Design, Modeling, and Control Strategies for Soft Robots

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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, 3D Printing.

Samenvatting

In de afgelopen twee decennia heeft het veld van de zachte robotica significant interesse opgewekt binnen verschillende wetenschappelijke disciplines. In tegenstelling tot rigide robots verkennen zachte robots zachte materialen die de behendigheid van de robot aanzienlijk verbeteren, een rijke collectie van bewegingsprimitieven mogelijk maken en de omgevingsbestendigheid ten aanzien van contact en impact vergroten. Sinds de oprichting heeft de zachte robotica haar potentieel aangetoond in diverse gebieden zoals veilige manipulatie, adaptief grijpen, verkenning onder omgevingsonzekerheid, revalidatie en de biomimetica van vele dieren. Door de veelzijdige aard van zachte materialen te verkennen, legt de zachte robotica de eerste stappen naar het bereiken van biologische prestaties in de moderne robotica. Deze scriptie heeft als doel de vooruitgang in de zachte robotica verder te bevorderen door enkele van de open multidisciplinaire uitdagingen binnen dit jonge onderzoeksgebied aan te pakken.

Hoewel zachte materialen, zoals systemen in de biologie, veel voordelen hebben, die soms moeilijk te bereiken zijn voor rigide robotica, brengt het ook veel fundamentele problemen met zich mee. Het eerste probleem is het ontwerp van zachte robots. Traditioneel robotica-ontwerp legt de nadruk op hoge structurele stijfheid en gewichtsminimalisatie - een goed doordachte discipline in de engineering. Aan de andere kant houdt het ontwerp van zachte robots van minimale structurele stijfheid voor beweging, wat leidt tot complexe, zeer niet-lineaire relaties tussen input en output. Bovendien leiden gedistribueerde zachte activering, toegepast door zwaartekracht- en traagheidskrachten die op het continu elastische lichaam werken, tot gewrichtsmobiliteiten die in veel gevallen niet te controleren zijn of niet zijn afgestemd op de controle-doelstelling, zoals nauwkeurig grijpen en manipulatie. Omdat het beschrijven van de onderliggende continue mechanica en het toepassen van dergelijke wiskundige theorie op systematisch ontwerp uitdagend is, worden nog steeds een groot aantal zachte robotsystemen *ad hoc* ontwikkeld.

Ten tweede vormt de directe dualiteit van de vorige uitdaging het omgaan met de intrinsieke oneindige-dimensionaliteit vanuit een controleperspectief - met name met modelgebaseerde feedback in gedachten. De overgang van rigide naar flexibel heeft een nieuw controleparadigma geïntroduceerd: de afweging tussen precisie en snelheid in een numerieke omgeving. Niet alleen bevindt de controletheorie voor zachte robotica zich in de beginfase, maar het afleiden van nauwkeurige en numeriek efficiënte modelgebaseerde controllers is uitdagend vanwege de grote niet-lineaire vervormingen van de zachte roboticacontinuüm.

Gezien deze uitdagingen stelt deze scriptie een reeks systematische tools voor met theoretische en experimentele toepassingen voor (*i*) het structurele ontwerp en de fabricage van continuüm-deformeerbare zachte actuators geoptimaliseerd voor door de gebruiker gedefinieerde gezamenlijke beweging, (*ii*) de ontwikkeling van efficiënte dynamische modellen voor zachte continuüm manipulatoren, en (*iii*) het toepassen van wiskundige modellen op modelgebaseerde controllers voor een subklasse van (pneumatische) zachte continuüm manipulatoren en zachte grijpers.

Het eerste deel van deze scriptie richt zich op het ontwerpprobleem door het voorstellen van nieuwe computer-geautomatiseerde ontwerpalgoritmen voor de ontwikkeling van efficiënte zachte actuators. Deze algoritmen houden rekening met de onderliggende continue mechanica die wordt beschreven door een set partiële differentiaalvergelijkingen, die de eerder genoemde niet-lineariteiten tussen de input en output beweging respecteren. Door een door de gebruiker gedefinieerd doel aan te passen aan een gewenste beweging en controlebereik, kan een impliciete representatie van de optimale zachte materiaalverdeling worden gevonden binnen een vast ontwerpruimte. Verschillende generatieve ontwerpen voor een diverse subset van zachte actuator-morfologieën worden geproduceerd, waaronder, maar niet beperkt tot, zachte rotatie-actuators, zachte kunstmatige spieren en zachte grijpers. Vervolgens wordt een optimaal ontwerp voor een zachte robotmanipulator met een adaptieve grijper gesynthetiseerd. Door middel van Additive Manufacturing (AM) van printbaar flexibel materiaal wordt de grens tussen simulatie en realiteit overschreden. De voorgestelde aanpak versnelt niet alleen het convergeren van het ontwerp, maar bouwt ook voort op de enorme bibliotheek van zachte robot-morfologieën die momenteel onontdekt zijn in de literatuur.

Het tweede deel van de scriptie richt zich op de modellering voor controle die van toepassing is op een klasse van zachte robotica-systemen - met name zachte continuüm manipulatoren. De scriptie stelt een modelleerstrategie voor met gereduceerde orde voor zachte robotica, waarvan de dynamica worden afgeleid door middel van differentiële geometrische theorie op ruimtelijke balken. Naast het bespreken van eerdere modelleerstrategieën stelt de scriptie ook een nieuwe spanninggebaseerde parameterisatiebenadering voor die ervoor zorgt dat de structurele informatie en de onderliggende continue mechanica behouden blijven bij het synthetiseren van de gereduceerde balkmodellen - een mogelijke oplossing voor het eerder genoemde controleparadigma van precisie versus snelheid. Om de numerieke prestaties verder te verbeteren, worden ook spatio-temporele integratieschema's voorgesteld die de geometrische structuur van dergelijke zachte balkmodellen benutten, wat resulteert in real-time simulatie met voldoende numerieke precisie die specifiek is afgestemd op controle.

Het derde deel van de scriptie behandelt de ontwikkeling van op modellen gebaseerde controllers die kunnen worden gebruikt in verschillende controle scenario's vergelijkbaar met de controle voor traditionele rigide robotica, bijvoorbeeld inverse kinematica en bewegingsplanning, set-point stabilisatie, traject volgen en multi-point grijpen van objecten. De stabiliserende controller is geworteld in een

op energie gebaseerde formulering, die robuustheid biedt, zelfs wanneer er sprake is van materiaalonzekerheden. De effectiviteit van de controller wordt zowel in simulatie als in experimenten aangetoond voor verschillende zachte robotica-systemen die een gelijkenis vertonen met de biologie, bijvoorbeeld de slurf van een olifant of de tentakel van een octopus.

De belangrijkste bijdrage van de scriptie is een verzameling multidisciplinaire tools gecomprimeerd in één algemeen framework voor het ontwerp, de modellering en de controle van een klasse van zachte robots, variërend van het theoretische tot het experimentele domein.

Trefwoorden: Trefwoord 1, Trefwoord 2, Trefwoord 3, ...

Societal summary

Soft robotics is an emerging field that focuses on the design, development, and implementation of robots made from soft, flexible materials. Unlike traditional rigid robots, soft robots are able to mimic the movements and behaviors of living organisms, making them well-suited for a wide range of applications in fields such as healthcare, manufacturing, and exploration.

One of the main benefits of soft robotics is their ability to interact with humans and delicate objects in a safe and gentle way. Soft robots can be designed to be compliant and adaptable, allowing them to work in close proximity to people without causing harm. They can also be used in healthcare applications, such as wearable devices and prosthetics, where their flexibility and ability to conform to the human body can provide greater comfort and functionality than traditional rigid devices. Another advantage of soft robotics is their ability to operate in unstructured and unpredictable environments, such as disaster zones or outer space. Soft robots can change shape and adapt to their surroundings, making them more versatile and capable of performing a wide range of tasks. For example, soft robots can be designed to crawl through small spaces, squeeze through tight openings, and manipulate objects with greater precision than rigid robots.

However, there are also challenges associated with the development and implementation of soft robotics. One major challenge is the complexity of designing and controlling soft robots, which often require sophisticated algorithms and advanced materials. Additionally, there is a need for more research into the long-term durability and reliability of soft robots, particularly in harsh or extreme environments.

Despite these challenges, the potential benefits of soft robotics are significant, and the field continues to grow and evolve. As more researchers and engineers develop new materials, technologies, and applications for soft robots, we can expect to see these versatile and adaptable machines play an increasingly important role in our lives and society.

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 of $\mathcal{Q}$

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
$\mathbb{T}$	Compact time domain
$\mathbb{X}$	Compact set in $\mathbb{R}$ (*i.e.*, line segment)
$\mathbb{V}$	Compact set in $\mathbb{R}^2$ or $\mathbb{R}^3$ (*i.e.*, volume)

Groups

id	Identity group
SO(3)	Lie group of rotations on $\mathbb{R}^3$ (*i.e.*, special orthonormal matrices)
SE(3)	Lie group of homogeneous transformations on $\mathbb{R}^3$
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
blkdiag	Block diagonal of matrices
$\mathrm{Ad}_{(\cdot)}$	Adjoint action on Lie group
$\mathrm{ad}_{(\cdot)}$	Adjoint action on Lie algebra
$\lVert \cdot \rVert$	Euclidean norm
$\lVert \cdot \rVert_X$	Matrix norm
$\lVert \cdot \rVert_{\mathrm{rms}}$	Root-mean-square norm
$\lfloor \cdot \rfloor_n$	Floor operator
$\lceil \cdot \rceil_n$	Ceiling operator

Acronyms

CoM	Center of mass
DoF	Degree of freedom
FEM	Finite element method (or model)
MDE	Matrix differential equation
ODE	Ordinary differential equation
PDE	Partial differential equation
PMDE	Partial matrix differential equation
PneuNet	Pneumatic network
SRM	Soft robotic manipulator

TopoOpt	Topology Optimization

Contents

I

Introduction

1
Soft Robotics – a new perspective on biomimicry

1.1 Soft robots: what are they?

Biological systems have long served as a source of inspiration for roboticists in their pursuit of developing more robust and capable machines. One might marvel at the ease with which we interact with a diverse array of objects in our daily lives. In contrast, conventional (rigid) robots require precise knowledge of an object's weight, shape, and orientation in order to interact with it in a safe and reliable manner. However, the methodologies often found in nature have slowly been adopted into a new robotics discipline known as "*soft robotics*". Unlike rigid robots, these machines are fashioned from less rigid materials characterized by low elasticity and their enveloping properties. An examination of common materials employed in robotics reveals a conspicuous gap in comparison to natural materials and their corresponding elastic moduli, as illustrated in Figure 1.1. The absence of material diversity in robotics is believed to be a crucial missing element that could enable modern machines to achieve bio-analogous performance.

