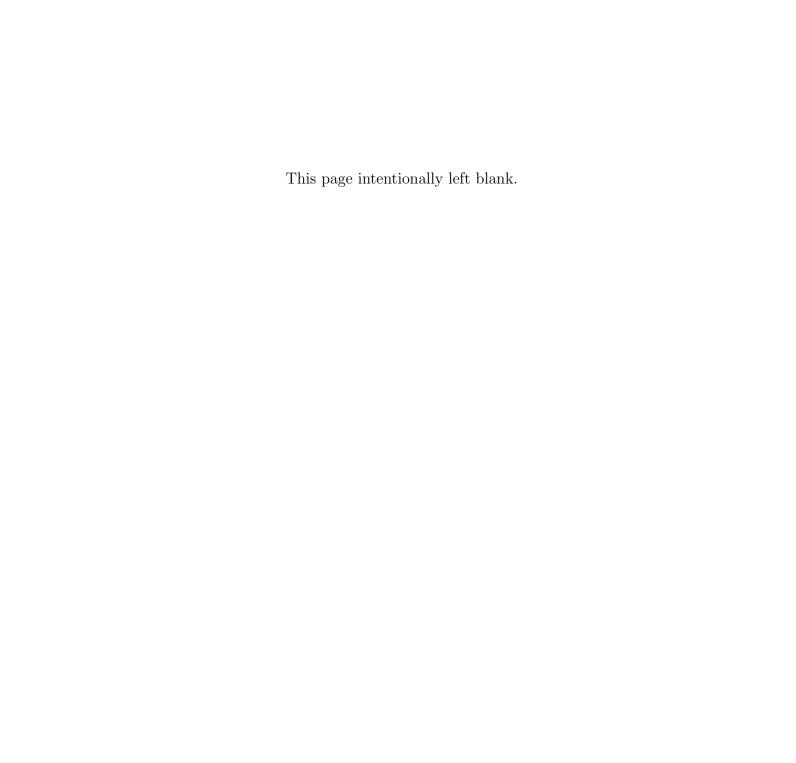# 3-DIMENSIONAL MODEL-BASED DYNAMIC FEEDBACK CONTROL FOR SOFT ROBOTS

by

Nashr El Auliya
B.Sc., Boston University, 2024

Submitted in partial fulfillment of the requirements for the degree of

Master of Science

2025

This page intentionally left blank.

Contents

1 Abstract

The physical characteristics of soft robots inherently promise an ability to perform complex motions, as well as to safely and compliantly interact with sensitive environments. While trajectory tracking and environmental interaction control strategies for planar motion have been developed along with motion plans for it, it has yet to be robustly translated to three dimensions. This thesis thus aims to develop a three-dimensional, model-based, closed loop dynamic controller for continuous soft robots. To develop a robust formulation of this controller, gravitational loads that could potentially violate model assumptions must be dynamically accounted for. Kinematic singularities inherent to the dynamic model used must also be analytically or numerically managed. A suitable dynamic model to underpin the control system must then either be formulated, augmented from an existing one, or selected. Then the model must be validated either analytically or simulatively, before the control system can subsequently be built around it. The controller may then finally be validated through hardware implementation.

2 Topic Background

Model-based controls → dependence on the dynamics model [1]

Some content from [2]
Model-based
→ (+) meaningful information regarding dynamics and input of system
→ (-) robustness and adaptability may be compromised in more unpredictable settings [3]
Learning-based
→ (+) can achieve higher performance w.r.t. more complex actions
→ (-) computationally more demanding and may sacrifice stability [3]

The challenge of formulating control-oriented dynamics models
Piecewise Constant Strain models as a Finite-dimensional approximation of a soft robot's continuum mechanics
Different implementations of PCS

3 Prior Work

CD Santina developed a controller built around the most straightforward implementation of PCS [4]
Planar PCC model matched with an *augmented* rigid body model [5]
Not 3D, but preliminary results on 3D-fying it available

