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Design, fabrication and control of soft robots

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Conventionally, engineers have employed rigid materials to fabricate precise, predictable robotic systems, which are easily modelled 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 such as 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.

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 show 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 that we, and others, refer to as soft robots[3–6]. Conventional, rigid-bodied robots are used 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 humans. A common practice is to separate human and robotic work spaces 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 (for example, silicone rubbers) that can deform and absorb much of the energy arising from a collision. These 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 compared with their hard-bodied counterparts. They (Fig. 1) have the potential to exhibit unprecedented adaptation, sensitivity and agility. Soft robots promise to be able to bend and twist with high curvatures and thus can be used in confined spaces[7]; to deform their bodies in a continuous way and thus achieve motions that emulate biology[8]; to adapt their shape to the environment, employing compliant motion and thus manipulate objects[9], or move on rough terrain and exhibit resilience[10]; or to execute rapid, agile manoeuvres, such as the escape manoeuvre 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, and that together enable the body to deliver the desired behaviour. Conventional approaches to robot control assume rigidity in the linkage structure of the robot and are a poor fit for controlling soft bodies, thus 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. Although 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 conventionally used in robotics (for example, metals or hard plastics) have moduli in the order of 10^9–10^{12} pascals, whereas natural organisms are often composed of materials (for example, skin or muscle tissue) with moduli in the order of 10^4–10^9 Pa (orders of magnitude lower than their engineered counterparts; Fig. 2). We define soft robots as systems that are capable of autonomous behaviour, and that are primarily composed of materials with moduli in the range of that of soft biological materials.

The advantages of using materials with compliance similar to that of soft biological materials include a considerable 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 such as 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. In addition, algorithms that drive the body to deliver the desired behaviours 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, in which the body can be viewed as augmenting 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 future) will run on some sort of computing hardware. Although both body and brain must be considered in concert, the challenges involved are distinct enough that, in this Review, we find it useful to organize them 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 discuss persistent challenges facing soft robotics, and suggest areas in which we see the greatest potential for societal impact.

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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 a hard continuum robot; OctArm[19] (Fig. 3b) is an example of a 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[11,22]. A soft robot encases in a soft body all the subsystems 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 subsystems 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 road map, the robot is ready to be fabricated.

Actuation

The segments of a soft robot are usually actuated in one of two ways (Fig. 4): 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); or 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 fibre 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[10,27–30] 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 bidirectional 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 the desired way (Fig. 4). The resulting continuous, adaptive motions can seem surprisingly lifelike. Other groups[29,33–35] (Fig. 2b, 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 fibres, 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 moulding and/or free-form fabrication techniques,

