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Viewpoint

Designing Soft Robots as Robotic Materials

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INTRODUCTION

The differences between built and biological machines are innumerable. For example, robots struggle to adapt to and engage with real-world environments, whereas living organisms effortlessly do so. Unlike the multifunctional behaviors of living organisms, robots' capabilities possess limited versatility. Living organisms source energy from their environment, while robots face nontrivial power and computational challenges that complicate their remote deployment. The stark performance gap between living organisms and artificial machines arises from their bodies' different material compositions and physicochemical behaviors.[1] Living organisms bypass many shortcomings of modern robots due to their soft matter construction and the distributed nature and complexity of biological sensorimotor systems.[2] Following these lessons from biology, the field of soft robotics has made significant strides in bringing bioinspired capabilities to machines by employing soft materials/structures in robotics design.[3]

Roboticists have historically focused on advancing the computational, or cognitive, side of machine intelligence. Intelligence in living organisms, however, emerges both cognitively and physically.[1,2] Soft robotics represents a new, multidisciplinary frontier for creating physically intelligent machines. Despite much progress—from the design of new soft matter hardware to investigations in morphological computation—the field still faces key challenges in the design, fabrication, and control of soft robots.[3]

Here, a vision is presented for designing soft robots as *robotic materials* to improve their performance. This vision is inspired by recent work in the design of hardware-free soft robots, electrically driven artificial muscles, and sensorized soft machines. Targeted research in robotic materials can lead to a new generation of machines more closely aligned to the likeness of living organisms—especially if engineered to meaningfully bridge the physical *and* computational sides of machine intelligence.

ROBOTIC MATERIALS

A robotic material is a self-contained material system whose form and composition enable multiple, distributed robotic functionalities for actuation, perception, power, and/or control. Robotic materials should bridge the physical and computational sides of machine intelligence to improve the performance, practical use, and autonomy of the agent built from them. Thus, robotic materials are distinct from responsive or "intelligent" materials and most soft robotic components, which are unifunctional.[4] While this Viewpoint focuses on designing robotic materials for soft robotics, robotic materials can be designed from any class of material and for any artificial machine.

Design and Fabrication

Figure 1a provides a materials science and engineering-inspired paradigm for robotic materials. It highlights the interrelationships between the key elements of robotic functionality: actuation, perception, power, and control. A robotic materials approach to soft robotics motivates codesign strategies where compatible actuators, power supplies, sensors, and controllers are made to synergistically work together without limiting the final agent's capabilities. Examples of simple robotic materials include sensorized[5,6] (actuation-perception) and chemically powered[7,8] (actuation-power) artificial muscles, self-powered sensors[9] (perception-power), and soft electro-chemotactic hardware[10] (power-control). Ideal robotic materials exhibit all robotic functionalities in a single material system. A holy grail demonstration would be a truly cognitive, autonomous composite that behaves much like a simple artificial organism.

Robotic functions for target applications are attained by aligning the requisite material properties, structures, and processing methods (Figure 1b). 3D printing is well-suited for fabricating robotic materials, especially multimaterial direct ink writing (DIW), embedded 3D (EMB3D) printing, and digital projection lithography (DPL).[11] We have recently used these methods to spatially and hierarchically program materials for novel actuators,[12−14] sensorized soft robots,[5,15] and hardware-free machines.[7]

Strategies for Integrating Robotic Functions

Designing soft robots as robotic materials requires strategies for integrating robotic functionalities. Promising integration strategies include fluidics, optoelectronics, and electronics. Table 1 lists current and potential robotic material components for each approach and the functions they enable.

Fluidic strategies are most common in soft robotics. Pressurized working fluids displaced via electrically powered pumps are typical energy sources in fluidic actuation.[3] Any sensors and controllers in fluidic soft robots are generally

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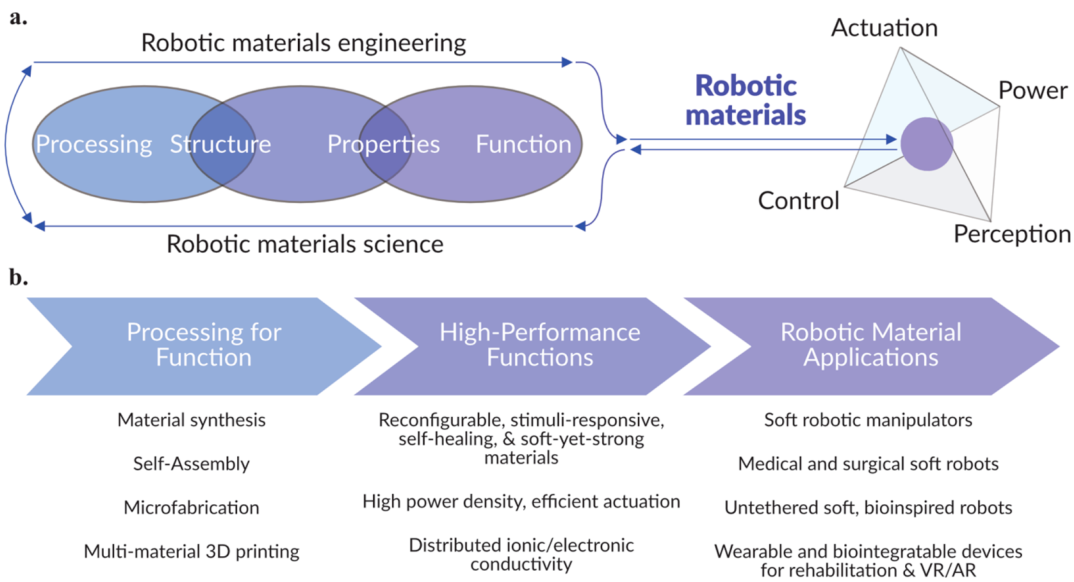

Figure 1. A paradigm for robotic materials design. (a) Inspired by design approaches in materials science and engineering, robotic materials couple robotic behaviors in self-contained material systems through considerations of material processing-structure-properties-function relationships. (b) Opportunities for robotic innovations via robotic materials are illustrated through relevant processing methods for target robotic functions in emerging applications.

