Design, Modeling, and Control Strategies for Soft Robots

Brandon Jonathan Caasenbrood

EINDHOVEN UNIVERSITY OF TECHNOLOGY

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
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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

geboren te Roermond

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Abstract

Design, Modeling, and Control Strategies for Soft Robots

In the past two decades, the field of soft robotics has sparked significant 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. Since its inception, soft robotics has exemplified its potential in diverse areas such as safe manipulation, adaptive grasping, exploration under environmental uncertainty, rehabilitation, and the bio-mimicry of many animals. By exploring the uncharted versatile nature of soft materials, soft robotics places the first steppingstones towards achieving biological performance in modern-day's robotics. This thesis aims to further the advances in soft robotics by addressing some of the open multi-disciplinary challenges within this young field of research.

Although soft materials harbor many advantages akin to biology, which are difficult to achieve for rigid robotics, it also roots many fundamental problems. First is the issue of soft robotic design. Traditional robotic design emphasizes high structural rigidity and weight minimization – a well-established practice in engineering. On the other hand, soft robotic design relishes minimal structural rigidity for motion, leading to complex, highly nonlinear relations between the input and output. Besides, distributed soft actuation, imparted by gravitational and inertial forces acting on the continuum elastic body, introduce joint mobilities that are in many cases uncontrollable nor aligned with the control objective, *e.g.*, precise grasping and manipulation. Since describing the underlying continuum mechanics and applying such mathematical theory to systematic design is challenging, a large number of soft robotic systems are still developed *ad hoc*.

Second, a direct duality of the previous challenge is dealing with the innate infinite-dimensionality from a control perspective – particularly with model-based feedback in mind. The transition from rigid to flexible has introduced a new control paradigm: the trade-off between precision and speed in a numerical setting. Not only is control theory for soft robotics in stages of inception, but deriving accurate and numerically efficient model-based controllers is challenging due to large nonlinear deformations of the soft robotic continuum.

In light of these challenges, this thesis proposes a set of systematic tools with theoretical and experimental applications for (*i*) the structural design and fabrication of continuum-deformable soft actuators optimized for user-defined joint motion, (*ii*) the development of efficient dynamic models of soft continuum manipulators, and (*iii*) applying such mathematical models to model-based controllers for a subclass of (pneumatic) soft continuum manipulators and soft grippers.

The first part of the thesis addresses the design problem by proposing novel computer-automated design algorithms for developing efficient soft actuators. These algorithms account for the underlying continuum mechanics described by a set of partial differential equations, which respect the aforementioned nonlinearities between the input and output motion. Tailoring a user-defined objective to a desired motion and control reachability, an implicit representation of the optimal soft material distribution can be found within a fixed design space. Several generative designs for a diverse subset of soft actuation morphologies are produced including, but not limited to, soft rotational actuators, soft artificial muscles, and soft grippers. In what follows, an optimal design for a soft robotic manipulator with an adaptive gripper is synthesized; and through Additive Manufacturing (AM) of printable flexible material, the sim-to-real boundary is passed. The proposed approach does not only accelerate design convergence but also builds upon the vast library of soft robot morphologies currently unexplored in literature.

The second part of the thesis addresses the question of modeling for control applicable to a class of soft robotic systems – most notably soft continuum manipulators. The thesis proposes a reduced-order modeling strategy for soft robotics, whose dynamics are derived through the differential geometric theory on spatial beams. Besides discussing earlier modeling strategies, the thesis also proposes a new strain-based parametrization approach that ensures the structural information and the underlying continuum mechanics are preserved when synthesizing the reduced-order beam models – a possible solution to the aforementioned control paradigm of precision vs. speed. To enhance numerical performance further, spatio-temporal integration schemes are also proposed that exploit the geometric structure of such soft beam models, resulting in real-time simulation with sufficient numerical precision purposefully tailored for control.

The third part of the thesis treats the development of model-based controllers that can be employed in various control scenarios akin to control for traditional rigid robotics, *e.g.*, inverse kinematics and motion planning, set-point stabilization, trajectory tracking, and multi-point grasping of objects. The stabilizing controller is rooted in an energy-based formulism, providing robustness even when faced with material uncertainties. The controller's effectiveness is demonstrated both in simulation and experiments for various soft robotic systems that share a resemblance to biology, *e.g.*, the elephant's trunk or the tentacle of an octopus.

The main contribution of the thesis is a collection of multi-disciplinary tools compressed into one general framework for the design, modeling, and control of a class of soft robots, ranging from the theoretical to the experimental domain.

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

Nomenclature

Vector and matrix notations

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

Set notations

$\emptyset$	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
SO(3)	Lie group of rotations on $\mathbb{R}^3$ (*i.e.*, special orthonormal matrices)
SE(3)	Lie group of homogeneous transformations on $\mathbb{R}^n$
se(3)	Lie algebra of SO(3)
so(3)	Lie algebra of SE(3)

Vector- and matrix operations

$(\cdot)^\top$	Transpose
$(\dot{\cdot})$	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 $\mathrm{se}(3) \to \mathbb{R}^6$
$(\cdot)^\circ$	Reference or rest configuration
$(\cdot)^\star$	Optimal solution
$(\cdot)^{-1}$	Square matrix inverse
$(\cdot)^\dagger$	Moore-Penrose pseudo inverse
$(\cdot)^+$	Generalized matrix inverse
$(\cdot)^\perp$	Annihilator

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
diag	Diagonal of matrix
$\|\cdot\|_{\mathrm{ma}}$	Mean absolute norm
$\|\cdot\|_{\mathrm{rms}}$	Root-mean-square norm

Acronyms

CoM	Center of mass
CoR	Coefficient of restitution
FEM	Finite element method (or model)
ODE	Ordinary differential equation
PDE	Partial differential equation
PneuNet	Pneumatic network
SRM	Soft robotic manipulator
TopoOpt	Topology Optimization