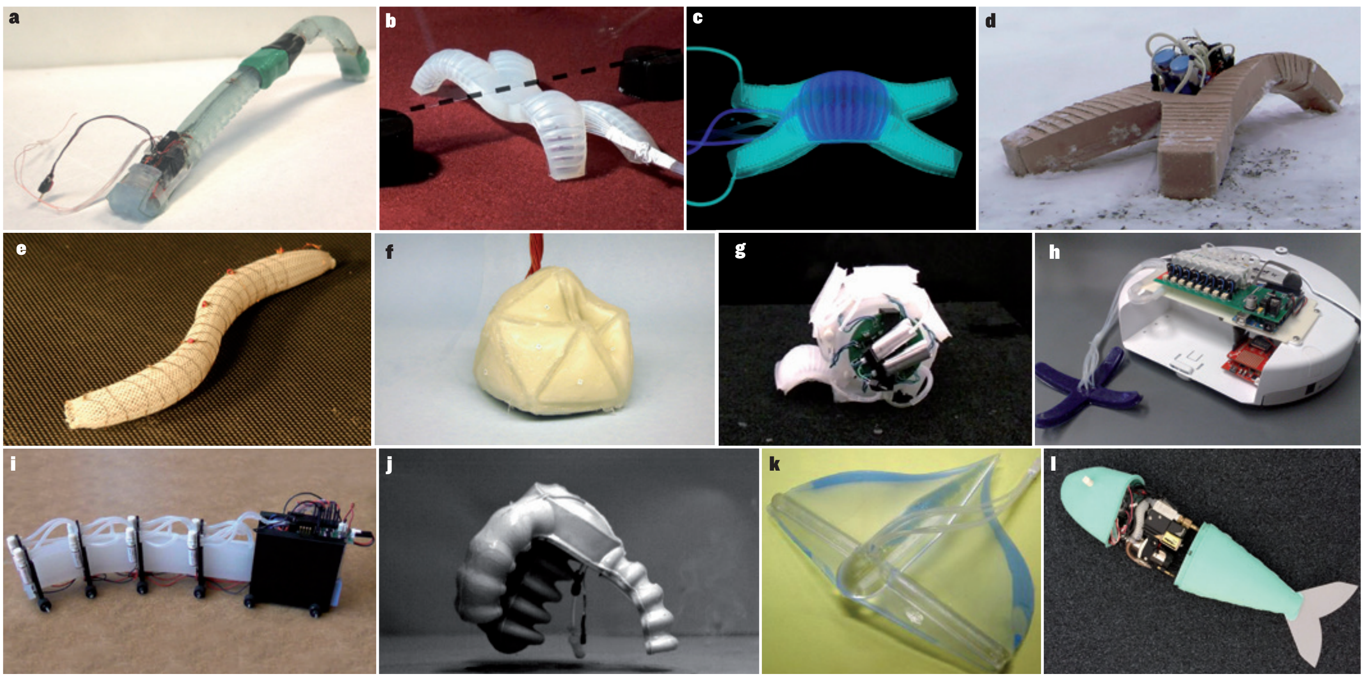

Figure 1 | Mobile soft-robotic systems inspired by a range of biological systems. **a**, Caterpillar-inspired locomotion[20]. **b**, A multi-gait quadruped[29]. **c**, Active camouflage[35]. **d**, Walking in hazardous environments[10]. **e**, Worm-inspired locomotion[88]. **f**, Particle-jamming-based 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]. **l**, An autonomous fish[11].

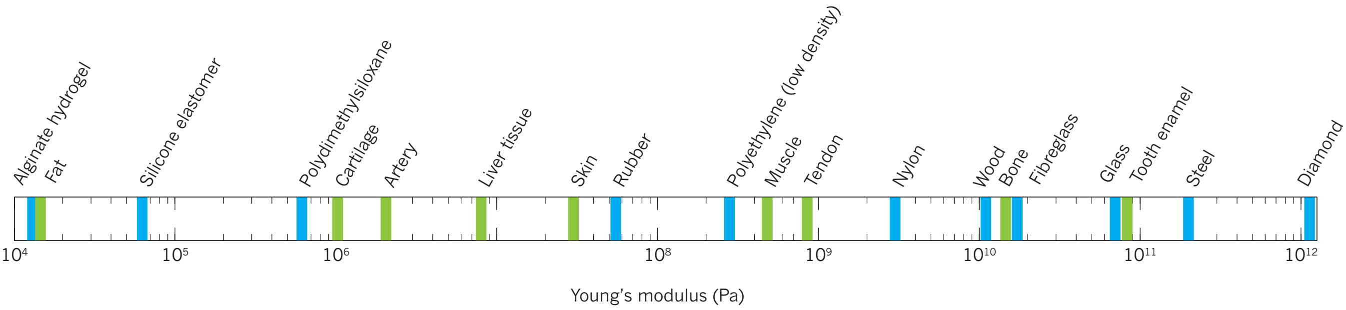

Figure 2 | Approximate tensile modulus (Young's modulus) of selected engineering and biological materials. Soft robots are composed primarily of materials with moduli comparable with those of soft biological materials (muscles, skin, cartilage, and so on), or of less than around 1 gigapascal. These materials exhibit considerable compliance under normal loading conditions.

it is possible to embed fibres directly into pneumatic elastomeric actuators to achieve agile motions based on bending[13,27,37].