In engineering, it is common to use the Young's modulus as a measure of elasticity. While limited to homogenous materials subject to small deformations, it can still be applied to classify rigidity in robotics. To aid the reader's understanding, we have included a spectrum of different materials in Figure 1.1. An observation of this spectrum reveals that biological organisms are primarily composed of low-modulus materials in the range of 10^4 to 10^7 Pa, such as muscle and skin tissue, with rigid materials (such as bone) being much less prevalent. In contrast, classic robotics predominantly rely on hard materials such as metals and hard plastics. Furthermore, it is worth noting that materials which undergo repeated deformation during motion possess correspondingly low elastic moduli, as opposed to the use of rigid materials in classic robotics. The concept of exploring low-elasticity

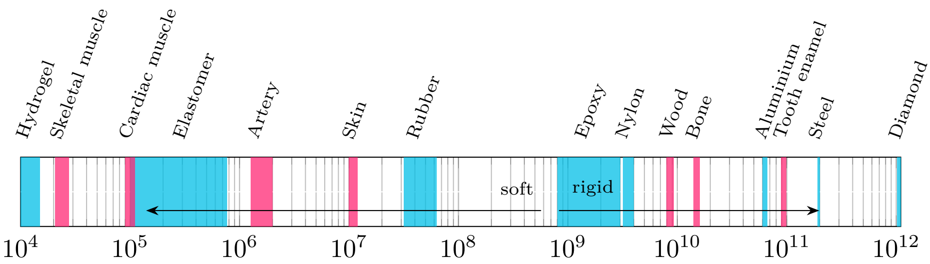

Figure 1.1. Young's modulus spectrum in (Pa) of rigid and soft materials, where ( ) are the organic (*i.e.*, biological) materials and ( ) inorganic materials.

materials, referred to as *"soft materials"*, has fostered a new direction in robotics aimed at unifying robots and biology. Although there exist many definitions on soft materials, we propose the following description before proceeding:

> ***Soft materials*** *are a class of homogenous materials with a Young's modulus (i.e., the modulus of elasticity) typically lower than* $E \leq 10^9$ Pa*. Following, the word 'soft' or 'softness' refers to the collection of mechanical properties that are often associated with these low moduli materials.*

Now, despite the fact that the words *"soft"* and *"robotics"* have a clear definition independently, the collocation of the two sparked many vivid discussions and new idealogies within the robotics community for the past two decades. Throughout its young academic life, several definition have been coined. Throughout its relatively brief academic existence, various definitions have been proposed. Initially, soft robotics referred to robots with variable joint stiffness [4] or artificial compliance achieved through control [3]. The term was also used to underline the shift from rigid-linked robots to *"bio-inspired continuum robots are inherently compliant and that exhibit large strains in normal operations"* [145]. Paraphrasing the work of Robison et al. [113]: *"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. [79] simply referring to soft-bodied robots as *"an analogy to soft-bodied animals"*. A concise (but generic) definition was proposed by Laschi et al. [84], as soft robots being *"any robot built by soft materials"*. Rus et al. [117] 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"*.

The ongoing debate regarding the precise terminology for soft robotics may never reach a definitive conclusion. However, it is crucial to establish consistent terminology not only for the purpose of this thesis, but also proper communication towards a broader scientific community. Previous definitions coined by the scientific community have placed great emphasis on the natural motion that arises from soft materials with high similarities to nature. Our definition of *"soft robots"* is based on the historical development of soft robotics and current scientific trends in literature (discussed in Chapter 2) with particular focus on design and control. Given the interdisciplinary nature of the field, the terms used in this thesis may differ from those used in existing literature. We will consistently refer to the following definition when discussing "*soft robotics*":

> ***Soft robotics*** *is a subclass of robotics with purposefully designed compliant actuators embedded into their soft material body whose goal is to enable the robot control over its ability to perform bio-inspired behavior.*

The formulation above, modified from an early definition proposed in [36], emphasizes the significance of soft materials in replicating biological motion, also known as "*bio-mimicry*" or "*bio-mimetics*". Despite the prominent role of classical robotics is automation, robotics orginally owes its origins to bio-mimicry [????]. In response, soft robotics represents a significant advancement in the pursuit of harmonizing robotics and biological principles. The field not only explores the use of soft materials from a design perspective but also considers their implications for control in order to recover biological morphologies.

1.2 A biometic perspective on soft robotics

A remarkable studycase, common to soft robotics, is the tentacle of an octopus. The octopus' tentacles can move in any direction, using a virtually infinite number of Degrees of Freedom (DoF) [72, 75, 130]. The exceptional dexterity of the octopus arms results from them behaving like a muscular hydrostat. In fact, these arms are composed of densely packed muscle fibers whose orientation can be grouped into transverse, longitudinal, and oblique axes [76]. Moreover, each flexible arm of the organism is governed by a sophisticated peripheral nervous system that runs axially along each tentacle, composed of approximately 30,000 nerve fibers. Through appropriate communication between the muscle fiber network, the embedded nervous system, and the central motor cortex, complex yet coordinated motions of bending, twisting, and extension can be facilitated. An example of the amazing behavioral motor abilities of the octopus is given in Figure 1.2 provided by Sumbre et al. [130]. The figure presents a visual segment of the bending propagation in an octopus tentacle. The purpose of this motion is to reduce the proximinal distance between the tentacle and an object of interest, such as food particle in this case. Interestingly, the octopus also employs a simulatenous bending and twisting propegation motion to orient the bottom side of its tentacles towards the direction of the objective. This leads to an efficient tranversal wave of bending and twist with speeds of about $12.5 \pm 4.7\ \mathrm{cm\,s^{-1}}$ [130]. Such coordination enables

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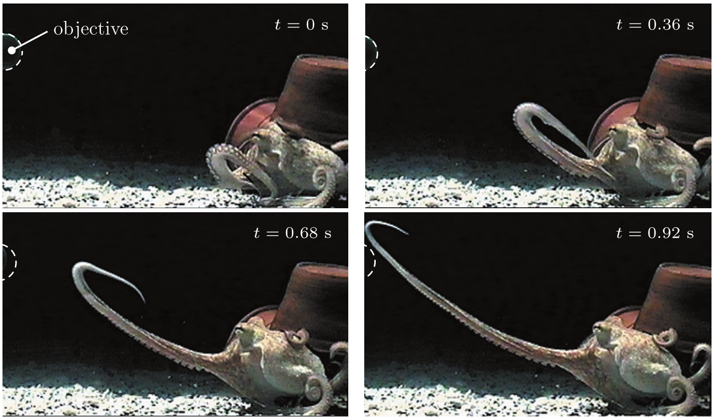


Figure 1.2. Recording by Sumbre et al. [130] of an octopus extending its tentacle towards an object of interest using coordinated activation of a tightly packed network of muscle fibers. The highly flexible appendage allows for traveling bending wave propagation, while the octopus orients its suckers towards the object to ensure secure grip.

an octopus to orient the tentacle's suckers towards a target object thus enabling effective grasping. The octopus is known for its remarkable ability to accomplish a hierarchy of tasks, which can be attributed to hyper-redundancies in its soft arm. Specifically, these organisms possess more degrees of freedom (DoFs) than are strictly necessary to complete a given task. Consequently, additional DoFs can be assigned to subtasks that run parallel to the main task. This ability allows the organism to passively adapt to uncertainties in its environment without affecting the primary motion. These attributes are highly desirable in modern robotic systems as they enable improved robustness in unstructured environments, allow for less conservative safety requirements regarding human-robot interactions, and greatly improve environmental durability, especially during impact.

As illustrated by Figure 1.2, a key observation to be made is that the success of these biological system cannot be limited to morphological design problem alone. To effectively implement biomimetic design, it is crucial to tailor the problem towards the entire embodiment of the biological system which encompasses both its design and control. In light of the multidisciplinary nature of the soft robotics community, it is crucial to clarify these fundamental aspects:

> ***Design*** *is the process of developing mechanical structures that enable a robot to perform specific tasks within a predefined workspace.* ***Control****, on the other hand, refers to the process of finding control laws that steers a dynamical system towards a desired state or desired behavior.*

Recognizing the significance of both design and control in soft robot biomimicry,

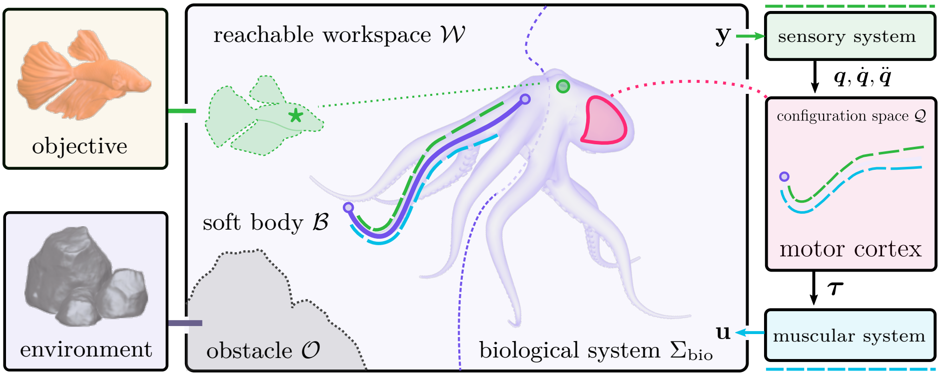


Figure 1.3. A schematic representation of the control architecture of a octopus-inspired soft robots with embodied intelligence. The architecture shows how information flows between important biological components such as the body (*e.g.*, soft deformable arm), actuators (*e.g.*, muscle fibers network), sensors (*e.g.*, the nervous system), and the brain (*e.g.*, the motor cortex) that coordinates information throughout the system.

we hypothesize a systematic deconstruction of the fundamental principles that underlie the morphological grasping behavior of the octopus. This is illustrated in Figure 1.3, which presents a schematic representation of the biological system Σ_{bio} seen in Figure 1.3.