Contents

I

Opening

1

Soft Robotics – a new perspective on biomimicry

1.1 History of soft robotics: what are they?

The term '*soft robotics*' is the abbreviated form of '*soft material robotics*'. *Soft* or *softness* here refers to the enveloping properties of low-elasticity materials. Examples include: high compressibility, low rigidity, high structural damping, and (often) environmental resilience. An objective measure of a material's elasticity is the Young's modulus. Although it only applies to homogenous media that are subjected to axial loads and small deformations, it can be explored to classify the rigidity of materials. We provided a spectrum of different materials in Figure 1.1. Observing the spectrum, we observe that convectional materials used in *rigid* robotics (like metals and hard plastics) have elasticity moduli in the order of $10^9 - 10^{12}$ Pa. Yet, biological organisms are composed of materials with predominantly low moduli $10^4 - 10^7$ Pa (*e.g.*, muscle tissue) and sparse high moduli $10^8 - 10^9$ Pa (*e.g.*, bone). It is interesting to observe that the materials responsible for motion, which naturally undergo repeated deformation, have accordingly low elasticity. As opposed to the use of rigid materials in classic robotics. The idea of exploring low elasticity materials in robotics, so-called '*soft materials*', has sparked a new directions in robotics research aimed at harmonizing robotics and biology.

Now, although the words '*soft*' and '*robotics*' have a clear definitions independently, the collocation of the two sparked many vivid discussions and new idealogies within the robotics community for the past decades. Throughout its

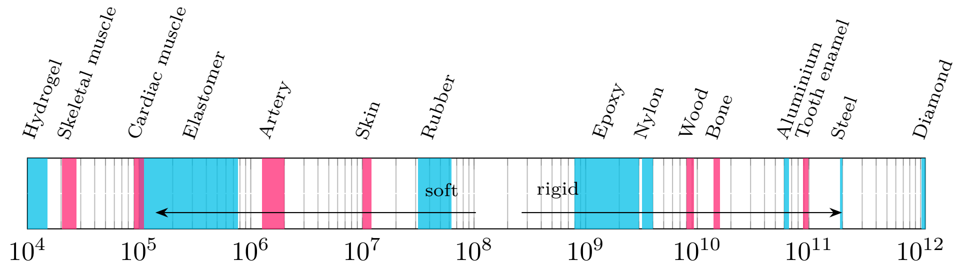


Figure 1.1. Young's modulus spectrum in (Pa) of rigid and soft materials, where (—) are the organic (*i.e.*, biological) materials and (—) inorganic materials.

young academic life, several defintions have been coined. Early terms for soft robotics were used to indicate robots with variable joint stiffness [1], or robots with artificial compliance using control [2]. The term was also used to underline the shift from rigid-linked robots to bio-inspired continuum robots with *inherently compliant and exhibit large strains in normal operations* [3]. Paraphrasing the work of Robison et al. (1999, [4]): *soft robotic manipulators are continuum robots made of soft materials that undergo continuous elastic deformation and produce motion through the generation of a smooth backbone curve.* Alternatively, a broader definition was coined in a review by Kim et al. ([5], 2013) simply referring to soft-bodied robots as *an analogy to soft-bodied animals.* A concise (but perhaps too general) definition was proposed by Laschi et al. ([6], 2014), as soft robots being *any robot built by soft materials.* Rus et al. (2015, [7]) defined soft robots in terms of their structural elasticity: *Systems that are capable of autonomous behavior, and that are primarily composed of materials with moduli in the range of that of soft biological materials.*

Although the debate on its exact terminology is still ongoing, and perhaps may never be closed; we will propose soft robotics terminologies and related topics in the field based an ensemble of soft robotic history and literature. Naturally, given its multi-disciplinary extensiveness, the terms used in this thesis will deviate from the aforementioned literature. Yet, introducing these defintions is deemed necessary to mitigate ambiguity in this thesis. Following, let us propose a definition for soft robotics:

> **Terminology I.** ***Soft robotics*** *is a robotics subclass with purposefully designed compliant elements embedded into their mechanical structure whose goal is to endow the robot with natural (or biological) motion or compliance.*

This definition is adopted from the work of Della Santina et al. (2020, [8]), but

