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The new material science of robots

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A B S T R A C T

Robots have been built to accomplish specific tasks with high repeatability instead of general utility. Taking inspiration from the evolution of animals to survive and adapt to changing environments, we discuss how a bottom up approach that begins with new materials could lead to robots that may address needs for autonomy and general utility across industries.

Robotics is evolving to play an increasingly impactful role in our society. For more than 70 years, the field of robotics has been dominated by mechanical engineering, computer science, and electrical engineering. With a top-down approach, robot designs have been guided on the system level by the integration of technologies developed for other tasks. These efforts have yet to produce robots capable of general utility, instead they are produced to perform limited functions numerous times. For example, most industrial robots are designed to handle objects of specific shape, weight, and size for a specialized task of assembly, welding, packaging and labeling or palletizing. While actions with high repeatability and accuracy are useful for manufacturing plants, in many robotic applications where a high level of uncertainty and multiple task goals are involved, such as exploration of unpredictable environments and domestic and medical applications with close human-robot interaction, robots that can adapt to changing environments and perform multiple tasks have seen much slower advancement. To break this mold, a historical perspective could provide guidance: most disruptive technologies are established from the bottom-up, enabled by breakthroughs on the material level. For instance, the advances of a single class of material for computation—n- and p-doped silicon—gave rise to the creation of microprocessors, leading humans into the digital age. Robotics, using a similar materials-centric and bottom-up approach have the potential to unleash functions previously unattainable. In this paper, we discuss how the new material science of robots have introduced novel concepts and unprecedented functions in the actuation, sensing, and control of a robotic system.

The new material science of robots comes at a time when a global pandemic is further accelerating the need for autonomy in manufacturing, healthcare, supply chain management, and many other aspects of our lives. At issue in the adoption timeline of robots is the need for extreme customization for highly specific tasks; generally useful robots are few and unimpressive compared to alternatives. For example, universal industrial robots that can handle a variety of objects for multiple tasks are still in their infancy; search and rescue robots that could navigate harsh environments, gather information, find and rescue survivors have yet to be seen; domestic robots still have a long way to go from autonomous vacuums to robotic butlers. As animals must routinely adapt to changing circumstances for survival, biology provides a materials guideline for what could comprise generally useful robots. An example of how totally different the material composition of our metal or plastic machinery is compared to organisms can be seen in the large percentage of their mass devoted to compliant materials. The fraction of bone mass to total body mass for land mammals ranges from 6% for the smallest mammals to ~27% for elephants with humans at 12%; birds have similar fraction to land mammals at the same weight from 6% for the smallest birds to 8% for the heaviest flying birds; marine mammals also have similar bone mass percentage with 8% for the smallest dolphins to ~18% for the Blue Whale (>100 ton total body mass) [1,2]. These materials of the animal kingdom, stiff or soft, are arranged in groups of organs which perform multiple functions (e.g., the heart pumps energy, removes waste, and thermally regulates the body) in coordination with one another for a goal of species level survival. Survival is, therefore, a multi-objective function towards endurance and adaptability.

The catalog of exciting materials that have been applied to robotics has only recently been expanded to those of organic chemistry; however, even in this nascent state, the resulting embedded systems already resemble the organs of animals in terms of mechanical properties and multiplicity of function. In this paper, we discuss why soft materials are a good choice to expand the capabilities of robots and, specifically, how to use them for improving their endurance and adaptability to unpredictable environments. In essence, using material science to improve

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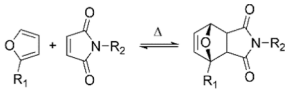
their ability to survive without supervision.

We first identify self-healing materials as an essential element for damage resilient robot and discuss recent advances of self-healable robots. Next, we categorize the developments of material science (with a focus on soft matter) for the three building blocks of a robotic system–actuation, sensing, and control, and suggest potential future research directions that may eventually bridge the gap between advances in material science and generally useful robotic systems.