Although 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 thermally softened. Embedded heaters can thus be used to adjust the structure's effective stiffness and allow for compliant behaviour 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. 2f), or even for grasping an impressive array of objects[44] (Fig. 3c).

Stretchable electronics

So far, most integrated soft-robotic systems have relied on conventional, rigid electronics to store the control algorithms and connect to the systems' actuators, sensors and power sources. However, there has recently been much research in the area of soft and stretchable electronics[45–47]. A full discussion of this area is beyond the scope of this Review, but, as this field of 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 conventional sensors including encoders, metal or semiconductor strain gauges, or inertial measurement units (IMUs). Although flexible-bending sensors based on piezoelectric polymers are available as commercial products, these may not be appropriate owing 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. Because 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, in which multiple thin elastomer layers are patterned with microfluidic channels by soft lithography. The channels are subsequently filled with a liquid conductor (for example, 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 in 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 curvature 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 of useful form factors do not offer longevity. What has been missing for fluidic systems is the equivalent of a battery, whereby a chemical reaction generates the necessary energy for actuation using a fuel. The chemically operated portable pressure source, or pneumatic battery[28] (Fig. 2g), 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 batteries based on graphene[60], organic polymers[61] and embedded conductive fabric[62].

Design

Existing soft robotic systems have typically been designed with conventional 3D computer-aided design (CAD) software. However, current CAD software was not created with free-form 3D fabrication processes in mind, and does not easily accommodate the complex non-homogeneous 3D designs that may be desired for soft robotics. This has led researchers to either rely on relatively simple '2.5D'

