

Soft Robotics: Materials, Actuation, Modeling, and Control - A Comprehensive Review

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Abstract - Soft robotics replaces the rigid links and discrete joints of conventional manipulators with compliant materials whose stiffness approaches that of biological tissue, allowing a robot to adapt its shape to unfamiliar environments and to interact safely with fragile objects and humans. This compliance, however, gives a soft robot an effectively infinite-dimensional configuration space, so the modeling and control tools developed for rigid robots cannot be applied directly. This paper reviews the field through four closely linked aspects. Materials and actuation are discussed first, covering silicone elastomers, stimuli-responsive smart materials, fiber-reinforced composites, fabrication techniques, and pneumatic, tendon-driven, smart-material, and variable-stiffness actuators. Modeling and control are then examined together, ranging from the low-order piecewise constant curvature model to Cosserat rod, finite element, and data-driven models, and from model-based feedback to model-free, learning-based, and energy-aware control. The paper concludes with applications in grippers, medical and wearable devices, and locomotion, and outlines the open challenges of embedded sensing, actuator durability, and energy efficiency together with directions for future research.

Index Terms - Cosserat rod, finite element modeling, piecewise constant curvature, smart materials, soft actuators, soft robot control, soft robotics

I. INTRODUCTION

Industrial automation has relied on rigid-link robots with discrete motors for years because of their accuracy. However, this rigidity is counterproductive as soon as the robot operates in the vicinity of people, on a cluttered path or while dealing with delicate objects. The solution introduced by soft robotics is to replace most of a robot's body with the material that exhibits stiffness close to that of biological tissue, which is in the range of several kilopascals [1]–[3]. This means that the soft robot is more compliant and requires less complex adjustment due to its flexibility. The continuous deformation of the soft gripper allows it to grasp an object without precision modeling. The control theory developed for rigid objects, apart from its reference to some robotic elements (actuators, sensors), cannot be used in this case due to the infinite-dimensional nature of deformation configuration space [4].

Soft robots are commonly defined as systems built predominantly from materials with a Young's modulus comparable to that of soft biological materials, roughly 10^4 to 10^9 Pa, in contrast to the metals and hard plastics, with moduli of about 10^9 to 10^{12} Pa, from which conventional robots are made [1]. The idea is not entirely new: pneumatic artificial muscles of the McKibben type were developed in the 1950s for orthotic devices, and continuum and hyper-redundant manipulators have been studied for decades [5]. What has changed over the past fifteen years is the availability of castable silicone elastomers, multi-material 3-D printing, and inexpensive pneumatic and electronic components, which together allow a soft body to be designed, fabricated, and tested within days [2], [3].

A conventional manipulator is a chain of rigid links joined by revolute or prismatic joints, and its configuration is fully captured by a finite list of joint angles. The dynamics follow

standard Euler–Lagrange or Newton–Euler formulations [6], and decades of work on controllers like computed-torque control [7] (and its many refinements) get very good tracking performance out of that setup. A soft robot doesn't offer that shortcut. Deformation is spread continuously along the body, so a single segment of a soft arm might bend, twist, and stretch all at once under actuation, and its actual state is a continuous curve in space rather than a short list of numbers.

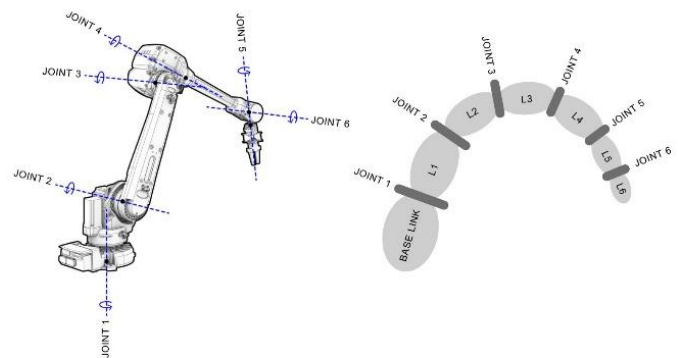


Fig. 1. A rigid manipulator's state is a short list of joint angles at discrete points, while a soft manipulator's state is a continuous curve along the whole body.

