REVIEW SUMMARY

MATERIALS SCIENCE

Materials that couple sensing, actuation, computation, and communication

M. A. McEvoy and N. Correll*

BACKGROUND: The tight integration of sensing, actuation, and computation that biological systems exhibit to achieve shape and appearance changes (like the cuttlefish and birds in flight), adaptive load support (like the banyan tree), or tactile sensing at very high dynamic range (such as the human skin) has long served as inspiration for engineered systems. Artificial materials with such capabilities could enable airplane wings and vehicles with the ability to adapt their aerodynamic profile or camouflage in the environment, bridges and other civil structures that could detect and repair damages, or robotic skin and prosthetics with the ability to sense touch and subtle textures. The vision for such materials has been articulated repeatedly in science and fiction ("programmable matter") and periodically has undergone a renaissance with the advent of new enabling technology such as fast digital electronics in the 1970s and microelectromechanical systems in the 1990s.

ADVANCES: Recent advances in manufacturing, combined with the miniaturization of electronics that has culminated in providing the power of a desktop computer of the 1990s on the head of a pin, is enabling a new class of "robotic" materials that transcend classical composite materials in functionality. Whereas state-of-the-art composites are increasingly integrating sensors and actuators at high densities, the availability of cheap and small microprocessors will allow these materials to function autonomously. Yet, this vision requires the tight integration of material science, computer science, and other related disciplines to make fundamental advances in distributed algorithms and manufacturing processes. Advances are currently being made in individual disciplines rather than system integration, which has become increasingly possible in recent years. For example, the composite materials community has made tremendous advances in composites that integrate sensing for nondestructive evaluation, and actuation (for example, for shape-changing airfoils), as well as their manufacturing. At the same time, computer science has created an entire field concerned with distributed algorithms to collect, process, and act upon vast collections of information in the field of sensor networks. Similarly, manufacturing has been revolutionized by advances in three-dimensional (3D) printing, as well as entirely new methods for creating complex structures from unfolding or stretching of patterned 2D composites. Finally, robotics and controls have made advances in controlling robots with multiple actuators, continuum dynamics, and large numbers of distributed sensors. Only a few systems have taken advantage of these advances, however, to create materials that tightly integrate sensing, actuation, computation, and communication in a way that allows them to be mass-produced cheaply and easily.

OUTLOOK: Robotic materials can enable smart composites that autonomously change their shape, stiffness, or physical appearance in a fully programmable way, extending the functionality of classical "smart materials." If mass-produced economically and available as a commodity, robotic materials have the potential to add unprecedented functionality to everyday objects and surfaces, enabling a vast array of applications ranging from more efficient aircraft and vehicles, to sensorial robotics and prosthetics, to everyday objects like clothing and furniture. Realizing this vision requires not only a new level of interdisciplinary collaboration between the engineering disciplines and the sciences, but also a new model of interdisciplinary education that captures both the disciplinary breadth of robotic materials and the depth of individual disciplines. ■

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The list of author affiliations is available in the full article online.
*Corresponding author. E-mail: ncorrell@colorado.edu
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(Top) Biological systems that tightly integrate sensing, actuation, computation, and communication and (bottom) the engineering applications that could be enabled by materials that take advantage of similar principles. (From left) The cuttlefish (camouflage), an eagle's wings (shape change), the banyan tree (adaptive load support), and human skin (tactile sensing).

CREDITS: CUTTLEFISH: N. HOBGOOD/WIKIMEDIA COMMONS; BALD EAGLE ALASKA: C. CHAPMAN/WIKIMEDIA COMMONS; BANYAN TREE: W. KNIGHT/WIKIMEDIA COMMONS; HUMAN SKIN: A. MCEVOY; MEN IN CAMOUFLAGE HUNTING GEAR: H. RYAN/U.S. FISH AND WILDLIFE SERVICE; 21ST CENTURY AEROSPACE VEHICLE: NASA; SYDNEY HARBOUR BRIDGE: I. BROWN/WIKIMEDIA COMMONS; CYBERHAND: PRENSILIA S.R.L./PRENSILIA.COM

REVIEW

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M. A. McEvoy and N. Correll*

Tightly integrating sensing, actuation, and computation into composites could enable a new generation of truly smart material systems that can change their appearance and shape autonomously. Applications for such materials include airfoils that change their aerodynamic profile, vehicles with camouflage abilities, bridges that detect and repair damage, or robotic skins and prosthetics with a realistic sense of touch. Although integrating sensors and actuators into composites is becoming increasingly common, the opportunities afforded by embedded computation have only been marginally explored. Here, the key challenge is the gap between the continuous physics of materials and the discrete mathematics of computation. Bridging this gap requires a fundamental understanding of the constituents of such robotic materials and the distributed algorithms and controls that make these structures smart.

Advancements in material science, manufacturing processes, and the continual miniaturization of electronic components have enabled a class of multifunctional materials that tightly integrate sensing, actuation, communication, and computation. We refer to such materials as "robotic materials," analogous to the field of robotics, which combines mechanisms with sensing and control. Unlike conventional stimuli-response materials that change one or two physical properties in response to an external stimulus, robotic materials make the relationship between signals measured from embedded sensors and the material properties activated by embedded actuators fully programmable. Such materials are inspired by the multifunctionality of biological systems and have a wide range of applications, examples of both of which are shown in Fig. 1.