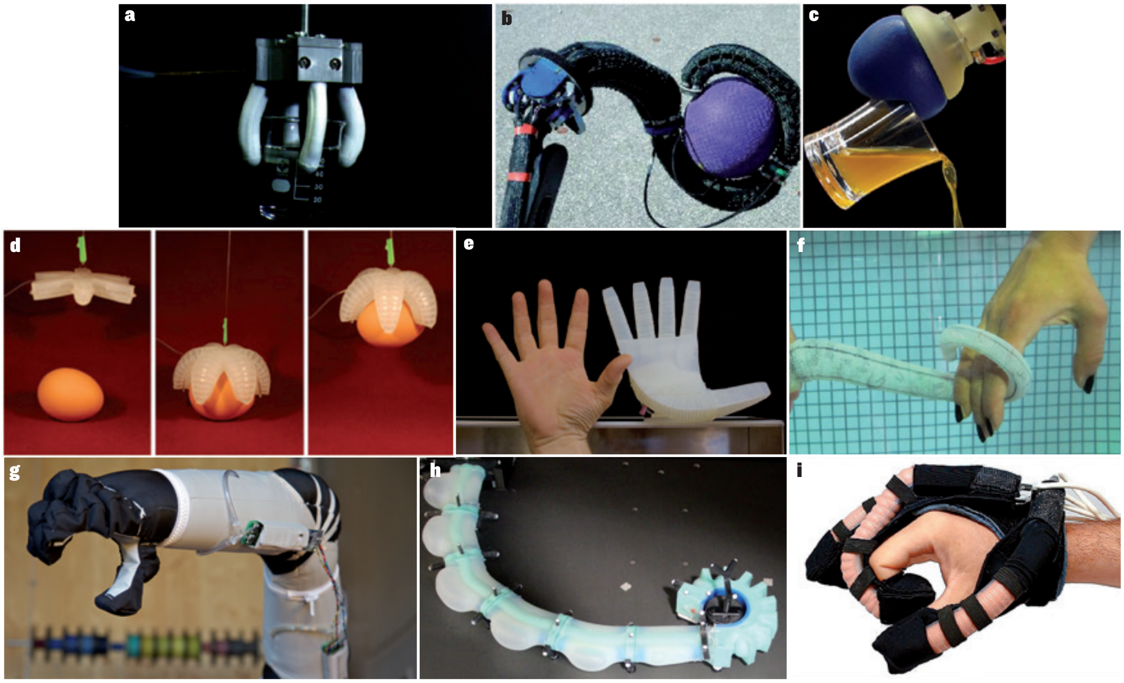

Figure 3 | Grasping and manipulation, which are canonical challenges in robotics, can be greatly simplified with soft robotics. Examples of experimental soft-robotic manipulation systems demonstrating microactuation[27] (**a**), soft-continuum manipulation[19] (**b**), grasping with particle jamming[44]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

layered designs, or come up with customized approaches to the design and fabrication of each system, typically based on commercial 3D moulding techniques[11,58]. 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 (for example, 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 variety of robot bodies can be fabricated using these techniques. The next section discusses control systems supporting a wide range of soft-robot applications.

Computation and control
Unlike the control of rigid bodies, the movements of which 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 and so on. Such motion can be viewed as offering an infinite number of degrees of freedom, which makes the control of soft robots very challenging. Controlling soft robots requires new approaches to modelling, control, dynamics, and high-level planning.

The muscle analogy for soft actuators has driven a number of biologically inspired approaches to modelling 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. Octopuses form pseudo-joints and use 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, in turn, reflected back on our understanding of the mechanics and control of the associated natural systems[74].

Modelling and kinematics
The kinematics and dynamics of soft-robotic systems are unlike those of conventional, rigid-bodied robots. When composed of a series of actuation elements, these robots approach a continuum behaviour. In theory, the final shape of the robot can be described by a continuous function, and modelling this behaviour requires continuous mathematics. Because soft robots are different from conventional 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. In addition, soft robots are often under-actuated; 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. Designers often model the kinematics of soft robots using a simplifying assumption that leads to the piecewise constant curvature (PCC) model. The PCC model is equivalent to many other modelling approaches[75]. Building on the PCC model, researchers have developed methods to map the actuation space to the 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[3,75,76]; another develops a relationship between the joint variables and the curvature arc parameters[77], and this applies to high and medium pressure robots; and a third presents models that describe the deformation of robots actuated with low pressures[11,28,29]. 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, non-constant curvature models have been developed[78].

The inverse-kinematics problem, as posed in ref. 75 (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[77,79]. A limitation of existing approaches to solving the inverse-kinematics problem for linear soft bodies (for example, arms) is that currently neither the whole body, nor the pose of the end effector (which may be important for manipulation, sensing, and so on), are not considered in the solution. Autonomous obstacle avoidance and movement through a confined environment are difficult without a computational solution to the inverse-kinematics 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. One method for closed-loop curvature control of a soft-bodied planar manipulator[30] uses the PCC assumption with a cascaded curvature controller. An alternative visual servo control approach for cable-driven soft-robotic manipulators has also been proposed[80].

The inverse-kinematics algorithm enables task–space planning algorithms to autonomously position their end effector (or some other part of their body) in free space; manoeuvre in confined environments; and grasp and place objects. These task–space algorithms require the planner to consider the entire robot body (the whole arm, for example, 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 owing to compliance. One computational approach[30] to whole-body planning for soft planar manipulators considers 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[7,30].

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 by 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[10,21,28,29,34]. Continuously adjustable, variable pressurization using a fluidic drive cylinder has been demonstrated[30]. Recent work has sought to develop control elements for pneumatic soft robots (for example, valves), which do not require electrical control signals. In this study, 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 manoeuvre 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 (the soft manipulator, fluidic actuators and continuous drive cylinders or valving), and a planning algorithm that computes locally optimal dynamic manoeuvres through iterative learning control. 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[76,83,84].