This difference has practical consequences at every level of the design process. Because a soft body deforms in response to both actuation and contact, the boundary between the robot and its environment is no longer sharp, and the same compliance that makes interaction safe also makes the robot's shape uncertain. Sensing becomes harder, since conventional encoders cannot be mounted on a continuously deforming body; actuation becomes distributed rather than localized at joints; and the models used for planning and control must trade physical accuracy against computational tractability [8]. These coupled difficulties are the reason that materials, actuation,

modeling, and control cannot be studied in isolation in soft robotics.

A large portion of this field is inspired by biological structures — from octopus arms to the trunks of elephants to various soft-bodied invertebrates, all of which achieve dexterous movements without rigid skeletons [9]. Organisms are able to exhibit sophisticated behaviors as a result of cooperation between muscular hydrostats and a large number of controllable degrees of freedom, all aided by a relatively rudimentary nervous system. This leads to a shift of attention of the engineers working on soft robotics toward the designs that would allow achieving system behaviors without actively calculating numerous parameters, a notion known as morphological computation [10], with mechanical characteristics working in the same way as some of the controller's functions.

Bio-inspiration also explains why compliance is treated as a resource rather than a defect. In a rigid gripper, adapting to an unknown object requires sensing its geometry and computing a suitable grasp; in a soft gripper, the fingers conform passively to the object, and much of that computation is effectively performed by the material itself [11]. Exploiting this effect, however, requires designers to specify stiffness distributions, chamber geometries, and reinforcement patterns with the same care that rigid-robot designers give to link lengths and joint placements.

This review talks about four concepts that appear together in the literature, which are materials, actuation, modeling, and control, and seeks to analyze the trade-offs between them. Since going from a continuously deformable structure to a controllable set of equations is often the most challenging task, the review focuses mostly on control-oriented modeling. The review ends by linking soft robots to the larger discussion on energy-aware control of soft robots since these concepts have already been applied successfully to rigid robots.

The main contributions of this review are threefold. First, it organizes the literature around the four coupled aspects of materials, actuation, modeling, and control. Second, it compares actuation mechanisms and modeling approaches qualitatively in terms of their practical trade-offs. Third, it relates energy-aware gain optimization, an established technique for rigid manipulators, to the control of soft robots. The remainder of this paper is organized as follows. Section II reviews soft materials, fabrication techniques, and actuation mechanisms. Section III covers modeling approaches and the control strategies built on them. Section IV discusses applications, open challenges, and future research directions, and Section V concludes the paper.

II. MATERIALS, FABRICATION, AND ACTUATION

The behavior of a soft robot is determined to a large extent by what it is made of and how it is driven. This section therefore treats materials and actuation together, since the choice of elastomer, reinforcement, and fabrication route largely fixes which actuation principles are practical for a given design.

A. Elastomers and Smart Materials

Silicone elastomers such as polydimethylsiloxane and platinum-catalyzed rubbers are ubiquitous structural materials in soft robotics owing to their high elasticity, mechanical stability, and ease of casting [3]. The mechanics of these materials under loading conditions can be explained using hyper-elastic strain-energy models such as Neo-Hookean, Mooney-Rivlin, and Ogden Models, which were designed to deal with extreme nonlinear deformations of these materials, unlike the simpler small-strain, linear-elastic models for rigid links.

For a nearly incompressible Neo-Hookean solid, the strain-energy density per unit reference volume can be written as

$$W = C_{10}(\bar{I}_1 - 3) + (1/D_1)(J - 1)^2 \quad (1)$$

where $\bar{I}_1$ is the first deviatoric invariant of the right Cauchy–Green deformation tensor, J is the volume ratio, and C_{10} and D_1 are material constants related to the shear and bulk moduli. Mooney–Rivlin and Ogden models add further invariant or principal-stretch terms to capture the stiffening that silicones show at large strains. Platinum-cure silicones used in soft actuators can typically be stretched to several hundred percent of their original length before failure, which is why a single material can serve as both structure and actuator wall [3].

