# Soft-Material Robotics

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# Contents

## Abstract

There has been a boost of research activities in robotics using soft materials in the past ten years. It is expected that the use and control of soft materials can help realize robotic systems that are safer, cheaper, and more adaptable than the level that the conventional rigid-material robots can achieve. Contrary to a number of existing review and position papers on soft-material robotics, which mostly present case studies and/or discuss trends and challenges, the review focuses on the fundamentals of the research field. First, it gives a definition of soft-material robotics and introduces its history, which dates back to the late 1970s. Second, it provides characterization of soft-materials, actuators and sensing elements. Third, it presents two general approaches to mathematical modelling of kinematics of soft-material robots; that is, piecewise constant curvature approximation and variable curvature approach, as well as their related statics and dynamics. Fourth, it summarizes control methods that have been used for soft-material robots and other continuum robots in both model-based fashion and model-free fashion. Lastly, applications or potential usage of soft-material robots are described related to wearable robots, medical robots, grasping and manipulation.

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# 1

# Introduction

In the biological world we find structures made of soft materials everywhere, starting from leaves, bacteria and spider silks, to skins, hairs, brains, and muscles. In fact it is known that over 80% of body weight of an adult human consists of soft substances. In general, it is crucial for biological systems to have soft materials because deformation of structures is the origin of many functions necessary for their survival, such as heart deformation for circulating blood, eye lens deformation for optical focus, and muscle deformation for limb motions [Pfeifer et al., 2014].

In contrast, most of today's robots are made of rigid materials such as metals and hard plastics. The underlying reason is manifold. Rigid materials are easier to handle for conventional manufacturing technologies. They are also easier for mathematical modeling and control purposes. Also they are often more stable as materials and robust against various decays. Body articulations based on rigid parts facilitate replacement and repair if necessary. The drawback of the robots is their tendency to be highly specialized and lack of many properties owned by their natural counterparts in dealing with unstructured environments, such as adaptability, energy efficiency of safe interaction with human.

In the recent years, there has been an increasing interest in the more active use of soft materials in robotic systems. Having a soft body like the ones in biological systems can potentially provide a robot with superior capabilities. For example, soft body can help the robots to adaptively navigate through small opening, softness can prevent injuries in human-robot interaction, while deformable body can also store and release energy, which may lead to energy efficiency in locomotion tasks. As it will be shown in the review, by building robotic systems with soft materials, we are able to realize systems that are safer, cheaper, and more adaptable than the level that the conventional robots can achieve.

For this reason, there have been a number of review papers on robotics using soft materials (further detail in §1.3). Different from those papers, this review focuses on the fundamental aspects of the research field which have not been covered in depth, to give a strong foundation for understanding the essential stream of this field. In the rest of the review, we start with the characterization of soft robots and the brief history of them, which are followed by more technical chapters about materials, actuators and sensors, modeling, control, and applications.

## 1.1 What is soft-material robotics

The term “soft-material robotics” is sometimes loosely used with “soft robotics”. The term “soft robotics” has been used in different meanings and contexts. Its definition has not been widely agreed on but it is converging. According to a review paper [Laschi and Cianchetti, 2014] and the First Working Paper released in September 2014 from the European Future and Emerging Technologies Open Coordination Action, RoboSoft [1], softness may refer to both structural compliance and inherent material compliance. Thus soft robotics may be defined as robotics that encompasses solutions that interact with environment relying on inherent or structural compliance. According to a position paper [Rossiter and Hauser, 2016], soft robotics is an umbrella term that covers all

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[1] http://www.robosoftca.eu

types of active and reactive compliant systems. For those interested in the part of soft robotics which deals with structural or active compliance, further information may be found in [Albu-Schaeffer et al., 2008, Verl et al., 2015] and other papers related to active impedance control [Hogan, 1985], series elastic actuators [Groothuis et al., 2014, Austin et al., 2015], and variable stiffness actuators [Pratt and Williamson, 1995, Vandeborght et al., 2013, Austin et al., 2015].