Department of Computer Science, University of Colorado at Boulder, Boulder, CO, USA.
*Corresponding author. E-mail: ncorrell@colorado.edu

For example, inspired by the impressive abilities of the cuttlefish or chameleon (*1*) to change their appearance in response to the environment, various artificial mechanisms, ranging from optical metamaterials (*2*, *3*) to smart composites (*4*), have been proposed. Although these mechanisms have the potential to induce appearance change, few works have attempted the system-level integration of sensing, pattern recognition, and distributed control into a composite material that can actually respond to the environment in the way that animals do.

Morphing aerodynamic surfaces could improve efficiency during different flight regimes, reduce noise, and save fuel. Early designs used mechanical actuators in series that would distort the shape of the wing (*5*–*8*). However, these concepts do not scale: Every additional actuator increases the required load-carrying capacity of all actuators in the chain. This leads to increased weight, which again requires stronger (and heavier) actuators. Robotic materials might alleviate this problem through a tighter integration of sensing, actuation, and control—for example, by combining variable stiffness with bending actuation.

Materials that self-diagnose and self-repair are ubiquitous in biological systems, some of which can adapt to changing structural loads such as human bones or trees that can grow additional roots to accommodate changing load requirements. In an engineering context, nondestructive evaluation (NDE) devices embedded into wings, bridges, and other safety critical systems should make it possible to detect potential problems before they appear while reducing costs for inspection and maintenance (*9*). Combined with actuators, materials could self-repair by releasing chemical agents in the material (*10*), or locally change their stiffness to redistribute loads.

Artificial skins promise to equip prosthetic and robotic hands with tactile sensing that comes close to that of human performance. Existing systems do not yet provide the resolution, bandwidth, and dynamic range of the human skin (*11*). Here, integrating computation into the skin

Fig. 1. Biological systems that tightly integrate sensing, actuation, and controls and the engineering applications that could benefit from a similar approach. (**Top**) Biological systems exhibiting multifunctionality such as the cuttlefish (camouflage), an eagle's wings (shape change), the banyan tree (adaptive load bearing), and human skin (tactile sensing). (**Bottom**) Engineering applications that could take advantage of similar principles, motivating novel materials that tightly integrate sensing, actuation, computation, and communication. Credits: cuttlefish: N. Hobgood/WikiMedia Commons; bald eagle Alaska: C. Chapman/WikiMedia Commons; banyan tree: W. Knight/WikiMedia Commons; human skin: A. McEvoy; men in camouflage hunting gear: H. Ryan/U.S. Fish and Wildlife Service; 21st century aerospace vehicle: NASA; Sydney Harbour Bridge: I. Brown/WikiMedia Commons; cyberhand: Prensilia S.R.L/ Prensilia.com

can alleviate the bandwidth requirements of high-resolution, high–dynamic range sensing by preprocessing and help to discern task-relevant information from background noise.

Creating robotic materials that address the above applications with seamlessly integrated, mass-produced products will require advances in material science and manufacturing. However, macroscopic robotic materials with useful functionality can already be realized with existing materials and processes. Examples shown in Fig. 2 include an amorphous façade that recognizes a user's input gestures and responds with changes in its opacity and color (*12*), a dress that can localize sound sources and indicate their direction using vibro-tactile feedback (*13*), a shape-changing variable stiffness beam (*14*), and a robotic skin that senses touch and texture (*15*).

High-value applications such as airfoils, prosthetics, and camouflage might be among the first to find favorable trade-offs between added functionality and increased cost, weight, and inferior structural properties of embedding sensing, actuation, and computation. In the long run, solving system integration and manufacturing challenges that are common to robotic materials, and therefore reducing the cost to make them, might enable a new class of smart everyday materials: dinner tables that selectively keep dishes hot or cold by locally sensing the presence of objects and their initial temperature and then controlling appropriate actuators; insoles that measure pressure and locally change their cushioning to adapt to fatigue of their wearer; or print magazines that use semiconducting ink to implement computation, capacitive sensing, and light emission to print video games or movie previews on their back.

Background

An early vision of smart materials with embedded, networked computation are networks of microelectromechanical systems (MEMS) (*16*). MEMS allowed for the manufacturing of microscale structures with the same processes that are used for making conventional analog and digital semiconductor circuits, permitting their tight integration. An example of a mainstream MEMS device is an accelerometer that consists of a cantilevered beam with a small mass and circuitry to measure its displacement during acceleration, and can easily be mass-produced. Whereas (*16*) emphasizes the use of MEMS for creating high-density sensing arrays and proposes the concept of "smart dust," tiny MEMS sensing devices that could be deployed in large numbers and carried away by the wind, this vision is extended by (*17*) to millimeter-scale units that can locomote by themselves, allowing the resulting structures to reconfigure and form "programmable matter."

