Design, fabrication and control of soft robots

Daniela Rus[1] and Michael T. Tolley[2]

[1]Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology

[2]Department of Mechanical and Aerospace Engineering, University of California, San Diego

Abstract

Conventionally, engineers have employed rigid materials to fabricate precise, predictable robotic systems, which are easily modeled as rigid members connected at discrete joints. Natural systems, however, often match or exceed the performance of robotic systems with deformable bodies. Cephalopods, for example, achieve amazing feats of manipulation and locomotion without a skeleton; even vertebrates like humans achieve dynamic gaits by storing elastic energy in their compliant bones and soft tissues. Inspired by nature, engineers have begun to explore the design and control of soft-bodied robots composed of compliant materials. This Review discusses recent developments in the emerging field of soft robotics.

Introduction

Biology has long been a source of inspiration for engineers making ever-more capable machines[1]. Softness and body compliance are salient features often exploited by biological systems, which tend to seek simplicity and exhibit reduced complexity in their interactions with their environment[2]. Several of the lessons learned from studying biological systems are now culminating in the definition of a new class of machine we, and others, refer to as *soft robots*[3, 4, 5, 6]. Traditional, rigid-bodied robots are used today extensively in manufacturing and can be specifically programmed to perform a single task efficiently, but often with limited adaptability. Because they are built of rigid links and joints, they are unsafe for interaction with human beings. A common practice is to separate human and robotic workspaces in factories to mitigate safety concerns. The lack of compliance in conventional actuation mechanisms is part of this problem. Soft robots provide an opportunity to bridge the gap between machines and people. In contrast to hard bodied robots, soft robots have bodies made out of intrinsically soft and/or extensible materials (e.g. silicone rubbers) that can deform and absorb much of the energy arising from a collision. Soft robots have a continuously deformable structure with muscle-like actuation that emulates biological systems and results in a relatively large number of degrees of freedom as compared to their hard-bodied counterparts. Soft robots (Fig. 1) have the potential to exhibit unprecedented adaptation, sensitivity, and agility. Soft bodied robots promise to 1) Move with the ability to bend and twist with high curvatures and thus can be used in confined spaces[7]; 2) Deform their bodies in a continuous way and thus achieve motions that emulate biology[8]; 3) Adapt their shape to the environment employing compliant motion and thus manipulate objects[9], or move on rough terrain and exhibit resilience[10]; 4) Execute rapid, agile maneuvers, such as the escape maneuver in fish[11].

The key challenge for creating soft machines that achieve their full potential is the development of controllable soft bodies using materials that integrate sensors, actuators, and computation, that together enable the body to deliver the desired behavior. Traditional approaches to robot control assume rigidity in the linkage structure of the robot and are a poor fit for controlling soft bodies, thus new soft materials require new algorithms.

What is soft?

"Soft" refers to the body of the robot. Soft materials are the key enablers for creating soft robot bodies. While Young's Modulus is only defined for homogeneous, prismatic bars that are subject to axial loading and small deformations, it is nonetheless a useful measure of the rigidity of materials used in the fabrication of robotic systems[5]. Materials traditionally used in robotics (e.g. metals, hard plastics), have moduli on the order of 10^9–10^{12} Pa, whereas natural organisms are often composed of materials (e.g. skin, muscle tissue) with moduli on the order of 10^4–10^9 Pa (i.e. orders of magnitude lower than their engineered counterparts, see Fig. 2). We define soft robots as systems capable of autonomous behavior that are primarily composed of materials with moduli in the range of the moduli of soft biological materials.

Advantages of using materials with compliance similar to soft biological materials include a significant reduction in the harm that could be inadvertently caused by robotic systems (as has been demonstrated for rigid robots with compliant joints[12]), increasing their potential for interaction with humans. Compliant materials also adapt more readily to various objects, simplifying tasks like grasping[13], and can also lead to improved mobility over soft substrates[14].

For the body of a soft robot to achieve its potential, facilities for sensing, actuation, computation, power storage, and communication must be embedded in the soft material, resulting in smart materials. Additionally, algorithms that drive the body to deliver desired behaviors are required. These algorithms implement impedance matching to the structure of the body. This tight coupling between body and brain allows us to think about soft bodied systems as machines with mechanical intelligence, where the body can be viewed to augment the brain with morphological computation[15, 16]. This ability of the body to perform computation simplifies the control algorithms in many situations, blurring the line between the body and the brain. However, soft robots (like soft organisms) require control algorithms, which (at least for the foreseeable futures) will run on some sort of computing hardware. While both body and brain must be considered in concert, the challenges involved are distinct enough that we find it useful to organize them here into separate sections.

In the following three sections we review recent developments in the field of soft robotics as they pertain to design and fabrication, computation and control, and systems and applications. We then conclude with a discussion of persistent challenges facing soft robotics, and suggest areas where we see the greatest potential for societal impact.

Design and Fabrication

A robot is classified as hard or soft on the basis of the compliance of its underlying materials[3]. Soft robots are capable of continuum deformations, but not all continuum robots are soft. For example, the robotic elephant trunk manipulator[17] is a discrete hyper-redundant continuum robot composed of rigid materials; the articulated catheter robot[18] is an example of hard continuum robot; OctArm[19] (Fig. 3b) is an example of semi-soft continuum robot; while the caterpillar robot[20] (Fig. 1a) and the rolling belt robot[21] are examples of soft continuum robots. These soft machines have modular bodies consisting of soft rubber segments, which can be composed serially or in parallel to create complex morphologies. The body of a soft robot may consist of multiple materials with different stiffness properties[22, 11]. A soft robot encases in a soft body all the sub-systems of a conventional robot: an actuation system, a perception system, driving electronics, and a computation system, with corresponding power sources. Technological advances in soft materials and subsystems compatible with the soft body enable the autonomous function of the soft robot. The rest of this section describes recent progress in developing sub-systems for soft robots. With this range of components, design tools are used to create the topology of the robot body along with the placement of its functional components. Given the design roadmap, the robot is ready to be fabricated.

Actuation

The segments of a soft robot are usually actuated in one of two ways (See Fig. 4): 1) Variable length tendons (in the form of tension cables[23] or shape memory alloy actuators[24]) may be embedded in soft segments, to achieve, for example, robotic octopus arms (Fig. 3f). 2) In another common approach, pneumatic actuation is used to inflate channels in a soft material and cause a desired deformation. Pneumatic artificial muscles (PAMs), also known as McKibben actuators, are examples of compliant linear soft actuators composed of elastomer tubes in fiber sleeves[25, 26]. Fluidic elastomer actuators (FEAs) are a new type of highly extensible and adaptable, low-power soft actuator. FEAs comprise synthetic elastomer films operated by the expansion of embedded channels under pressure. Once pressurized, the actuator will keep its position with little or no additional energy consumption. FEAs can be operated pneumatically[27, 28, 29, 30, 10] or hydraulically[31, 32]. Given a small number of options for pressurized working fluid generation, and a significant difference between the time constants for the generators and actuators, pressure regulating components such as regulators and valves are necessary. Regardless of the actuation method, soft actuators are frequently arranged in a biologically inspired agonist-antagonist arrangement (like muscles) to allow bi-directional actuation. Another benefit of this arrangement is that co-contraction of muscle pairs leads to adaptable compliance.

The design and actuation of soft robotic systems dates back to at least 1992 when a team demonstrated the impressive capabilities of soft, flexible microactuators[27] (Fig. 3a). This work demonstrated the approach of pneumatic actuation of robotic elements composed of elastomer. In this approach, a fluid (usually air) is used to inflate channels in the elastomer, while some asymmetry in the design or constituent materials causes the component to actuate (move) in a desired way (see Fig. 4). The resulting continuous, adaptive motions can appear surprisingly lifelike. Other groups[29,33-35] (Fig. 1b, c) used soft lithography techniques adapted from microfluidics, as well as soft composite materials composed of various silicone polymers and elastomers at times embedded with paper or cloth, to design and fabricate pneumatically actuated soft systems. One challenge with these designs based on pneumatic networks (also referred to as pneu-nets) is that the high strains required for actuation can lead to slow actuation rates and rupture failures. A slightly more complex design for pneumatically actuated elastomeric soft robots reduced the material strain required for actuation[36], and allowed the untethered walking of a large, soft robot[10]. Soft-lithography fabrication approaches typically use a layer of stiffer rubber or elastomer sometimes with paper, fabric, or a plastic film embedded to achieve asymmetric strain for actuation. An alternative approach is to augment all elastomeric elements with flexible fibers, which limit the stress taken up by the elastomer during pneumatic actuation. The result is soft actuators with reduced extensibility and flexibility, but the ability to withstand higher actuation pressures, and hence apply larger forces. Using complex molding and/or freeform fabrication techniques, it is possible to embed fibers directly into pneumatic elastomeric actuators to achieve agile motions based on bending[27, 13, 37].