Soft-material robotics, which is the focus of the review, is the part that deals with inherent material compliance. Soft material (also called soft matter) includes liquids, polymers, foams, gels, colloids, granular materials, as well as most soft biological materials, according to the scientific journal *Nature* [2]. The common feature of soft material is that it consists of large molecules or assemblies of molecules that move collectively, and, as a result, it gives large, slow, and nonlinear response to small forces [Doi, 2013].

To elaborate on inherent material compliance, soft-material robotics may be defined as robotics that studies how deformation of soft material can be exploited or controlled to achieve robotic functions [Wang and Iida, 2015]. Other definitions exist [Laschi et al., 2016] but the shared keyword is “deformation”. In the case of solid soft-materials, many researchers focuses on materials with a relatively low modulus (below 1 GPa) at room temperature [Majidi, 2013, Rus and Tolley, 2015]. This excludes soft-materials such as certain thermoplastics, which have been used to build supporting structures or kinematic linkages as cheaper alternatives to metals. Since the novelty of soft-material robotics lies in deformation, technologies where other aspects (e.g. adhesion) of soft materials are exploited are also excluded (as opposed to including climbing technologies in [Laschi et al., 2016]). Furthermore, studies related to micro-robots or the so-called nano-robots are not considered here, even if soft materials such as certain biological materials are used. By doing this, we hope to define the research field more clearly and differentiate it from existing fields.

According to [Trivedi et al., 2008b, Marchese et al., 2016], soft(-material) robots are a subset of continuum robots [Robinson and

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[2] http://www.nature.com/subjects/soft-materials

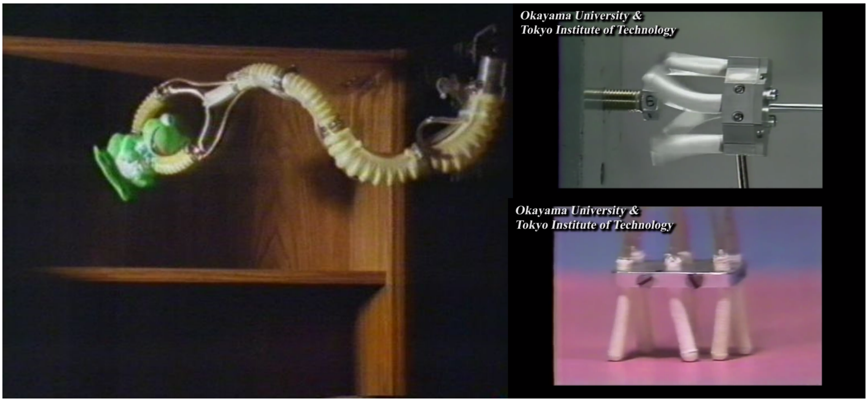

**Figure 1.1:** Early pneumatically-actuated robots with continuously-deforming air chambers or channels. Left, an arm comprised of pneumatically-actuated bellow-like segments [Wilson, 1984, Wilson and Mahajan, 1989]. Right, a hexapod and a hand whose legs and fingers were comprised of pneumatically-actuated tri-celluar segments [Suzumori et al., 1991a,b]. All figures are snapshots from videos [3]under Standard Youtube License.

Davies, 1999], which are a further subset of hyper-redundant robots [Chirikjian and Burdick, 1991]. However, not all continuum robots are soft and even continuum robots referred to as soft [Trivedi et al., 2008b] have varying degrees of rigidity [Marchese et al., 2016]. To the best of our knowledge, the first published paper to use the term "soft" to describe a robot is [Hirose and Umetani, 1978]. The "soft gripper" presented in that paper should be more appropriately seen as a hyper-redundant robot.