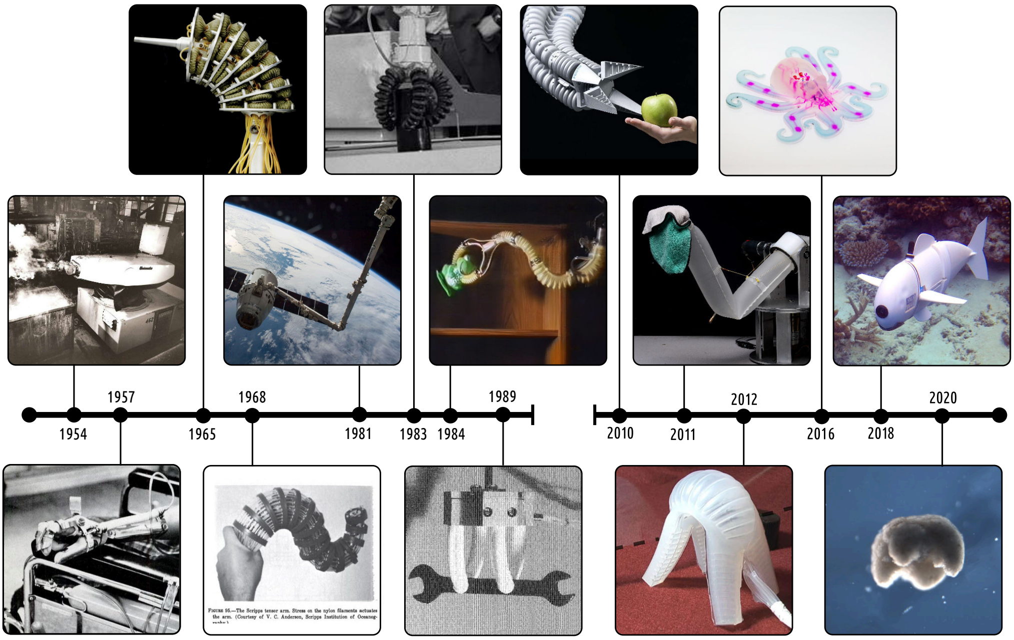


Figure 1.2. A brief timeline of the state-of-the-art of bio-inspired robotics throughout human history. (1954): Unimate, the first industrial robot. (1957): McKibben actuator, an early soft actuator inspired by the human muscle used for rehabilitation purposes. (1965): The Orm, believed to be the first soft robotic system designed by Scheinman and Leifer . (1968): Tensor Scripps arm developed by Anderson [9]. (1981): Canadarm-1, early flexible robotics employed on the International Space Station. (1983): Robot Arm with Pneumatic Gripper by Teleshev [10]. (1984): Bellows robotic arm by Wilson et al. [11]. (1989): The soft robotic gripper developed by Suzumori et al. [12, 13], seen as one of the earliest *academic* soft robot, developed before the word '*soft robot*' existed. (2010): Festo's Bionic arm inspired by the elephant's trunk [14]. (2012) Multi-gait soft robot capable of terrestial locomotion [15]. (2016): Octobot, the first autonomous 3D-printed soft robot that explores a stabilizing oscillator chemical network that produces preprogrammed repetitive motion [16]. (2018): Autonomous robotic fish made by Katzschmann [17]. (2020): Xenobot, an organic soft robot composed of skin and muscle cells made by Blackiston and Kriegman [18].

modified to 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 commonly associated with the field of robotics, given its importance in the automation industry, yet the inception of robotics can originally be found in bio-mimicry when regarding its rich history. We would like to invite the reader to embark with us a brief section into a short history of soft robotics. Hereby showing that the current trends of bio-mimicry and elasticity in robotics find roots in a periods way before the soft robotic boom in the early 2010's. To guide the reader, in Figure 1.2, we provide a historical overview of soft robotic systems. We will discuss the inception of bio-mimicry in robotics, flexibility in robotics and early soft robots.

(**Early robots with flexibility**) Before discussing robotic systems with flexibility, let us begin with the early rigid robotics. In 1954, George Devol filed a patent describing an autonomous robotic machine that could be preprogrammed to execute step-by-step motions [19]. The machine was designed to reduce the workload on the manufacturing work floor, with a major focus on mimicking repetitive, exhausting human labor. In 1958, those prototypes led to a robotic system under the name '*Unimate*'. The Unimate was used for manipulating metal die-casts and welding these to the main body of automobiles. In doing so revolutionizing the car industry shortly after. Much later (1969), Victor Scheinman created the Stanford Arm, recognized as the first electronic computer-controlled robotic arm because the Unimate's instructions (*i.e.*, setpoints) were stored on a magnetic drum. He later developed the PUMA robot in 1972 – the successor of the Unimate. Please keep Scheinman in mind, as he ultimately ties to early soft robots.

Nearly four years after the Unimate was developed, Joseph L. McKibben developed a pneumatic muscle-inspired actuator capable of linear contraction – called the McKibben actuator. The McKibben muscle is a type of Pneumatic Artificial Muscle (PAM) which is to this date the most frequently used and published artificial muscle in literature. According to [20], he developed the McKibben actuators to bring motion to his little daughter's polio-paralyzed hand. His aim was that eventually these pneumatic actuators may help patients with paralyzed fingers to move, to grasp, and even to write. Inspired by the human muscle, the McKibben actuator consists of an inflatable inner bladder enveloped with a double-helical weave. When pressurized, the fluidic actuator converts radial expansion into uniaxial contraction [21–23] since weave inhibits extensive '*ballooning*' – a term for undesired rapidly-accelerated volumetric expansion. The materials are typically latex or silicone rubber with nylon fibers. A schematic representation of a general pneumatic muscle and the effect of ballooning are shown in Figure 1.3. Ballooning is an (often undesired) nonlinear effect, where the hyper-elastic pressure vessel exhibits strain-softening after a critical point is reached. As a result, further increase

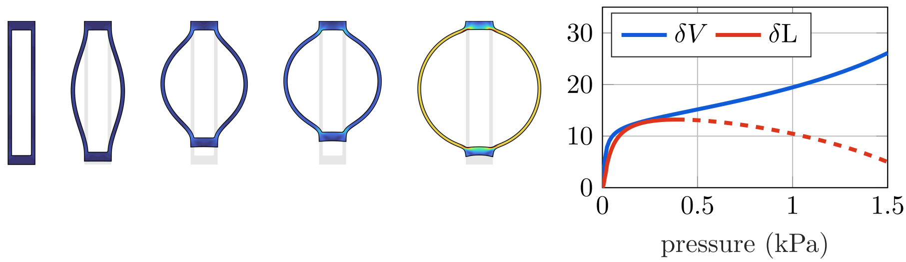
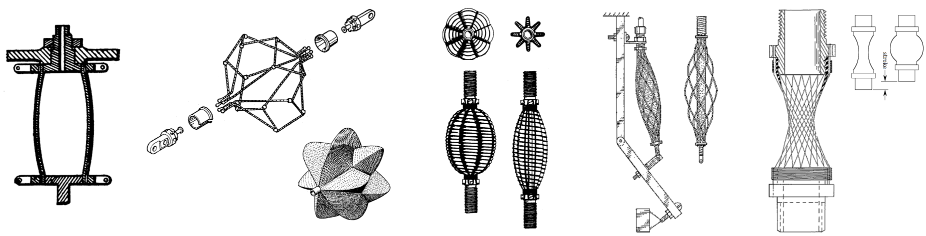


Figure 1.3. Working principle of a basic pneumatic artificial muscle (*i.e.*, Morin muscle [27]) with the internal volume (—) in mL, and the end-effector displacement (—) in mm and (- -) is the point at which the undesirable ballooning occurs.