The objective is to reduce the distance between the prey and one of the tentacles, denoted by $\mathcal{B}$. The soft body consists of a discrete bundles of muscle fibers for motion and nerve fibers for sensing. Due to physical design limitations, there is only a finite number of actuators and sensors that can be accommodated within the soft body, therefore, there exist a region called the "*reachable workspace*" $\mathcal{W}$ in which the system can operate. Although the body has virtually infinite DoFs, it can only be controlled via a finite set of actuators and thus this region is finite. Part of the design problem is therefore finding an appriopriate compostion of actuators and sensor such that the systems' reachability space $\mathcal{W}$ coincides with the desired task. Given the continuum nature of soft robots, as well as its distributed actuation and sensing, such design problems are not a trivial and has thus sparked an active discipline within the field.

Next, the control problem entails finding suitable control action $\mathbf{u}$ that steers the arm towards the prey. Using its sensory system, a measurement $\mathbf{y}$ of the soft body can be made. Since control law inside the motor cortex must be computable, this involves encoding the virtually infinite DoFs of the soft body onto a smaller finite joint respresentation $\boldsymbol{q}$ belong to a configuration space $\mathcal{Q}$.

1.3 Design and control strategies for soft robots

Summarizing the objective of the research within this thesis:

> *Developing tools for designing, modeling, and controlling soft robots to address challenges in structural design of soft fluidic actuators and model-based control for soft robot manipulators.*

1.4 Thesis objective and contributions

In this section, the research objectives and contributions are specified. The research is divided into three unique branches each related to a specific subproblem within the field of soft robotics: (*i*) design synthesis of soft actuators, (*ii*) modeling for control of soft robot manipulators, and (*iii*) the development of software aimed to support the soft robotics community. For each research objective, a number of contributions of the thesis are presented.

A: Design synthesis of soft actuators. As presented by abundance of literature on soft robotic design, either rooted in engineering principles or through optimization, achieving an optimal structural geometry that fully accounts for hyper-redundancies in soft materials is no easy feat. Unlike their rigid counterparts and many biological systems for that matter, the kinematics are inherently encoded in the topological structure of the soft materials and where actuation is presented in the system. This implies the workspace cannot be characterized analytically in closed from through joint motions stemming from one point (unlike joints in rigid robotics), see Figure 1.4a. Futhermore, any external inputs will result in parasitic motion, which are mainly induced by distributed continuum deformations that are antagonistic to the input. These parasitic motions – or better phrased *"passive joint displacements"* – arise from the redundant flexibility of the system that are often unaccounted for during design. As such, they should be kept at as minimum as they lead to imprecisions in the mechanical operation and lost of mechanical efficiency (*e.g.*, the balloon effect [33]). Futhermore, there exist many elasticity moduli for various options of soft material, ranging from soft gels to hard rubber [117]. It is therefore of paramount importance that the nonlinear behaviors of soft materials, both in hyper-elasticity and nonlinear geometrical deformation, is understood and accounted for during the design process. This deepens the research problem by imposing questions on optimality regarding material choice.

(Optimality in soft material design). Our first research objective therefore focusses on the design. The main design principles for any compliant mechanical device can be described rigorously through continuum mechanics. In the thesis we focus on harmonizing the underlying continuum theory with the automated design of efficient soft actuators with user-defined objectives in mind (Figure 1.4b). Rooted in continuum mechanics [61, 78] (and its subsequent discretization through finite elements), optimization algorithms are employed that aim to seek an optimal layout of soft materials such that user-specified objective functions are minimized (Figure 1.4c). Such problems are often referred to an *inverse design problem* – solving shape by knowing deformation, rather than solving for deformation based on the shape. The study of combining continuum mechanics and free-form optimization in compliant structures is well-established field called *topology optimization* [10]. Yet, such practices are not easily transferred to soft actuation, since soft materials introduce hyper-elasticity and nonlinear geometric deformations. Besides, fluidic or pneumatic actuation complicates the optimization, as these loads become

Figure 1.4. Schematic illustration of the inverse design problem in soft robotics. (a) Bending behavior of PneuNet actuator under linearly increasing pressure. (b) Desired end-effector position ($\star$) outside the robot's workspace, changing the input is not sufficient will not improve objective – the workspace is *a-priori* encoded into the soft topology. (c) Solution to inverse design problem by finding a soft topology that contains ($\star$) in its workspace.

both design and state-dependent. This brings us to the first contribution:

Contribution I. *Development of efficient algorithms, applicable to the general design of fluidic soft actuators, solving 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?*

(Fabrication through Additive Manufacturing). Following these automated algorithms, many variations of soft actuation system with various joint mobility can be developed with relative ease. Yet, being of simulation origin, this raises the questions on the transferability of the numerical studies to practice. Hence, our second research objective therefore focusses on the transferring simulation design to feasible, functional soft actuators. Through the recent advances in Additive Manufacturing, many complex three-dimensional geometries can be fabricated with relative ease and effort.

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

B: Modeling for control of soft manipulators. Besides design, modeling for control is another important topic in soft robotics. In particular with the aim of achieving biological performance in modern soft robotic systems, models must be both accurate and fast. However, the infinite-dimensionality that are inherent to these soft continuum robots present some challenges. Augmented rigid-body models, like [45, 69**?**], offer exceptional computation speeds but do not respect the fundamental continuum mechanics, therefore invoking strict operation constraints on any soft system, *i.e.*, small deformation as to limit hyper-elastic nonlinearities; or slow actuation to prevent inertial mismatching.

(Accurate control-oriented models through PCC condition). Our second research objective therefore focusses on the reduced-order modeling, aiming to balance precision and speed for control. By building upon the original works of Chirikjian et al. [21] and Mochiyama et al. [93] in the 90's, the thesis presents a dynamic modeling formulation for soft manipulators that respects its continuum nature. To address the issue of infinite-dimensionality, a reduced-order modeling

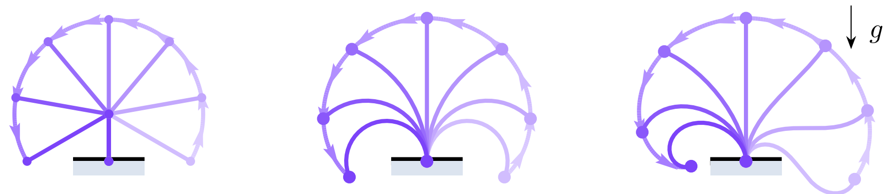


Figure 1.5. Stages of kinematic complexity in (soft) manipulators. (a) Standard 1-DOF rigid manipulator with analytic workspace. (b) Ideal soft manipulator deformed under uniform curvature (*i.e.*, PCC model). Workspace can be analytically expressed for non-complexity cases, *e.g.*, stiffness dominates gravity or homogenous deformation. (c) Truly under-actuated soft manipulator starting from initial (gravity-balanced) condition. Workspace can often not be derived analytically and depends highly on the initial conditions and actuation constraints.

strategy for soft robot manipulators is proposed, whose mathematical framework is based on the differential geometric theory of spatial curves. Such framework allows for easy transferability to classical ROM models in soft robotics, like the PCC strain [39, 42, 69] (see Figure 1.5b). However, the thesis proposes two improvements that are essential development of model-based controllers. Inspired by the success of FEM-based models in soft robotics [40, 51], we bridge the gap between the PCC model and the underlying continuum mechanics by matching the quasi-static behavior to a Finite Element Model (FEM). The numerical FEM approaches used are analogous to Contribution I. Second, to enhance computational efficiency, we propose a reduced-order integration scheme using Matrix Differential Equations (MDEs) to compute the spatio-temporal dynamics in real-time. The proposed reduced-order soft beam model is tested rigorously in simulation; however, for practical control tests demand experimental rigorousness. As such, a 3-DOF soft robot manipulator is developed *ad-hoc* through Additive Manufacturing. The system is loosely inspired by the *Orm* soft manipulator from the early 60's [48]. The proposed dynamic model is tested under various experimental conditions. For example, natural oscillations, forced inputs, and under tip-disturbances of various inertial mass. Various performance measures are introduced to compare the proposed model objectively with respect to linear elastic alternatives. This brings us to our third contribution:

> **Contribution III.** *Development of fast, efficient, and accurate dynamic models for soft manipulators composed of hyper-elastic soft materials that are directly applicable to classical control theory akin to rigid robotics.*

(Models beyond the PCC). As mentioned in Section 2.3.2, the piecewise conti-

nuity inhibits many kinematic redundancies – and therefore the hyper-redundant nature of these soft robotic systems cannot be explored to its full potential. For example, any large nonlinear deflection due to gravity (see Figure 1.5c) cannot be captured using these constant descriptions. Also, the study of (true) under-actuation through such kinematically lumped models is (nearly) impossible as the modeling framework infers homogenous strain and actuation. Herein lies the third research objective that focusses majorly on relaxing the PCC condition, to closely pursue its true infinite-dimensionality. Adopting the prior modeling strategies of differential curves, spatially-varying strain fields are considered and approximated (closely) through sets of orthogonal shape functions rather than prior piecewise representations. Building upon prior models presented in the thesis, the under-actuated and hyper-redundant soft system can be casted into a port-Hamiltonian framework [104, 122]. This allows for classic controller design through energy-shaping by modifying the closed-loop potential energy of the system – a well-known practice in classic robotics [103, 104, 122]. Exploring the hyper-redundancy in soft robotics, more advanced control objectives can be realized such as shape regulation and full-body grasping of rigid objects. However, spatial discretization in these model-based controller play a crucial part in their dexterity to achieve various control tasks. Within this context, the fourth contribution reads:

Contribution IV. *Investigation of spatial discretization in low-order energy-shaping controllers applied to high-order soft robotic models with a focus on closed-loop performance in shape and full-body grasping control.*