## 1.2 History of soft-material robotics

The history of soft-material robotics dates back to at least the late 1970s, when robot grippers based on granular materials were first published [Cardaun, 1978, Schmidt, 1978, Perovskii, 1980]. Recent reviews [Rus and Tolley, 2015, Laschi et al., 2016] date the history back to middle 1980s or early 1990s, which may be due to their focus on a par-

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[3] https://www.youtube.com/watch?v=Dh7dsLCazss, https://www.youtube.com/watch?v=kHGLYRUKWeM

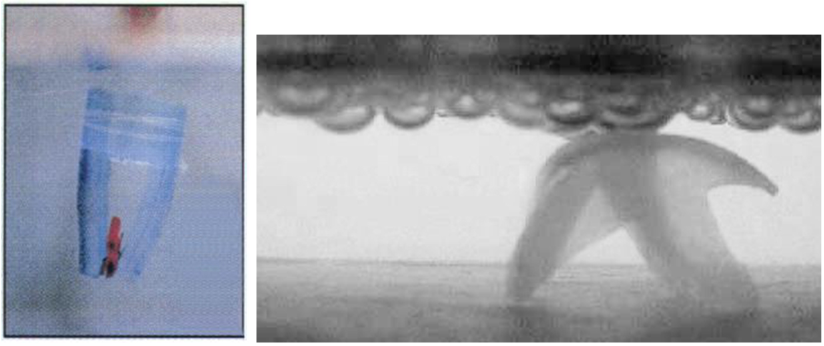

**Figure 1.2:** Early robots made from gels. Left, a fingered gripper made from temperature-sensitive N-isopropylacrylamide gel and acrylamide gel [Hu et al., 1995]. Right, a legged robot made from electroactive polymer gel [Otake et al., 2000]. All figures are reproduced with permission of the copyright owners.

ticular type of soft material such as elastomers and overlooking earlier published work on other types of soft material such as granular materials. Robots based on other soft materials, such as elastomers, fluids, and gels emerged in the 1980s and 1990s.

The first piece of published work on using elastomers for a continuously-deforming body is [Wilson, 1984, Wilson and Mahajan, 1989]. The pneumatically-actuated robot arm was comprised of 4-5 bellows with two additional bellows used as grippers. Upon bending of these bellows, the arm was able to pick, move and place an irregularly shaped object (see Figure 1.1). The second piece of published work with a similar robot is probably [Suzumori et al., 1991a,b]. Instead of bellow-like units, tri-cellular units were designed and made, where the three cells are distributed about a central axis with each spanning 120°. With a number of these units, hands and hexapod could be made for manipulation and walking (see Figure 1.1).

The first piece of published work on using electrorheological (ER) fluid in robot grippers is [Kenaley and Cutkosky, 1989]. The first piece of published work on using gels in robot grippers is probably [Hu et al., 1995] (see Figure 1.2). Other work using gels which is worth mentioning includes the crawling robot made from electroactive polymer gel

Otake et al. [1999]. Both ER fluid and electroactive polymer gel belong to electroactive polymers (EAPs) [Bar-Cohen, 2004]. However, not all EAPs are soft-materials e.g. ionometic polymer-metal composites may not be considered as soft-material due to the presence of metals, despite its use in robot grippers in the late 1990s.

The influences of shape, deformation, and material properties to functions and behaviors of robots have also been attracting many robotics researchers for a long time. Probably one of the earliest attempt to establish the conceptual formulations was in the context of Embodied Artificial Intelligence research [Pfeifer, 2000, 2003]. The work highlighted how control of robots is related to "morphology" of them by introducing several earlier case studies of rigid shape changing robots, with an additional notation about how the concept can be extended for soft-material robots. In the last decade, this research area was populated by a number of biologically inspired robot case studies to learn how nature takes advantage of softness and deformation for adaptive functions and behaviours [Pfeifer et al., 2007, 2014]. As discussed more details in Chapter 6, based on these bio-inspired soft robotics research, body deformation can be explained and exploited for the purposes of actuation, sensing, and computation of robots, that provides an alternative way to design and construct intelligent robots not fully relying on the conventional sensory-motor control architectures.

## 1.3 Soft-material robotics today

Today the landscape of soft-material robotics research has changed, even though the basic concepts haven't. Technologies have been improved and made finer. [Wang and Iida, 2015] listed five probable reasons why soft-material robotics has resurfaced and gained substantial traction at the beginning of the 21st century, which has led to the branding of the research field.

