
The logo of Boston University, featuring the words "BOSTON" and "UNIVERSITY" in white, serif, all-caps font, stacked vertically within a red rectangular border.

COLLEGE OF ENGINEERING

Thesis

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

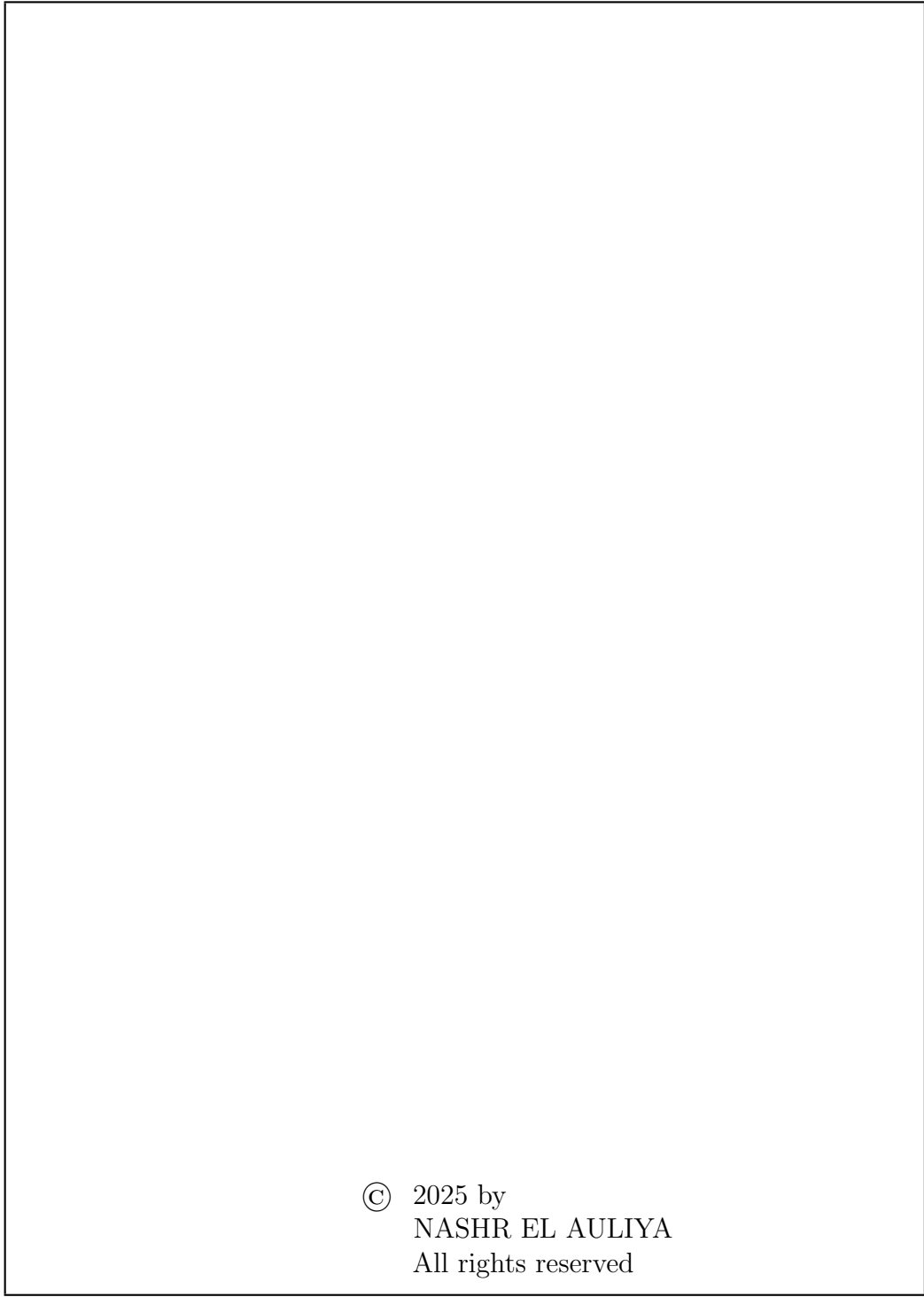
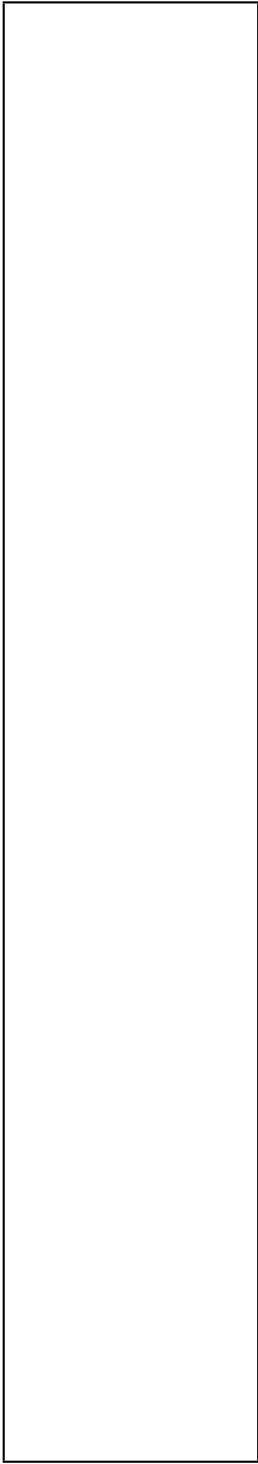
by