Passive elastomers alone do not define soft robotics anymore; many modern soft robots utilize such materials as active components that can alter their shape and/or stiffness in response to external stimuli. Shape memory alloys and polymers can change their shape when heated; dielectric elastomer actuators change shape when experiencing an electric field; ionic polymer-metal composites bend under an electric field; magnetically active elastomers enable electrically independent movement of devices. Each of these options can provide its own combination of strain, resulting force, response time, and energy consumption so that the best choice turns out to be application-specific.

B. Fiber-Reinforced Structures and Fabrication

In order for a soft actuator to change shape in a specified direction — that is, to bend along some axis rather than simply expand under pressure — it often requires the wall of the actuator to be strengthened by wrapping the fibers, fabric, or other layer that limits strain in the elastomer. The use of the material which has this kind of reinforcement was one of the most common solutions in the development of bending pneumatic actuators [12].

Most silicone soft actuators are still made by multi-part moulding: liquid elastomer is cast into a 3D-printed or machined mould, cured, and then bonded to whatever strain-limiting or reinforcement layers the design calls for. Additive manufacturing — multi-material and direct-ink-writing 3D printing especially — is increasingly used to build soft structures with graded stiffness or embedded channels in a single print, cutting down on assembly steps and allowing internal geometries that molding alone can't easily achieve. Soft lithography and laser cutting round out the toolkit for thin-film devices such as dielectric elastomer and ionic polymer-metal composite actuators.

The fabrication route also determines how reproducible a design is. Small variations in wall thickness, curing temperature, or mixing ratio change the stiffness of a cast actuator, so two nominally identical actuators can respond differently to the same input pressure. This variability is one reason that data-driven models and closed-loop control, discussed in Section III, are attractive in soft robotics.

C. Fluidic and Tendon-Driven Actuation

Fluidic elastomers, which can be pressurized using air or liquid, are widely seen as the most widely used actuating techniques in soft robotics mainly because they are lightweight but efficient, effective and can be easily moulded [13], [14]. A chamber with one stretchable elastomer wall and other strain-relief layer and pressurizing the chamber leads to bending or twisting motion, depending on design and implementation. However, using this process requires a compressor to be installed along with hoses and valves, thus making the process more complicated than with some alternatives and causing slower performance of the fluidic actuators compared to electromagnetic ones.

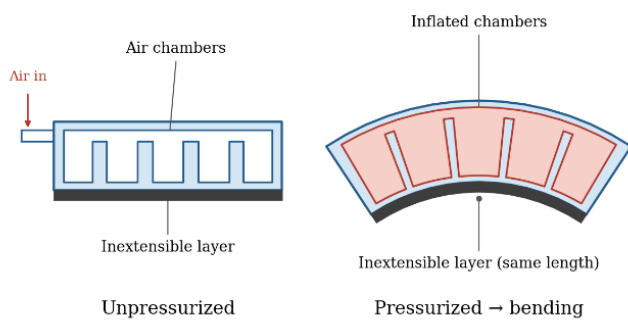


Fig. 2. A fluidic elastomer actuator at rest (left) and pressurized (right). The inextensible bottom layer forces the chamber array to bend rather than simply balloon outward.

The tendon-controlled soft actuators utilize either a single or multiple wires in channels formed inside a flexible backbone; by employing a wire from a motor mounted elsewhere, the design is bent in the direction of the wire. This mechanism is particularly necessary for the soft and surgical instruments, since the weight of the motor is left in a remote location [15].

The two approaches are often complementary. Fluidic actuation distributes force over a large area and produces smooth, conformable motion, while tendon actuation offers higher bandwidth and more precise positioning but concentrates loads at the anchor points along the body. Several continuum manipulators therefore combine the two, using tendons for fast steering and pressurized chambers for elongation or stiffening.

D. Smart-Material and Variable-Stiffness Actuation

Shape memory alloy springs and wires are capable of generating considerable energy from a relatively small unit and operate silently but are slow and ineffective. While resistive heating is fast, passive cooling does not work well. Dielectric elastomer actuators move fast and work well in freed designs; however, they require quite a high driving voltage [16]. Ionic polymer-metal composites require low voltage and can operate underwater or in biomedical applications, but they have low

force output. In real life, the decision depends on the question of which technology to choose based on the bandwidth, operating voltage, duration, and force needed for the respective application.

