Design and Control Strategies for Soft Robotic Systems

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The work described in this thesis was carried out at the Eindhoven University of Technology.

The research reported in this thesis is part of the research program of the Dutch Institute of Systems and Control (DISC). The author has successfully completed the educational program of the Graduate School DISC.

A catalogue record is available from the Eindhoven University of Technology Library.
ISBN: 123-45-678-9012-3

Typeset by the author using the pdf LaTeX documentation system.
Cover design: Name of cover designer
Reproduction: Name of printer || www.printerswebsite.nl

Design and Control Strategies for Soft Robotic Systems

Proefschrift

ter verkrijging van de graad van doctor aan de
Technische Universiteit Eindhoven, op gezag van de
rector magnificus prof.dr.ir. F.P.T. Baaijens, voor een
commissie aangewezen door het College voor
Promoties, in het openbaar te verdedigen
op maandag 30 december 2022 om 16:00 uur

door

Brandon Jonathan Caasenbrood

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Abstract

Design and Control Strategies for Soft Robotic Systems

B.J. Caasenbrood (Brandon)   Date: March 15, 2022

In the past two decades, the field of soft robotics has kindled a major interest among many scientific disciplines. 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 that benefactors human-robot safety. 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 subject to environmental uncertainty, 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*'. Furthermore, as soft materials undergo large nonlinear mechanical responses paired with distributed actuation, expressing the robot's workspace often leads to highly nonlinear kinematic descriptions. Using traditional engineering principles for soft materials is perhaps outdated and computer-assisted design principles for soft robotics might mandate the next steps for the field, especially with the recent advances in Additive Manufacturing (AM). As for modeling, its innate infinite-dimensionality poses fundamental problems for model-based controllers. An important question arises during the modeling of such soft robots; '*how to deal with the trade-off between accuracy and computational efficiency?*'. Besides, the presence of soft materials imbue the system with nonlinear mechanical responses that are perhaps alien to standard robot modeling. As a result, in terms of closed-loop performance, soft robots nowadays are easily outclassed by their rigid counterparts due to a lack of modeling knowledge. 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 generative design strategies for soft robots as well as model-based control strategies 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.*, tendons, hydraulics, and pneumatics. Contrary to traditional design, such as bio-mimicry, a gradient-based topology optimization is explored to find sub-optimal soft robotic morphologies that satisfy user-defined motion criteria. Two difficulties are addressed here. First, pressure-based topology optimization yields distributed adaptive loadings that changes at each optimization step; and second capturing the hyper-elastic nature of soft materials. A Finite Element Method (FEM) solver is proposed such that the physics under large nonlinear deformations of hyper-elastic materials and pneumatic actuation are accurately preserved. The optimization-driven algorithm yields generative designs for a diverse set of soft morphologies: soft rotational actuators, soft artificial muscles, and soft grippers. By assembly of smaller soft sub-components, a full soft robot can be developed and through AM of flexible materials the feasibility is validated.

The second part of the thesis will focus on the model-based control of soft continuum manipulators, where the emphasis lies on the efficiency and accuracy in low-dimensional models. The continuous dynamics of the soft robot are modeled through the differential geometry of spatial curves. Using a finite-dimensional truncation, the system can be written as a reduced port-Hamiltonian model that preserves desirable control condition, *e.g.*, passivity. However, this modeling techniques introduces gaps between the underlying material mechanics and control-structured dynamic model. Since useful information is attainable through FEM a-priori, new system identification tools are proposed that give inside into the dominant dynamic modes, the hyper-elasticity, and the reachable workspace spanned by soft materials and actuation. The approach yields accurate low-dimensional models with real-time control capabilities but also gives physical insight into optimal sensor placement applicable to proprioceptive sensing.

Following, the thesis treats the development of model-based controllers that can be employed in various control scenarios, *e.g.*, motion planning, set-point stabilization, tracking, and grasping; akin to rigid robotics. The stabilizing controller utilizes an energy-based formulation, providing robustness even when faced with material uncertainties. The controller's effectiveness is demonstrated in simulation for various soft robotic systems that share a close resemblance to biology.

Lastly, the thesis will implement the proposed computationally efficient systematic strategies for the design and control on physical soft robotic systems, including soft grippers, soft manipulators, and soft exoskeletons. As a concluding remark, this thesis contains several new techniques for design and model-based control of the increasingly fast evolving and multi-disciplinary field of soft robotics.