While most soft robot prototypes have used pneumatic or hydraulic actuation, a great deal of research has focused on the development of electrically activated soft actuators composed of electroactive polymers (EAPs)[38, 39], which have also led to prototype systems[22]. Since energy is typically most readily stored in electrical form, and computation is usually done on electronic circuits, it may be more efficient to directly use electrical potential to actuate soft robots. Types of EAPs include Dielectric EAPs, ferroelectric polymers, electrostrictive graft polymers, liquid crystal polymers, ionic EAPs, electrorheological fluids, ionic polymer-metal composites, and stimuli-responsive gels. Since a detailed discussion is beyond the scope of this review, we refer the reader to refs 38, 39 for details. In general, fabrication, performance, and long-term stability are active areas of research in EAPs.

Instead of designing the stiffness of robotic systems by tuning their constituent materials, another line of soft robotics research has sought to control material stiffness on-the-fly. One approach is to embed or encase soft materials with stiffer materials such as wax[40] or metal[41], which can be softened thermally. Embedded heaters can thus be used to adjust the structure's effective stiffness and allow for compliant behavior or actuated repositioning. Similarly, isothermal phase change caused by particle jamming has also been explored as a method of adjusting a soft robot's rigidity for actuation[42, 43] (Fig. 1f), or even for grasping an impressive array of objects[44] (Fig. 3c).

Stretchable Electronics

To date, most integrated soft robotics systems have relied on traditional, rigid electronics to store the control algorithms and connect to the systems' actuators, sensors, and power sources. However, there has recently been a great effort in the area of soft and stretchable electronics[45, 46, 47]. A full discussion of this area is beyond the scope of the current review, however as the field of soft/stretchable electronics matures, we expect greater integration with soft robots, resulting in completely soft prototypes.

Sensing

The compliance and morphology of soft robots precludes the use of many traditional sensors including encoders, metal or semiconductor strain gages, or inertial measurement units (IMUs). While flexible-bending sensors based on piezoelectric polymers are available as commercial products, these may not be appropriate due to the need for all elements of the system to be both bendable and stretchable. Soft, stretchable electronics may enable new sensing modalities[48, 49]. The basis of proprioceptive sensors for a soft robot is usually either non-contact sensors or very low modulus elastomers combined with liquid-phase materials. Since soft robots are actuated by generating curvatures, proprioception relies on curvature sensors. The low modulus of proposed elastomer sensors (which have characteristic moduli in the range of 10^5-10^6 Pa) impart minimal change on the impedance of the underlying structures. These sensors generally have layered structures, where multiple thin elastomer layers are patterned with microfluidic channels by soft lithography. The channels are subsequently filled with a liquid conductor (e.g. gallium-containing alloys such as eutectic gallium-indium or eGaIn). With layered channel geometries, it is possible to tailor sensors for measuring various strains including tensile, shear[50], or curvature[51]. To address the fabrication challenges involved with injecting complex channel networks with liquid conductor, recent work has investigated mask deposition of the conductor[52], or direct 3D printing of conductive material[53]. Alternatively, exteroceptive sensing may be used to measure the curvatures of a soft robot's body segments in real time[30]. To expand the applications of soft robotics, compatible chemical and biological sensors[54] may be used to sense environmental signals. Such sensors may be more compatible with soft robots than the optical and audio recorders typically used in robotics.

Power Sources

A big challenge for soft robots is stretchable, portable power sources for actuation. For pneumatic actuators, existing fluidic power sources are not soft and are usually big and bulky. Current off-the-shelf pressure sources are generally limited to compressors or pumps and compressed air cylinders[55]. If we draw an analogy to electrical systems, compressors are similar to generators as they convert electrical energy into mechanical energy, and compressed gas cylinders are similar to capacitors as they store a pressurized fluid in a certain volume to be discharged when required. Miniature compressors use valuable electrical energy inefficiently, and cylinders in useful form factors do not offer longevity. What has been missing for fluidic systems is the equivalent of a battery, where a chemical reaction generates the necessary energy for actuation using a fuel. The chemically operated portable pressure source, or *pneumatic battery*[28] (Fig. 1g) generates pressurized gas using a hydrogen peroxide monopropellant[56]. Combustible fuels are another promising high energy density chemical fuel source[57, 58].

Electrically powered actuators (as well as the electrical controllers for pneumatic systems) require soft, flexible, lightweight electrical power sources[59]. As with soft electronics, this is an active area of research. Recent promising developments include graphene[60], organic polymer[61], embedded conductive fabric[62] based batteries.

Design

Existing soft robotic systems have typically been designed with traditional 3D computer-aided design (CAD) software. However, today's CAD software was not created with freeform 3D fabrication processes in mind, and does not easily accommodate the complex non-homogenous 3D designs, which may be desired for soft robotics. This has led researchers to either rely on relatively simple "2.5-D" layered designs, or come up with customized approaches to the design and fabrication of each system, typically based on commercial 3D molding techniques[58, 11]. Following an alternative approach, researchers have used design automation algorithms inspired by evolution to design soft robots[63]. Soft robot designs have been automatically generated using custom finite element analysis software (VoxCAD), which accommodates materials with a large range of moduli, coupled with design optimization using an evolutionary algorithm[64]. In addition, evolutionary algorithms have been used to automatically generate soft robot designs[65].

Fabrication

Recent progress in the field of soft robotics has been enabled by the development of rapid digital design and fabrication tools. Researchers have manufactured complex soft robotic systems by taking advantage of rapid and adaptable fabrication techniques[66], including multimaterial 3D printing[67], *shape deposition manufacturing* (SDM)[68], and *soft lithography*[69]. These techniques can be combined to create composites with heterogenous materials (e.g. rubber with different stiffness moduli), embedded electronics, and internal channels for actuation[31, 70]. Direct digital printing with soft materials may be another option for fabricating arbitrary soft structures. A wide range of robot bodies can be fabricated using these techniques. The next section discussed control systems supporting a wide range of soft robot applications.

Computation and Control

Unlike the control of rigid bodies, whose movements can be described by six degrees of freedom (three rotations and three translations about the x, y, and z axes), the movements of soft bodies cannot be confined to planar motions. Soft materials are elastic and can bend, twist, stretch, compress, buckle, wrinkle, etc. Such motion can be viewed as offering an infinite number of degrees of freedom, a fact which makes the control of soft robots very challenging. Controlling soft robots requires new approaches to modeling, control, dynamics, and high-level planning.

The muscle analogy for soft actuators has driven a number of biologically-inspired approaches to modeling and control for soft materials. The octopus' arm is the prototypical example of a highly adaptive, soft actuator in nature that has been the source of inspiration for several biomimetic designs. The study of the octopus shows that it forms pseudo-joints and uses human-like strategies for precise point-to-point movements such as fetching[71]. An understanding of the working principles and control of soft organisms (such as the octopus) has led to a model for the control of soft robots[72]. Likewise, the caterpillar has provided an ideal model for mobile soft robots[73]. The study of these systems for the development and implementation of soft robotic systems, has also, in turn, reflected back on our understanding of the mechanics and control of the associated natural systems[74].

Modeling and Kinematics

The kinematics and dynamics of soft robotic systems are unlike those of traditional, rigid-bodied robots. When composed of a series of actuation elements, these robots approach a continuum behavior. In theory, the final shape of the robot can be described by a continuous function and modeling this behavior requires continuous mathematics. Because soft robots are different than traditional rigid linkage-based systems, researchers have developed new static, dynamic and kinematic models that capture their ability to bend and flex[75].