In addition to the material science challenges, such a vision poses a series of deep challenges in networking and computation, which has inspired two active fields, namely, sensor networks and amorphous computing. Amorphous computing (*18*) has laid the foundation for computation in large-scale distributed systems in which individual computing elements can be unreliable and do not need to be manufactured in a precise geometrical arrangement. Hardware demonstrations that came out of this movement include "paintable computing" (*19*), a distributed system of locally communicating nodes that used gradient information to display lines and simple characters; pattern formation in bacterial colonies that are receptive to chemical gradients and can be designed to act as simple high-, low- and band-pass filters (*20*); and a modular robotic (*21*) system that can adapt its shape to the environment via local sensing (*22*). At the same time, the sensor network community has begun to explore the foundations of networking and routing in these systems (*23*), although focusing almost exclusively on geospatial sensing applications rather than integrating sensor networks into materials.

The vision of materials that can change their physical properties has also been explored in the context of designing new interactions between computers and people. "Tangible bits" (*24*) or "radical atoms" (*25*) promote the idea of presenting information in physical form, not limited to pixels. This concept has found physical implementation in "pushpin computing" (*26*), which seeks to engineer additional layers of information in everyday objects such as push pins and floor tiles, and a series of works that involve interaction with materials that change their physical properties such as stiffness (*27*), physical extension (*28*), or weight (*29*). As such, these works explore a series of applications as well as their enabling principles, but leave their implementation in systems or products to science and engineering.

Distributed MEMS, the related concepts it helped spawn, and modular robotics emphasize the system-level integration of sensing, actuation, computation, and communication, but fall short in addressing the structural properties of the resulting systems. The structural properties of a composite are an integral part of "multifunctional materials," a field that traditionally aims to optimize design by addressing both structural (e.g., strength and stiffness) and nonstructural (e.g., sensing and actuation, self-healing, energy harvesting) requirements of a system (*30*), but largely ignores the opportunities

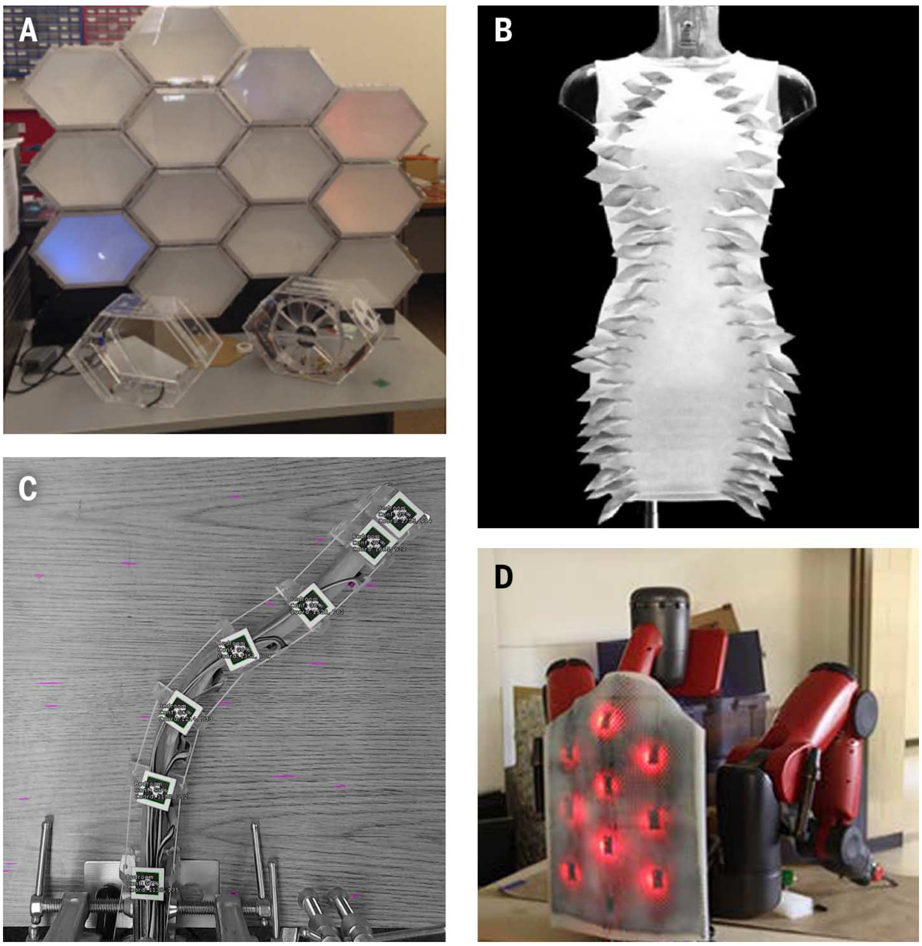

Fig. 2. Examples of robotic materials that combine sensing, actuation, computation, and communication. (**A**) An amorphous façade that recognizes gestures and changes its opacity and color (*12*); (**B**) a dress that can localize sound sources and indicate their direction through vibro-tactile feedback (*13*); (**C**) a shape-changing variable stiffness beam (*14*); and (**D**) a robotic skin that senses touch and texture (*15*).

of integrated computation that have been articulated by (16, 18, 31). Multifunctionality at the nano- and microscale has also been studied in physics in the context of metamaterials. Metamaterials are "macroscopic composites having a man-made, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation" (32). Metamaterials classically exploit the frequency properties of structures to deflect optical waves in nonnatural ways, but the above definition allows a broader interpretation, both in terms of the constituents of individual cells and their scale, making it applicable to some of the computational systems discussed here.