(Exploiting geometry for reduction). Contribution IV provides a stable modeling platform for a variety of possible shape functions tailored to unique joint mobilities in soft robotic systems. Yet, many works in modeling literature choose such functions in *ad-hoc* fashion, *e.g.*, polynomial bases [15, 22, 39]. Within this context, the thesis explores a (geometric) modal decomposition approach. Similar to the eigenmode analysis in continuum mechanical systems, geometric strain modes are extracted from higher-order (volumetric) FEM models and used to construct optimal soft beam models. The approach leads to fast, accurate, and generic low-dimensional models that encode the geometric features and elasticity of the true soft body into a new strain parameterization - we call a Geometry-Informed Variable Strain (GIVS) basis. A merit benefit of the approach can be naturally expanded to identify the hyper-elastic material parameters and the actuation map of the reduced beam model. Robustness of the technique is investigated experimentally for several soft robotic systems, including PneuNets, soft grippers, and soft manipulators. In context of robustness, the nonlinearities with increasing actuation frequency, under environmental contact modeled by signed distance functions, and multi-input pneumatic actuation are also considered. The thesis continues with a qualitative comparison between existing strategies, demonstrating that our

approach can improve accuracy and speed compared traditional techniques. Our fifth contribution therefore reads:

Contribution V. *A novel method for finite-dimensional model reduction in soft manipulators that explores the mechanical interconnection between structural geometry and flexibility modes of the soft manipulator body.*

C: Software development. Finally, the thesis collects all theoretical material into one unifying soft robotics software package called `Sorotoki` – short for SOft RObotics TOolKIt. The software aims to bridge the gaps between different disciplines of soft robotics, applicable to design, modeling and control. Using a minimal programming framework, complex problems can be coded using minimal lines of code. The toolkit is heavily interwoven with Contributions I to V of the thesis, and is publicly available at `https://github.com/BJCaasenbrood/SorotokiCode` [18]. The last contribution therefore reads:

Contribution VI. *Developement of a versatile, user-friendly, open-source software called* `Sorotoki` *that envelops the presented theory on design, modeling and control of the thesis into one coherent Matlab toolkit.*

1.5 Outline of the thesis

This thesis discusses the design, modeling and control of soft robotic systems. Including this introductory materials, the thesis consists of seven chapters.

Chapter 2 presents the design algorithm for soft actuators that aim to solve the inverse design problem. The chapter start with a brief introduction into continuum mechanics applied to three-dimensional deformation of hyper-elastic materials, followed by its numerical implementation using finite elements. From here, numerical optimization procedures are introduced that solve the inverse design within the context of (fluidic) soft actuation. Chapter 3 follows with the second objective of the thesis, namely modeling for control. Instead of volumetric soft robotic models, lower-dimensional soft beam models are introduced that are tailored for fast and accurate model-based controllers. The chapter focusses primarily on PCC soft beam models. Chapter 4 address the limitation of the PCC model, and instead extends upon it. The chapter formulates a finite-dimensional port-Hamiltonian modeling approach for soft beams, where spatial shape functions are used to discretize the modal flexibilities of the soft robot. From here, energy-shaping controller are introduced that allow for shape control and grasping of objects. A major emphasize on the chapter is the effects of discretization in soft robotics and choice of control gain, and their subsequent effects on the closed-loop solutions.

Chapter 5 focusses on the Geometry-informed Variable Strain description that ties together Chapter 2 and Chapter 4 into an (optimal) reduced-order modeling and control framework. Chapter 6 presents the culmination of all theoretical material presented in the thesis into a concise, user-friendly, toolkit called `Sorotoki`. The chapter presents an overview of the included programming tools for the design, modeling and control of soft robots. Finally, Chapter 7 closes the main body of the thesis by summarizing the research deliverable of prior chapters, and provides a list of recommendations that could sculp future work.

Note for the reader. Chapters 3-6 are all based on published or submitted researcher articles and can therefore be read independently. A reference to the corresponding research paper is provided at every beginning of these chapters. This thesis, however, provide some minor modifications to these works, either in the context of mathematical or material improvement, or connection between other chapters. An overview of these modifications can be found as a supplementary chapter at the end of the thesis in the chapter named *Modifications*.

2

A brief historical overview on the progress of soft robotics

Abstract - This chapter presents a detailed chronology of the evolution of soft robotics, from its inception in the early 1950s to current research trends. The aim is to provide readers with an insightful introduction to the extensive field of soft robotics. The chapter commences by tracing the origins of soft robotics in pneumatic muscles, including the pioneering work of Joseph McKibben and Victor Scheinman. Subsequently, we explore the emergence of novel concepts and technologies that facilitated the development of increasingly sophisticated soft robots through the utilization of exotic material properties. Throughout the chapter, significant milestones in the development of soft robotics are highlighted, such as the creation of the first soft gripper, the integration of robotics with soft actuations, and the introduction of design and modeling principles for these systems, and early control approaches. Additionally, the chapter highlights some of the key challenges that lie ahead for the field, which serve as a basis for standardization of terminology.In short, this chapter offers an insightful and comprehensive perspective on the history of soft robotics, and will aid the reader in solify the thesis's objectives introduced in the chapter prior.

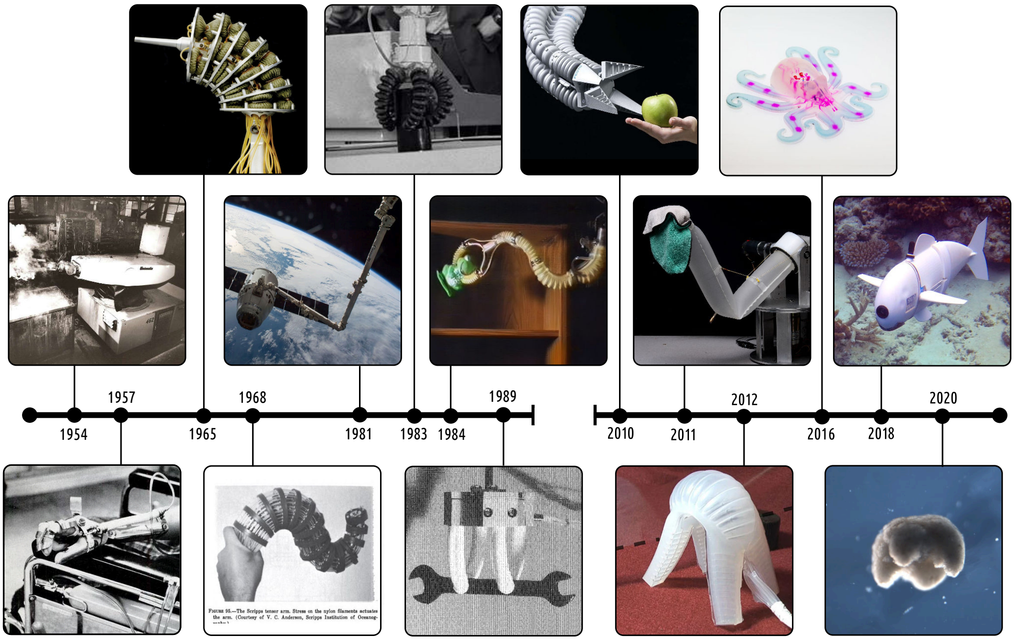


Figure 2.1. A brief timeline of the state-of-the-art of bio-inspired robotics throughout human history. (1954): Unimate, the first industrial robot . (1957): McKibben actuator, an early soft actuator inspired by the human muscle used for rehabilitation purposes [59]. (1965): The Orm, believed to be the first soft robotic system designed by Scheinman and Leifer [48]. (1968): Tensor Scripps arm developed by Anderson [6]. (1981): Canadarm-1, early flexible robotics employed on the International Space Station. (1983): Robot Arm with Pneumatic Gripper by Teleshev [60]. (1984): Bellows robotic arm by Wilson et al. [155]. (1989): The soft robotic gripper developed by Suzumori et al. [131, 132], 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 [53]. (2011): Soft inflatable robot arm by Sanan and Atkeson [8, 120]. (2012) Multi-gait soft robot capable of terrestial locomotion [26]. (2016): Octobot, the first autonomous 3D-printed soft robot that explores a stabilizing oscillator chemical network that produces preprogrammed repetitive motion [153]. (2018): Autonomous robotic fish made by Katzschmann [68]. (2020): Xenobot, an organic soft robot composed of skin and muscle cells made by Blackiston and Kriegman [82].

2.1 Early soft robots

The ambition of closely mimicking biological creatures is perhaps not commonly associated with the field of robotics, given its important role in the automation industry, yet the inception of robotics can originally be found in bio-mimicry when regarding its rich history. In this section, we will present a short historical overview 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 2.1, we provide a graphical, historic overview of soft robotic systems from 1960 to 2022. We will discuss the inception of soft actuation, early soft robotic designs, and modeling and control strategies for these continuum robotics.

To relate the historical progress of soft robots to rigid robots, let us begin with early rigid robots. In 1954, George Devol filed a patent describing an autonomous robotic machine that could be preprogrammed to execute step-by-step motions [92]. 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*. An illustration of this early rigid robot is shown in Figure 2.1. 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 [2, 48], recognized as the first electronic computer-controlled robotic arm because the Unimate's instructions (*i.e.*, predefined setpoints in joint space) were prerecorded on a magnetic drum. He later developed the well-known PUMA robot in 1972 (video available at [1]) – the successor to the Unimate. Keep Scheinman in mind, as he ultimately ties to early soft robots.

Nearly four years after the Unimate was developed, Joseph 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 [59], he developed the McKibben actuators to bring motion to his little daughter's polio-paralyzed hand. His aim was that eventually such pneumatic actuators may help patients with paralyzed fingers to move, grasp, and even 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 uni-axial contraction [33, 34, 123] since weave inhibits extensive *ballooning* – a term for undesired rapidly-accelerated volumetric expansion. Its material composition is often silicone rubber with a nylon-fiber exterior. A schematic representation of a general pneumatic muscle and the effect of ballooning are shown in Figure 2.3. 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

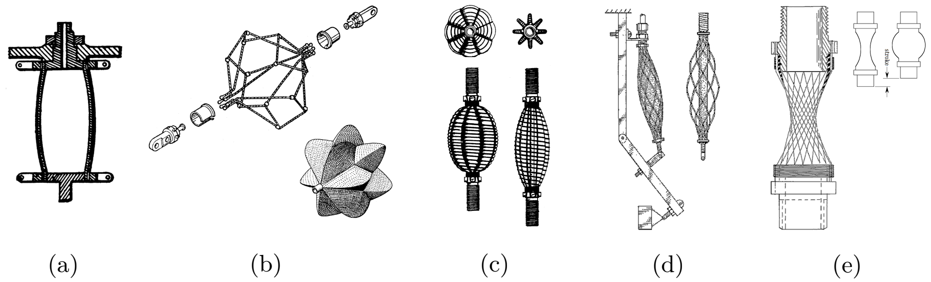


Figure 2.2. Patent diagrams of pneumatic artificial muscle from 1953 till 1988. (a) Morin Muscle [97]; (b) ROMAN muscle [64]; (c) Yarlott muscle [161]; (d) Kukolj muscle [83]; (e) Paynter Hyperboloid [106].