Self-Healing. Across plant and animal kingdoms, all living organisms have evolved the ability to heal to various extents. An important step towards longevity for a robot, therefore, should be introducing self-healing functions in the constructing material. Pioneered at University of Illinois, the concept of self-healing composite materials was first introduced in 2001, where a polymeric material was designed to autonomically heal from damages through the release of microencapsulated healing agent [Fig. 1(a)] [3]. Since then, the field of self-healing materials is quickly evolving, expanding in material systems from polymers to ceramics and metals, and broadening in self-healing mechanisms from composites with microencapsulation of healing agent to materials with dynamic bonds [Fig. 1(b)]. We refer the readers to Refs. [4–6] for detailed reviews of self-healing materials. These materials, self-healing from damage with little or no external intervention, could give robots the opportunity to mimic the healing process of living organisms, which is partially attributed to the unconscious autonomic interactions happening local to the damage site. Several recent works have demonstrated this idea in soft robotic actuators: (i) a thermally reversible Diels-Alder synthesis for fluid elastomeric actuators, Eq. (1), Fig. 1(c), [7] (ii) synthesis of azobenzene derived elastomers for light actuated grippers that can autonomously self-heal via hydrogen bonding networks, Eq. (2), Fig. 2(c), [8] (iii) and liquid metal microdroplets encapsulated in rubber for self-healing electronics [Fig. 1(d)] [9]. These self-healing materials have enabled actuators to heal from mechanical damage and resume their actuating functions respectively through thermal treatment and autonomy. [Fig. 1(c) and (d)] [7,9]. There are still many opportunities in this important space. The future of enduring robots requires the ability to adapt to damage.



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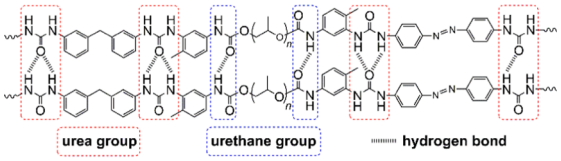

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Actuation. Adaptive and responsive material composites for use as actuation is a well explored field. Within it lie several materials that cause mechanical actuation in direct response fields such as heat, solution chemistry, light, and other mechanical inputs [8,10–13]. Refs. [14,15] provide detailed reviews of stimulus responsive materials that can be pre-programmed to generate motions. Most of these actuator classes are diffusion limited mechanisms. This limitation means that, while high force or power densities are impressive, the volume over which they can operate is small and, therefore, the maximum force or power output for the systems are low relative to natural muscle. The ability to apply the same input fields over large surface areas within a volume (i.e., high surface area to volume ratios) will theoretically allow for force and power densities comparable or exceeding natural muscle but over size scales that allow performing useful work.

Osmotic actuators change shapes by varying the degree of swelling of polymeric gels, most notably hydrogels, immersed in solutions. Various