The physical properties of the material itself affect not just sensing and actuation, but also computation. Indeed, material dynamics allow one to shift classes of computation such as feedback control (e.g., by exploiting thermal or chemical deformation to regulate a process), rectification [e.g., to compensate for motion parallax in an insect's eye (33)], or transformation of a signal into the frequency domain (e.g., in the cochlea in the inner ear), by simply tuning the geometry and material properties of a structure. This effect is known as "morphological computation" (34) and has become an important aspect of the design of robotic systems.

Constituent parts of robotic materials

Robotic materials consists of sensors, actuators, computing, and communication elements. While these terms are very broad, this section focuses on elements that have been developed, or are suitable for, integration into composites, and have the potential to enable robotic materials with novel, unprecedented functionality.

Sensing

Classical stimuli-response materials "sense" their environment in that they change some of their properties in response to one or more external stimuli, including acoustic, electromagnetic, optical, thermal, and mechanical. Robotic materials integrate dedicated sensors that, in combination with appropriate signal processing, let the composite identify and respond to environmental patterns of arbitrary complexity, limited only by available sensors and computation. An example of complex signal processing that can be accomplished in a robotic material is to sense and localize textures that touch an artificial skin (15) (Fig. 2D). This artificial skin is made by distributing nodes throughout a silicon-based material. Each node is equipped with a microphone and can analyze the high-frequency sound signal generated by a texture rubbing the skin. Local communication between nodes allows the position of the touch to be triangulated. Once triangulated, the node closest to the source analyzes the material and classifies it. With this approach, the nodes sample and process high-bandwidth information locally and then route high-level information back to a central computer only when important events occur. This example, using embedded MEMS microphones, lends itself to many related material-centric applications such as sound localization (13, 35), vibration analysis (36, 37), or—when combined with piezo actuators—structural health monitoring (9, 38–40).

Similarly, accelerometers can detect impacts (9) or determine orientation of a robotic material with respect to gravity. Capacitive touch sensors (11) can be embedded into the surface of a robotic material as input devices. Optical sensors such as color sensors, infrared sensors, or photoresistors can measure ambient light levels for camouflage applications. Thermistors would allow robotic materials to measure temperature of either the environment or the material itself at high resolution (41, 42). Mechanical sensors that measure applied force (43, 44), strain (45, 46), or deflection (47) can monitor the flow over an aerodynamic surface and monitor its shape change as it morphs into an optimal shape.

Most of the sensors discussed above have been developed for, or are at least suitable for, operation while embedded in a material. Deploying such sensors in large numbers and at high densities requires, however, solving problems in system integration, which can partly be alleviated by colocating those sensors with computing elements to preprocess and network information, as discussed below.

Actuation

In a robotic material, actuation refers to changing the material properties of the underlying base material. Some possible actuations are expanding, contracting, changing stiffness, changing surface texture, or changing color (Fig. 3), while possible actuators include heat, electricity, light, magnetism, or the release of chemicals.

Variable stiffness actuators have received attention as the basis for morphing airfoils and active vibration control, resulting in a large number of actuators that are potentially suitable for use in robotic materials. One common approach to variable stiffness is sandwiching a thermoplastic between two metal plates (48, 49) and then exploiting the thermoplastic's change in stiffness with increasing temperature. When the thermoplastic is at a low temperature, the metal plates are tightly coupled together, acting as a single stiff composite. At higher temperatures, the thermoplastic has much less resistance to shear and the plates act as if they were uncoupled from each other, creating a composite with a much lower stiffness. A similar approach is shown in (50, 51), which segments the rigid layers and uses a shape memory polymer (52) as the sandwich layer. Instead of melting, friction between plates can also be altered pneumatically. In (27), a number of sheets are inserted into a vacuum bag, which remains extremely flexible until a vacuum is applied and the deformed shape is locked in place. Similarly, particle jamming (53) is a technique where a granular material is encased in a very flexible material. When pressed against an object, the granular material conforms to the object's shape. Evacuating the case causes the material to contract and harden, pinching the object.