(a) (b) (c) (d) (e)

Figure 1.4. Patent diagrams of pneumatic artificial muscle from 1953 till 1988. (a) Morin Muscle (1953, [27]); (b) ROMAN muscle (1986, [25]); (c) Yarlott muscle (1972, [24]); (d) Kukolj muscle (1988, [26]); (e) Paynter Hyperboloid (1974, [29]).

of the pressure leads to an exponential growth in volume, which ultimately leads to actuator tearing. At stages of ballooning, mechanical performance significantly drops and even produces adverse effects, like actuation reversal. McKibben solved this problem through a combination of soft and inextensible fiber weaves. These inextensible were placed at the exterior wall of the soft muscle, thereby limiting the radial expansion before ballooning could occur. According to Daerden (1999, [21]), there a many variations of pneumatic muscle besides braided muscles, such as the '*netted muscles*' (e.g, Yarlott [24], ROMAC [25], and Kukolj [26]) and '*embedded muscles*' (*e.g.*, Morin [27], Paynter Hyperboloid [28]). Illustration of their patent schematics are shown in Figure 1.4.

Pneumatic muscles are perhaps one of the first fundamental technologies that enabled soft robotics and to this day it remains a framework for many soft robotic systems. Nevertheless, besides the many examples of fluidics [12, 17, 30–32], there exist many other technologies employed in soft robotic motion: such as thermal [33] or chemical expansion/contraction [16, 34, 35], crystal re-alignment [36–39], di-electric elastomers [40], magnetism [41–44], and naturally the use of tendons paired with electro-mechanical actuation [45–49]. Some predate the invention of the McKibben actuator. An early example of popular actuation techniques in soft robotics is the Dielectric Elastomer Actuators (DEA) developed by Röntgen in (1880, [50]). Therefore, given the abundance of soft robotic actuation, it is difficult to pinpoint the exact origin of soft actuation technology. Although these systems are not categorized as soft robots, they are; however, categorized as soft actuators. We like to emphasize here the difference between soft actuators and soft robots in view of a terminology relevant to the thesis:

> **Terminology II.** ***Soft actuators*** *are controllable flexible actuation units of the constitute soft robot that through external stimuli allow for controllable motion, or change in compliance or texture.*

Remark 1.1. *The terminology above attempts to address an ambiguity common to soft robotics, namely the interchangeable use of soft actuator and soft robot.*

Returning to 1965, nearly a decade after the invention of the McKibben actuator, Scheinman and Leifer proposed an novel pneumatic robotic arm named the '*Orm*' – Norwegian for snake (recall that he also developed the popular PUMA robots). Clearly the name was inspired by the morphology of snakes, but it was also an abbreviation for Object-Relational Mapping tool [51]. To the author's knowledge, this is believed to be the first soft robot. Surprisingly the system predates any rigid, redundant, snake-like robot, like the Scripps tensor arm by Anderson (1968, [9]). Similar to the anatomy of the snakes, the system featured 28 rubber pneumatic artificial muscle (*i.e.*, bellows) distributed along the backbone (*i.e.*, skeletal support) of the robot. The network of artificial muscles were sandwiched between steel plates to prevent misalignment. Note that this technology is analogous the pneumatic muscles of McKibben, where a fiber weave was used to prevent ballooning. Yet, contrary to a single McKibben actuator, the soft robotic system could undergo three-dimensional movement by inflation or deflation of embedded pneumatic network. This led to a rich set of movements previously unseen in rigid robotics. As an illustrative example, we provided the mechanics of the Orm soft robot in Figure 1.5. The soft robot could achieve bending in any preferred direction by differential pressurization of each channel, and elongation through synchronized actuation. Most notably, comparing the volume vs. strain response of the Orm w.r.t the McKibben actuator, *i.e.*. Figure 1.3 against 1.5, the actuation response is noticeably more linear. Although not documented at the time, the comparison highlights the importance of structural geometry in pneumatic networks.

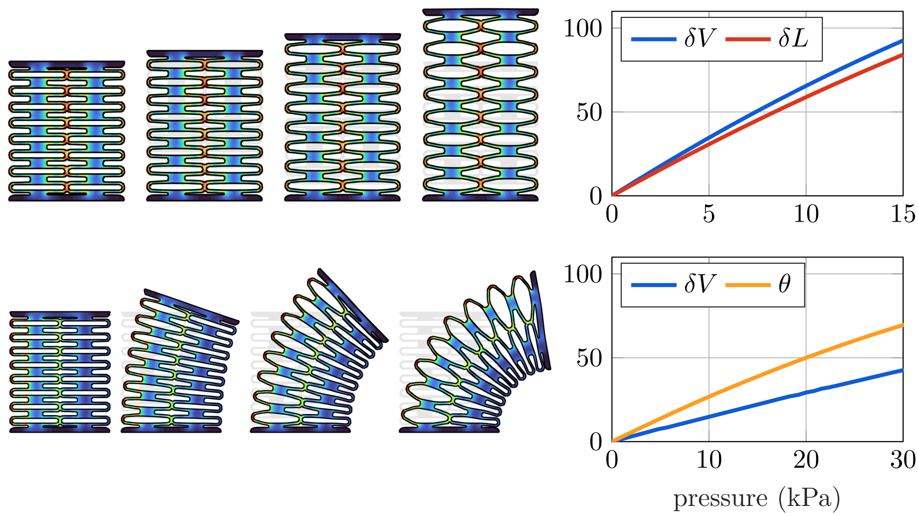
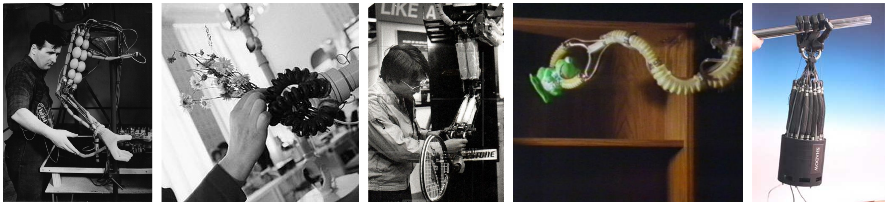


Figure 1.5. Working principle of the Orm robotic manipulator with the internal volume (—) in mL, and the end-effector displacement (—) in mm and bending-angle (—) in °. By actuation of the pneumatic network, both elongation and bending are achievable. Observe that the response is significantly more linear than McKibben actuators in Fig. 1.3, emphasizing the importance of geometry.