An increasing number of research has been conducted to link soft actuators with switching techniques that allow one to alter rigidity as necessary. Among the methods are granular jamming [11], low-temperature alloy, and layer jamming. Such actuators have the ability to be compliant and soft throughout the work process, allowing for interaction with the surrounding environment, and then transition to the rigid state while engaging in the process of carrying loads or maintaining the right position.

TABLE I
 QUALITATIVE COMPARISON OF COMMON SOFT-ACTUATION MECHANISMS
 DISCUSSED IN SECTION II

Actuator type	Force	Bandwidth	Driver	Best fit
Pneumatic	Moderate force	Low–moderate	Pump, valves, tubing	Grippers
Tendon-driven	High force, moderate strain	Moderate	Remote motor + cable	Continuum arms
Shape memory alloy	High force density	Low	Resistive heating	Compact
Dielectric elastomer	Low–moderate force	High	High voltage (kV)	Fast
Ionic polymer composite	Low force	Moderate	Low voltage (V)	Underwater

Table I summarizes these mechanisms qualitatively. No single mechanism dominates across all criteria: pneumatic actuators remain the default choice for grippers because of their simplicity and robustness, tendon drives are preferred for continuum arms that must be slender and fast, and dielectric elastomers and ionic polymer composites are chosen where speed or low-voltage operation matters more than force.

III. MODELING AND CONTROL

Modeling and control are closely linked in soft robotics, because the choice of model largely determines which controllers can be applied. Low-order models permit classical feedback design and real-time computation, whereas high-fidelity models capture more of the physics at the cost of speed. This section reviews the principal modeling approaches and then the control strategies built on them.

A. Kinematic and Continuum Mechanics Models

In the case of soft continuum manipulators, the widely acknowledged low-order kinematic model is called piecewise constant curvature (PCC) [5]. It is based on the premise that the sections of the body have a single piecewise constant curvature throughout, which reduces what fundamentally describes an infinite-dimensional configuration into just three parameters of curvature, bending angle, and elongation. Since this makes it possible to calculate forward and differential kinematics using

closed-form equations similar to those employed in rigid serial arms, it is the reason for PCC being frequently employed.

For a single segment with curvature κ , bending-plane angle ϕ , and arc length ℓ , the position of the segment tip relative to its base is

$$p = (1/\kappa)[\cos \phi(1 - \cos \kappa \ell), \sin \phi(1 - \cos \kappa \ell), \sin \kappa \ell]^T \quad (2)$$

and the bending angle is $\theta = \kappa \ell$ [5]. Chaining the homogeneous transformations of successive segments gives the forward kinematics of the full manipulator, in direct analogy with the product of link transformations used for rigid serial arms.

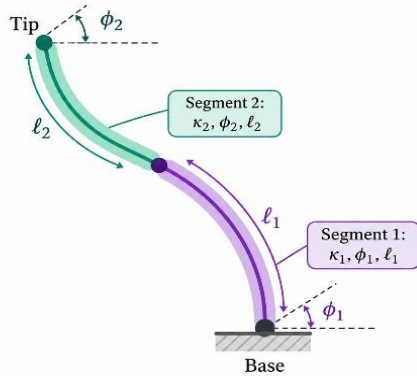


Fig. 3. A two-segment PCC parameterization: each segment is described by a curvature κ , a bending-plane angle ϕ , and a length ℓ .

If PCC fails to provide satisfactory results, appropriate versions of soft continuum media would be represented in form of Cosserat rods instead: one-dimensional curves possessing full cross-sectional pose with six degrees of freedom, defined by nonlinear partial differential equations connecting internal forces and moments, curvature and given loads. What we get is a model which takes bending and twisting, shear and axial coupling into account simultaneously, and also can be applied to underactuated, loaded externally or segmented manipulators as well; but the downside of that approach is that it is heavier computationally than PCC [15].