Table 1. Integration Strategies in Robotic Materials[a]

integration strategy	energy source	actuation	control	perception
fluidic	electronic power + pump	fluidic (direct)	electronic	electronic
		fluidic (direct)	mechanical or fluidic	mechanical/fluidic components that affect mechanical/fluidic controller
	flow battery + pump	fluidic (direct)	electronic	electronic
		fluidic (direct)	mechanical or fluidic	mechanical/fluidic components that affect mechanical/fluidic controller
	chemical fuel	fluidic or thermoresponsive (indirect)	mechanical or fluidic	mechanical/fluidic components that affect mechanical/fluidic controller
optoelectronic	electronic power + light source	photoresponsive actuators (direct/indirect)	electronic	electronic
		photoresponsive actuators (direct/indirect)	optical logic	photonically active components, optoelectronic
electronic	electronic power	electrostatic, ionic, electrochemical, or piezoelectric (direct)	electronic	electronic
		thermoresponsive (indirect)	electronic	electronic
		motor-driven (direct)	electronic	electronic

[a]For actuation, direct and indirect methods refer to actuation strategies that do or do not require an energy conversion step, respectively.

electronic ones,[3] though fluidic computing and sensing components are emerging.[16] One example of a fluidically integrated soft robot designed as a robotic material is the *Octobot*, a first embodiment of a hardware-free, untethered soft robot.[7] The Octobot sidesteps bulky power and control hardware by using hydrogen peroxide (H_2O_2) as a chemical energy source and a microfluidic controller that autonomously regulates the catalytic decomposition of the fuel. H_2O_2 decomposition into pressurized oxygen and water vapor drives fluidic actuation of the Octobot's tentacles. Although the Octobot does not possess sensors, future versions could employ fluidic sensors like those recently demonstrated in an untethered, turtle-inspired soft robot.[17]

Despite their popularity, fluidic integration strategies face many challenges: fluidic actuators are relatively weak, and tethers to off-board hardware are common in these systems.[3] While advances in chemical fuels[8] and fluidic controllers and sensors[16] are in their infancy, it is unclear how sophisticated robotic materials or soft robots based on these components would actually be. In light of fluidic design challenges, optoelectronic and electronic integration strategies are gaining popularity. These strategies rely on electric power to drive photoresponsive actuation via a light source or actuation of electroactive composites.[4] They are compatible with electronic sensors and controllers, though one can anticipate the emergence of photoresponsive materials for optical logic or sensing in optoelectronic approaches. As with fluidics, (opto)-electronic integration strategies will likely rely on auxiliary power and control hardware for the foreseeable future.

One material driving interest in (opto)electronic approaches is liquid crystal elastomers, which can be designed for optically or electrically stimulated, high-force and large-strain contractile

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actuation.[4] Thermotropic liquid crystal elastomer actuators (LCEAs) readily contract upon heating above a nematic−isotropic transition temperature[4] and can be 3D printed to create artificial muscles with spatially programmed contractile and shape morphing properties.[12] LCEA composites with conductive fillers have recently been developed for Joule-heated actuation in untethered soft robots[18] and sensorized artificial muscles.[6] They are representative of a simple robotic material. Progress in architected materials is also encouraging the field to revisit the use of motor-driven actuation in soft robots. For example, handed shearing auxetics[19] can be 3D printed via DPL to create servo-driven soft actuators that provide the compliance and deformability of fluidic soft actuators without the disadvantages that come with powering them.[14] Continued advances in architected material design and additive manufacturing point to mechanical metamaterials as another interesting avenue for robotic materials.

Robotic Materials for Machine Intelligence

The design, fabrication, and control challenges of soft robotics arguably stem from the field's strong focus on advancing the physical side of machine intelligence. Ideas of programmable stimuli-responsive materials behaving as autonomous machines that use bodily compliance for computation or passive adaptability are compelling. However, sophisticated, truly autonomous machines must also be cognitively intelligent. Cognition requires sensorization and sensory feedback control systems to be integrated within physical agents that can meaningfully interact with their environment.[2]

To address these needs, we are actively focused on sensorizing soft robots through new materials and manufacturing methods. We recently EMB3D printed elastomer-ionogel composites as soft somatosensitive actuators with distributed proprioceptive, tactile, and thermoceptive sensors for manipulation.[5,15] We are simultaneously developing new control strategies for soft robots using feedback from embedded soft sensors[15] and machine learning. We recently used recurrent neural networks to estimate body configuration from a distributed sensor skin of conductive elastomers.[20] Developing new varieties of soft sensorized robots as robotic materials will facilitate the design of autonomous soft machines with appropriate sensor networks and control elements.

■ OUTLOOK

Robotic materials as envisioned here will help close the performance gap between artificial machines and biological organisms that has long motivated roboticists. Concerted interdisciplinary efforts in robotic materials will not only impact soft robotics and related disciplines like micro and biorobotics[21,22] but will also inspire new research directions for material design and processing in materials science and engineering, chemistry, mechanical engineering, and beyond. Short-term efforts will likely motivate the design of new actuators and sensors, though robotic materials should stimulate advances in robotic power and computational capabilities as well. If robotic materials can help us create operator-free machines as autonomous and intelligent as living organisms, then they will herald a future where deployable, bioinspired robots can help us solve countless societal and global challenges.

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Notes

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