Nevertheless, according to [], the positional accuracy of the system was poor, yet the concept of pneumatically-driven soft arms has continued. The positional inaccuracy of pneumatic soft actuators at the time may have caused a lost of academic interest in the 60s - 70s. Yet, three years later, in 1968, an improved hyper-redundant robot manipulator was proposed and patented by Anderson and Horn [9]. Improving upon the Orm, which was deemed slow and had limited positional accuracy, Anderson proposed an array of nylon tendons that were connected to rigid discs distributed along the redundant backbone of the robot. The configurable backbone was comprised of universal spherical joints that allow for pivoting motion with respect to other discs – totalling 16 Degrees-of-Freedom (DOFs) in the system. The entire arm was actuated hydraulically, yet the actuators were placed outside the robot's body rather than placed at each joint, like the Orm. To improve positional accuracy further, Anderson placed sensor tendons parallel the actuator tendons which allowed for operator position feedback. Although Anderson's robot does not categorize as a soft robot since it relies mostly on rigid materials, its flexibility arose from the thin nylon tendons that were used for both actuation and sensing. Anderson showed that a network of distributed sensors are necessary to describe and control the complex morphology of the robotics system,



(a) (b) (c) (d) (e)

Figure 1.6. Early robotic systems that explored soft pneumatic muscles of various sorts. (a) Teleshev's soft grippers [10]. (b)

while mitigating the sensor's effect on the mobility.

> **Terminology III.** ***(Proprioceptive) soft sensors*** *are flexible measurements units embedded into soft robotic system that through external stimuli measure the (local) changes of the system. Softness here implies that the sensor minimally alters the mechanical behavior of the full robotic system.*

Remark 1.2. *As the emphasize lies on "minimally alters the mechanical behavior of the robot", soft sensors may be composed of stiff (perhaps even rigid) components. Our definition infers that these sensors must be placed into or onto the soft body, minimally affecting the compliance of the soft actuator network in static or dynamic conditions.*

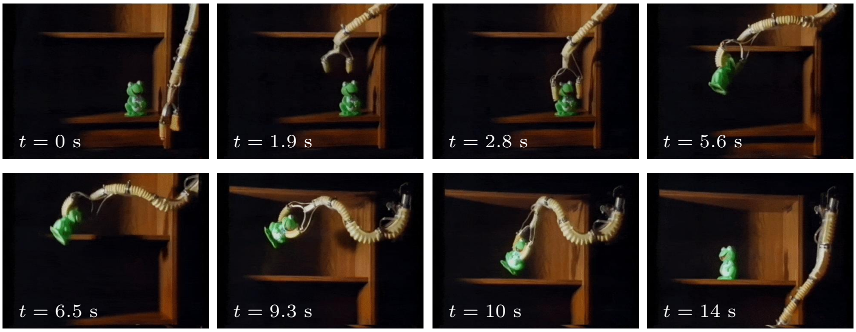


Figure 1.7. Three-link soft robotic manipulator with two-fingered soft gripper by James Wilson from Stanford university (1984, [11]). Unlike classic manipulators, where links and joints are separated, Wilson's robot consisted of three pneumatic bending actuators – being link and joint simultaneously. Each sequential link is placed with a twist offset of $\phi = \frac{\pi}{2}$ w.r.t to the previous one.

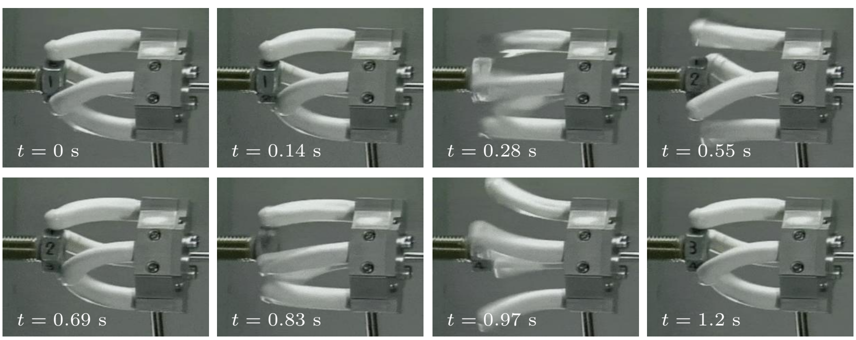


Figure 1.8. Four-fingered soft robotic gripper by Suzumori and Saiko (1989, [12, 13]). Each finger possess three pneumatic chambers that allow for directional bending – analogous the Orm. Through proper coordination of the set of soft fingers various gripping complexity can be achieved, such as the clock-wise turning a mechanical hex bolt (as shown above). Suzumori et al. showed these intricate finger motions can be easily achieved without any feedback control, by simply exploiting the adaptability of soft materials.