In the static case, the Cosserat rod equations reduce to the equilibrium conditions

$$\partial n / \partial s + f = 0, \quad \partial m / \partial s + (\partial p / \partial s) \times n + l = 0 \quad (3)$$

where s is the arc-length coordinate, n and m are the internal force and moment, p is the backbone position, and f and l are the distributed external force and moment per unit length. Together with constitutive laws that relate n and m to strain and curvature, these equations form a boundary-value problem that is usually solved numerically by shooting methods [15].

B. Finite Element and Data-Driven Models

The technique of finite element methods divides a complete multi-dimensional elastic body into numerous small elements governed by some hyperelastic constitutive law. This always gives you the maximum precision possible when dealing with intricate actuator shapes, contact scenarios, as well as mixed-material composites. Real-time finite element frameworks – the SOFA framework [17], perhaps the most widely cited – have made it possible to implement model-based control directly on finite element descriptions, although high computational costs

have it reach upper limits in control bandwidth due to the size of the mesh.

Soft body first principle models are challenging to define due to the non-linearities of the material, hysteresis, and the usual variability in manufacturing methods. So newer studies tend to bypass the standard methods in favour of developing a model based on sensor data. This approach has included the use of Gaussian processes, recurrent networks, and physics-informed neural networks. While you lose some interpretability from a physical perspective, you gain the ability to model the behaviour of complex systems that often cannot be modelled using traditional means.

TABLE II
 QUALITATIVE COMPARISON OF MODELING APPROACHES DISCUSSED IN SECTION III

Modeling approach	Fidelity	Computational cost	Typical use
Piecewise constant curvature (PCC)	Low–moderate	Very low	Real-time control, kinematic planning
Cosserat rod	Moderate–high	Moderate	Underactuated / externally loaded arms
Finite element	Highest	High	Detailed simulation, contact-rich tasks
Data-driven / learned	Task-dependent	Low–moderate (after training)	Hard-to-model effects, MPC/RL control

C. Model-Based Control

Control based on models typically uses a model of a robot that has a smaller number of degrees of freedom — usually a PCC or a model based on the Cosserat theory — and through this representation, the manipulation inputs (in terms of actuation) are converted into motion in the operational space by means of the Jacobian. Thus, some feedback schemes developed for rigid-arm manipulators (e.g., proportional-derivative control, computed torque, etc.) have been adapted to flexible arms; however, this mapping is nonlinear, coupled, and affected by the viscoelasticity and hysteresis of the materials used [4].

Under a reduced-order description with configuration vector q , the dynamics of a soft manipulator are commonly written in a form that mirrors the rigid case,

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + Kq + D\dot{q} = A(q)u \quad (4)$$

where M is the inertia matrix, C collects the Coriolis and centrifugal terms, G is the gravity vector, K and D are stiffness and damping matrices that represent the elasticity and dissipation of the body, and $A(q)$ maps the actuation inputs u to generalized forces [8]. The elastic term Kq is the key structural difference from rigid manipulators, and it can be exploited in controller design, since the body has a natural rest configuration to which it returns when the actuation is removed.

D. Model-Free and Learning-Based Control

Because accurate first-principles models are hard to come by for many soft actuators, model-free methods have picked up momentum — online Jacobian estimation, iterative learning control, and reinforcement learning among them [4]. These

approaches learn the mapping from actuation to motion straight from interaction data, which avoids needing an explicit dynamic model, but they generally need a lot of training data and offer weaker guarantees on stability and on generalizing beyond the conditions they were trained under, compared to model-based approaches.

E. Energy-Aware Control and Gain Optimization

Energy efficiency hasn't gotten nearly as much attention in soft robot control as it has in rigid manipulator research, even though it matters enormously for soft platforms that run untethered off a battery or a pump. Rigid computed-torque controllers have long used constrained optimization to tune proportional and derivative gains — minimizing an integral-squared-torque energy cost while staying within a tracking-error tolerance [7] — and soft robotics research is starting to borrow that same idea, exploring pressure or voltage input profiles that minimize actuation energy while still meeting trajectory-accuracy requirements. Given how much energy pneumatic actuation loses to compressor and valve-switching overhead, cutting peak and cumulative actuation effort should produce efficiency gains comparable to what gain optimization has already delivered for rigid computed-torque control.