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

Submitted in partial fulfillment of the requirements for the degree of

Master of Science

2025



© 2025 by
NASHR EL AULIYA
All rights reserved



--

Approved by

--

	Acknowledgments
	Acknowledgments here

--

Abstract

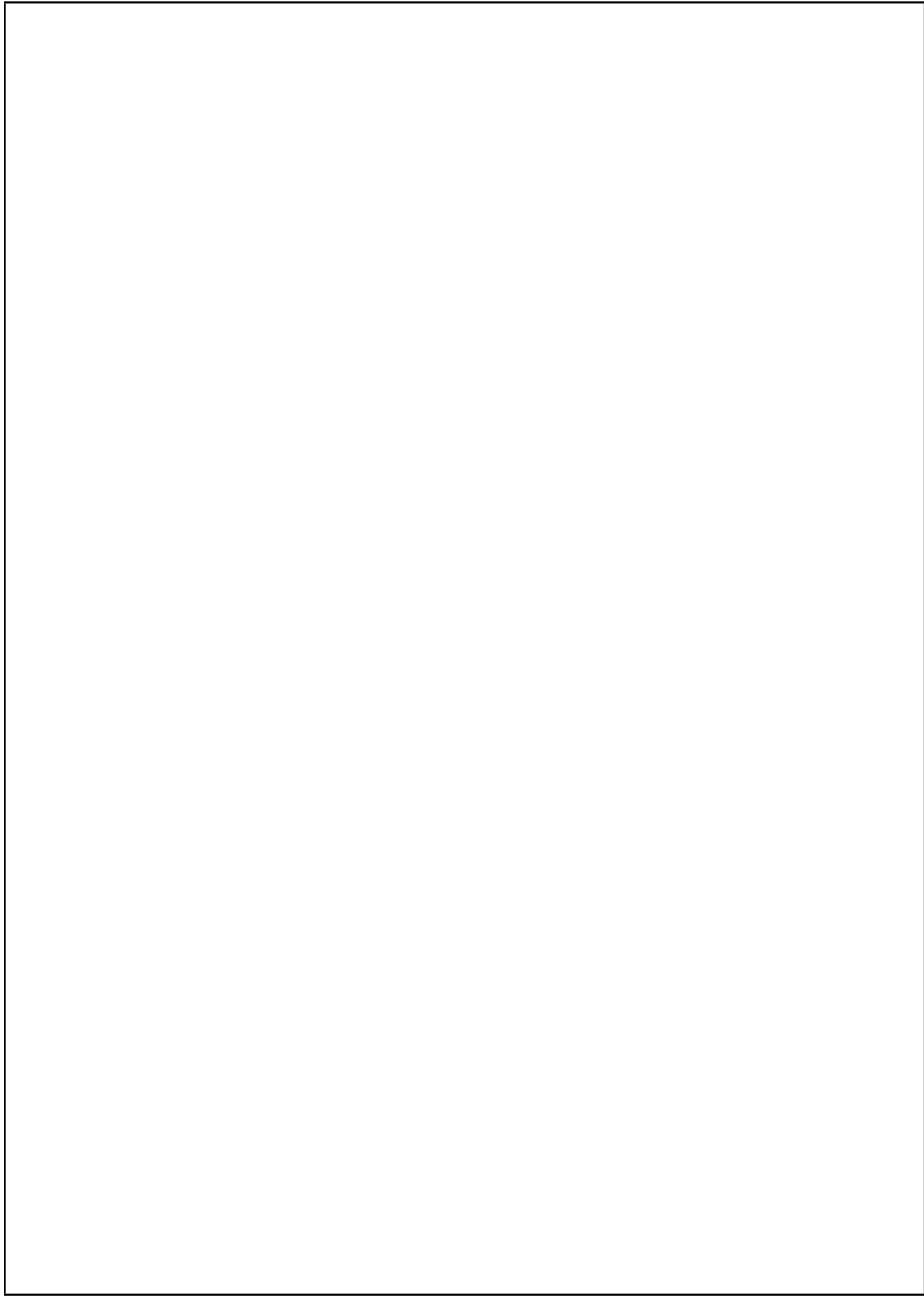
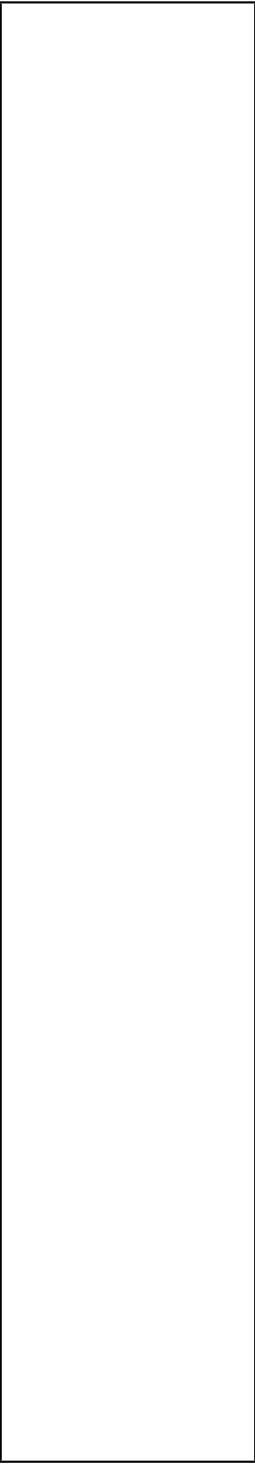
The physical characteristics of soft robots inherently promise an ability to perform complex motions, as well as to safely and compliantly interact with sensitive environments. While trajectory tracking and environmental interaction control strategies for planar motion have been developed along with motion plans for it, it has yet to be robustly translated to three dimensions. This proposed 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 first 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.