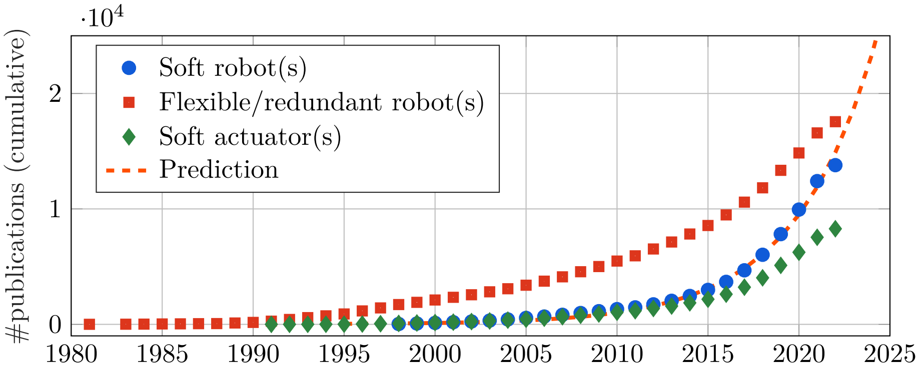


Figure 1.9. Cumulative number of (scientific) publications on the topic of '*soft robots*' or related topics. Data acquired from the Web of Sciences data repository.

(**Soft robotics in academia**) The exact date of the academic boom of soft robotics is unclear, but it is believed to be the late 2000's. To motivate the argument, we have provided a graph of scientific publications on the topic *soft robot(s)* from 1980 till 2022 (see Figure 1.9). It shows the cumulative number of publications related to the term soft robot in the title, keywords, or abstract. We also provided related topics to soft robotics, such as '*soft actuators*' and '*flexible*' and '*redundant robot(s)*'. The publication data from Figure 1.9 is obtained using the Web of Sciences data repository.

1.2 Modern trends and challenges in soft robotics

Given the history of soft robots detailed earlier, let us dive into some dominant research topic in soft robotics. To ease our review here, we limit ourselves to topics related to *i*) design and fabrication, and *ii*) modelling and control.

1.2.1 Tailoring soft actuator design

As the name soft robots arises from its use of soft materials, it follows that design and fabrication using soft materials play a huge role in their technological development. Contrary to rigid robots, many soft robots explore whole body movement rather than localized regions of the robot undergoing motion – called *joints*. In classic robotics, robots are composed of a countable number of rigid links and joints [52–54], either arranged in series or parallel. Together they span a workable range of motion called the *workspace* [52]. Focussing on robot manipulators, whose base is often structurally fixated, the workspace for rigid robots can be obtained through a system of kinematics, often derived through a set of geometrical equalities. Rigid manipulators often have a bounded workspace (assuming actuation limits). In robotic locomotion, similar kinematic descriptions can be obtained for the legs and feet, with the exception of an additional free-floating base. However, in these systems, the bounds of the workspace are of less interest, rather the different *gait cycles* that are possible due the configuration of joints and link determine the system's locomotion.

Returning to soft robots, such classic descriptions *joints*, *workspace* and *gait cycles* also apply here. However, for many soft robots, their description is less exact. The high flexibility allows for many non-restricted joint displacements which make deriving an exact kinematic description challenging. The shape of workspace and locomotion patterns are majorly influenced by geometry of the soft actuator, its flexibility modes, and how forces are transferred with the continuum soft body. Controlling the motion within soft actuation – so to speak reducing parasitic mobility – is an active topic in soft robotics research for decades.

(**Engineering principles for soft actuators**) In the past decade, researcher have developed various techniques of exploiting the high-elasticity of soft materials for *controllable* actuation. One key development, similar working principles to the pneumatic muscle groups (see [20, 27] or Figure 1.3), are Soft Pneumatic Actuators (SPAs). They are also referred to as Fluidic Elastomeric Actuators (FEAs). SPAs undergo similar mechanics akin to McKibben actuators [20] or Morin actuators [27], yet they envelop a diverse collection of motion besides uniaxial. Examples include: contraction and elongation [55], axial growth [56], bending [**?**], helical and twisting, and a hybridization of all the aforementioned motions. An example

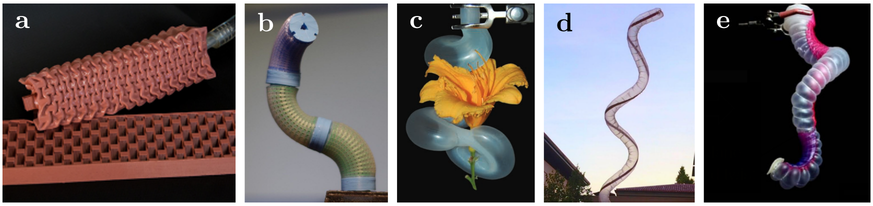


Figure 1.10. Various examples of continuum-bodied joint mobilities in soft actuation. (a) Soft actuator undergoing contraction by Yang et al. (2016, [55]). (b) Set of serial-chain of bending soft actuator (c) Soft tentacle composed of twisting soft actuators. (d) Vine-inspired soft actuators capable of growth. (e) Soft manipulator composed of hybrid bending and twist actuators.

of soft actuators capable of contraction is the Vacuum-Actuated Muscle-inspired Pneumatic (VAMP) structures by Yang et al. (2016, [55]). Their work proposes an tailored geometrical structure embedded into an soft elastomer medium that is highly sensitive towards buckling. When subjected to a sufficiently large negative differential pressure, the internal structure undergoes a (reversible) mechanically instable leading to uniaxial contraction we see in Figure 1.10. Their work is inspired by a similar buckling behavior of patterned elastomer [57–59] when subjected to axial loads. These muscle-inspired vacuum soft actuators are fast, produce stable, repeatable motion; and more importantly, explore structural geometry to reduce parasitic motion. An example of soft bending actuators is the FLIP-FLOP system. Akin the ORM system, it has three pressure chambers embedded into a soft cylindrical-shaped elastomer. To prevent ballooning, inextensible rings are placed orthogonal to the principle axis of the backbone.

(**Exploring optimization and evolutionary algorithms**)

1.2.2 Gaining performance through modelling and control

1.3 Research objectives and contributions

In this section, the research problem of the thesis is divided into three research challenges for the given topics: design synthesis of soft actuators, modeling of soft robot manipulators, and control of soft robot manipulators. For each research challenges, a contribution of this thesis is presented.