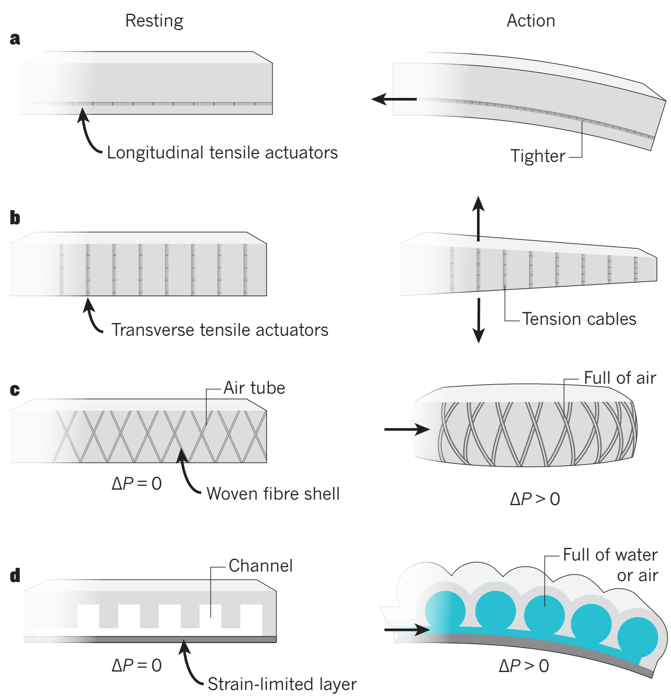

Figure 4 | Cross-section of common approaches to actuation of soft-robot bodies in resting (left) and actuated (right) states. **a**, Longitudinal tensile actuators (for example, tension cables or shape-memory alloy actuators, which contract when heated) along a soft-robot arm cause bending when activated. **b**, Transverse tensile actuators cause a soft-robot arm to extend when contracted (a muscle arrangement also seen in octopuses[72]). **c**, Pneumatic artificial muscles composed of an elastomeric tube in a woven fibre shell. A pressure applied internally causes the tube and shell to expand radially, causing longitudinal contraction. **d**, Fluidic elastic actuator or PneuNet 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 (for example, a stiffer rubber or elastomer embedded with paper or other tensile fibres).