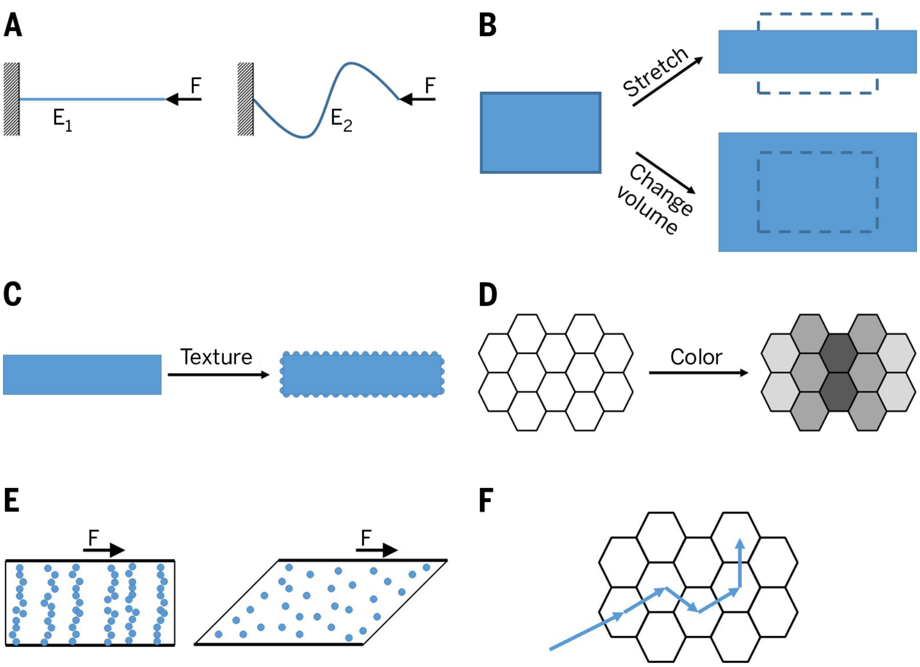

Fig. 3. The in situ actuators of a robotic material work to change the material properties of the base material. Changes in (**A**) stiffness and (**B**) volume could enable shape-changing robotic materials. Robotic skins could utilize changes in (**C**) appearance and (**D**) surface texture. Self-healing and self-regenerating robotic materials could use venous systems enabled by (**E**) variable viscosity fluids or (**F**) the rerouting of the healing compounds through the material.

Simply changing the stiffness of a material, however, will not result in a shape-changing material; actuation forces must be applied to the material to initiate the change. Recent advances in the development of artificial muscles might make their large-scale integration into robotic materials feasible. An artificial muscle made from fishing line or conductive sewing thread is described in (54). The artificial muscles are created by twisting the threads until they start to coil up on themselves. The stroke and actuation force can be tuned by changing the weight used when coiling the thread, using multiple coils, or by coiling around a mandrel. Shape memory alloys have been used in many artificial muscle applications (55). Typically nickel-titanium or copper-aluminum-nickel alloys, shape memory alloys can change from a deformed shape back to their parent shape when heated above their transition temperature. Shape memory alloy actuated joints were used in a fabricated bat wing (56) and in origami-inspired robots (57), demonstrating how artificial muscles could be embedded into a robotic material. McKibben actuators are pneumatic artificial muscles that are light weight, flexible, and can achieve large displacements (58–60). McKibben actuators place an inflatable bladder inside of a woven mesh. When the bladder is inflated, the diameter of the woven mesh expands while the length contracts. Efforts to miniaturize these devices are reviewed in (60), while (59) presents a McKibben actuator that makes use of shape memory polymer to maintain the actuator's displacement without continuous control, demonstrating how a robotic material could use both variable stiffness materials and artificial muscles to achieve shape change.

Pneumatic and hydraulic systems that create volumetric changes have been extensively used in soft robots and could be implemented in a robotic material to create distributed volumetric changes for shape-changing and morphing applications. Chambers embedded into a soft elastomer can be filled with fluid or air, causing the elastomer to expand and change its shape. This effect has been used for locomotion in (61–64) where soft robots are able to crawl, roll, swim, and bend into an arbitrary two-dimensional (2D) configuration, respectively. A challenge of pneumatic and hydraulic robotic materials is not only pressure distribution, but also the requirement for possibly large numbers of miniature valves. A miniature electrorheological fluid based valve (65) or a miniature latchable microvalve based on low–melting point metals (66) could be embedded into such robotic materials and enable the control of fluidic channels in a self-healing composite (10) or the control of embedded fluidic channels for camouflage and display in soft robots (4). Here, the soft robots are designed with microfluidic networks that can be filled with colored, temperature-controlled fluid to change their appearance in both the visible and infrared spectrum.

Volumetric change can also be influenced by the construction of the base material itself. In a cellular material, changing the geometry allows designs with different Poisson ratios (67). This also allows large changes in a material's area or volume; for example, (68) describes geometries that are allowed to buckle in local regions, drastically reducing their surface area. Similar to sensors for robotic materials, the acutators discussed here lend themselves to implementation in large numbers and parallel operation. Furthermore, computation might overcome integration challenges by reducing communication requirements due to local control.

Local computation

Although it might be possible to route actuation signals and sensing information in and out of the material to where this information is processed centrally, this approach becomes increasingly difficult with both the required bandwidth and the number of sensors and actuators to be embedded. A system such as the sensing skin (15) illustrates this difficulty with respect to sensing, a shape-changing material such as (14) with respect to actuation, and the smart façade with respect to a combination of both. Routing vibration signals sampled at 1 kHz becomes increasingly difficult when the number of sensors increases. Instead, when computing information locally, only selected information needs to be transferred outside of the material. In the shape-changing material (14) that controls local stiffness by melting, temperature readings are only used locally for feedback control and are not needed outside of the material. Therefore, the desired stiffness profile needs only to be sent once and can then be controlled locally. Finally, a facade whose transparency and color can be adjusted by a user does not need to disseminate sensed gestures through the system, but only the resulting actuation command that the user intends.

Algorithms that run on a robotic material must have the following properties: (i) They must scale as the material grows in size; (ii) they must be able to run with the limited computation and memory resources provided in each node; and (iii) they have to be robust with respect to the failure of individual nodes. A necessary condition for scalability is to limit information exchange to local communication, and algorithms that run in constant time, independent of the size of the network, are known as local algorithms. An overview of such algorithms is presented in (69, 70) in the context of wireless sensor networks. These local algorithms are used to determine conflict-free sets of activities, such as simultaneous data transmissions, by using matching, independent sets, and coloring algorithms, which are important primitives in higher-level distributed algorithms. One major limitation of the algorithms discussed in (69) is that they assume synchronous communication, which creates additional overhead; see, e.g., (71).