Keywords: Soft Robots, Flexible Robots, Design Optimization, Continuum Mechanics, Reduced-order Modeling, Model-based Control, Additive Manufacturing.

Samenvatting

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Societal summary

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Nomenclature

Vector and matrix notation

x	Scalar notation
$\boldsymbol{x}$	Vector notation
$\boldsymbol{X}$	Matrix notation
$\boldsymbol{\mathcal{X}}$	Tensor notation
$\boldsymbol{\mathcal{Q}}$	Manifold

Compact sets

$\emptyset$	Empty set
$\mathbb{R}$	Set of real numbers
$\mathbb{R}^n$	n-dimensional Euclidean space
$\mathbb{R}_{>0}$	Strictly positive reals
$\mathbb{R}_{\geq 0}$	Positive reals
$\mathbb{N}$	Set of natural numbers
$\mathbb{T}$	Finite time horizon
$\mathbb{X}$	1-dimensional spatial set or domain (*i.e.*, line)
$\mathbb{V}$	3-dimensional spatial set or domain (*i.e.*, volume)

Groups

id	Identity
$\mathrm{SO}(n)$	Lie group of rotations on $\mathbb{R}^n$ (*i.e.*, special orthonormal matrices)
$\mathrm{SE}(n)$	Lie group of homogeneous transformations on $\mathbb{R}^n$
$\mathrm{so}(n)$	Lie algebra of $\mathrm{SO}(n)$
$\mathrm{se}(n)$	Lie algebra of $\mathrm{SE}(n)$

Vector- and matrix operations

$\dot{(\,\cdot\,)}$	First time derivative
$\ddot{(\,\cdot\,)}$	Second time derivative
$\hat{(\,\cdot\,)}, (\,\cdot\,)^{\wedge}$	Isomorphism from $\mathbb{R}^6 \to \mathrm{se}(3)$
$\check{(\,\cdot\,)}, (\,\cdot\,)^{\vee}$	Isomorphism from $\mathrm{se}(3) \to \mathbb{R}^6$
$(\,\cdot\,)_0$	Reference configuration
$(\,\cdot\,)^{\top}$	Transpose
$(\,\cdot\,)^{-1}$	Square matrix inverse
$(\,\cdot\,)^{\dagger}$	Moore-Penrose pseudo inverse
$(\,\cdot\,)^{+}$	Generalized matrix inverse
$(\,\cdot\,)^{d}$	Generalized matrix inverse

Operators and letter-like symbols

δ	Variation of a field
∂	Boundary of a set
int	Interior of a set
$\sup_t$	Supremum over continuous time t
dim	Dimension of vector
trace	Trace of matrix
$\|\cdot\|_{\mathrm{ma}}$	Mean absolute norm
$\|\cdot\|_{\mathrm{rms}}$	Root-mean-square norm

Acronyms

CoM	Center of mass
CoR	Coefficient of restitution

1
Introduction

1.1 The Origin of Soft Robotics

The term '*soft robotics*' is the abbreviated form of '*soft material robotics*'. Although the words '*soft*' and '*robotics*' have a clear definitions independently, the collocation of the two has sparked vivid discussions in the robotics community for many years – even touching the territories of the philosophical. Consequently, the exponential scientific interest in soft robotics around 2011 may be seen as a historical cornerstone that has revolutionized our perspective on the branching field of robotics and rekindled its original ambition even before the term '*robot*' was introduced. Although the debate on the exact terminology is still ongoing, and perhaps may never be closed; we propose a definition for '*soft robotics*' applicable to this thesis based on an ensemble of prior literature:

> **Terminology:** **Soft robotics** *is a subclass of robotics with purposefully designed compliant elements embedded into their mechanical structure whose goal is to endow the robot with biological motion and/or compliance.*

The definition above is mostly adopted from Della Santina et al. [], yet modified to purposefully highlight the importance of soft materials to mimic biological motion – also referred to as '*bio-mimicry*'. The ambition of closely mimicking biological creatures is perhaps not often associated with the field of robotics in general, yet the inception of robotics can originally be found in bio-mimicry when regarding its rich history. We would like to implore the reader to embark with us this brief section into the history of (soft) robotics, as to show that the current trends of bio-mimicry in robotics finds roots in a period before classic robotics.