For a rigid manipulator, the computed-torque law

$$\tau = M(q)(\ddot{q}_d + K_d\dot{e} + K_p e) + C(q, \dot{q})\dot{q} + G(q) \quad (5)$$

where $e = q_d - q$ is the tracking error, linearizes and decouples the closed-loop dynamics, leaving the gain matrices K_p and K_d free to be chosen [7]. Energy-aware tuning selects these gains by solving

$$\min J = \int_0^T \tau^T \tau dt \quad \text{subject to} \quad \|e(t)\| \leq \varepsilon \quad (6)$$

so that the actuation effort is minimized while the tracking error stays within a tolerance ε . Extending this formulation to soft robots requires replacing τ with the physical actuation input, such as chamber pressure or electrode voltage, and accounting for the elastic and dissipative terms that appear in (4).

IV. APPLICATIONS, CHALLENGES, AND FUTURE DIRECTIONS

The trade-offs described in Sections II and III ultimately determine where soft robots are useful in practice. This section reviews the main application areas, the challenges that still limit deployment, and promising directions for future research.

A. Soft Grippers and Manipulation

Soft grippers are probably the most commercially successful soft robotic product so far. They rely on passive conformability to grasp objects of different sizes, shapes, and fragility without needing precise pose estimation or high-gain force control, which makes them a good fit for food handling, warehouse picking, and harvesting produce.

A well-known example is the universal jamming gripper, in which a membrane filled with granular material flows around

an object and is then stiffened by evacuating the air inside it, holding the object without any articulated fingers [11]. Multi-finger fluidic-elastomer grippers are also used in food and logistics applications, where hygiene and the ability to handle irregular, delicate items outweigh the need for a high payload.

B. Medical and Wearable Robotics

Because soft actuators are compliant and generally safe to be near, they suit applications involving sustained contact with the human body especially well — exosuits that assist walking and rehabilitation, pneumatic gloves that help with grip, and soft continuum robots for minimally invasive surgery [18], where a compliant tip lowers the risk of damaging tissue while navigating through the body's internal passages.

Soft robotic gloves, for example, use fiber-reinforced fluidic actuators aligned with the fingers to assist flexion and extension during rehabilitation, and they can be worn for long periods because they add little mass and do not constrain the joints when unpressurized [19].

C. Locomotion and Field Robotics

Soft-bodied locomotion — peristaltic crawling, pneumatically driven undulation, jamming-based rolling — lets a robot get through confined or irregular terrain that would stop a wheeled or legged rigid platform cold, and it's been applied in search-and-rescue, pipe inspection, and early concepts for planetary exploration [13].

A milestone in this area was the demonstration of an entirely soft, autonomous robot that used a microfluidic logic circuit and a chemical fuel in place of rigid electronics and batteries [20]. It showed that untethered operation without any rigid component is possible, although with very limited speed and endurance.

D. Open Challenges

There have been significant advancements in soft robotics; however, they still face several hurdles when it comes to their use in practice. Sensors embedded in soft robots represent a challenge because regular sensors, such as strain gauges and encoders, tend to fail when faced with ongoing disturbance. Other issues involve the reliability of actuators when subjected to strain cycles and the costs of implementing projects involving the use of the soft robots, because each model requires continuous modeling. Furthermore, energy efficiency is key for the field because it will determine whether it is feasible to use soft robots without cables.

Promising sensing approaches include stretchable conductors such as liquid-metal and ionic-hydrogel strain sensors, optical waveguides embedded in the elastomer, and proprioceptive estimation from actuator pressure. Integrating such sensors without stiffening the body or creating new failure points, however, remains difficult.