Robots made entirely from soft elastomer and powered by fluids do not yet have well understood models or planning and control algorithms primarily because their intrinsic deformation is continuous, complex, and highly compliant. Additionally, soft robots are often underactuated; they can contain many passive degrees of freedom, and when driven with low pressure fluids the available input fluid power is unable to compensate for gravitational loading. Soft robot designers often model the kinematics of soft robots using a simplifying assumption which leads to the piecewise constant curvature (PCC) model. Webster and Jones showed that the PCC model is equivalent to many other modeling approaches[75]. Building on the PCC model, researchers have developed methods to map the actuation space to configuration space. These approaches are robot-specific in that they integrate the morphology of the robot and the characteristics of the actuation system. One approach uses Bernoulli-Euler beam mechanics to predict deformation[76, 75, 3]; Another develops a relationship between the joint variables and the curvature arc parameters[77] which applies to high and medium pressure robots; A third presents models that describe the deformation of robots actuated with low pressures[28, 11, 29]. These models are the basis for the forward kinematics of their respective systems. However, the PCC model does not capture all aspects of soft robots and in an effort to increase the envelope of the model, Renda et al developed non-constant curvature models[78].

The inverse kinematics (IK) problem, as posed in[75] (i.e. computing the curvatures required to place a specified point on the robot body at a desired location), is more challenging. Existing literature has provided several approaches for semi-soft robots[79, 77]. A limitation of existing approaches to solving the IK problem for linear soft bodies (e.g. arms) is that currently neither the whole body, nor the pose of the end effector (which may be important for manipulation, sensing, etc.), are not considered in the solution. Autonomous obstacle avoidance and movement through a confined environment are difficult without a computational solution to the IK problem that is aware of the whole body of the robot in space. Real-time, closed-loop curvature controllers are required that drive the bending of the soft pneumatic body segments of the manipulator despite their high compliance and lack of kinematic constraints. Marchese et al. developed a method for closed-loop curvature control of a soft bodied planar manipulator[30]. This work used the PCC assumption with a cascaded curvature controller. Wang et al. proposed an alternative visual servo control approach for cable-driven soft robotic manipulators[80].

The inverse kinematics algorithm enables task-space planning algorithms to autonomously 1) position their end-effector (or some other part of their body) in free-space, 2) maneuver in confined environments, and 3) grasp-and-place objects. These task-space algorithms require that the planner considers the entire robot body (e.g. the whole arm not just the end effector for manipulators). Existing algorithms for whole body control[81] assume rigid body systems and have not been extended to soft bodied robots. For whole body control of soft robots, it is difficult to control the configuration of the whole soft body due to compliance. Marchese et al.[30] presented a computational approach to whole body planning for soft planar manipulators. This approach considered both the primary task of advancing the pose of the end effector of the soft robot, and the secondary task of positioning the changing envelope of the whole robot in relation to the environment[30, 7].

Control

Researchers have used these models to develop new approaches to low-level control, inverse kinematics, dynamic operations, and planning for soft robotic systems. An important aspect of these algorithms is the use of compliance when the robot interacts with its environment. Compliance allows the robot to adapt its shape and function to objects of unknown or uncertain geometry and is the basis for new control and planning algorithms for soft robots in the presence of uncertainly. For example, soft robots can execute pick and place operations without precise positioning or accurate geometric models of the object to be grasped[44].

Low-level control for soft robots is done as pressure control using pressure transducers or volume control using strain sensors. Pressure control accommodates differences in actuator compliance. Volume control is an avenue to configuration control and supports setting a maximum safe displacement limit. Most fluid-powered soft robots use open-loop valve sequencing to control body segment actuation. Valve sequencing means that a valve is turned on for some duration of time to pressurize the actuator and then turned off to either hold or deflate it. Many soft robotic systems use this control approach[21, 28, 29, 34, 10]. Marchese et al. demonstrated continuously adjustable, variable pressurization using a fluidic drive cylinder[30]. Recent work has sought to develop control elements for pneumatic soft robots (e.g. valves), which do not require electrical control signals. In this work, passive valves with memory allow the addressable control of many soft robotic actuators from a single controlled pressure source[82].

The dynamics of soft robots open the door for new robot capabilities. Much like a child on a swing set, repeatable positioning of a soft tentacle places it outside of its gravity compensation envelope, where the end effector could accomplish tasks. Physical phenomena common to soft robots—including actuation limits, the self-loading effects of gravity, and the high compliance of the manipulator—can be represented as constraints within a trajectory optimization algorithm that operates on a dynamic model of the soft robot[7]. One example dynamic maneuver enables soft robots to interact with humans by quickly grabbing objects directly from the hand of a human[7]. Dynamic control of soft robots can be achieved using a new dynamic model for a spatial soft fluidic elastomer manipulator, a method for identifying all unknown system parameters (i.e. the soft manipulator, fluidic actuators, and continuous drive cylinders or valving), and a planning algorithm that computes locally-optimal dynamic maneuvers through iterative learning control. The this approach represents actuation limits, the self-loading effects of gravity, and the high compliance of the manipulator, as constraints within the optimization.

Dynamic models of hard and semi-soft continuum robots provide examples for a variety of control techniques for soft robots[83, 76, 84]. Other work has modeled dynamic polymeric pneumatic tubes subject to tip loading using a bending beam approximation[85], but this has not been used for control. Tatlicioglu et al. developed a dynamic model for, and provided simulations of, a planar extensible continuum manipulator using a Lagrangian approach[86]. Luo et al.[87] modeled the dynamics of a soft planar snake.

Systems and Applications

In this section we review some of the systems and that have been developed to date to address a variety of potential applications to locomotion, manipulation, and human-machine interaction.

Locomotion

Recent work has explored the modes of locomotion possible with (or enabled by) soft bodies (Fig. 1). Notably, studies of caterpillars have led to a soft robotic systems[20, 73], as well as a further understanding of the control of motion in these animals[74]. An understanding of worm biomechanics also led to a bioinspired worm design composed of flexible materials and actuated by shape memory actuators (SMAs)[88], and an annelid inspired robot actuated by dielectric elastomer[22]. A European initiative studied the biomechanics and control of the octopus to produce a soft robotic prototype[24, 9]. Likewise, a self-contained, autonomous robotic fish actuated by soft fluidic actuators was demonstrated to be capable of forward swimming, turning, and depth adjustment[11, 31] (see Fig. 5). This robot can execute a c-turn escape maneuver in 100 milliseconds, which is on par with its biological counterpart, enabling the use of this robot as an instrument (i.e. a physical model) for biological studies. Soft robotics projects have also explored quadrupedal locomotion[29, 10], rolling[28, 73], and snake-like undulation[8]. Jumping has also been achieved using internal combustion of hydrocarbon fuels to achieve rapid energy release[57, 58].

Many of the exciting applications for soft robotics (e.g. search-and-rescue, environmental monitoring), require an autonomous, mobile system. However, most experimental soft robotic systems rely on power and/or control signals delivered through pneumatic and/or electrical tethers. Since typical actuation power sources (e.g. air compressors, batteries) are relatively heavy (e.g. 1.2 kg[10]), tethers greatly simplify system design by significantly reducing the required carrying capacity. One approach to achieving mobile systems is to tether a soft robot to a mobile rigid robot with a greater carrying capacity[89]. Untethered mobile systems have circumvented the challenge of carrying heavy power sources by operating underwater[11, 31] or rolling on a surface[28, 8] such that actuation system masses do not have to be lifted against gravity. Another approach has developed materials and designs tailored to operate at working pressures high enough to carry large payloads[10].

Manipulation

Manipulation is one of the canonical challenges for robotics (Fig. 3). Soft systems have a natural advantage over rigid robots in grasping an manipulating unknown objects since the compliance of soft grippers allows them to adapt to a variety of objects with simple control schemes. Grippers which employ isothermal phase change due to granular jamming have taken advantage of this feature of soft systems[44, 90]. Underactuated grippers composed of silicone elastomers with embedded pneumatic channels have also demonstrated impressive adaptability[33,13]. Commercially developed systems have also demonstrated manipulation with lightweight grippers composed of inflated flexible (but not extensible) material[91]. As one of the more mature applications of soft robotic technology, companies have begun to produce soft robotic manipulators (e.g. Pneubotics an Otherlab Company, Empire Robotics Inc., Soft Robotics Inc.).

Medical/Wearable Applications

One of the natural advantages of soft robotic systems is the compatibility of their moduli with those of natural tissues for medical and wearable applications. Rigid medical devices or orthoses run the risk of causing damage or discomfort to human or animal tissue. Additionally, it can be difficult to perfectly replicate the motion of natural joints with rigid orthodics. One possibility is to integrate a degree of compliance into wearable devices, for example for orthopedic rehabilitation. Recently, researchers have begun to look at medical wearable applications for soft robotics including soft wearable input devices (e.g. wearable keyboards[92]), soft orthodics for human ankle-foot rehabilitation[37], soft sensing suits for lower limb measurement[93], soft actuated systems for gait rehabilitation of rodents who have had their spinal cord surgically cut[94], and a soft system for simulation of cardiac actuation[95].