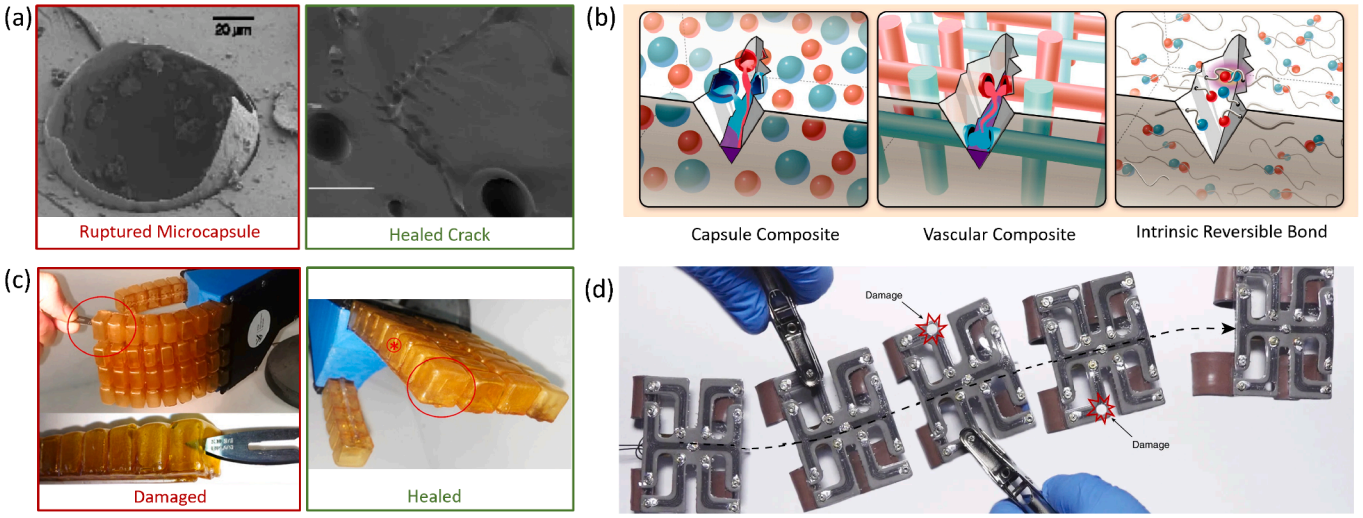

Fig. 1. Self-healing materials and systems. (a) Capsule-based self-healing composite: a structural composite matrix containing microencapsulation of healing agent that polymerizes upon contact with catalyst in the matrix. Left: scanning electron microscope image of a ruptured microcapsule caused by a crack in the matrix, releasing the healing agent; Right: environmental scanning electron microscope image of a healed crack from the polymerization triggered by contact of healing agent and catalyst. (Reprinted from [3], Copyright (2001), with permission from Springer Nature). (b) Self-healing approaches. Capsule composite (left): Healing agent is encapsulated in discrete capsules within a matrix. Crack in the matrix leads to rapture of the capsules, releasing the healing agent and leading to reactions that locally heals the damage. The healing agent is depleted after the release and therefore the local healing event could only happen once. Vascular composite (middle): Healing agent is encapsulated in interconnected channels. After the healing agent is depleted from rapture at one location, it can be refilled from a remote undamaged location, enabling multiple local healing events. Intrinsic reversible bond (right): There is no external healing agent encapsulated in the matrix. Self-healing relies on reversible polymerization that comprises of cleavage and formation of either covalent bonds, such as Diels-Alder based polymers and thiol-based polymers, or non-covalent interactions, such as hydrogen bonds and metal-ligand coordination polymers. The reversible reactions could be autonomous or need external stimuli and the material could be damaged and heal multiple times locally. Reprinted from [4], Copyright (2010), with permission from ANNUAL REVIEWS). (c) Self-healing pneumatic hand actuator via thermoreversible Dials-Alder polymer. Macroscopic damage is healed with heat treatment and allows nearly full performance of the actuator. (Reprinted from [7], Copyright (2017), with permission from The American Association for the Advancement of Science). (d) Soft quadruped with self-healing electronics via liquid metal droplets suspended in elastomer. Upon damage, droplets rapture and form electrical connections with the neighbors to allow reroute of electric signals without interruption. (Reprinted from [9], Copyright (2018), with permission from Springer Nature).