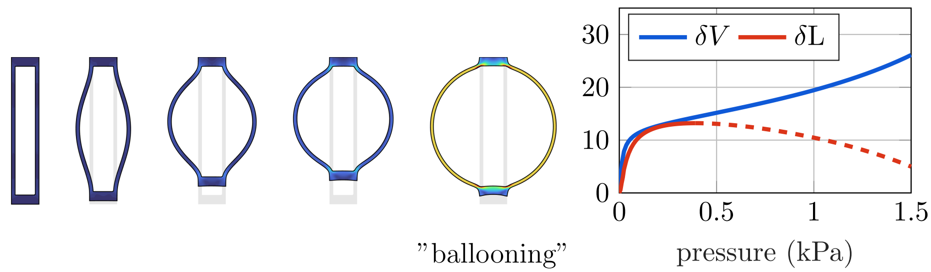


Figure 2.3. Working principle of a basic pneumatic artificial muscle (*i.e.*, Morin muscle [97]) with the internal volume (—) in mL, and the end-effector displacement (—) in mm and (- -) is the point at which the undesirable ballooning occurs.

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, [33]), there exist many variations of pneumatic muscle besides braided muscles, such as the *netted muscles* (e.g, Yarlott [161], ROMAC [64], and Kukolj [83]) and *embedded muscles* (*e.g.*, Morin [97], Paynter Hyperboloid [105]). Illustration of their patent schematics are shown in Figure 2.2.

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 [68, 86, 87, 98, 131], there exist many other technologies employed in soft robotic motion: such as thermal [159] or chemical expansion/contraction [9, 142, 153], crystal re-alignment [85, 108, 109, 146], di-electric elastomers [73], magnetism [16, 81, 90, 114], and naturally the use of tendons paired with electro-mechanical actuation [11, 29, 77, 111, 147]. Some predate the invention of the McKibben actuator. For example, a popular soft actuation principle still applied in soft robotics today are Dielectric Elastomer Actuators (DEA) developed by Röntgen in 1880 [115]. Therefore, given the abundance of soft robotic actuation, it is difficult to pinpoint the exact date of origin of soft actuation technology. Note, however, that these systems are not categorized as soft robots, they are categorized as soft actuators. Here, we emphasize the difference between soft actuators and soft robots in view of the modeling and control terminology relevant to the thesis:

> ***Soft actuators*** *are controllable flexible actuation units of the constitute soft robot that through external stimuli are responsible for natural motion within the system or a change in its compliance.*

Remark 2.1 The terminology above attempts to address an ambiguity common to soft robotics, namely the interchangeable use of soft actuator and soft robot. The thesis invokes that soft robots must be comprised of multiple soft actuators that connect to a passive deformable body. Here, the soft body functions as a mechanical conduit between actuators, sensors, and the environment.

2.2 Recognition of soft robotics' potential

Returning to 1965, nearly a decade after the invention of the McKibben actuator and the Unimate robot, Scheinman and Leifer proposed a novel pneumatic robotic arm named the *Orm* – Norwegian for snake (recall that he also developed the popular PUMA robot [1]). The name was also an abbreviation for Object-Relational Mapping tool [32]. To the author's knowledge, this is believed to be the first instance of a soft robotic system. Surprisingly the system predates any rigid snake-like robot, like the Scripps tensor arm by Anderson (1968, [6]). Inspired by the anatomy of snakes, the system featured 28 rubber pneumatic artificial muscle (*i.e.*, bellows) distributed along a flexible backbone (*i.e.*, skeletal support). The network of artificial muscles were sandwiched between steel plates to prevent misalignment. It is worth mentioning that the technology is analogous to the pneumatic McKibben muscle, where fiber weaves are 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 an 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 2.4. 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-strain response of the Orm with respect to the McKibben actuator, *i.e.*, comparing Figure 2.3 against 2.4, it is noticeably more linear in nature. Although not documented at the time,

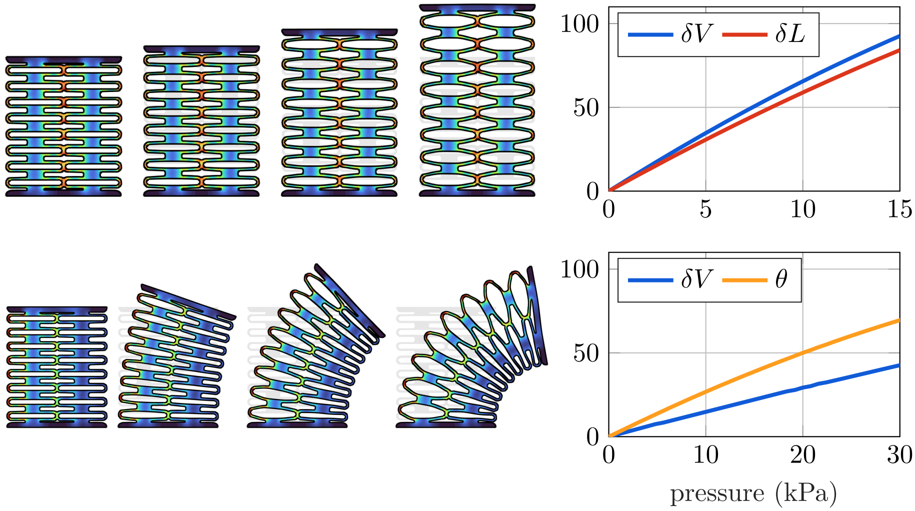


Figure 2.4. Working principle of the Orm robotic manipulator [48] with the internal volume (—) in mL, and the end-effector displacement (—) in mm and bending-angle (—) in deg. By actuation of the pneumatic network, both elongation and bending can be achieved. Observe that the response is significantly more linear than McKibben actuators in Fig. 2.3, emphasizing the importance of geometry.

the comparison highlights the importance of structural geometry in pneumatic muscle networks.

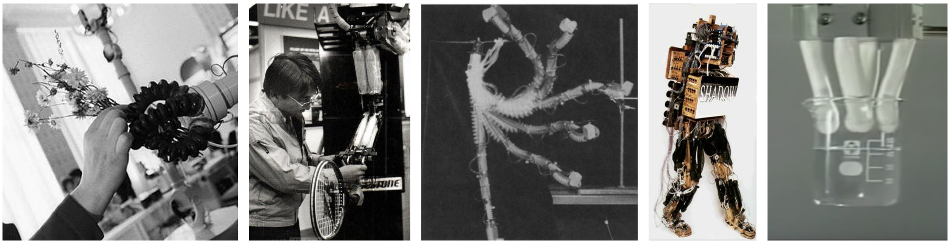
According to an interview with Scheinman led by Asaro et al. [107] in 2010, the positional accuracy of the system was poor, yet the concepts of pneumatically-driven soft arms continued for many years. The positional inaccuracy of pneumatic soft actuators at the time may have caused its lost of academic interest in the 60's. Three years later, in 1968, an improved hyper-redundant robot manipulator was proposed and patented by Anderson and Horn [6] (see Figure 2.1). 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). The entire arm was actuated hydraulically, yet the (soft) 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-based positional feedback. Although Anderson's robot does not categorize as a soft robot since it relies mostly on rigid materials, its flexibility arose from thin nylon tendons that were used for both actuation and sensing. Anderson showed that a network of distributed sensors are necessary to control the complex morphological shapes in hyper-redundant robotic systems, while also mitigating the sensor's effect on mobility. Within this context, let us introduce the notion of soft sensors – the dual of soft actuators:

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

Remark 2.2 As the emphasize lies on "minimally alters the global mechanical behavior", 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 operational workspace of the soft actuator network in static or dynamic condition.

Soft robotics in the 80's. Following the fundamental works of McKibben, Scheinman and Anderson, the field of soft Pneumatic Artificial Muscles (PAMs) in robotics evolved rapidly in the early 80's. A few soft robotic systems are shown in Figure 2.5. Teleshev (1981, [60]) developed a soft gripper reminiscent of modern PneuNet actuators [26, 47, 98] – a rectangular bellow-shaped soft actuator. Unlike uniaxial PAMs, which are radially symmetric, these soft grippers explored an asymmetrical design of bellows. The geometry led to a stiffness differential around the circumference, resulting in their icon bending motion. Still popular today, these pneumatic bending actuators find their origin back in early 1974, see Andorf et al. (1974, [7]). A decade later, Takagi et al. ([133], 1983) developed a soft multi-joint robot manipulator that resembles the human arm with its movements and antagonistic muscle pairs. Although, their PAMs – called *Rubbertuator* – had a function and design identical to McKibben's PAMs, their system showed the merits of combining soft and rigid. They observed not only a high-degree of positional control of the robot arm, force control was easily regulated by the pressure control. This naturally had safety benefits. The soft robot arm could perform delicate low-force tasks while simultaneously blocking motion when encountering a human. These (soft) properties were lacking in rigid robotic manipulators at the time but reminiscent in its biological counterpart – the human arm. Note that, at that time, force and impedance control for rigid robotics had been topics of academic research for years [5, 56, 57, 74], dating back to the early 1970's. (*e.g.*, see also [88]). Yet achieving similar properties without control were rarely explored at the time.