Soft Cyborgs

Recent work has begun to investigate robotic systems that directly integrate biological (as opposed to artificial, biologically compatible) materials. Since biological materials are often very soft, the resulting systems are soft robotic systems (or perhaps they would be more aptly named *soft cyborgs*). For example, microbes which digest organic material and produce electricity have powered artificial muscles for autonomous robots[96], and cardiomyocytes have been used to power a jellyfish inspired swimming cyborg[97]. One challenge with using swarms of inexpensive soft robots for exploration is that of retrieving the robots once the task is completed. One way to avoid this problem is to develop biodegradable and the soft robots powered by gelatin actuators[98]. Since gelatin is edible, there may also be medical applications for this technology.

Future Directions

The field of soft robotics aims to create the science and applications of soft autonomy by asking the questions: How do we design and control soft machines, and how do we use these new machines? Current research on the algorithmic and device-level aspects of soft robots has demonstrated soft devices that can locomote, manipulate, and interact with people and their environment in unique ways. Soft mobile robots capable of locomotion on unknown terrain and soft robot manipulators capable of pose-invariant and shape-invariant grasping rely on compliance to mitigate uncertainty and adapt to environment and task. These basic behaviors open the door for applications where robots work closely with humans. For example, a soft robot manipulator could handle and prep a wide variety of food items in the kitchen while a soft mobile robot could use contact to guide patients during physiotherapy exercises. The soft home robot could assist the elderly with monitoring their medicine regiments while a soft factory robot could support humans in delicate assembly tasks. But how do we get to the point where soft robots deliver on their full potential? We need (1) rapid design tools and fabrication recipes for low-cost soft robots, (2) novel algorithmic approaches to the control of soft robots that account for their material properties, (3) tools for developing device-specific programming environments that allow non-experts to use the soft machines, (4) creative individuals to design new solutions, and (5) early adopters of the technology.

The soft robotics community is creating materials that have the ability to compute, sense, and move, leading to a convergence between materials and machines. The materials are becoming more like computers due to embedded electro-mechanical components, and machines are getting softer due to the alternative materials used to create them. This convergence requires tools for functional specification and automated co-design of the soft body (including all the components necessary for actuation, sensing, and computation) and the soft brain (including all software aspects of controlling the device and reasoning about the world and the goal task). Progress in new materials with programmable stiffness properties, proprioceptive sensing, contact modeling, and recipes for rapid fabrication will enable the creation of increasingly more capable soft machines.

But how soft should a soft robot be in order to meet its true potential? As with many aspects of robotics, this depends on the task and environment. For domains that require extreme body compliance (e.g. inspecting a pipe with complex geometry or laproscopic surgery) or dealing with a great amount of uncertainty (e.g. locomotion on rocky uneven terrain or grasping unknown objects), soft machines can bring the capabilities of robots to new levels. However, soft robots are difficult to model and control, especially when they need to retain a desired body configuration without external support (e.g. an elephant trunk holding an object at a desired height in the presence of gravity). Augmenting soft machines with skeletons, much like vertebrates, could simplify such tasks. An important consideration for the future of soft machines is how to match the softness of the body to the range of capabilities expected from the machine in a way that most effectively leverages the body.

Rapid fabrication recipes and tools for soft robots with embedded electronics are needed to expand the user base beyond experts. Additionally, more advances are needed to expand the computation and control capabilities of existing systems. The current approaches to robot control rely on external localization. But soft robots that operate autonomously need the ability to localize proprioceptively. Current models for soft robots do not capture their dynamics. Improved dynamics models will lead to more capable controllers. Although the current planners for soft robots allow the systems to collide harmlessly with their environments, the collision are not detected. However, contact with the environment can be a useful aspect of task-level planning.

Soft robots have the potential to provide a link between living systems and artificial systems at multiple levels: high-level tasks, in interaction between humans and robots, and in cognition. Pfeifer and Bongard have argued that bodies are central to the way that we think[99]. This view, *embodied artificial intelligence*, holds that robotic bodies and brains must be considered and developed in concert, much as the bodies and brains of their biological counterparts co-evolved. Soft robotic systems have the potential to exploit morphological computation to adapt to, and interact with, the world in a way that is difficult or impossible with rigid systems. Following the principles of embodied artificial intelligence, soft robots may allow us to develop biologically inspired artificial intelligence in ways that are not possible with rigid bodied robots.

Bibliography

1. Full, R. J. Invertebrate locomotor systems. *Comprehensive Physiology* (1997).

2. Dickinson, M. H. *et al*. How animals move: an integrative view. *Science* **288**, 100–106 (2000).

3. Trivedi, D., Rahn, C. D., Kier, W. M. & Walker, I. D. Soft robotics: Biological inspiration, state of the art, and future research. *Applied Bionics and Biomechanics* **5**, 99–117 (2008).

   This paper discusses the biological inspiration for soft robotics and reviews the first generation of soft robotic systems which employ primarily pneumatic artificial muscle or electroactive polymer actuators.

4. Kim, S., Laschi, C. & Trimmer, B. Soft robotics: a bioinspired evolution in robotics. *Trends in biotechnology* **31**, 287–294 (2013).

   This paper reviews design and actuation approaches for soft robots, and discusses the biomechanics of three organisms which frequently serve as inspiration.

5. Majidi, C. Soft robotics: A perspective–current trends and prospects for the future. *Soft Robotics* **1**, 5–11 (2013).

6. Laschi, C. & Cianchetti, M. Soft robotics: new perspectives for robot bodyware and control. *Frontiers in bioengineering and biotechnology* **2** (2014).

7. Marchese, A. D., Tedrake, R. & Rus, D. Dynamics and trajectory optimization for a soft spatial fluidic elastomer manipulator. *The International Journal of Robotics Research*, to appear (2015).

   This paper describes a new algorithm for dynamic control of soft robots and demonstrates the use of this method to achieve reachability outside of the static envelope of the robot.

8. Onal, C. D. & Rus, D. Autonomous undulatory serpentine locomotion utilizing body dynamics of a fluidic soft robot. *Bioinspiration & biomimetics* **8**, 026003 (2013).

   This paper presents a mobile soft robot composed of bidirectional fluidic elastomer

actuators to achieve snake-like locomotion.

9. Mazzolai, B., Margheri, L., Cianchetti, M., Dario, P. & Laschi, C. Soft-robotic arm inspired by the octopus: from artificial requirements to innovative technological solutions. *Bioinspiration & biomimetics* **7**, 025005 (2012).

   This paper presents the design of a biologically inspired artificial muscular hydrostat for underwater soft robotics.

10. Tolley, M. T. *et al.* A resilient, untethered soft robot. *Soft Robotics* **1**, 213–223 (2014).

    This paper addresses the design of a legged soft robot system capable of carrying the components required for untethered walking without a skeleton, and demonstrates that soft robots can be resilient to harsh conditions such as large external forces and extreme temperatures.

11. Marchese, A. D., Onal, C. D. & Rus, D. Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. *Soft Robotics* **1**, 75–87 (2014).

    This paper describes a self-contained autonomous robot fish that is capable of executing biologically inspired escape maneuvers (i.e. rapid changes in direction) in hundreds of milliseconds, which is on par with similarly sized fish.

12. Albu-Schaffer, A. *et al.* Soft robotics. *Robotics & Automation Magazine, IEEE* **15**, 20–30 (2008).

13. Deimel, R. & Brock, O. A novel type of compliant, underactuated robotic hand for dexterous grasping. *Robotics: Science and Systems, Berkeley, CA* 1687–1692 (2014).

    This paper describes the design and testing of an inexpensive, modular, underactuated soft robot hand with pneumatically actuated fiber-reinforced elastomer digits.

14. Majidi, C., Shepherd, R. F., Kramer, R. K., Whitesides, G. M. & Wood, R. J. Influence of surface traction on soft robot undulation. *The International Journal of Robotics Research* **32**, 1577–1584 (2013).

15. Paul, C. Morphological computation: A basis for the analysis of morphology and control requirements. *Robotics and Autonomous Systems* **54**, 619–630 (2006).