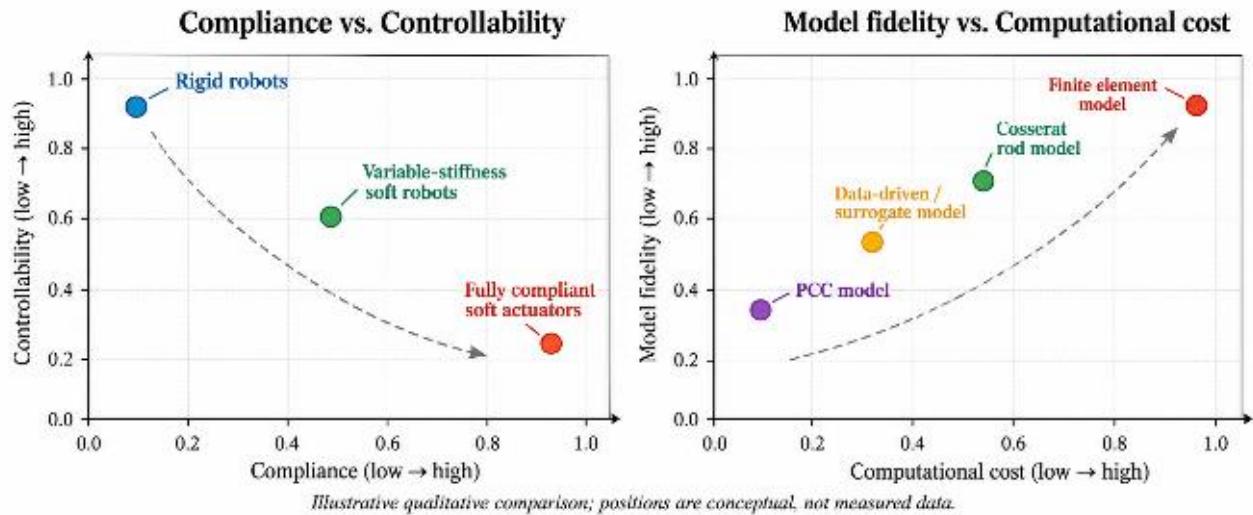


Fig. 4. Two recurring design trade-offs discussed throughout this review: compliance against controllability (left), and model fidelity against computational cost (right). Positions are qualitative, based on the comparisons drawn in Sections II and III.

These trade-offs rarely resolve cleanly in one direction. A platform pushed toward full compliance for safety and adaptability gives up positioning accuracy unless it is paired with a higher-fidelity model, and that model in turn costs more compute than most embedded, battery-powered systems can spare in real time. Much of the current research effort in soft robotics, whether in variable-stiffness hardware or in learned reduced-order models, can be read as an attempt to move a design up and to the left in the charts above — retaining compliance or model accuracy while cutting the corresponding cost in controllability or compute.

E. Future Directions

Several directions appear particularly promising. First, co-design methods that optimize body morphology, material distribution, and controller together could replace the current practice of designing the body first and the controller afterwards. Second, hybrid models that combine reduced-order physics with learned residual terms may offer the interpretability of PCC or Cosserat models with the accuracy of data-driven approaches. Third, self-healing elastomers and more durable bonding methods could address the fatigue and puncture failures that currently limit actuator lifetime. Finally, as discussed in Section III-E, energy-aware control synthesis offers a systematic way to extend the operating time of untethered soft robots, which is essential if they are to move from laboratory demonstrations to field deployment.

V. CONCLUSION

Soft robotics provides a new option compared to traditional rigid-link robotics as, instead of relying on precise and clear kinematics, it utilizes flexibility, suitability, and in-built safety factor. In order to convert these benefits into usable and controllable devices, progress needs to be achieved in several fields: material science, actuator designs, modeling (including reduced-order and data-based modeling) and control theory. Nowadays, despite being superseded by new techniques, most of the control systems are still based on reduced-order kinematics such as piecewise constant curvature; at the same time Cosserat-rod and finite-element methods provide more

accuracy at higher computation costs and machine learning methods fill the gaps in the knowledge left behind. Looking to the future, energy-management synthesis has a good chance of being one of the more important areas for development, as the techniques already applied for rigid robots can be effectively employed for control of soft robots as well.