- Soft material has been established as a field in material science since the 1990s.
- A large amount of new soft material has been synthesized and made commercially available.

- Diverse fabrication techniques for soft material have been invented and made accessible.
- An increasing amount of work demonstrating the use of soft material in robotics has been published in high-profile journals.
- Researchers generally agree that soft-material-based technologies should be used in robotic applications in the future as they are intrinsically cheaper, safer, and more adaptive in complex task environments as compared with the conventional rigid systems.

An important aspect lies in the fact that we are beginning to understand the boundaries of what the conventional rigid robots can and cannot do. Elegant natural motions we often encounter in very small animals to large ones, for example, cannot be realized without considering the exploitation of material dynamics and functions. The impressive work done by conventional engineers in the last decade made it explicit that there are many things rigid robots cannot do even if we push them to the limit; this in turn has led many researchers to start exploring new dimensions, especially those related to mechanical dynamics and materials.

Another aspect is that integration of essential components for a soft robot is possible because of the maturity and accessibility of individual technologies such as those for materials, actuators, sensors and electronics, etc. As a result, research has progressed towards integration of these technologies and demonstration of superior functions at the system level.

A third aspect that has progressed from decades ago is that soft-material robotics research no longer requires high cost in time and budget. Off-the-shelf technologies, including materials, sensors, motors, and prototyping machines, allow even a hobbyist to make a robot in a matter of hours with pocket money. Computational tools such as physics engines, computer vision, and high-power microprocessors also facilitate the ways younger students are becoming involved in research projects. The Internet provides countless ready-made sample programs to set a stage for the research, most of which one had to develop from scratch decades ago. This naturally allows a number of interdisciplinary researchers, not only engineers but also chemists, material scientists, and biologists, to join the community.

To give a clear picture of the growth of the research field and to show our contribution with this review effort, we summarize eight review papers on soft-material robots and compare them to our work in Table 1.1. We only select those review papers which cover various technical aspects of a soft-material robotic system. Hence review papers on a single aspect, such as design [Manti et al., 2016], fabrication [Cho et al., 2009] and sensing [Nanshu and Hyeong, 2013] are not listed for comparison. System integration is challenging and a technological component may not work for a robotic system unless proven.

In addition to all the review papers, there have been a number of notable position papers related to soft-material robotics [Pfeifer et al., 2012, Lipson, 2013, Majidi, 2013, Kovac, 2013, Pfeifer et al., 2014, Nurzaman et al., 2014a], where opinions on principles, activities, trends and challenges are presented.

**Table 1.1:** A summary of review papers on soft-material robotic systems (in chronological order)

| Reference | History | Design & material | Fabrication | Actuation | Sensing | Modelling | Control | Comments |
|---|---|---|---|---|---|---|---|---|
| [Trivedi et al., 2008b] | × | ✓ | × | ✓✓ | × | ✓ | ✓ | Bioinspiration, EAPs, PAMs |
| [Kim et al., 2013] | × | ✓✓ | × | ✓✓ | × | ✓ | × | Bioinspiration, three case studies |
| [Laschi and Cianchetti, 2014] | × | ✓ | ✓ | ✓✓ | × | ✓ | ✓ | - |
| [Bauer et al., 2014] | × | ✓✓ | ✓ | ✓✓ | ✓✓ | × | × | Energy harvester |
| [Rus and Tolley, 2015] | ✓ | ✓✓ | ✓ | ✓✓ | ✓ | ✓ | ✓ | - |
| [Wang and Iida, 2015] | ✓ | ✓✓✓ | × | ✓✓✓ | × | × | × | Categorization based on deformation and functions |
| [Hughes et al., 2016] | ✓ | ✓ | ✓✓ | ✓✓ | ✓✓✓ | ✓ | × | Focus on manipulation and gripping |
| [Laschi et al., 2016] | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓ | ✓ | ✓ | Categorization based on functions |
| This review | ✓✓✓ | ✓✓✓ | × | ✓✓✓ | ✓✓✓ | ✓✓✓ | ✓✓✓ | - |

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