16. Hauser, H., Ijspeert, A. J., Fuchslin, R. M., Pfeifer, R. & Maass, W. Towards a theoretical foundation for morphological computation with compliant bodies. *Biological cybernetics* **105**, 355–370 (2011).

17. Hannan, M. W. & Walker, I. D. Kinematics and the implementation of an elephant's trunk manipulator and other continuum style robots. *Journal of Robotic Systems* **20**, 45–63

(2003).

18. Camarillo, D. B., Carlson, C. R. & Salisbury, J. K. Configuration tracking for continuum manipulators with coupled tendon drive. *Robotics, IEEE Transactions on* **25**, 798–808 (2009).

19. McMahan,W. *et al.* Field trials and testing of the octarm continuum manipulator. In *Robotics and Automation (ICRA), IEEE International Conference on*, 2336–2341 (IEEE, 2006).

20. Lin, H., Leisk, G. & Trimmer, B. Soft robots in space: a perspective for soft robotics. *Acta Futura* **6**, 69–79 (2013).

21. Correll, N., Onal, C., Liang, H., Schoenfeld, E. & Rus, D. Soft autonomous materials – using active elasticity and embedded distributed computation. In Experimental Robotics 227-240 (Springer 2014)

22. Jung, K., Koo, J. C., Lee, Y. K., Choi, H. R. *et al.* Artificial annelid robot driven by soft actuators. *Bioinspiration & biomimetics* **2**, S42 (2007).

23. Calisti, M. *et al.* An octopus-bioinspired solution to movement and manipulation for soft robots. *Bioinspiration & biomimetics* **6**, 036002 (2011).

24. Laschi, C. *et al.* Soft robot arm inspired by the octopus. *Advanced Robotics* **26**, 709–727 (2012).

25. Schulte, H. The characteristics of the McKibben artificial muscle. *The application of external power in prosthetics and orthotics* **874**, 94–115 (1961).

26. Chou, C.-P. & Hannaford, B. Measurement and modeling of McKibben pneumatic artificial muscles. *Robotics and Automation, IEEE Transactions on* **12**, 90–102 (1996).

27. Suzumori, K., Iikura, S. & Tanaka, H. Applying a flexible microactuator to robotic mechanisms. *Control Systems, IEEE* **12**, 21–27 (1992).

28. Onal, C. D., Chen, X., Whitesides, G. M. & Rus, D. Soft mobile robots with on-board chemical pressure generation. In *International Symposium on Robotics Research (ISRR)*, 1–16 (2011).

29. Shepherd, R. F. *et al.* Multigait soft robot. *Proceedings of the National Academy of Sciences* **108**, 20400–20403 (2011).

This paper describes the rapid design and fabrication of a soft robot body capable of walking and undulating tethered to a pneumatic actuation system.

30. Marchese, A. D., Komorowski, K., Onal, C. D. & Rus, D. Design and control of a soft and continuously deformable 2d robotic manipulation system. In *Robotics and Automation (ICRA), IEEE International Conference on* (2014).

31. Katzschmann, R. K., Marchese, A. D. & Rus, D. Hydraulic Autonomous Soft Robotic Fish for 3D Swimming. In *International Symposium on Experimental Robotics (ISER)*, 1122374 (Marrakech, Morocco, 2014).

32. Polygerinos, P., Wang, Z., Galloway, K. C., Wood, R. J. & Walsh, C. J. Soft robotic glove for combined assistance and at-home rehabilitation. *Robotics and Autonomous Systems* in press (2014).

This paper demonstrates a wearable soft robotic system which augments the grasping force of wearers for rehabilitation.

33. Ilievski, F., Mazzeo, A. D., Shepherd, R. F., Chen, X. & Whitesides, G. M. Soft robotics for chemists. *Angewandte Chemie* **123**, 1930–1935 (2011).

This paper demonstrates the effective use of methods and materials from chemistry and soft-materials science in the fabrication of soft robots.

34. Martinez, R. V. *et al.* Robotic tentacles with three-dimensional mobility based on flexible elastomers. *Advanced Materials* **25**, 205–212 (2013).

35. Morin, S. A. *et al.* Camouflage and display for soft machines. *Science* **337**, 828–832 (2012).

36. Mosadegh, B. *et al.* Pneumatic networks for soft robotics that actuate rapidly. *Advanced Functional Materials* **24**, 2163–2170 (2014).

37. Park, Y.-L. *et al.* Design and control of a bio-inspired soft wearable robotic device for ankle– foot rehabilitation. *Bioinspiration & biomimetics* **9**, 016007 (2014).

38. Bar-Cohen, Y. *Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential, and Challenges* (SPIE Press, 2004).

39. Wallace, G. G., Teasdale, P. R., Spinks, G. M. & Kane-Maguire, L. A. *Conductive electroactive polymers: intelligent polymer systems* (CRC press, 2008).

40. Cheng, N.G., Gopinath, A., Wang, L., Iagnemma, K. &Hosoi, A.E. Thermally tunable, self-healing composites for soft robotic applications. *Macromolecular Materials and Engineering* (2014).

41. Shan, W., Lu, T. &Majidi, C. Soft-matter composites with electrically tunable elasticrigidity. *Smart Materials and Structures* **22**, 085005 (2013).

42. Steltz, E., Mozeika, A., Rodenberg, N., Brown, E. & Jaeger, H. M. Jsel: Jamming skin enabled locomotion. In *Intelligent Robots and Systems (IROS). IEEE/RSJ International Conference on*, 5672–5677 (IEEE, 2009).

43. Cianchetti, M. *et al.* Stiff-flop surgical manipulator: mechanical design and experimental characterization of the single module. In *Intelligent Robots and Systems (IROS). IEEE/RSJ International Conference on*, 3576–3581 (IEEE, 2013).

44. Brown, E. *et al.* Universal robotic gripper based on the jamming of granular material. *Proceedings of the National Academy of Sciences* **107**, 18809–18814 (2010).

45. Rogers, J. A., Someya, T. & Huang, Y. Materials and mechanics for stretchable electronics. *Science* **327**, 1603–1607 (2010).

46. Hammock, M. L., Chortos, A., Tee, B. C.-K., Tok, J. B.-H. & Bao, Z. 25th anniversary article: The evolution of electronic skin (e-skin): A brief history, design considerations, and recent progress. *Advanced Materials* **25**, 5997–6038 (2013).

47. Kaltenbrunner, M. *et al.* An ultra-lightweight design for imperceptible plastic electronics. *Nature* **499**, 458–463 (2013).

48. Yang, S. & Lu, N. Gauge factor and stretchability of silicon-on-polymer strain gauges. *Sensors* **13**, 8577–8594 (2013).

49. Kim, D.-H. *et al.* Epidermal electronics. *Science* **333**, 838–843 (2011).

50. Vogt, D. M., Park, Y.-L. & Wood, R. J. Design and characterization of a soft multi-axis force sensor using embedded microfluidic channels. *Sensors Journal, IEEE* **13**, 4056–4064 (2013).

51. Majidi, C., Kramer, R. & Wood, R. J. A non-differential elastomer curvature sensor for softer-than-skin electronics. *Smart Materials and Structures* **20**, 105017 (2011).

52. Kramer, R. K., Majidi, C. & Wood, R. J. Masked deposition of gallium-indium alloys for liquid-embedded elastomer conductors. *Advanced Functional Materials* **23**, 5292–5296 (2013).

53. Muth,J.T. *etal.* Embedded 3d printing of strain sensors within highly stretchable elastomers. *Advanced Materials* **26**, 6307–6312 (2014).

54. Taylor, R. F. & Schultz, J. S. *Handbook of chemical and biological sensors* (CRC Press, 1996).

55. Wehner, M. *et al.* Pneumatic energy sources for autonomous and wearable soft robotics. *Soft Robotics* **1**, 263–274 (2014).

56. Goldfarb, M., Barth, E. J., Gogola, M. A. & Wehrmeyer, J. A. Design and energetic characterization of a liquid-propellant-powered actuator for self-powered robots. *Mechatronics, IEEE/ASME Transactions on* **8**, 254–262 (2003).

57. Shepherd, R. F. *et al.* Using explosions to power a soft robot. *Angewandte Chemie* **125**, 2964–2968 (2013).

58. Tolley, M. T. *et al.* An untethered jumping soft robot. In *Intelligent Robots and Systems (IROS). IEEE/RSJ International Conference on*, 561–566 (IEEE, 2014).