Contents		
1	Abstract	1
2	Topic Background	1
3	Prior Work	1
4	Research Approach	1
5	Proposed Timeline	1
6	References	3

--

1	Abstract
2	Topic Background
3	Prior Work
4	Research Approach
5	Proposed Timeline

--



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](https://doi.org/10.1109/MCS.2023.3253419).
- [2] 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](https://doi.org/10.1109/LRA.2020.2967269).
- [3] 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](https://doi.org/10.48550/arXiv.2504.14755). arXiv: [2504.14755\[cs\]](https://arxiv.org/abs/2504.14755).
- [4] 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](https://doi.org/10.1109/RoboSoft63089.2025.11020810).
- [5] 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](https://doi.org/10.1177/0278364919897292).
- [6] 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](https://doi.org/10.21595/rsa.2025.25014).
- [7] 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](https://doi.org/10.1146/annurev-control-042920-020211).

-
- | | |
|--|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| | <p>[8] 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 <i>2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)</i>, Apr. 2019, pp. 454–461. DOI: 10.1109/ROBOSOFT.2019.8722799.</p> <p>[9] K. Wong, M. Stölzle, W. Xiao, C. D. Santina, D. Rus, and G. Zardini, <i>Contact-aware safety in soft robots using high-order control barrier and lyapunov functions</i>, May 5, 2025. DOI: 10.48550/arXiv.2505.03841. arXiv: 2505.03841[cs].</p> <p>[10] F. Renda, F. Boyer, J. Dias, and L. Seneviratne, “Discrete cosserat approach for multisection soft manipulator dynamics”, <i>IEEE Transactions on Robotics</i>, vol. 34, no. 6, pp. 1518–1533, Dec. 2018. DOI: 10.1109/TR0.2018.2868815.</p> <p>[11] C. D. Santina and D. Rus, “Control oriented modeling of soft robots: The polynomial curvature case”, <i>IEEE Robotics and Automation Letters</i>, vol. 5, no. 2, pp. 290–298, Apr. 2020. DOI: 10.1109/LRA.2019.2955936.</p> <p>[12] R. J. Webster III and B. A. Jones, “Design and kinematic modeling of constant curvature continuum robots: A review”, <i>The International Journal of Robotics Research</i>, vol. 29, no. 13, pp. 1661–1683, Nov. 1, 2010. DOI: 10.1177/0278364910368147.</p> <p>[13] C. Della Santina, R. K. Katzschmann, A. Biechi, and D. Rus, “Dynamic control of soft robots interacting with the environment”, in <i>2018 IEEE International Conference on Soft Robotics (RoboSoft)</i>, Apr. 2018, pp. 46–53. DOI: 10.1109/ROBOSOFT.2018.8404895.</p> |
|--|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|