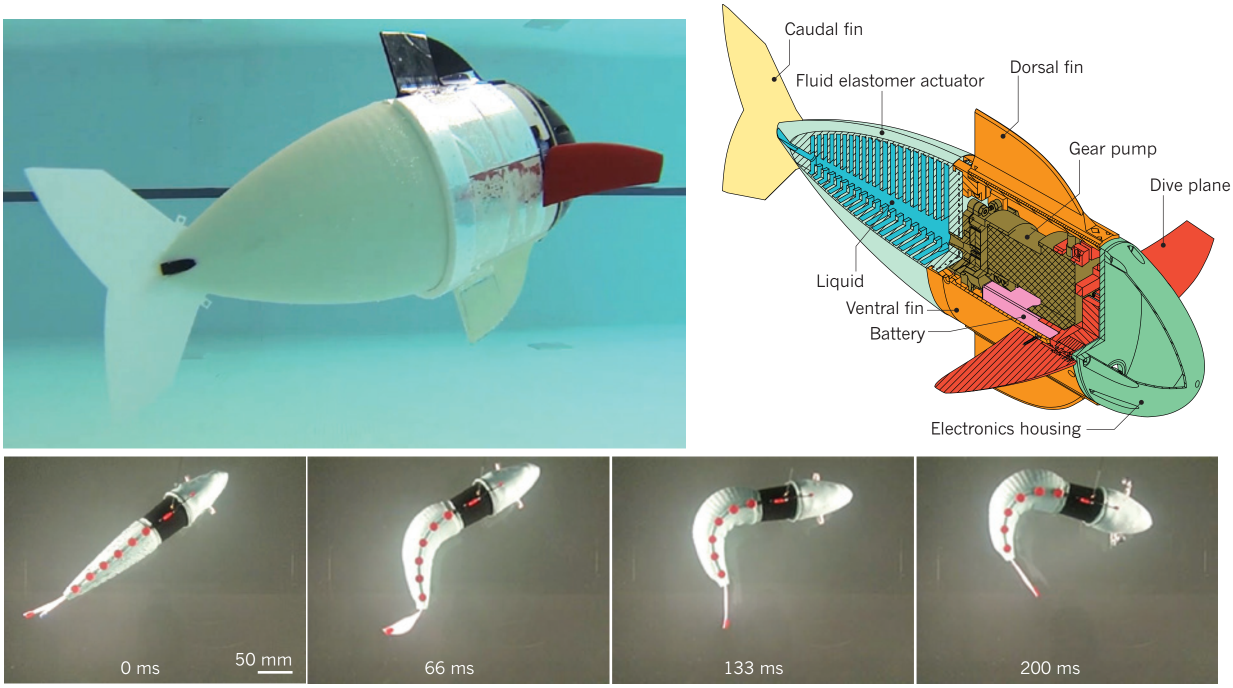

Figure 5 | A soft robotic fish. Soft robotic fish physical prototype (top) and design schematic[31]. Images from a high-speed video of the fish executing a C-turn escape manoeuvre with elapsed time indicated[11] (bottom).

Other work has modelled 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.*[86] developed a dynamic model for, and provided simulations of, a planar extensible continuum manipulator using a Lagrangian approach. Luo *et al.*[87] modelled the dynamics of a soft planar snake.

Systems and applications

In this section we review some of the systems that have been developed so far 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 soft-robotic systems[20,73], as well as to 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[9,24]. Likewise, a self-contained, autonomous robotic fish actuated by soft fluidic actuators could swim forward, turn and adjust its depth[11,31] (Fig. 5). This robot can execute a C-turn escape manoeuvre in 100 milliseconds, which is on a par with its biological counterpart, enabling it to be used as an instrument (a physical model) for biological studies. Soft-robotics projects have also explored quadrupedal locomotion[10,29], rolling[28] 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 (such as search-and-rescue operations or 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 (for example, air compressors or batteries) are relatively heavy (for example, 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[8,28] such that actuation system masses do not have to be lifted against gravity. Another approach has led to materials and designs tailored to operate at working pressures that are 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 and manipulating unknown objects because the compliance of soft grippers allows them to adapt to a variety of objects with simple control schemes. Grippers that employ isothermal phase change owing to granular jamming have taken advantage of this feature of soft systems[44,90]. Under-actuated grippers composed of silicone elastomers with embedded pneumatic channels have also shown impressive adaptability[13,33]. 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 (for example, Pneubotics an Otherlab company, Empire Robotics and Soft Robotics).

Medical and 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. In addition, 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 orthopaedic rehabilitation. Recently, researchers have begun to look at medical, wearable applications for soft robotics, including soft wearable input devices (for example, wearable keyboards[92]), soft orthodics for 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. Because 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 that 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 retrieving the robots once the task is completed. One way to avoid this problem is to develop biodegradable and 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 their environment and task. These basic behaviours open the door to applications in which robots work closely with humans. For example, a soft-robot manipulator could handle and prepare 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 regimens, whereas 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 rapid design tools and fabrication recipes for low-cost soft robots, novel algorithmic approaches to the control of soft robots that account for their material properties, tools for developing device-specific programming environments that allow non-experts to use the soft machines, creative individuals to design new solutions and 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 owing to embedded electro-mechanical components, and machines are getting softer owing 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 modelling, 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 (for example, inspecting a pipe with complex geometry or laproscopic surgery) or dealing with a great amount of uncertainty (for example, 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 (for example, 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. In addition, 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 collisions are not detected. Contact with the environment, however, 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 interactions between humans and robots, and in cognition. Pfeifer and Bongard[99] have argued that bodies are central to the way that we think. 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. ■

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