59. Xu, S. *et al.* Stretchable batteries with self-similar serpentine interconnects and integrated wireless recharging systems. *Nature communications* **4**, 1543 (2013).

60. Li, N., Chen, Z., Ren, W., Li, F. & Cheng, H.-M. Flexible graphene-based lithium ion batteries with ultrafast charge and discharge rates. *Proceedings of the National Academy of Sciences* **109**, 17360-17365 (2012).

61. Suga, T., Ohshiro, H., Sugita, S., Oyaizu, K. & Nishide, H. Emerging n-type redox-active radical polymer for a totally organic polymer-based rechargeable battery. *Advanced Materials* **21**, 1627–1630 (2009).

62. Gaikwad, A. M. *et al.* Highly stretchable alkaline batteries based on an embedded conductive fabric. *Advanced Materials* **24**, 5071–5076 (2012).

63. Lipson, H. Challenges and opportunities for design, simulation, and fabrication of soft robots. *Soft Robotics* **1**, 21–27 (2014).

64. Hiller, J. & Lipson, H. Automatic design and manufacture of soft robots. *Robotics, IEEE Transactions on* **28**, 457–466 (2012).

65. Rieffel, J., Knox, D., Smith, S. & Trimmer, B. Growing and evolving soft robots. *Artificial life* 20, 143–162 (2014).

66. Cho, K.J. *etal.* Review of manufacturing processes for soft biomimetic robots. *International Journal of Precision Engineering and Manufacturing* **10**, 171–181 (2009).

67. Lipson, H. & Kurman, M. *Fabricated: The New World of 3D Printing* (John Wiley & Sons, 2013).

68. Cham, J. G., Bailey, S. A., Clark, J. E., Full, R. J. & Cutkosky, M. R. Fast and robust: Hexapedal robots via shape deposition manufacturing. *The International Journal of Robotics Research* **21**, 869–882 (2002).

69. Xia, Y. & Whitesides, G. M. Soft lithography. *Annual review of materials science* **28**, 153–184 (1998).

70. Marchese, A. D., Katzschmann, R. & Rus, D. A recipe for soft fluidic elastomer robots. *Soft Robotics* **2**, 7–25 (2015).

71. Sumbre, G., Fiorito, G., Flash, T. & Hochner, B. Octopus uses human-like strategy to control point-to-point arm movement. *Current Biology* **16**, 767–772 (2006).

72. Margheri, L., Laschi, C. & Mazzolai, B. Soft robotic arm inspired by the octopus: I. from biological functions to artificial requirements. *Bioinspiration & biomimetics* **7**, 025004 (2012).

73. Lin, H.-T., Leisk, G. G. & Trimmer, B. GoQBot: a caterpillar-inspired soft-bodied rolling robot. *Bioinspiration & biomimetics* **6,** 026007 (2011).

This paper describes a soft mobile robot developed as a tool to study caterpillar locomotion including crawling and ballistic rolling.

74. Saunders, F., Trimmer, B. A. & Rife, J. Modeling locomotion of a soft-bodied arthropod using inverse dynamics. *Bioinspiration & Biomimetics* **6**, 016001 (2011).

75. Webster, R. J. & Jones, B. A. Design and kinematic modeling of constant curvature continuum robots: A review. *The International Journal of Robotics Research* **29**, 1661–1683 (2010).

76. Gravagne, I. A., Rahn, C. D. & Walker, I. D. Large deflection dynamics and control for planar continuum robots. *Mechatronics, IEEE/ASME Transactions on* **8**, 299–307 (2003).

77. Jones, B. A. & Walker, I. D. Kinematics for multisection continuum robots. *Robotics, IEEE Transactions on* **22**, 43–55 (2006).

78. Renda, F., Giorelli, M., Calisti, M., Cianchetti, M. & Laschi, C. Dynamic model of a multi-bending soft robot arm driven by cables. *Robotics, IEEE Transactions on* **30**, 1109–1122 (2014).

79. Neppalli, S., Csencsits, M. A., Jones, B. A. & Walker, I. D. Closed-form inverse kinematics for continuum manipulators. *Advanced Robotics* **23**, 2077–2091 (2009).

80. Wang, H. *et al.* Visual servo control of cable-driven soft robotic manipulator. In *Intelligent Robots and Systems (IROS). IEEE/RSJ International Conference on*, 57–62 (2013).

81. Khatib, O., Sentis, L., Park, J. & Warren, J. Whole body dynamic behavior and control of human-like robots. *International Journal of Humanoid Robotics* **1**, 29–43 (2004).

82. Napp, N., Araki, B., Tolley, M. T., Nagpal, R. & Wood, R. J. Simple passive valves for addressable pneumatic actuation. In *Robotics and Automation (ICRA), IEEE International Conference on*, 1440–1445 (IEEE, 2014).

83. Chirikjian, G. S. Hyper-redundant manipulator dynamics: a continuum approximation. *Advanced Robotics* **9**, 217–243 (1994).

84. Yekutieli, Y. *et al.* Dynamic model of the octopus arm. I. biomechanics of the octopus reaching movement. *Journal of neurophysiology* **94**, 1443–1458 (2005).

This paper describes a 2D dynamic model for a soft manipulators based on muscular hydrostats.

85. Snyder, J. & Wilson, J. Dynamics of the elastic with end mass and follower loading. *Journal of applied mechanics* **57**, 203–208 (1990).

86. Tatlicioglu, E., Walker, I. D. & Dawson, D. M. Dynamic modeling for planar extensible continuum robot manipulators. In *Robotics and Automation (ICRA), IEEE International Conference on*, 1357–1362 (IEEE, 2007).

87. Luo, M., Agheli, M. & Onal, C. D. Theoretical modeling and experimental analysis of a pressure-operated soft robotic snake. *Soft Robotics* **1**, 136–146 (2014).

88. Seok, S. *et al.* Meshworm: a peristaltic soft robot with antagonistic nickel titanium coil actuators. *Mechatronics, IEEE/ASME Transactions on* **18**, 1485–1497 (2013).

89. Stokes, A. A., Shepherd, R. F., Morin, S. A., Ilievski, F. & Whitesides, G. M. A hybrid combining hard and soft robots. *Soft Robotics* **1**, 70–74 (2013).

90. Amend, J. R., Brown, E. M., Rodenberg, N., Jaeger, H. M. & Lipson, H. A positive pressure universal gripper based on the jamming of granular material. *Robotics, IEEE Transactions on* **28**, 341–350 (2012).

91. Sanan, S., Lynn, P. S. & Griffith, S. T. Pneumatic torsional actuators for inflatable robots. *Journal of Mechanisms and Robotics* **6**, 031003 (2014).

92. Kramer, R. K., Majidi, C. & Wood, R. J. Wearable tactile keypad with stretchable artificial skin. In *Robotics and Automation (ICRA), IEEE International Conference on*, 1103–1107 (IEEE, 2011).

93. Mengüç, Y. *et al.* Wearable soft sensing suit for human gait measurement. *The International Journal of Robotics Research* **33**,1748-1764 (2014).

94. Song, Y. S. *et al.* Soft robot for gait rehabilitation of spinalized rodents. In *Intelligent Robots and Systems (IROS). IEEE/RSJ International Conference on*, 971–976 (IEEE, 2013).

95. Roche, E. T. *et al.* A bioinspired soft actuated material. *Advanced Materials* **26**, 1200–1206 (2014).

96. Ieropoulos, I., Anderson, I. A., Gisby, T., Wang, C.-H. & Rossiter, J. Microbial-powered artificial muscles for autonomous robots. In *SPIE Smart Structures and Materials+ Non-destructive Evaluation and Health Monitoring*, 728708–728708 (International Society for Optics and Photonics, 2009).

97. Nawroth, J. C. *et al.* A tissue-engineered jellyfish with biomimetic propulsion. *Nature Biotechnology* **30**, 792–797 (2012).

98. Chambers, L., Winfield, J., Ieropoulos, I. & Rossiter, J. Biodegradable and edible gelatine actuators for use as artificial muscles. In *SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring*, 90560B–90560B (International Society for Optics and Photonics, 2014).

99. Pfeifer, R., Bongard, J. & Grand, S. *How the body shapes the way we think: a new view of intelligence* (MIT Press, 2007).

