MATERIALS ROBOTICS

Will robots be bodies with brains or brains with bodies?

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Biology motivates how complex functionality results from systems of simple materials.

Are robots simply machines that run bits of code, or are they software "bots" interacting with the world through a physical instrument? The material robotics community unravels the basic assumptions behind this question by taking a third path: one that imbues intelligence into the very matter of a robot and removes the dichotomy of brain versus body. Examples of such material intelligence abound in nature. Textured camouflage skin follows the example set by the cuttlefish's ability to blend into its environment (*1*). Spines and structured surfaces inspired by remora suckers lead to strong underwater attachment (*2*). Hearts and colons are autonomous systems that can provide complex functionality like pumping liquids or material support without external control (*3*). Such complexity motivates our research and begs the question: Should it be materials scientists or roboticists that "build" such systems? The answer is both.

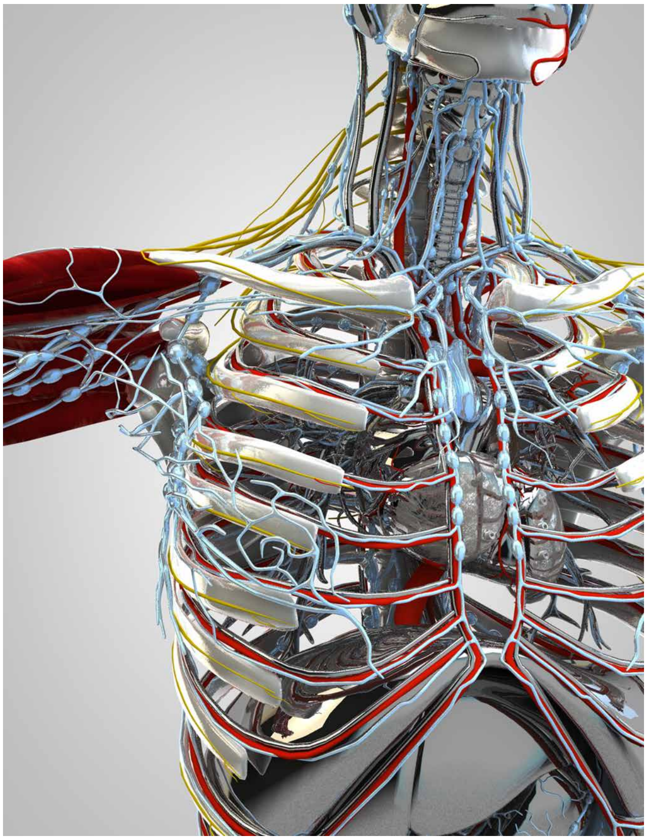

Fig. 1. Material-enabled robotics. A future robot's body may combine soft actuators and stiff structure, with distributed computation throughout.

Because robots are placed in the real world, they must reliably and robustly measure, interpret, and respond to variable environments and physical requirements. Material robotics represents an acknowledgment that materials can absorb some of the challenges of acting and reacting to an uncertain world. The spectrum of possible approaches spans from soft grippers with zero knowledge and zero feedback all the way to humanoids with full knowledge and full feedback (Fig. 1). Embedding distributed sensors and actuators directly into the material of the robot's body engages computational capabilities and offloads the rigid information and computational requirements from the central processing system.

Two distinct approaches remain in creating composite materials that match the complexity of functional biological tissue: new materials synthesis and system-level integration of material components. We acknowledge the immense advancements of materials science, but the challenges in system integration are not merely a technical matter of physically combining distinct materials. There exist new fundamental scientific and engineering questions related to how to fabricate, model, and design the sensing, processing, and actuation materials in a robotic system (*4*). Solving these challenges has the potential to accelerate the distribution of robots into our daily lives by making them more autonomous, physically robust, easier to design, and faster to manufacture (*5*).

GRAND CHALLENGES

Material robotics research represents the vertical integration of simple capabilities at the molecular or microscale enabled by materials science that turn into pragmatic robotic applications at the human scale—a process that we loosely ascribe to five distinct activities: (i) materials synthesis, (ii) mechanical design, (iii) system integration, (iv) sensing and control, and (v) manufacturing.

Examples of materials synthesis include efforts to create novel material capabilities ranging from phase-change actuators and shape memory to biocompatible conductors and biodegradable elastomers. These represent efforts to directly introduce functional components at the material level and are closest in spirit and scope to traditional materials science research.

Mechanical design uses the passive and nonlinear behavior of soft matter to enable capabilities, such as snake-like undulatory locomotion, gripping fingers that can twist, and jellyfish-inspired swimming [see contents of the Material Robotics workshop (*6*)]. The control of these systems can often be markedly simplified by smart mechanical design, a concept also known as "morphological computation." Trading off mechanical design with computation, an idea just emerging in materials science, is deeply rooted in robotics, where mechanism design strongly affects the complexity of the necessary control strategy.

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System integration resembles traditional robotics effort but with notable emphasis on incorporating heterogeneous materials and functionalities (*7*). Prototypical examples of system-level efforts include integrating sensors, computation, energy storage, and wireless communication into substrates such as rubber to enable smart tires and soft grippers capable of identifying the traction characteristics of different surfaces and grasps, respectively. Integration of actuation and sensing and control into elastic polymers and fabrics results in active "skins" that produce locomotion and manipulation behaviors based on the shape of the passive structure that is enveloped (*8*).

Sensing and control represent the processes of controlling new materials' actions. Established techniques of modeling material properties are limited when applied to time- and use-variant materials. We therefore require new materials with tightly integrated sensing and actuation, as well as new approaches leveraging machine learning, to achieve feedback and model-predictive closed-loop control (*9*). The results of these efforts will lead to controllers capable of exploiting material nonlinearity in locomotion of and manipulation by soft-bodied robots.

Manufacturing represents the largest plurality of current research, and considering its prevalence to some degree in nearly every research effort, we consider it a foundational topic in the community. For example, system integration as a topic is strongly coupled to new techniques in manufacturing: Embedding integrated circuit electronics into soft materials addresses manufacturing challenges and necessary mechanical gradations of stiffness. Molding and casting are accessible but require a great deal of skill to create a reliably functional soft robot. Nonlinear material properties such as hyperelasticity and viscoelasticity make small manufacturing defects, such as an inconsistent wall thickness in an elastic membrane, extremely sensitive to operating conditions. New techniques in rapid manufacturing draw heavily from materials sciences to facilitate scientific replicability in robotics. Thus, efforts in three-dimensional printing are great examples of such a collaboration where understanding materials and controls is equally important and can directly facilitate further acceleration of material robotics research (*10*).

THE PATH FORWARD

Material robotics as a field has proliferated in part because of the ease of access to the methods and materials. As a young field being built on the novelty of repurposing technologies, the low barrier to entry has enabled materials scientists and roboticists alike to establish a common foundation. However, we have now established only proofs of concept. The path forward is transitioning these concepts to application context, which will require tight integration of sensing, actuation, and computational functions into materials that embody learning and control. Materials scientists are developing new bulk materials with inherent multifunctionality sufficient for robotic applications. Roboticists are developing new material systems with tightly integrated components. The convergence of these approaches will ultimately yield the next generation of material-enabled robots. We see the burgeoning community as a natural partnership that will lead to robots with brains in their bodies—the foundation of inexpensive and ubiquitous robots that will step into the real world.

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