From a computational perspective, robotic materials can be viewed as an amorphous (18) or spatial computer (72), which attempt to formalize a distributed computation model for systems that are limited to local communication and limited computational resources at each node. A key challenge in amorphous computing is how to design local interactions so that a desired global behavior can emerge. One approach to address this problem is using programming languages that provide abstractions that allow one to describe desired global behaviors and then automatically compile the corresponding local rules. What programming paradigm (i.e., procedural or functional) is most conducive to programming large numbers of distributed computing elements remains an open question, and (72) provides a comprehensive survey of the field.

Designing distributed algorithms and solving the global-to-local challenge are hard problems. Their solution is not on the critical path for large-scale deployment of computing infrastructure into robotic materials, which might benefit from enhanced signal processing, local control, and networking, all of which are established fields.

Local communication

Robotic materials require embedded communication not only to transport sensing and control information, but also for more complex spatial dynamics to emerge. The key challenge for transporting data is that point-to-point connections from sensing locations to a central processing unit quickly become infeasible owing to the large number of cable crossings, the effect of embedded wiring on the material's structural properties, or radio-frequency challenges. The local computation in robotic materials offers not only local preprocessing of sensing information, but also the routing of information through a computer network; i.e., a shared communication channel that is arbitraged by all participants of the network, a problem that has been widely studied in sensor networks (73, 74).

Local computation becomes particularly interesting when individual processing nodes can access information from neighboring nodes via local communication. Some example robotic materials that take extensive advantage of this feature are distributed gesture recognition in an amorphous façade (12), where local communication is used to pass tactile sensing events along the physical path where they occur; texture identification in a robotic skin (15), where local communication allows triplets of nodes to triangulate the location of a vibration event by comparing local measurements; and distributed sensor-based control of a rolling robot (62), where local communication is used to infer the overall orientation of the material with respect to the ground.

The speed of communication through a robotic material has a notable effect on the performance of the robotic material. For example, a robotic skin that touches a hot surface needs to process and route that event quickly through the material, and might forgo the processing and forwarding of high-bandwidth texture information. In addition to actual bandwidth, communication speed is also highly dependent on the network topology (75) and node density (76), which leads to important design considerations in robotic materials, as density and topology affect not only the computational properties of the system, but also its structural properties. Finally, tighter integration of future robotic materials, consisting of possibly millions of tiny computing elements, might require a departure from traditional networking and routing algorithms, necessitating solutions that trade-off performance with memory (77) or computational (78, 79) requirements.

There are only a few works that address hardware implementations of wired communication infrastructure embedded into materials. Various robotic skins use hierarchical standard industry bus-systems, which, however, scale poorly both with respect to bandwidth as well as to the total number of nodes that the system can support (11). A distributed optical sensor network built into multifunctional materials that allows the distribution of both power and information for structural health monitoring applications is described in (80). Here, the use of optical wave guides that can transport both power and information has the potential to minimize impact on structural properties, but is limited in the power density that it can achieve. In practice, combinations of peer-to-peer wired communication and long-range, high-bandwidth backbones using wired buses or wireless links might allow a robotic material to maintain both scalability and overall throughput.

System integration and manufacturing

Being able to integrate sensing, actuation, computation, communication, and power infrastructure into composites at high densities in a scalable fashion is a key challenge in making robotic materials viable. This challenge is illustrated in Fig. 4A, which shows a block of the amorphous façade and the robotic skin before embedding in rubber, providing a glance at the different manufacturing and integration steps these systems require. Yet, turning the amorphous façade prototype (12) shown in Figs. 2 and 4 into a composite material that looks like glass to the naked eye, but can change its opacity and integrates high-resolution sensing to interact with its user, could be accomplished by layering existing technology such as liquid crystal sheets, organic light-emitting diodes, and silicon-based analog electronics. Similarly, a single element of a texture-sensitive skin (15)—computation, analog electronics, and MEMS microphone—is small enough to fabricate in dense arrays on a soft, stretchable substrate that would seamlessly integrate with robotic systems. A key challenge here is that the scales of the individual computational nodes and that of the resulting robotic material vary by multiple orders of magnitude. Current manufacturing techniques for nano- and microscale manufacturing do not scale well to create systems at the meter scale, and vice versa.

If the required sensing and actuation can be reduced to a single integrated system, CMOS and MEMS processing techniques can be used to create highly stretchable sensor and actuator networks such as those of (81, 82). Such a system is illustrated in Fig. 4B, which shows a network of temperature sensors that can be embedded into a fiber composite. In (81), piezo sensor and actuator arrays that can be used as sensors for structural health monitoring were screen printed and then deposited onto a polyimide layer. In both systems, the interconnects are made in a spiral spring-like shape so that they can stretch to cover an area that is orders of magnitude larger. These approaches are currently limited by the number of interconnect wires that can be run in parallel while preserving the high degree of flexibility and also by the feasibility of creating complex circuits that require a variety of base materials.