100. Suzumori, K., Endo, S., Kanda, T., Kato, N. & Suzuki, H. A bending pneumatic rubber actuator realizing soft-bodied manta swimming robot. In *Robotics and Automation (ICRA), IEEE International Conference on*, 4975–4980 (IEEE, 2007).

Acknowledgements

The authors would like to thank Andrew Marchese, Robert Katzschmann, and the anonymous reviewers for their insightful comments and suggestions in editing this paper. This work was done with partial support from the National Science Foundation grant number IIS-1226883. We are grateful.

Competing Interests

The authors declare that they have no competing financial interests.

Correspondence

Correspondence and requests for materials should be addressed to D. Rus (email: rus@csail.mit.edu).

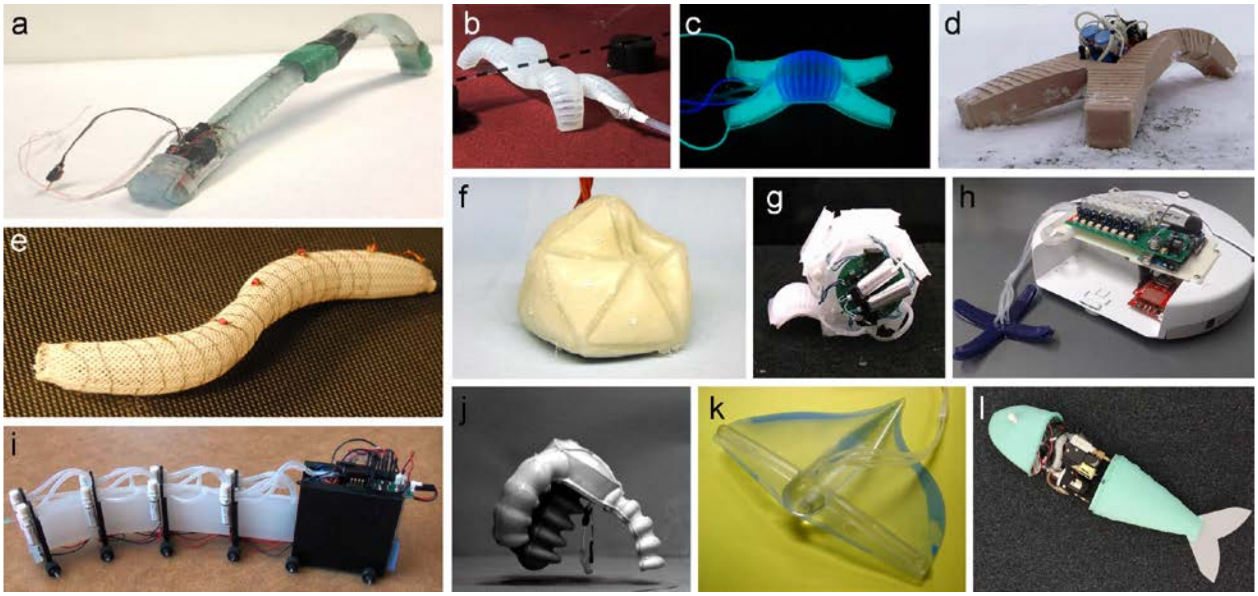

Figure 1: Mobile soft robotic systems inspired by a range of biological systems, demonstrating a) caterpillar-inspired locomotion[20], b) a multi-gait quadruped[29], c) active camouflage[35], d) walking in hazardous environments[10], e) worm-inspired locomotion[88], f) particle jamming-based actuation[42], g) rolling powered by a pneumatic battery[28,] h) a hybrid hard/soft robot[89], i) snake-inspired locomotion[8], j) jumping powered by internal combustion[58], k) manta-ray inspired locomotion[100], and l) an autonomous fish[11].

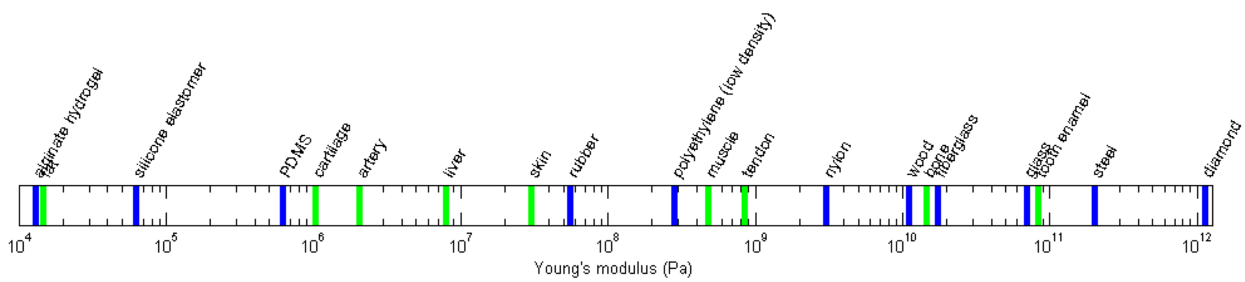

Figure 2: Approximate tensile modulus (Young's modulus) of selected engineering and biological materials. Soft robots are composed primarily of materials with moduli comparable to those of soft biological materials (muscles, skin, cartilage, etc.), or less than approximately 1 GPa, which exhibit considerable compliance under normal loading conditions.

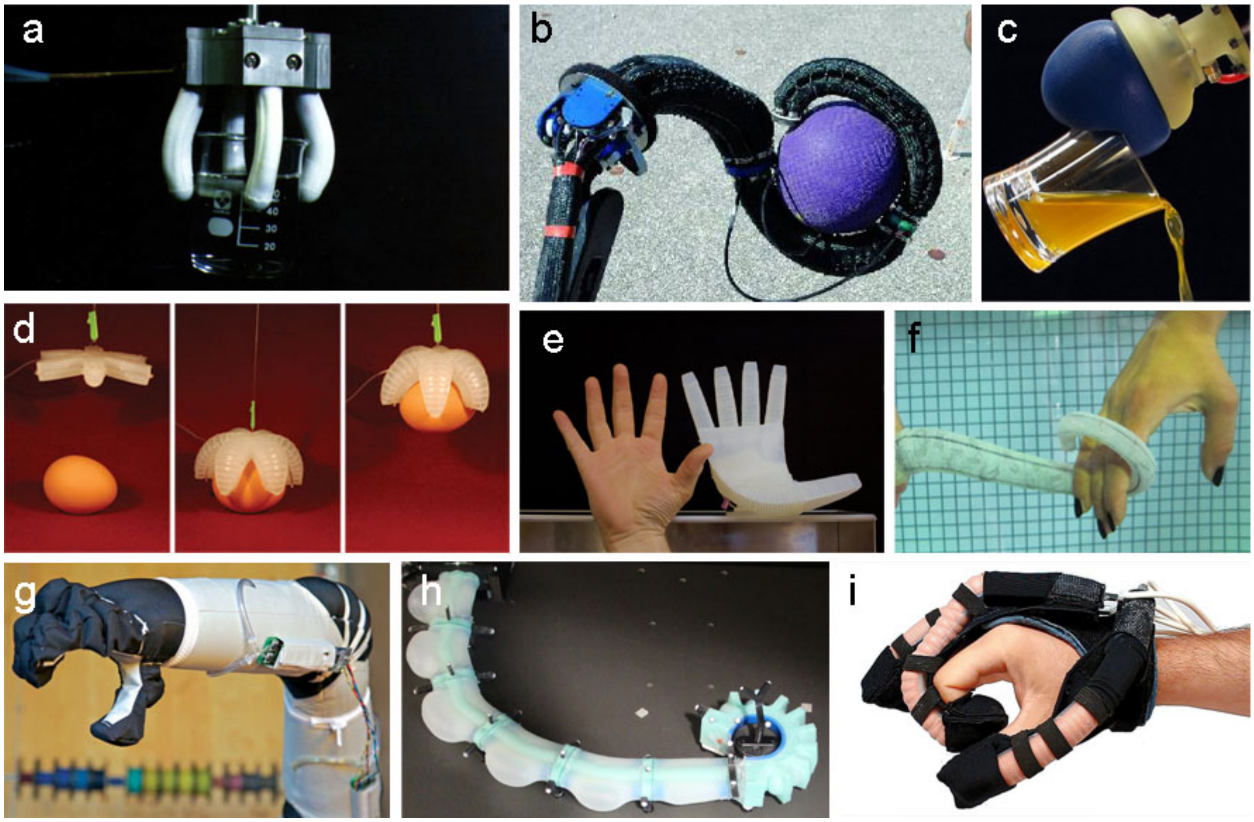

Figure 3: Grasping and manipulation, canonical challenges in robotics, can be greatly simplified with soft robotics. Examples of experimental soft robotic manipulations systems demonstrating a) microactuation[27], b) soft continuum manipulation[19], c) grasping with particle jamming[44], d) simple gripper fabrication by soft lithography[33], e) underactuated dextrous grasping[13], f) octopus-inspired manipulation[24], g) inflatable robotic manipulators[91], h) feedback control of a multisegmented arm[30], i) a soft glove for rehabilitation[32].