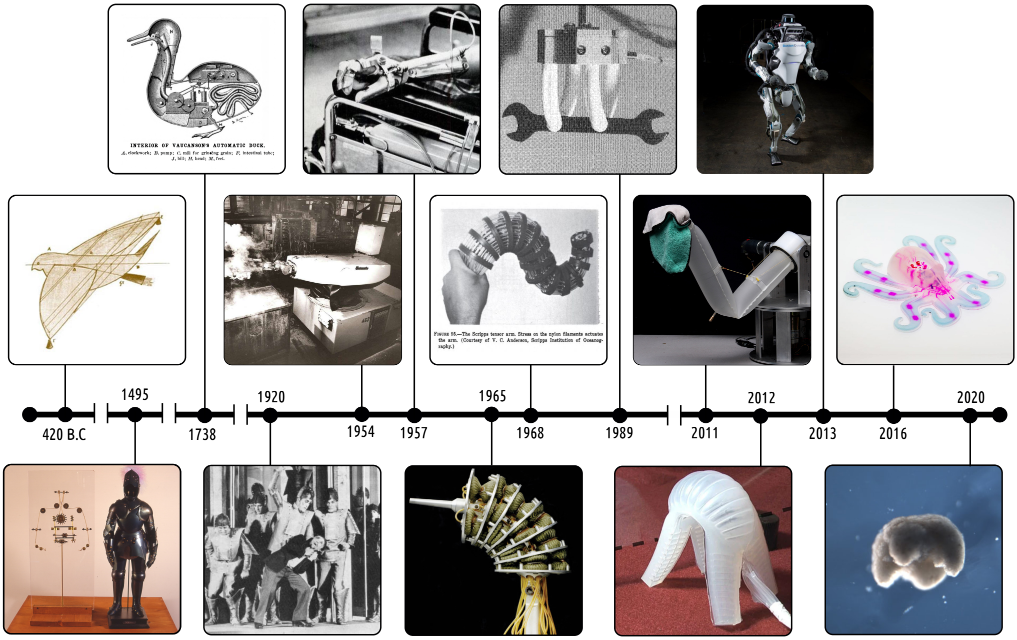

Figure 1.1. A brief timeline of the state-of-the-art of robotics throughout human history. *a)* One of the earliest examples of bio-mimicry – the flying mechanical bird using steam-powered propulsion. *b)* The Mechanical Knight by Leonardo Da Vinci. *c)* A mechanical monk adopted by the designs of Da Vinci. *d)* Digesting duck patent of Jacques de Vaucanson. *e)* The science-fiction play by Karel Čapek on robots, who introduced the word '*robot*' into the Oxford English Dictionary originally from his brother Josef Čapek.

One of the earliest examples of bio-mimicry is a mechanical wooden dove developed by mathematician Archytas of Tarentum in 350 BC. According to historians, the system was driven by compressed air or an internal steam-driven engine to achieve forward propulsion, capable of traveling distances of ~200 m (see note[1]). Archytas's invention could be considered as one of the earliest robotic systems – a machine or device that operates automatically or by remote control – whose main principles are somewhat analogous to nowadays '*drone*' technology. A millennium later, in the period of the High Renaissance, Leonardo da Vinci designed and constructed a mechanical knight around the 1490's. Such mechanical constructions were perhaps closer to conventional rigid robotics given our current robotics perspective. It is well-known that his work was built upon extensive anatomical research, which may have facilitated a deep understanding of the human body into the mechanical knight's robotic design.

In the 1920's, shortly after the second industrial revolution (1870 - 1914) and the first world war (1914), the first usage of the work '*robot*' appeared – originally meaning 'forced labor by serfs' (*i.e.*, peasants) derived from the Czech word '*robota*'. An common misconception is that robot implies slave, although incorrect, its origin is somewhat related. The word was popularized by Karel Čapek in his play R.U.R. (Rossum's Universal Robots) that involves an inventor named Rossum who discovers the secret of creating human-like machines. In his play, Rossom's robots assisted or fully alleviated mankind from any labor. Through human's ambition to assimilate man and machine, the robots ultimately gained the capacity for emotions – including pain. Shortly after, the robots, who were created to serve humans, have come to dominate mankind completely. The word '*robotics*' was later solidified by Isaac Asimov, adapting the term from Čapek. These works of science fiction are perhaps the fundamental groundwork of modern robotics which have led to the base practices of robotics and its corresponding academic field.