(**Design synthesis of soft actuators**): As presented by abundance of literature on soft robotic design, either rooted in engineering principles or optimization, achieving an optimal structural geometry that fully accounts for hyper-elasticity in soft materials is no easy feat. Unlike their rigid counterparts and many biological systems for that matter, any external inputs will result in parasitic motion in soft actuators; mainly as distributed continuum deformations that are antagonistic to the input. These parasitic motions – or better phrased *passive joint displacements* – lead to imprecisions in the mechanical operation and lost of mechanical efficiency. The challenge of design soft actuators by exploring the intrinsic flexibility of the system is a new

The main principle of any compliant mechanical device can be described rigorously through continuum mechanics.

> **Contribution I.** *Development of efficient algorithms, applicable to the general design of soft actuators, that solve the inverse design problem: Given a desired motion and input, what is accordingly the optimal (soft) material distribution within a design domain to realize such joint motion?*

Following

> **Contribution II.** *Fabrication of an array of computer-optimized pneumatic soft actuators through Additive Manufacturing, whose collective assembly can be explored for soft robotic manipulation.*

(**Modeling of soft robot manipulators**):

1.4 Outline of the thesis

Beyond this introductory material, the thesis is divided into

	Chapter 1	**Introduction**
Part I	Chapter 2	**Contribution I**: Development of efficient algorithms, applicable to the general design of soft actuators, that solve the inverse design problem: Given a desired morphological motion, what is the according (soft) material distribution within the design domain to realize the desired joint motion or displacement? **Contribution II**:
Part II	Chapter 3 Chapter 4 Chapter 5	

II

Design of Soft Robots

2

Optimal Design of Soft Robots – a Gradient-based Approach

Abstract - In this chapter, we present a novel framework for synthesizing the design of pressure-driven soft robots. Contrary to traditional design methods, a topology optimization scheme is employed to find the optimal soft robotic structure given user-defined requirements. To our knowledge, the combination of pressure-driven topology optimization and soft robotics is, to date of this thesis, unexplored. Two difficulties are related to this problem. 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 mesh tesselations to efficiently simulate the physics involving pneumatic actuation in soft robotics. The second issue is describing the hyper-elastic nature of soft materials. Here, nonlinear finite element is explored such that large deformations can be described accurately. Numerical investigation shows that the framework can produce meaningful and insight-full material layouts with little to no prior knowledge of soft robotic design. This framework does not only accelerates design convergence, but it could also extend to the development of new and unexplored soft robot morphologies.

This chapter is based on:

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A detailed list of the differences between this chapter and the article on which it is based is provided in the '*Modifications*' chapter of this thesis.

2.1 Introduction

The field of soft robotics has attracted the interest of many researchers from different backgrounds. Soft robots use compliant and hyper-elastic materials, while the use of rigid materials is minimized. The introduction of soft materials into robotics greatly expanded the field of application for robotics. For example, due to their dexterity and environmental robustness, soft robots are often used in medical applications [? ? ?], adaptive grasping [60?], and locomotion in uncertain environments [?]. Unlike its rigid counterpart, soft robots undergo large continuum-bodied motion that, to some extent, resembles morphologies found in nature. These morphologies arise by virtue of the low compliance in soft materials and, more importantly, the structural layout of the soft robot. As of today, many of the fundamental engineering principles in rigid robotics, like design, actuation, sensing, and control, are often not applicable to soft robotics systems. Since its inception, most of these engineering problems have remained challenging or unresolved.

Although the diversity in soft robotics is significant, ranging from adaptive grippers to soft manipulators, most topologies in soft robotics can be associated with nature or engineered geometries for minimal compliance (e.g., bellow shapes). Soft robots often mimic living creatures and their morphologies, e.g., the tentacle of an octopus [16, 60], or the trunk of an elephant [?]. Hypothetically, the abundance of bio-mimicry in soft robotics might be associated with the design complexity of developing robots from soft materials. The large number of degrees-of-freedom and exotic mechanical nature of soft robots makes design significantly challenging, and consequently, the design process can be iterative and time-consuming [16]. Therefore, it becomes potentially advantageous to use computational tools that assist or develop appropriate soft robotic topologies given a set of user-defined requirements, like desired motion or force.

In the past, researchers have made efforts to finding morphologies through mathematics, in particular through evolutionary algorithms. The concept of automated creature designs was first introduced by Sims [?], who showed that, given a set of basic geometries, locomotive organisms could be generated from evolutionary algorithms. These virtual organisms resembled biological morphologies to some extent; however, the complexity of the material layout was limited. More recent work involving the synthesis of virtual soft robots includes Cheney et al. [?], who successfully produced intricate locomotive morphologies using artificial neural networks and multi-material parameter spaces of active and passive soft voxels. Other work involving morphological synthesis includes [46? ?]. Unfortunately, the synthesis of morphologies from previous approaches, though novel, remains only in ideal simulated environments. An accurate representation of the nonlinear material properties in soft robotics can be challenging, and in favor of computational efficiency, little detail is spent on the nonlinear nature governing soft materials. Besides, these evolutionary frameworks typically involve a network of 'activation' cells or voxels that perform ideal volumetric deformation, biologically resembling muscle functionality while unfortunately lacking resemblance to conventional actuation in soft robotics, e.g., pneumatics, dielectrics, and smart metal alloys (SMA).