Shortly after, Wilson (1984, [155]) developed a soft robot manipulator based on the elephant's trunk at Duke University, Durham. His design effectively combined the works of Teleshev [60] and Takagi et al. [133] into a robot with similar dexterity but minimal use of rigid components. According to [154], his idea stemmed from the work of Kier and Smith (1985, [75]) who studied the biomechanics of muscular-hydrostats in animals, like cephalopods (*e.g.*, squids). The work of Kier et al. [75] studied how complex motions are produces in muscular organs, like



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

Figure 2.5. Early robotic systems that explored soft PAMs for various tasks. (a) Soft robotic grippers by Teleshev [60]. (b) The soft arm using *Rubbertuator* actuators by Takagi and Sakaguchi [133]. (c) Three-link soft robotic manipulator with gripper reminiscent of the elephant's trunk, developed by Wilson at Duke University [154, 155]. (d) Shadow bipedal walker by Buckley et al. [58] using McKibben muscle in antagonistic pairs to produce locomotion.

elongation, shortening, bending and torsion. Inspired by the muscular hydrostat in the elephant's trunk, Wilson developed a soft arm composed of polyurethane tubes that work as half-bellows, which enabled expansion and bending under positive pressurization [154]. To accommodate for three-dimensional movement, each soft pneumatic link was placed at a $\phi = \frac{\pi}{2}$ twist offset w.r.t. to the previous link. To illustrate the motion of the soft arm, a few snapshots are provided in Figure 2.6. Wilson hypothesized that these highly-complaint robots will be more mechanically robust and be sufficiently dexterous for tight workspaces, contrary to its rigid counterparts. Although the dexterity was novel, the positional accuracy was poor. The main problem stemmed from the soft arm being controlled in open-loop (*i.e.*, remote tele-operation) without proprioceptive sensing nor any positional feedback control. An issue akin to the Orm (1965).

A few years later, Buckley et al. (1988, [58]) developed the Shadow walker – a bipedal rigid robot comprised of antagonistic McKibben muscle pairs. Although not fully soft, their system did explore proprioceptive sensing. The hip, knee, and ankle joints were equipped with resistance-variable potentiometers for position feedback, whereas all the muscles had tension sensors for force feedback. Later on, these resistive sensors were replaced by analog optical sensors to improve robustness [58]. Although the system was top-heavy, due to the pneumatic control hardware (*e.g.*, valves and piping), rudimentary locomotion was possible. Interestingly, a similar artificial muscle system is still explored in nowadays humanoid robotics, like the Atlas from Boston Dynamics. The success of pairing soft muscles with proprioceptive sensing eventually led to the development of the McKibben Shadow hand [50, 58], comprised of 40 uniquely addressable soft muscles.

Following, Suzumori and Saiko [131, 132] developed a micro flexible soft actuator driven by an electro-hydraulic system (intrinsic length $L \approx 12$ mm). Each

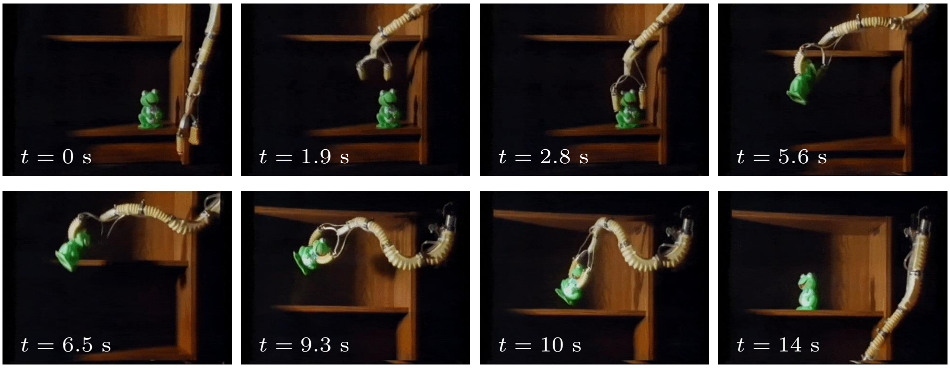


Figure 2.6. Three-link soft robotic manipulator with two-fingered soft gripper by James Wilson from Stanford university (1984, [155]). Unlike classic manipulators, where links and joints are separated, Wilson's robot consisted of three pneumatic bending actuators – being link and joint simultaneously.

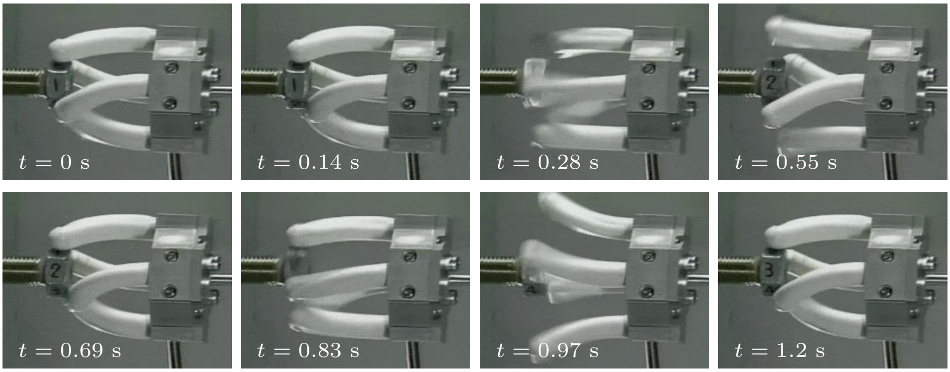


Figure 2.7. Four-fingered soft robotic gripper by Suzumori and Saiko (1989, [131, 132]). Each finger possess three pneumatic chambers that allow for directional bending – analogous the Orm. Through proper coordination of the set of soft fingers various gripping complexity can be achieved, such as the clock-wise turning a mechanical hex bolt (as shown above). Suzumori et al. showed these intricate finger motions can be easily achieved by careful modeling of the fingertip dynamics, and exploring the adaptability of soft materials.

end-effector enables three DOFs including pitch, yaw, and stretch – making it ideal for fingers, arms and legs. Figure 2.7 shows the level of dexterity in their system. By placing the four PAMs parallel on a gripper mount, and assigning a pre-defined trajectory, they showed their soft robotic system has sufficient dexterity to mount an hex-bolt at an incredible speed and precision. To achieve such dexterity and precision, Suzumori et al. [131] employed various modeling and control strategies to account for the dynamical characteristics under high-frequency, fluid compressibility, and the closing mechanics of pressure valves. Futhermore, the kinematics of each finger was derived using generalized homogenous transformation, not unlike traditional robotics. Knowing both the compliance characteristics (pressure-deformation relations) and the forward kinematics, a Jacobian-based positional controller was employed to regulate the Cartesian coordinates of the finger-tips (successfully one might add).

Early controllers for hyper-redundant (soft) robots. Following the increasing interest in highly-flexible robots around the late 80's, academic research into controlling these *hyper-redundant* robots boomed shortly after. At the time, the term hyper-redundancy – being an extension to redundancy in robotics [91] – was defined as the relative degree of kinematic and/or actuator redundancy which is large or even infinite [21, 25]. The term was first introduced by Chirikjian and Burdick (1989, [20]). Others referred to these robots as *highly redundant* [102, 157] or *High Degree-of-Freedom* (HDOF) manipulator [95, 119]. Around that time, Chirikjian and Burdick provided a plenary of mathematical foundation [21–25] focussed on the kinematics and motion planning of hyper-redundant manipulators. Their work presented a modal discretization approach to describe the shape of the deformable backbone [24], and from this geometric approaches were introduced to solve obstacle avoiding trajectories using generalized *follow-the-leader* strategies [23]. Especially the latter showed the limitation in rigid redundant manipulators. Although Chirikjian laid the foundation for the control of hyper-redundant robot, basic principles of motion planning in pneumatic hyper-redundant robots were already presented by Wilson et al. (1988, [156, 157]) – yet were not called hyper-redundant robots nor soft robots yet. Recall also that the work of Wilson et al. has been sown earlier in Figure 2.1 and Figure 2.6. In Brock et al. (1991, [17]), a similar analysis was used for optimal shape design of thin elastic rods to realize desired robotic compliance. Besides, there exist an abundance of literature prior to [21] on Variable Geometry Truss Manipulators (VGTMs) – a variant of hyper-redundant tensegrity robotics – that dealt with motion planning for such systems [101, 102, 119]. Later, Mochiyama et al. [94, 95], built upon Chirikjian's work by extending it to a dynamic formulation for elastic rods such that classic controller design is possible. They proposed shape-regulation controllers for HDOF manipulator by projecting them onto time-invariant curves, thereby showing that the estimation the desired curve parameters is the crucial key to solving the problem by Lyapunov design [94]. Although there existed a variety of modeling and control strategies, computational power in relation to modeling complexity was the limiting factor for the simulation-to-reality transfer at the time.

2.3 State-of-the-art in soft robotics

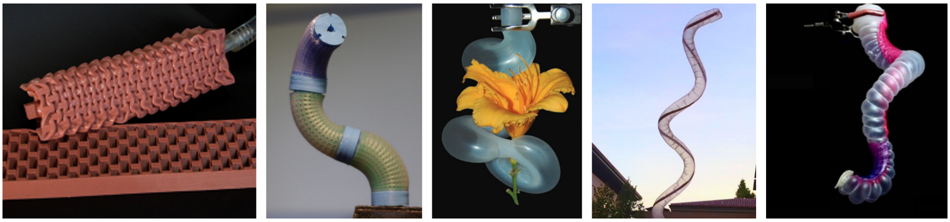
In this section, we will examine several unresolved research issues in the field of soft robotics. These topics primarily concern the design and control of soft robots. It should be emphasized that while these problems may seem distinct, they are often interconnected. For instance, the structural design of a soft robot influences its workspace and consequently affects the feasibility of *a-prioiri* defined control objectives. This section aims to underscore such scientific interconnections and demonstrate the essential components required to address common paradigms.

2.3.1 Tailoring design of fluidic soft actuation

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 undergoing motion called *"joints"*. In classic robotics, robots are composed of a countable number of rigid links and joints [31, 100, 129], either arranged in series or parallel. Together they span a workable range of motion called the *workspace* [129]. Focussing on rigid manipulators, whose base is often structurally fixated, their workspace 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. In these cases, however, the workspace is of less interest, rather the different possibility of *"gait cycles"* that arise from the link-joint configuration and actuator dynamics determine system's success for locomotion.

Returning to soft robots, the definitions such as joints, workspace and gait cycles also apply here. Yet, the high flexibility allows for many non-restricted joint displacements which make deriving closed-form mathematical descriptions 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 and tailoring motion based on structural geometry – is an active topic in soft robotics research for decades.