Instead of silicon-based computation, robotic materials could also perform computation using polymer electronics (83). Although a series of computational devices have been demonstrated with ink-jet printing (84), this technology has reached only a few mainstream applications because of the large size, low speed, and poor yield of the resulting circuits. While these challenges limit the use of polymer electronics in conventional computing applications that require millions of transistors to function in concert, they do not apply to a distributed computing system in which each computational element performs a limited number of functions.

The integration of rigid components into a soft flexible substrate is also an active area of study. Silicon-based materials, as well as other elastomers, do not bond well with many materials. Embedding of components into such materials requires perforation of the material (62) or attaching the rigid components to an embedded mesh (15). Alternatively, rigid components can be integrated into soft substrates by embedding them into substrates with gradually decreasing stiffness (85). A promising approach to integrate electronic components into solid materials of arbitrary shapes comes from the local functionalization of a base polymer so that a copper solution adheres to the surface (86). The resulting structural part with embedded copper traces can then be populated in a modified printed circuit board assembly machine.

Electromechanical components, printed circuit boards, and interconnects can also be integrated by shape deposition manufacturing (87). In this process, placeholders for parts or interconnects are subtracted from the base material. Once the components have been placed, they can be embedded into the structure by adding another precision machined layer. Another approach to create structural parts with embedded interconnects is 3D printing with conductive carbon-infused ABS (acrylonitrile butadiene styrene) or PLA (polylactic acid) filaments (88). However, this approach is currently limited by the high electrical resistance of the filaments. Finally, multifunctional materials can be manufactured by layering composites from which

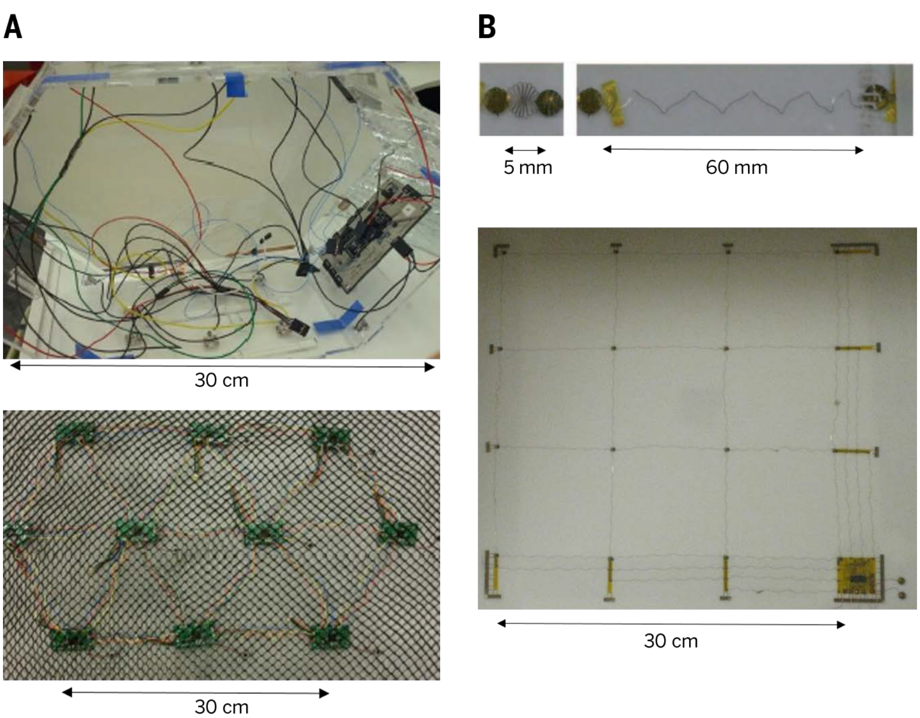

Fig. 4. Macroscale and microscale manufacturing techniques for robotic materials. (**A**) The inside of the amorphous façade (12) (top) and the texture-sensitive skin (15) (bottom), both consisting of discrete printed circuit boards, wiring, and structural materials. (**B**) A network of temperature sensors for embedding into a composite from (82). The micromanufactured structure is produced by semiconductor manufacturing techniques and is then stretched by an order of magnitude.

unneeded pieces are removed by laser cutting, before another layer is added. Together with folding, this approach allows articulated, miniature 3D objects to be mass-produced (*89*).

Because power and interconnections between nodes must already be embedded into a robotic material, actuators that require only electric current promise to be the easiest type of actuator to embed. Hydraulic and pneumatic actuators, along with electro- and magnetorheological fluids and low–melting point alloys, are much more challenging to embed owing to the fluidic channels that must also be incorporated into the material, usually requiring the combination of molding and embedding of parts such as valves (*62*).

Despite the large selection of available sensors and actuators, the lack of automated manufacturing techniques that can bridge the micro and macro scales is a key challenge to achieving robotic materials that are economically viable. Solving these problems might require advances not only in processing techniques, but also in automation and robotics in order to better integrate the existing techniques described above.