Reviewing previous methods, a more efficient approach for solving the optimal morphology might be founded in topology optimization. Topology optimization is the general formulation of a material distribution problem for mechanical solids, where density-based topologies arise throughout an iterative (non-convex) optimization procedure. The synthesis of compliant mechanisms through topology optimization is investigated thoroughly [**?** **?** **?**]; however, its application to soft robotics is relatively unexplored [**?** **?**]. Yet, to obtain meaningful topologies for soft robotics, two problems need to be addressed. Since soft robots undergo large deformations, it becomes necessary to describe the nonlinear geometrical deformations accurately. Inherent to significant deformation of soft materials is the importance of nonlinear material behavior, like hyperelasticity. Another concern is the design-dependency of the external forces, in our case, the pneumatic loads. This class of structural problems is more challenging than traditional problems since the load is continuously interacting with the adaptive interface during the iterative optimization process [**?** **?**]. It should be mentioned that the use of compressed air or pressurized fluid is a popular actuation approach in soft robotics.

In this work, we present a novel framework for generating topologies of soft robotics. Contrary to biometry or convectional designs, finding the (optimal) material layout of the soft robot is accomplished through a gradient-based nonlinear topology optimization, where the distribution of soft materials is optimized given a user-defined objective. Our main contributions include the description of nonlinear geometrical deformation and pneumatic loading. We exploit the connectivity properties in polygonal meshes such that synchronized volumetric contraction or expansion of a group of polygonal elements can artificially mimic the geometrical loads in pneumatic actuation. The advantages of our framework in comparison to other literature are: (i) a better representation of pneumatic actuation in soft robotics; (ii) improved design convergence in contrast to evolution-based optimization methods. To our knowledge, our approach of pressure-driven nonlinear topology optimization is new for soft robotics, and its application could easily extend to other soft robotic systems.

The remainder of the paper is structured as follows. In section **??**, we will discuss the continuum mechanics for hyper-elastic materials, followed by a description of the optimization scheme for soft robotics. In section **??**, we propose a numerical example for developing a soft robotic structure to illustrate the effectiveness of our approach.

III

Modeling of Soft Robots

3

Dynamic Modeling – The Constant Strain Approach

Abstract - In this chapter, the continuum dynamics of the soft robot are derived through the differential geometry of spatial curves, which are then related to Finite-Element data to capture the intrinsic geometric and material nonlinearities. To accelerate numerical simulation, a reduced-order integration scheme is introduced to compute the dynamic Lagrangian matrices efficiently. This, in turn, allows for real-time (multi-link) models with sufficient numerical precision. By exploring the passivity and using the parametrization of the hyper-elastic model, we propose a passivity-based adaptive controller that enhances robustness towards material uncertainty and unmodeled dynamics – slowly improving their estimates online. As a study case, a fully 3D-printed soft robot manipulator is developed, which shows good correspondence with the dynamic model under various conditions, *e.g.*, natural oscillations, forced inputs, and subjected to external disturbances like tip-loads. The solidity of the approach is demonstrated through extensive simulations, numerical benchmarks, and experimental validations.

This chapter is based on: B.J. Caasenbrood, A.Y. Pogromsky, and H. Nijmijer. *Control-oriented Models for Hyper-elastic Soft Robots through Differential Geometry of Curves.* Soft Robotics, 2022. `doi:` 10.1089/soro.2021.0035.

A detailed list of the differences between this chapter and the article on which it is based is provided in the '*Modifications*' chapter of this thesis. Original work is found at [61]

4

Dynamic models – Beyond Constant Strain Approach

Abstract - In this chapter, we address some of the limitation of the previous *Piecewise-Constant-Curvature* (PCC) model presented in Chapter 3, in particular the infinite-dimensionality of the soft robot's deformable body. The continuous dynamics of the soft robot are modeled through the differential geometry of Cosserat beams. Contrary to the PCC model, a wide variety of spatial discretization can be used that better respect the spatial continuity and continuum mechanics of the system. Using a finite-dimensional truncation, the infinite-dimensional system can be written as a reduced-order port-Hamiltonian (pH) model that preserves desirable passivity conditions. Then, a model-based controller is introduced that produces a local minimizer of closed-loop potential energy for the desired end-effector configuration. The stabilizing control utilizes an energy-based approach and exploits the passivity of soft robotic system. The effectiveness of the controller is demonstrated through extensive simulations of various soft manipulators that share a resemblance with biology.

This chapter is based on: B.J. Caasenbrood, A.Y. Pogromsky, and H. Nijmijer. *Energy-shaping Controllers for Soft Robot Manipulators through Port-Hamiltonian Cosserat Models.* SN Computer Science, Springer, 2022. (under review)

A detailed list of the differences between this chapter and the article on which it is based is provided in the '*Modifications*' chapter of this thesis. Original work is found at [62]. Last modified on September 7, 2022.

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Acknowledgements

List of publications

Peer-reviewed journal articles

- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*Generative Design of Soft Robotic Actuators – a Gradient-based Approach*", Frontiers in Robotics and AI, 2022. (*in preparation for journal submission*);
- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*Reduced-order Cosserat Models for Soft Robotic Systems using FEM-driven Shape Reconstruction*", Robotics and Automation Letters, 2022. (*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. (*submitted*);
- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*Energy-shaping Controllers for Soft Robot Manipulators through Port-Hamiltonian Cosserat Models*", SN Computer Science Springer, 2022. (*accepted*);
- B. Caasenbrood, A. Pogromsky and H. Nijmeijer, "*Control-oriented Models for Hyper-elastic Soft Robots through Differential Geometry of Curves*", Soft Robotics, 2022.

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, pp 217-223.
- 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, talk on "*3D-printed Soft Robotics*," Symposium on Robotic Technologies, Ultimaker, 2022. (invited speaker).
- B. Caasenbrood, `SOROTOKI`: *an open-source MATLAB toolkit for Design, Modelling and Control of Soft Robots*," 4TU Federation's Symposium on Soft Robotics, Delft University, 2022. (invited speaker).
- B. Caasenbrood, "`SOROTOKI`*: an Open-source Toolkit for Soft Robotics written in MATLAB*," IEEE International Conference on Soft Robotics, RoboSoft 2022, Edinbrugh. (poster presentation). `Best Poster Award`
- 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 Design and Control of Soft Robotics*," 4TU Symposium on Soft Robotics (digital), 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).