Engineering principles in soft fluidic actuators. In the past decade, researchers 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 [59, 97] or Figure 2.3), are Soft Pneumatic Actuators (SPAs). A few examples are shown in Figure 2.8. SPAs undergo similar mechanics akin to McKibben actuators [59] or Morin actuators [97], yet they envelop a diverse collection of motion besides uniaxial. Examples include: contraction and elongation [160], axial growth [55], bending [47, 87, 98], helical and twisting, and a hybridization of all the aforementioned motions [80]. An example of soft actuators capable of contraction is the Vacuum-Actuated Muscle-inspired Pneumatic (VAMP) structures by Yang et al. (2016, [160]). Their work proposes a tailored geometrical structure embedded into a 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

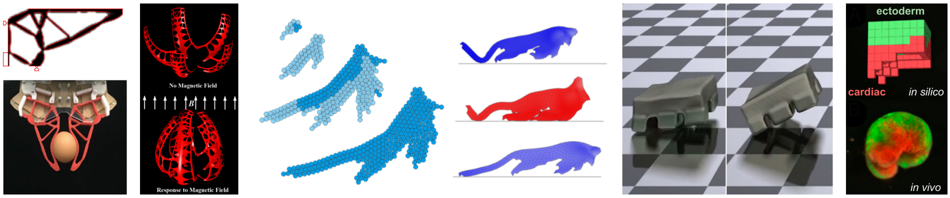


(a) (b) (c) (d) (e)

Figure 2.8. Various examples of continuum-bodied joint motions in modern soft actuation. (a) Soft actuator undergoing contraction by Yang et al. [160]. (b) Set of serial-chain of bending soft actuator by Cianchetti et al. [27, 28] (c) Soft tentacle composed of twisting soft actuators. (d) Vine-inspired soft actuators capable of growth by Hawkes et al. [55]. (e) Soft manipulator composed of hybrid bending and twisting soft actuators through laminate materials by Kim et al. [80].

instable leading to uniaxial contraction, we see in Figure 2.8. Their work is inspired by a similar buckling behavior of patterned elastomer [13, 99, 124] subjected to axial loads. These muscle-inspired vacuum soft actuators are fast, produce a stable, repeatable motion; and more importantly, explore structural geometry to reduce parasitic motion. An example of soft bending actuators is the FLIP-FLOP system [27]. Akin the ORM system [48], it has three pressure chambers embedded into a soft cylindrical-shaped elastomer. To prevent ballooning, inextensible rings are placed orthogonal to the deformable backbone. It design is also reminiscent of [131, 132]. Hawkes et al. (2017, [55]) developed a soft manipulator inspired by the growing behavior of vines. Kim et al. (2019, [80]) used laminates that adhere to the volumetrically expanding soft body as to govern the motion trajectory through bending and twisting.

Exploring optimization and evolutionary algorithms. Besides design through engineering principles, optimization in soft robotics is slowly gaining momentum recent years. Wang et al. (2020, [148]) used a topology optimization to find the optimal design for a cable-driven soft gripper (Figure 2.9a). Similarly, Tian et al. (2020, [140]) explored topology optimization for ferro-magnetic soft grippers. Besides soft grippers, evolutionary design algorithms are also employed for soft mobile like crawler and swimmers. Joachimczak et al. (2015, [66, 67]) explored evolutionary search algorithm with the purpose of automatically designing complex morphologies and controllers of multi-cellular, soft-bodied robots (Figure 2.9c). Hu et al. (2019, [63]) used a differential physics simulator called `DiffTachi` that efficiently computes gradient information for each simulation timestep. The gradient information can then be fed into neural network controllers to solve, for instance, the appropriate gait-cycles required in the locomotion of soft-bodied crawlers (Figure 2.9d).



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

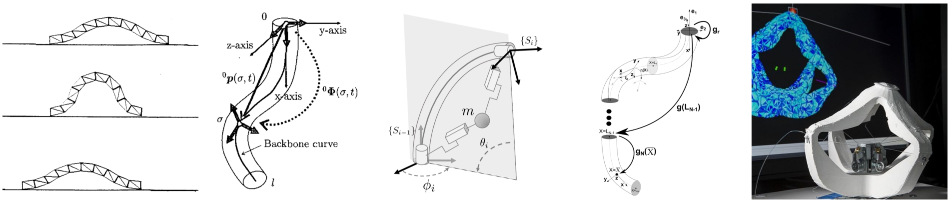
Figure 2.9. Optimization for design and motion of soft robots. (a) Soft gripper by Wang et al. [148]. (b) Evolutionary algorithms for multicellular soft-bodied robots by Joachimczak et al. [66, 67]. (c) `DiffTachi` result for soft crawler by Hu et al. [63]. (d) Voxel-based optimization for Xenobots [82].

2.3.2 Gaining performance through control

As the inherent properties in soft materials bring forth many benefits, *e.g.*, adaptability, hyper-redundancy, and passivity w.r.t. the environment; it too hinders the progress in model-based controllers. Earlier, we have touched upon these subject with the rise of kinematic and dynamic models for hyper-redundant robotics in the late 80's – early 90's. Chirikjian et al. (1992, [21]) provided a kinematic framework for hyper-redundant manipulators with application to motion planning (see Figure 2.10a). Here the elastic backbone is approximated using a modal formulation. Such modeling framework are one-to-one transferable to soft continuum manipulators. Mochiyama et al. (1998, [94, 96]) extended this work to a dynamics formulation – even providing Lyapunov-based control strategies for shape regulations (Figure 2.10b). However, both modeling frameworks were computationally inefficient – lacking transferability to real-time control. The root problem stems from the fact that soft continuum robots, belonging in their exact formulation to the field of continuum mechanics, lead to infinite-dimensional models often expressed as Partial Differential Equations (PDEs). Rigid multi-body systems, like robot manipulators or mobile robots on the other hand, have convenient Ordinary Differential Equation (ODEs) structures as they are rooted in Lagrangian or Newtonian mechanical principles. Rigid-body models were (and still are) fast computationally and their literature on controller design is vast and well-established [31, 100, 129]. The computational issues in early continuum robots may be reflected by its literature gap between the 1990's to 2010's.

A: Modern control-oriented models for soft robots. In the past decade, significant steps have been made to address the issues of infinite dimensionality [37]. The key is to formulate a finite-dimensional approximation of the soft robot's dynamic such that they can be written as standard ODEs. Reduced-Order Models – ROM for short – have paved the path of model-based controller for soft robots whose reduced formulations are both tractable and precise. In the years shortly after its academic boom, many different assumptions and model approximations have come forth to address the issue of control.

Remark 2.3 The reduced-order formulations for soft robotics are primarily ap-



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

Figure 2.10. Popular modeling strategies for soft robotics. (a) Hyper-redundant modeling description through tensegrity by Chirikjian [21, 25]). (b) Analytical continuum beam description by Mochiyama [95, 96]). (c) Augmented rigid-body model subjected to PCC kinematics by Katzschmann et al. [69]. (d) Geometric Cosserat model subjected to PCS kinematics by Renda et al. [111]. (e) Diamond-shaped soft robot manipulator controlled using the FEM-based `SOFA` software by Duriez et al. [40] and related [30, 51].

plicable to slender soft robots, leading to a focus on soft robot manipulators in control-oriented studies. This approach is well-motivated given that many soft robots have one dominant physical dimension compared to the other two [37]. As such, this thesis primarily focuses on the modeling and control of soft manipulators rather than a broader scope.

Focussing on soft robot manipulators first, a popular choice of finite-dimensional reduction is the so-called *Piecewise Constant Curvature* (PCC) soft beam model. The PCC modeling approach is by far the most adopted in the soft robotics community [151]. As the name implies, the soft robot is modelled as an elastically deformable beam with all strains but curvature neglected. Examples of this approximation include [38, 42, 45, 68, 69, 87, 116, 151]. Highlighting a few, Katzschmann et al. (2018, [68]) proposed to connect the PCC formulation to an augmented rigid robot dynamical model with parallel elastic actuation (see Figure 2.10c). A similar approach was proposed earlier by Falkenhanh et al. (2015, [42]) and applied to Festo's bionic arm [53]. Although such lumped models may seem like a major over-simplification, the proposed model allows sufficient speed and accuracy such that model-based feedback is applicable. This formulation was also employed later in an adaptive sliding mode control scheme [71] for the SoPra soft arm [144]. Following, Renda et al. (2018, [111]) extended the PCC model to *Piecewise Constant Strain* (PCS) formulation. This formulation allowed for all strain if and only if considered spatially piece-wise constant (Figure 2.10d). Rooted in SE(3) geometry of the Cosserat approach [126], it provided a closer relation with the rigid body geometry of the traditional robotics. The formulation also extends to soft manipulators with fluidic actuation [112, 141] The PCS model was later employed to feedforward controllers by Thuruthel et al. (2018, [139]) using model-based policy learning algorithms. To improve efficiency, a recurrent neural network was trained using an offline PCS model. Grazioso et al. (2019, [52]) explored a similar path of geometric Cosserat beams using helical strain functions. Nevertheless, Constant Strain (CS) models have severe limitations. They often do not originate from continuum mechanics and thus are only applicable in restrictive settings. Although computationally performance might surpass continuous models, due to intrinsic kinematic restrictions, they are unable to capture important continuum phenomena, like buckling, environmental interaction, or wave propagation.

In response to its limitation, many researchers continued their search for efficient and more generalizable alternative. Della Santina et al. (2020, [39]) proposed a polynomial description to described the continuum dynamics, a description analogous to [21]. In their work, they expressed the curvature function of the soft robot in terms of a standard polynomial bases. Not only can an exact infinite dimensional formulation of the problem be obtained (in theory), truncation at any level is changed easily. The technique is also widely used for flexible-link robot manipulators to capture small vibrations, see DeLuca et al. (2016, [35]). Della Santina et al. also showed that PCC-rooted assumptions as control output produce a minimum phase system [39] – a fundamental stepping-stone for nonlinear control. Following, Boyer et al. (2021, [15]) extended upon their prior Cosserat models [110, 111], and presented a tractable and generalizable beam model for slender soft manipulators. A similar approach to [39] was followed but all strains are discretized using a finite set of strain basis functions. Renda et al. (2020, [110]) improved computation by introducing a two-stage Gauss quadrature [162] to derive the Magnus expansion [54]. Other examples of the Cosserat beam descriptions, but more focussed on the continuum mechanics rather than control, is the work Gazzola et al. (2018, [49]). Their work allowed for efficient Cosserat beam models suitable for self-collision, thus providing various simulation for twirling and coiling of beams under increasing torsional loads.