Direct (?) successor to the previous paper [6]
Solved the main limitations of the previous model's parametrization
New parametrization is based on arc-lengths of a CC segment

An alternative model *still* using the PCS principles [7]
Uses PCS to discretize an otherwise continuous (and infinite-dimensional) model
Leans much more into the continuum mechanics of soft robots

4 Research Approach

Formulation unlikely
Rough outline of model assessment;tabulated or other
Justify model selection based on table assessments

Analytically (?) assess model behavior?
Motor babble pneumatically-actuated soft robot at hand
Simulate output using model, and look at the error

Development of the controller
What does hardware implementation look like?
What does *validation of* the hardware implementation look like?

5 Proposed Timeline

Research Approach 1: Dec 2025
Research Approach 2: Jan 2025
Research Approach 3: Mar 2025
aaaa

aaaa
aaaa

6 References

[1] C. Della Santina, C. Duriez, and D. Rus, "Model-based control of soft robots: A survey of the state of the art and open challenges," *IEEE Control Systems Magazine*, vol. 43, no. 3, pp. 30–65, Jun. 2023. DOI: 10.1109/MCS.2023.3253419.

[2] L. Brunke, M. Greeff, A. W. Hall, *et al.*, "Safe learning in robotics: From learning-based control to safe reinforcement learning," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 5, pp. 411–444, Volume 5, 2022 May 3, 2022. DOI: 10.1146/annurev-control-042920-020211.

[3] J. Rakhmatillaev, V. Bucinskas, and N. Kabulov, "An integrative review of control strategies in robotics," *Robotic Systems and Applications*, Jul. 10, 2025. DOI: 10.21595/rsa.2025.25014.

[4] 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, Mar. 1, 2020. DOI: 10.1177/0278364919897292.

[5] R. K. Katzschmann, C. D. Santina, Y. Toshimitsu, A. Bicchi, and D. Rus, "Dynamic motion control of multi-segment soft robots using piecewise constant curvature matched with an augmented rigid body model," in *2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)*, Apr. 2019, pp. 454–461. DOI: 10.1109/ROBOSOFT.2019.8722799.

[6] C. Della Santina, A. Bicchi, and D. Rus, "On an improved state parametrization for soft robots with piecewise constant curvature and its use in model based control," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 1001–1008, Apr. 2020. DOI: 10.1109/LRA.2020.2967269.

[7] F. Renda, F. Boyer, J. Dias, and L. Seneviratne, "Discrete cosserat approach for multisection soft manipulator dynamics," *IEEE Transactions on Robotics*, vol. 34, no. 6, pp. 1518–1533, Dec. 2018. DOI: 10.1109/TRO.2018.2868815.

[8] A. K. Dickson, J. C. P. Garcia, M. L. Anderson, *et al.*, *Safe autonomous environmental contact for soft robots using control barrier functions*, Apr. 20, 2025. DOI: 10.48550/arXiv.2504.14755. arXiv: 2504.14755[cs].

[9] A. Dickson, J. C. P. Garcia, R. Jing, M. L. Anderson, and A. P. Sabelhaus, "Real-time trajectory generation for soft robot manipulators using differential flatness," in *2025 IEEE 8th International Conference on Soft Robotics (RoboSoft)*, Apr. 2025, pp. 1–7. DOI: 10.1109/RoboSoft63089.2025.11020810.

[10] K. Wong, M. Stölzle, W. Xiao, C. D. Santina, D. Rus, and G. Zardini, *Contact-aware safety in soft robots using high-order control barrier and lyapunov functions*, May 5, 2025. DOI: 10.48550/arXiv.2505.03841. arXiv: 2505.03841[cs].

[11] C. D. Santina and D. Rus, "Control oriented modeling of soft robots: The polynomial curvature case," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 290–298, Apr. 2020. DOI: 10.1109/LRA.2019.2955936.