Only three decades later, in the 1950's, the first robotic arm called the 'Unimate' was employed in industry. The robot was used for manipulating die cast and welding these to welding these to the main body of automobiles. Interestingly, the robot explored both electric as hydraulic-mechanical actuation, similar to nowadays popular Atlas robot (2013) by the company Boston Dynamics. Note that these robots were still controlled remotely, and rudimentary levels of closed-loop control were applied then. The 1950's brought forth the McKibben actuators developed by Joseph Laws McKibben. These McKibben actuator consists of an inflatable inner bladder enveloped with a double-helical weave. When pressurized, the fluidic actuator converted radial expansion into uni-axial contraction since weave inhibited extensive '*ballooning*' – a term for undesired radial expansion. The McKibben actuators are perhaps seen as one of the first fundamental technologies that enabled soft robotics and to this day it remains a framework for many soft artificial muscle. Nevertheless, besides fluidics, there exist many other technologies employed in soft robotic motion that predate the invention of the McKibben

[1] It was unclear if the devices was attached to a rope, or autonomous flight was achieved.

actuator: such as thermal or chemical expansion/contraction, re-alignement of crystals, di-electric elastomers, magnetism, and naturally electro-mechanical actuation. Although they do not fall under the class soft robot, they are; however, categorized as soft actuators. We like to emphasize here the difference between soft actuators and soft robots in view of the terminology corresponding with the thesis:

> **Terminology: Soft actuators** *are controllable flexible components of the constitutive soft robotic system that through external stimuli allow for motion or adaptability of compliance and/or texture.*

This terminology attempts to address a common ambiguity in the field of soft robotics, being that the term of soft actuators and soft robots are sometimes used interchangeably. For instance, the earliest Dielectric Elastomer Actuators (DEA) were developed W. C. Röntgen in 1880; and some literature catagorizes these actuator as soft robotics. In the mid-1950's, the work of ??? designed one of the soft robotics systems – even before rigid hyper-redundant robotics. The system consisted of three pneumatic soft actuators aligned in parallel to the backbone of the robot. blat

1.2 Modern Soft Robotics

The first robotic manipulator arm used in the orbital environment was the Space Shuttle remote manipulator system. It was successfully demonstrated in the STS-2 mission in 1981 and is still operational today.

First soft robot: Victor Scheinman and Larry Leifer developed an air-powered robot arm called Orm, which is the Norwegian word for snake.

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- W. C. Röntgen, “Ueber die durch Electricität bewirkten Form—und Volumenänderungen von dielectrischen Körpern,” Ann Phys Chem, no. 11, pp. 771-786, 1880.

Preliminary titles, committee members, and list of publications

Preliminary titles

1. A Control-oriented Perspective on Design and Modeling of Soft Robotic Systems;
2. Towards a Unified Framework for Design and Model-based Control of Soft Robots;
3. Addressing the Open Challenges in Soft Robotics: from Design to Model-based Control
4. Design and Control Strategies for Soft Robotic Systems;
5. Design, Modeling, Simulation and Control of Soft Robots.
6. Design, Modeling and Control Strategies for Soft Robotics Systems;
7. (Soft Manipulators/Soft Robotic Manipulators?)

Preliminary committee members

- prof. J. den Toonder (TU/e, Microsystems, ICMS)
- dr. R. Luttge (TU/e, Microsystems) - Backup for Jaap

....

- prof. G. Krijnen (Twente University) Technologies)
- prof. C.C.L. Wang (Delft University) [1], [2]
- prof R. Carloni (Rijksuniversiteit Groningen) - backup for Gijs

....

- dr. E. Franco (Enrico, Imperial College London) [1], [2]
- prof. H. Mochiyama (University of Tsukuba) [1], [2]
- dr. C. Duriez (INRIA Lille) [1],[2]
- prof. R. Katzschmann (ETH Zurich) [1],[2]
- dr. S. Grazioso (University of Naples) [1]
- dr. M. Bächer (ETH Zurich) [1],[2]
- Antonio Bicchi - Italian
- Annibal Olero - Spain
- Bas Overvelde??

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. (accepted)

- 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 (accepted).

- 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, IFAC-PapersOnLine, 2020, pp. 9238-9243.

Invited Talks and Non Peer-reviewed 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).