Another popular alternative, better suited for general soft robotic systems like soft mobile robots, are reduced-order finite element models [29, 30, 40, 51, 70, 136, 137, 143, 158, 164] or neural-network trained using offline FEM simulations [43]. Starting from high-order FEM data (*e.g.*, state dimensions of the order 10k) that capture the whole workspace spanned by the network of soft actuators, Proper Orthogonal Decomposition (POD) techniques are employed to drastically to reduce the state dimension of the soft robot model. These techniques can even retain external loads (*e.g.*, contact and friction) with precision as long as they are included in the offline data set [51]. By far, this FEM-driven method has shown the most success in the experimental control regime.

Soft robot simulation and programming environments. The rapid development of soft robotic models in recent years have also increased the demand for (open-access) software packages. Especially since many of the aforementioned ROM models require an advanced level of mathematical understanding. In an attempt to help the soft robotics community, many researchers have provided open-source, documented simulators interwoven in their soft robotics research. A popular FEM-based software on soft robotic modeling and control is `SOFA` by

2

Duriez et al. (2013, [30, 40]). `DiffTachi` by Hu et al. [62, 63] explores differential simulations to produce soft machine capable of locomotion. Bern et al. (2022, [11, 12]) developed `SoftIK`, a software for soft deformable plushy robots. Among beam or rod-based models there exist many options. Examples included `Elastica` (or `pyElastica` [135]) by Gazzola et al. [49, 163], `TMTDyn` by Sadati et al. [118], `SimSOFT` by Grazioso et al. [52], and `SoRoSim` by Mathew et al. [89] based on the work of Renda et al. [110] and Boyer et al. [15]. The `Sorotoki` toolkit by Caasenbrood et al. [18] – open-source software package presented as a part of this thesis – explores a combination of FEM models and soft beam models. The toolkit written in Matlab aims to bridge the gaps between design, modeling, and control of (hyper-elastic) soft robots.

Closing the loop in soft robotics. Following the many developments in computational efficiency of reduced-order models (and accordingly the advances in soft sensing), academic research in model-based or model-free control for soft robots is significantly growing since early 2019. Note that feedforward controllers for soft manipulators have been proposed years prior, *e.g.*, [41, 42, 121, 138].

By far, experimental validation of PCC model has been used more intensively than other models. In Della Santina et al. (2019. [38], the augmented rigid-body PCC model is used to design a closed-loop controller for a continuous soft manipulator, presenting two architectures designed for dynamic trajectory tracking and surface following. Prior work is provided here [69]. A similar approach was followed by Milana et al. (2021, [**?**]) and applied to an artificial soft cilia. They showed that soft bending actuators could mimic the asymmetric motion of the cilia through model-based control. Cao et al. (2021, [19]) explored a reduced analytical model [149], somewhat equivalent to a linear pendulum model (apart from quadratic terms in the potential force); to develop robust tracking controllers without velocity observers. Their controller was tested experimentally on a soft PneuNet actuator. Wang et al. (2022, [150]) developed a computed torque controller (see [129]) using the augmented rigid-body PCC model and applied it to a soft Honeycomb Pneumatic Network Arm [65]. Franco et al. (2020, [45, 46]) used a port-Hamiltonian modeling framework akin to rigid-body PCC model (*i.e.*, three-link pendulum) and applied such principles to energy-shaping controllers. The performance of their controller was assessed via simulations and via experiments on two soft continuum prototypes. On a side note, Franco et al. (2022, [44]) also developed an energy-shaping control law together with nonlinear observers for the control of soft growing robots [55] with pneumatic actuation subject to the (ideal) gas laws.

As mentioned previously, the PCC model has significant limitation that impose questions on the useability, dexterity, and robustness of their control derivation. Although majorly focussed on simulation, higher-order dynamics have been used for the development of feedback controller in soft manipulators. Della Santina et al. ([37]) developed swing-up controllers for a soft pendulum modelled by the affine curvature models (*i.e.*, a polynomial curvature model [39] of order $k = 2$). Their approach mirrors the path of classic control problem of inverted pendulums in the 90s and early 2000s [103, 125, 127, 128]. Later, Weerakoon et al. (2021, [152]) extended upon their work by introducing a revolute base. A common control problem here is under-actuation [100, 129, 134] – implying that not all control actions can be realized to steer the configuration space to a desired position. In the work of Borja et al. (2022, [14]) developed a general control framework that can stabilize soft manipulators based on potential energy shaping based on the affine curvature model. Their work showed that some linear matrix inequalities can be derived based on the gradient of the potential energy related to the passive and active states, such that local stability can be proven. In laymen terms, elasticity must dominate the forces resulting from the gravity in the underactuated states for (potential) energy-shaping controllers (and mostly-like others) to work.

II

Design Optimization for Soft Robots

3
Optimal Design of Soft Robots – a Gradient-based Approach

This chapter is based on: B.J. Caasenbrood, A.Y. Pogromsky, and H. Nijmeijer. *A Computational Design Framework for Pressure-drivenSoft Robots through Nonlinear Topology Optimization.* IEEE International Conference on Soft Robotics (RoboSoft), 2020. doi: 10.1109/RoboSoft48309.2020.9116010

III

Model-based Control for Soft Robots

4
Dynamic Modeling – The Constant Strain Approach

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

5

Model-based control for soft robots – Beyond the Constant Strain Approach

Abstract - In this chapter, we address some of the limitation of the previous *Piecewise-Constant-Curvature* (PCC) model presented in Chapter 4, 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-looppotential 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. `doi: 10.1089/soro.2021.0035`.

IV

Open-access Software for Soft Robots

6

Sorotoki: A Matlab Toolkit for Design, Modelling, and Control of Soft Robots

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. `doi: 10.1089/soro.2021.0035`.

V

Closing

7 Conclusions and recommendations

7.1 Conclusions

Design synthesis of soft actuators. In Chapter **??**, the thesis proposes a new framework for the synthesis of soft robot topologies from hyperelastic materials. Generally speaking, the design process of soft robots is complicated by material nonlinearities and numerical implementation issues. To address these challenges, we introduced a nonlinear finite element method for polygonal elements. Our approach provides a more accurate representation of the physical nature of soft robotics, including hyperelasticity and pneumatic actuation, compared to previous research. Numerical analysis indicates that our framework can produce meaningful and insightful material layouts for developing pressure-driven soft robots from soft materials. Additionally, the proposed framework can be adapted to express other actuation principles in soft robotics, such as dielectric polymers or thermal expansion with minor modifications.

Modeling for control of soft manipulators.

Software developement. This thesis has introduced *Sorotoki*, an open-source toolkit in MATLAB that provides a comprehensive and modular programming environment for the design, modeling and control of soft robots. The toolkit consists of a libary of Object-Oriented classes designed to solve a wide range of problems in the field of soft robotics, including inverse design of soft actuators, passive and active soft locomotion, object manipulation with soft grippers, model reduction, model-based control of soft robots, and shape estimation. Most notably is its ability to succinctly represent complex soft robotics systems with minimal code, making it accessible to individuals with limited programming knowledge. In combinations with software, the toolkit also presents four open-hardware soft robotic systems that can be easily fabricated using commercially available 3D printers, futher enabling soft robotic technology for the community. Overall, *Sorotoki* is a versatile and flexible resource that can benefit many researchers and practitioners in the field of soft robotics.

7.2 Recommendations

In the present thesis, several research challenges have been addressed. However, as research is an ongoing endeavor, unexplored areas of research persistently emerge. In this section, we propose recommendations based on the chapters within this thesis. The author's recommendations for future research are summarized in Table **??**, categorized as short-term, medium-term, and long-term work.

(Inverse design) In Chapter **??**, the possibility of gradient-based design for soft robots through topology optimization has been discussed. It has been demonstrated that relatively simple techniques can be utilized to identify "optimal" structures based on desired motion. However, due to computational limitations, only optimizations of planar mechanical structures have been considered. Therefore, further steps are necessary to convert the topology into an actual structure. Additionally, it should be noted that fabrication constraints have not been taken into account during optimization. However, these limitations create many possible opportunities for future research regarding generative design.

Firsy, the optimization techniques presented in this thesis can be readily applied to the three-dimensional domain. It is highly recommended to extend these techniques to the aforementioned domain, as it simplifies the post-processing of the derived topological structure. It should be noted, however, that the computational complexity of finite element models increases with $\mathcal{O}(n^3)$ with n the global DOF of the mesh. Given this computational increase, exploring GPU parallel computation or cluster computation are highly encouraged for future research. Alternatively, one potential option is to consider adopting the Material Point Method (MPM). The MPM offers several advantages over FEM, including the ability to handle larger mesh distortions, and better conservation of mass and momentum. Additionally, complex geometries can be handled more eclasily without requiring remeshing. Although MPM is computationally more intensive than FEM, there exist software packages that offer massively parallel simulation on multi-GPU (Graphics Processing Unit) architectures, which have already been applied to the co-design optimization of soft robots for locomotion.

Secondly, one intriguing area of research can be found in multi-material topology optimization. Soft robots often face the issue of limited force transmissibility without significant deformations in their supporting structures. Multi-material investigation offers a promising solution, where material diversity, inspired by nature, can result in a wider range of mechanical compliance, ultimately benefiting poten-

Short term (<1 year)	• Bananis baidg ndgidog idngd kdnfd • Bananis baidg ndgidog idngd kdnfd • Bananis baidg ndgidog idngd kdnfd

tial applications. Moreover, recent progress in multi-material printing technology has facilitated the consolidation of soft, rigid, and flexible conductive materials. This provides a prospect to incorporate skeletal function along with proprioceptive sensing capabilities that can be directly integrated into the optimization loop. Generally speaking,

(Modeling for control)

7.3 Future outlook

(Chicken-and-egg problem in model-based control of soft robots)

(Synergy between design and control)

(Importance of sensing and its relation towards learning)

VI

Appendices

A
List of definitions

In this appendix, we present a compilation of the definitions and terminologies proposed in Chapter **??** and Chapter **??**. It should be noted that these definitions may diverge from those commonly used in literature. Nevertheless, we consider them essential to address the multi-disciplinary perspective inherent in the scientific field of soft robotics.

Soft materials

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Acknowledgements

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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, "*Energy-shaping Controllers for Soft Robot Manipulators through Port-Hamiltonian Cosserat Models*", SN Computer Science Springer, 2022.;
- 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

- H. Khanh Chu, B. Caasenbrood, , H. Nijmeijer 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.
- 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.
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- 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-Papers OnLine, 2020, pp. 9238-9243.

Talks, workshops, 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).

Curriculum Vitae

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