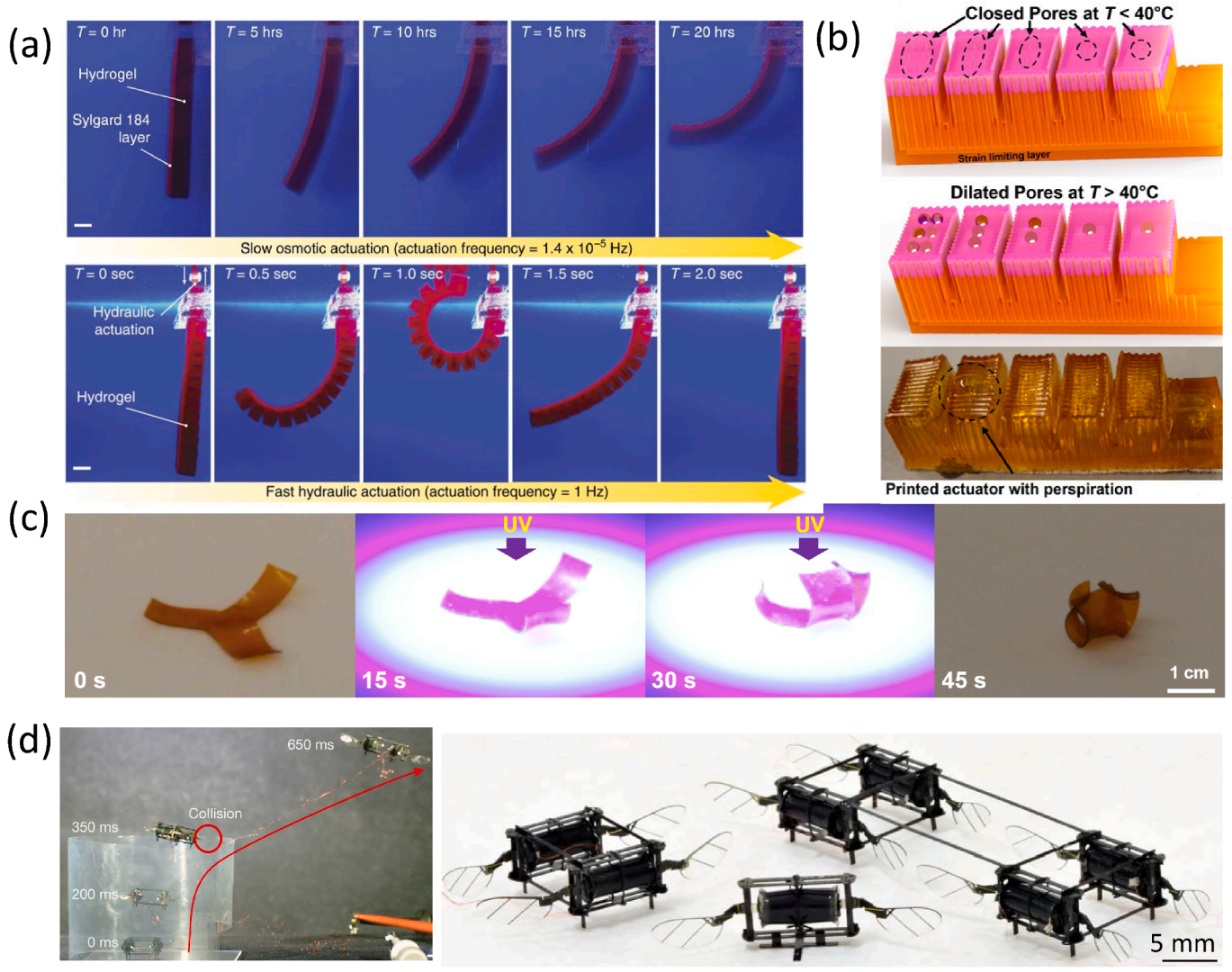

Fig. 2. Actuation with adaptive and responsive material composites. (a) Hydrogel actuators: Top: slow actuation by swelling-driven osmotic effect; Bottom: fast hydraulic driven actuation. Reproduced from Ref. [17]. (b) Hydrogel robotic actuator with autonomic perspiration. Micrometer size pores are embedded in the polyacrylamide (PAAm) robotic skin. The pores dilate at elevated temperature due to swelling of PAAm and allow evaporative cooling from localized perspiration. (Reprinted from [18], Copyright (2020), with permission from AAAS) (c) A soft robotic gripper assembled through the self-healing function from hydrogen bonds of the photomechanical polymer (PME) and actuated through light-induced azobenzene isomerization. (Reprinted from [8], Copyright (2019), with permission from John Wiley and Sons). (d) Insect-scale aerial robot driven by multilayered dielectric elastomer actuators with high power density (600 watts per kilogram) demonstrates various controlled flight modes and robustness from collisions. (Reprinted from [21], Copyright (2019), with permission from Springer Nature).

external stimuli, such as pH, heat and electric field, can change the osmotic pressure, which leads to the diffusion of solvents into or out of the polymer matrix. The diffusion process that governs the actuation also poses limitation on the actuation performance: high actuating force requires the swelling of a large volume, but the mass diffusion for a large volume sacrifices the actuating speed [16,17]. Combining hydraulic actuation and hydrogel actuators with PneuNets' construction allows fast actuation response [Fig. 2(a)] [17,18]. Notably, Mishra et al have leveraged the swelling response of the hydrogel material to achieve a soft robotic gripper that can regulate its body temperature through autonomic perspiration [18]. As shown in Fig. 2(b), the robotic skin made of polyacrylamide (PAAm) is fabricated with mircometer size pores embedded through stereolithography three-dimensional (3D) printing. At low temperatures (<30 °C), the pore size stays sufficiently small to allow the hydraulic actuation; at elevated temperatures (>30 °C), the swelling of PAAm leads to dilation of the pores, enabling localized perspiration that permits evaporative cooling. The sweating actuator achieves thermoregulatory performance of 107$\text{watts}\,\text{kilogram}^{-1}$, greater than the evaporative cooling capacity found in animals (35W kg^{-1}). This cooling capacity, however, comes at the cost of lower actuation efficiency while sweating [18].

Diffusion limitation also affects responsive materials with faster reaction to stimulus. Azobenzene based photomechanical elastomers undergo reversible shape change upon irradiation of light with appropriate wavelength. The molecular photo switch, azobenzene, absorbs light for isomerization that causes molecular structural change from elongated trans- isomer to kinky cis- isomer, leading to macroscopic shape change when linked to macromolecules. Actuators based on photoisomerization and other photo-deformable principles alike, however, are limited to only bending motions and thin film configurations [Fig. 2(c)] [8,19]. This is due to the conflict of light-absorbing actuation scheme and light penetration depth—light induces a gradient of photoisomerization through a thin layer of the material and quickly vanishes. Similar conflict also exists for thermal-active materials with thermal gradients due to heat absorption and diffusion [14]. One way to achieve large-force volumetric actuation with these 2-D structures could be grouping

repeating units of actuators in the appropriate direction for the desired actuation. This translates to high surface area to volume ratio patterning of the responsive material, and distributed stimulus field within the volume. Dielectric elastomer actuators (DEA) provide good examples in this aspect. DEAs are soft capacitors with an elastomeric dielectric layer sandwiched between two compliant electrodes. The electrostatic force between the electrodes squeezes the elastomeric dielectric and leads to actuation. Since the electrostatic pressure is inversely proportional to the square of the dielectric layer thickness, DEAs are generally limited to thin films in size. Researchers in this field have devised a myriad of configurations that convert the 2-D stretching of a DEA sheet into composites that produce sufficient force and deformation for useful robotic applications [Fig. 2(d)] [20,21].