Control of robotic materials

Robotic materials require control at two different levels: (i) local control of each actuator, either in open or closed loop using feedback from an appropriate sensor and/or state information from neighboring controllers; and (ii) global control that implements a desired spatiotemporal pattern across the material, either in a distributed or centralized manner. For example, to achieve shape change in (*42*), the material embeds a thermistor, power electronics, and a small microcontroller colocated with each heating element to implement feedback control of a precise temperature across a bar to vary its stiffness by melting. In (*14*), a global controller then solves the inverse kinematics of a beam with many such variable stiffness elements in series to achieve a desired shape, and disseminates appropriate stiffness values into the robotic material where they are controlled by local feedback. An example of local control that requires neighborhood information is the rolling belt from (*62*), where a state transition from deflated to inflated to induce rolling motion is a function not only of the local sensor, but also of those to the left and to the right of each controller.

These type of controllers pose two fundamental challenges: (i) Designing controllers requires a fundamental understanding of the material dynamics, e.g., how they heat, deform, or change appearance as a function of energy provided and time; and (ii) understanding how large numbers of distributed controllers interact. Both of these problems are further complicated by the fact that the dynamics of the underlying physics are continuous, whereas the computational aspects of the system are discrete. This is illustrated in Fig. 5.

There are two approaches to making these systems analytically tractable: discretizing the material by describing it as a lumped element model or maintaining its continuous properties by modeling it as a distributed parameter system. Lumped element models of mechanical systems can be solved relatively easily—e.g., by using variational integrators (*90*, *91*)—whereas distributed parameter systems require solving partial differential equations (PDEs). Assuming that the distribution of the computing elements is quasi-continuous—consistent with the amorphous computing paradigm (*18*)—allows part of this burden to be moved into the material itself and permits the individual computing elements to each solve parts of the relevant PDEs (*92*).

Despite the large body of work on the control of large-scale distributed systems, many of which are relevant to the control of robotic materials (*93*, *94*), only a few of these approaches have been explored experimentally owing to the absence of systems that provide access to thousands of sensors and actuators. In addition to providing the ability to implement distributed control inside the material, robotic materials also offer the possibility of predicting their own dynamics, which is an important capability in a distributed model-predictive control framework (*95*).

Education

Understanding robotic materials requires an interdisciplinary systems perspective, which is currently not provided by materials science, computer science or robotics curricula alone. While the lack of a common language is a recurrent challenge in interdisciplinary fields, the discrete nature of computation and continuous nature of material physics share almost no common concepts and do not provide a smooth transition such as exists between biology and chemistry, material science and physics, or even biology and physics. A possible way to introduce system-based thinking that spans both the computational and physical is by hands-on, introductory engineering courses (*96*). By providing students with the basic skills of rapid prototyping, embedding computation (e.g., via the Arduino platform), and materials knowledge, and tasking them to design a robotic material that combines sensing, actuation, and computation, the students can be led to think about how material properties affect computation and vice versa. For example, when designing a cell phone cover that changes its color using thermochromic polymers and embedded thermistors and heating, students can choose to either deepen their understanding of the feedback control aspects of the system or the relationships between energy, volume, and heat of the material. Graduate classes on robotic materials could follow a similar format, bringing together students with expert knowledge in the various subdisciplines.

Conclusion

Robotic materials are a new class of multifunctional materials that are enabled by recent advances in material science, electronics, distributed computation, and manufacturing. Although composites now include the ability to sense damage or self-repair, for example, none of the state-of-the-art composites fully integrate sensing, actuation, computation, and communication.

Of the applications highlighted, many would substantially benefit from integrated distributed computation. In general, decentralized computation is critical when either the required sensing bandwidth is high or when the material requires high-speed feedback control. In both cases, routing of information to a central processing system quickly becomes infeasible. These problems are common to seemingly unrelated applications such as camouflage or morphing airplane wings, which are currently being investigated by disjoint communities.

Although a number of manufacturing processes for robotic materials exist, ranging from deposition to folding, robotic materials will require vertical integration of a number of these processes. Additional challenges include programming techniques that synthesize low-level code from a high-level, emergent behavior provided by the designer, and creating interfaces between disciplines that allow experts from currently disjoint disciplines to address common system challenges. If these challenges can be overcome, robotic materials will lead to robotic systems with unprecedented sensitivity and adaptivity that address applications from shape-changing airplane wings to sensitive prosthetic devices.

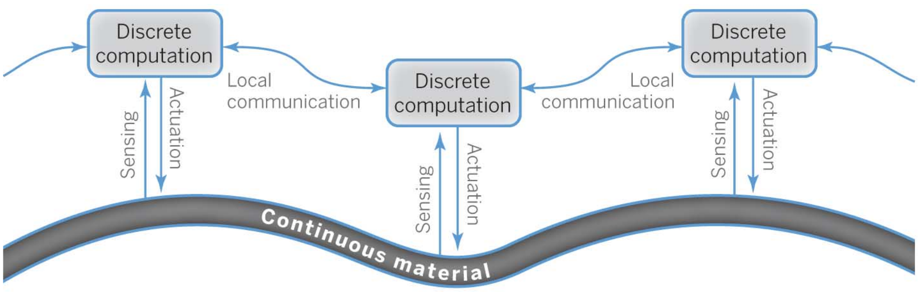

Fig. 5. Relationship between cyber and physical components of a robotic material. Continuous material properties can be sensed, processed in a computing element, and actuated upon. Whereas sensors, actuators, and computing elements are at discrete locations and can communicate locally, the material itself provides continuous coupling between sensors and actuators at different locations.

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