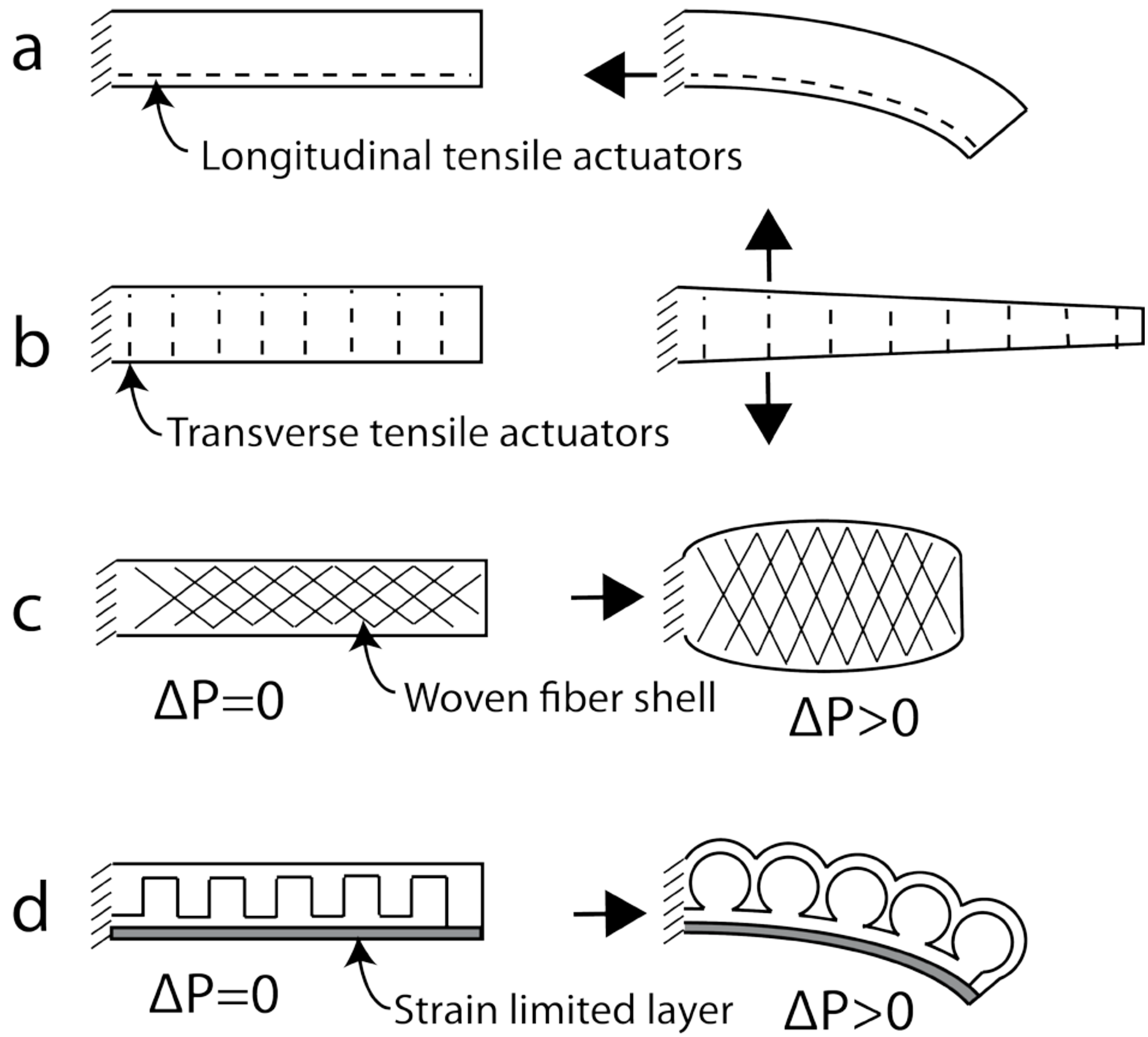

Figure 4: Common approaches to actuation of soft robot bodies in resting (left) and actuated (right) states. a) Longitudinal tensile actuators (e.g. tension cables or shape memory alloy actuators which contract when heated) along a soft robot arm cause bending when activated. b) Transverse tensile actuators cause a soft robot arm to extend when contracted (a muscle arrangement also seen in the octopus[72]). c) Pneumatic artificial muscles composed of an elastomeric tube in a woven fiber shell. A pressure applied internally causes the tube and shell to expand radially, causing longitudinal contraction. d) *Fluidic elastic actuator* or *Pneu-Net* design consisting of a pneumatic network of channels in an elastomer that expand when filled with a pressurized fluid, causing the soft body to bend toward a strain limited layer (e.g. a stiffer rubber or elastomer embedded with paper or other tensile fibers).

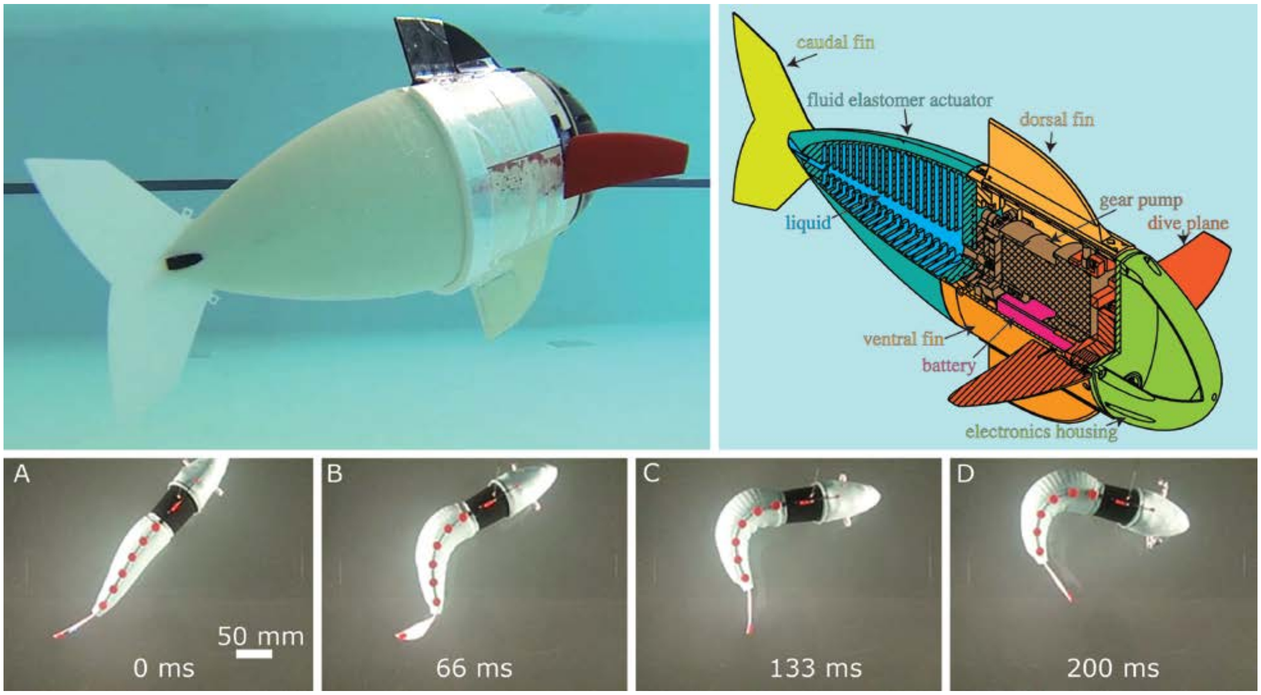

Figure 5: (Top) Soft robotic fish physical prototype and design schematic[31]. (Bottom) Images from a high speed video of the fish executing a c-turn escape maneuver, with elapsed time indicated[11].