Dissertation Title and Abstract

A Control-oriented Approach on the Design and Modeling of Soft Robotic Systems

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In the past two decades, the field of soft robotics has kindled a major scientific interest among many disciplines of engineering. Contrary to rigid robots, soft robots explore '*soft materials*' that significantly enhance the robot's dexterity, enable a rich family of motion primitives, and enhance environmental robustness regarding contact and impact with major safety merits. The main inspiration for soft robotic systems stems from biology with the aim to achieve similar performance and dexterity as biological creatures. Since its inception, soft robotics has exemplified its potential in diverse industrial areas such as safe robotic manipulation, adaptive grasping, aquatic and terrestrial exploration of uncertain environments, rehabilitation, and the bio-mimicry of many animals including birds, fish, elephants, octopuses, and various invertebrates. By exploring the uncharted merits of soft materials and soft actuation, soft robotics has placed the first steppingstones towards achieving biological performance in next-generation robotics.

Although some significant leaps have been made towards bridging biology and robotics, there exist major scientific challenges that hinder the advancement of the field. In particular: (I) the Design and (II) Modeling of soft robotic systems. Traditional design of rigid robotics emphasizes on maximum structural rigidity and weight minimization, as to allow for fast, repeatable motion with negligible structural flexibility. Soft robotics, on the other hand, primarily rely on minimal structural rigidity for motion – so called '*hyper-flexibility*'. Especially since soft materials undergo large nonlinear mechanical responses under actuation, which leads to highly nonlinear kinematic relations for the robot's workspace. Using traditional engineering principles for soft materials is perhaps obsolete and automated computer-aided design principles for soft robotics might mandate the next steps for the field. As for modeling, its innate infinite-dimensionality poses fundamental problems for model-based controllers. Besides, as these systems are composed of soft materials, large deformations lead to nonlinear mechanical responses that exotic to classic robotic theory. As a result, in terms of performance, soft robots are easily outclassed by their rigid counterparts nowadays and consequently lack the transferability to industry. The diligence of achieving similar precision and speed to current state-of-the-art robots, and ultimately nature, stresses the paramount importance on design, modeling and control tailored for soft robotics.

This thesis will address the design synthesis of soft robots as well as the development of model-based controllers for a subclass – soft continuum manipulators.

In the first part of this thesis, we present a novel framework for synthesizing the design of soft robotics with various types of soft actuation, *e.g.*, hydraulics and tendons, but primarily pneumatic actuation. Contrary to traditional design methods, such as bio-mimicry, a gradient-based topology optimization is employed to find the optimal soft robotic structure given a user-defined objective function (i.e., desired morphology). Two difficulties are addressed here. First, pressure-based topology optimization is challenging since the adaptive topology changes the pneumatic load at each optimization step. To deal with this issue, we exploit the facial connectivity in the mesh tesselation to efficiently simulate the physics involving pneumatic actuation akin to soft robotic systems. The second issue is describing the hyper-elastic nature of soft materials. Here, nonlinear Finite Element Method (FEM) simulations are explored such that large deformations of hyper-elastic materials can be described accurately. The proposed optimization-driven algorithm is used to obtained a diverse class of morphologies: soft bending actuators, soft artificial muscles, soft grippers, and rotational soft actuators.

Lastly, the

Summarizing, this thesis contains several new techniques on design and mode-based control for the increasingly fast evolving field of soft robotics. Specifically, n

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List of publications

Peer-reviewed journal articles

- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*Reduced-order Cosserat Models for Soft Robotic Systems using FEM-driven Shape Reconstruction*", Robotics and Automation Letters. (*in preparation for journal submission*);

- B. Caasenbrood, A. Amoozandeh Nobaveh, M. Janssen, A. Pogromsky, J. Herder, and H. Nijmeijer "*An Energy-efficient Gravity-balancing Wrist Exoskeleton by exploring Compliant Beams and Soft Robotic Actuation*," Wearable Technologies. (*in preparation for journal submission*);

- A. Amiri, B. Caasenbrood, D. Liu, N. van de Wouw, and I. Lopez Arteaga, "*An Electric Circuit Model for the Nonlinear Dynamics of Electro-active Liquid Crystal Coatings*", Applied Physics Letters, 2022. (*under review*);

- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*Energy-shaping Controllers for Soft Robot Manipulators through Port-Hamiltonian Cosserat Models*", SN Computer Science Springer, 2022. (*under review*);

- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*Control-oriented Models for Hyper-elastic Soft Robots through Differential Geometry of Curves*", Soft Robotics, 2021. (*under review*).

Peer-reviewed articles in conference proceedings

- B. Caasenbrood, F.E. van Beek, H. Khanh Chu, and I.A. Kuling, "*A Desktop-sized Platform for Real-time Control Applications of Pneumatic Soft Robots*," IEEE International Conference on Soft Robotics, RoboSoft 2022.

- A. Amoozandeh Nobaveh, and B. Caasenbrood, "*Design Feasibility of an Energy-efficient Wrist Exoskeleton using Compliant Beams and Soft Actuators*", Proceedings of the 18th International Consortium for Rehabilitation Robotics, 2022, pp. 311–319.

- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*Energy-based control for Soft Robots using Cosserat-beam models*", Proceedings of the 18th International Conference on Informatics in Control, Automation and Robotics, 2021, pp. 311–319.

- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*A Computational Design Framework for Pressure-driven Soft Robots through Nonlinear Topology Optimization*," 2020 3rd IEEE International Conference on Soft Robotics, 2020, pp. 633-638.

- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*Dynamic modeling of hyper-elastic soft robots using spatial curves*," IFAC World Congress 2020.

Invited Talks and abstracts

- B. Caasenbrood, "`SOROTOKI`*: an Open-source Toolkit for Soft Robotics written in MATLAB*," IEEE International Conference on Soft Robotics, RoboSoft 2022 (abstract).

- B. Caasenbrood, C. Della Santina, and A. Pogromsky, "*Workshop on Model-based Control of Soft Robots*," European Control Conference (ECC), 2021. (main organizer).

- B. Caasenbrood, talk on "*Towards Desing and Control of Soft Robotics*," 4TU Symposium on Soft Robotics, 2020. (invited speaker).

- B. Caasenbrood, talk on "*3D-printed Soft Robotics*," Symposium on Robotic Technologies, 2019. (invited speaker).

- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, talk on "*Forward Dynamics of Hyper-elastic Soft Robotics*," 39th Benelux Meeting on Systems and Control, 2019. (abstract).

- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, talk on "*Dynamical modeling and control of continuum soft robots*," 37th Benelux Meeting on Systems and Control, 2018. (abstract).