By organizing the literature around these four coupled aspects and comparing the principal actuation and modeling options side by side, this review aims to help researchers make design choices that are consistent with one another, rather than optimizing each aspect in isolation.

REFERENCES

- [1] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, pp. 467–475, 2015.
- [2] C. Laschi, B. Mazzolai, and M. Cianchetti, "Soft robotics: Technologies and systems pushing the boundaries of robot abilities," *Sci. Robot.*, vol. 1, no. 1, 2016.
- [3] C. Majidi, "Soft robotics: A perspective—Current trends and prospects for the future," *Soft Robot.*, vol. 1, no. 1, pp. 5–11, 2014.
- [4] T. George Thuruthel, Y. Ansari, E. Falotico, and C. Laschi, "Control strategies for soft robotic manipulators: A survey," *Soft Robot.*, vol. 5, no. 2, pp. 149–163, 2018.
- [5] R. J. Webster III and B. A. Jones, "Design and kinematic modeling of constant curvature continuum robots: A review," *Int. J. Robot. Res.*, vol. 29, no. 13, pp. 1661–1683, 2010.
- [6] M. W. Spong, S. Hutchinson, and M. Vidyasagar, *Robot Modeling and Control*. New York, NY, USA: John Wiley & Sons, 2006.
- [7] M. W. Spong, "Computed torque control of robot manipulators," *IEEE Control Syst. Mag.*, vol. 6, no. 4, pp. 13–24, 1986.
- [8] C. Della Santina, C. Duriez, and D. Rus, "Model-based control of soft robots: A survey of the state of the art and open challenges," *IEEE Control Syst. Mag.*, vol. 43, no. 3, pp. 30–65, 2023.
- [9] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, "Soft robotics: Biological inspiration, state of the art, and future research," *Appl. Bionics Biomech.*, vol. 5, no. 3, pp. 99–117, 2008.
- [10] R. Pfeifer, M. Lungarella, and F. Iida, "Self-organization, embodiment, and biologically inspired robotics," *Science*, vol. 318, no. 5853, pp. 1088–1093, 2007.
- [11] E. Brown *et al.*, "Universal robotic gripper based on the jamming of granular material," *Proc. Nat. Acad. Sci. USA*, vol. 107, no. 44, pp. 18809–18814, 2010.
- [12] J. Bishop-Moser and S. Kota, "Design and modeling of generalized fiber-reinforced pneumatic soft actuators," *IEEE Trans. Robot.*, vol. 31, no. 3, pp. 536–545, 2015.

- [13] R. F. Shepherd *et al.*, "Multigait soft robot," *Proc. Nat. Acad. Sci. USA*, vol. 108, no. 51, pp. 20400–20403, 2011.
- [14] J. Faudzi, J. Ooga, T. Goto, M. Takeichi, and K. Suzumori, "Index finger of a human-like robotic hand using thin soft muscles," *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 92–99, 2018.
- [15] F. Renda, M. Giorelli, M. Calisti, M. Cianchetti, and C. Laschi, "Dynamic model of a multibending soft robot arm driven by cables," *IEEE Trans. Robot.*, vol. 30, no. 5, pp. 1109–1122, 2014.
- [16] R. Pelrine, R. Kornbluh, Q. Pei, and J. Joseph, "High-speed electrically actuated elastomers with strain greater than 100%," *Science*, vol. 287, no. 5454, pp. 836–839, 2000.
- [17] C. Duriez, "Control of elastic soft robots based on real-time finite element method," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2013, pp. 3982–3987.
- [18] M. Cianchetti, C. Laschi, A. Menciassi, and P. Dario, "Biomedical applications of soft robotics," *Nat. Rev. Mater.*, vol. 3, no. 6, pp. 143–153, 2018.
- [19] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, "Soft robotic glove for combined assistance and at-home rehabilitation," *Robot. Auton. Syst.*, vol. 73, pp. 135–143, 2015.
- [20] M. Wehner *et al.*, "An integrated design and fabrication strategy for entirely soft, autonomous robots," *Nature*, vol. 536, no. 7617, pp. 451–455, 2016.