Most of these mechanisms, based on elastomeric material, offer the advantage of resilience. The entropic elasticity offered by these chemically or physically crosslinked networks is most simply described via the Affine Stretching Model in uniaxial deformation. The Affine Model assumes that the crosslinked junctions are fixed in space and are displaced affinely with the whole network, and the fluctuations of the junctions are suppressed by the intermolecular entanglement of the neighboring coils. When the elastomer is deformed macroscopically by stretch ratios of $\lambda_x, \lambda_y, \lambda_z$, the polymeric chain ends change by the same amount. The entropy of a single polymer chain with N Kuhn segments of length b is

$$S(N,R) = -\frac{3}{2}k_B\frac{< R^2 >}{Nb^2} + S(N,0)$$

Therefore, the entropic change induced by a single chain deformation is

$$\Delta S = -\frac{3}{2}k_B\frac{(\lambda_x{}^2 - 1) < R_x{}^2 > + (\lambda_y{}^2 - 1)\langle R_y{}^2 > + (\lambda_z{}^2 - 1)\langle R_z{}^2 >}{Nb^2}$$

The variation in Helmholtz free energy F due to chain length under constant temperature T and volume V is

$$(\frac{\delta F}{\delta L})_{T,V} = (\frac{\delta U}{\delta L})_{T,V} - T(\frac{\delta S}{\delta L})_{T,V}$$

Where in ideal networks, the energetic contribution to elasticity is negligible ($\frac{\delta U}{\delta L} = 0$) compared to the entropic contribution. Since $< R_x{}^2 > = < R_x{}^2 > = < R_x{}^2 > = \frac{Nb^2}{3}$ in the undeformed state of a single chain, the total free energy change of a polymer network with n chains is

$$\Delta F_{tot} = -T\Delta S_{tot} = \frac{n}{2}k_B T(\lambda_x{}^2 + \lambda_y{}^2 + \lambda_z{}^2 - 3)$$

With a uniaxial deformation λ along x, $\lambda_x = \lambda$, and $\lambda_y = \lambda_z = \frac{1}{\sqrt{\lambda}}$. And the total free energy change of the polymer network under this uniaxial stretch is

$$\Delta F_{tot} = \frac{n}{2}k_B T(\lambda^2 + \frac{2}{\lambda} - 3)$$

Thus, without considering excluded volume effects or enthalpic interactions, it is simple to see that elastomers offer ligament like behavior; offering the potential for storing and releasing energy when most energetically favorable. The entropic elasticity of elastomers allows soft robots to have rapid actuation through fast release of the stored elastic potential energy in a similar manner to their biological counterparts, such as the ballistic rolling of a caterpillar. GoQBot, composed of silicone rubber and driven by shape memory alloy coils, achieves ballistic rolling with 1 G acceleration and 200 rpm angular velocity, closely mimicking the escape reflex of a caterpillar [22]. In combustion powered soft robots, the elastomeric material absorbs large amount of elastic energy generated by the explosion and achieves rapid locomotion through jumping movements [23–25]. Recently, a fluidically powered soft actuator has demonstrated fast jumping actuation with the input of fluidic inflation at a slow rate by utilizing the isochoric snapping mechanism of a bistable elastomeric cap [26]. For a detailed review on energy considerations of pneumatically driven soft robots, we refer the readers to Ref. [27].

Mechanosensing. While self-healing materials could enable damage-resilient robot, to build an adaptive one that not only recovers from physical damage, but also avoids it; adapting to adverse environments like animals, the sole incorporation of self-healing materials is not enough. Sensing and reasoning need to be embedded in the system to enable reprogrammable objectives and actions adapted to the new environment. To this end, several synthetic material approaches to mechanoreception have been investigated.

Mammals experience fine tactile sensations of the physical world through rich mechanoreception systems embedded in their soft tissues. Taking inspiration from mammalian biology, researchers have developed several classes of mechanosensors that feature intrinsically soft and stretchable materials, as soft material is likely a critical component that allows detection of complex mechanical stimulus. For a comprehensive and detailed review on stretchable sensors, we refer the readers to Ref. [28]. Here, we provide a summary of working principles of stretchable sensors. The most widely explored sensing scheme with intrinsically soft materials to date is electronically based stretchable sensors composed of soft resistors or capacitors. Such resistive sensors are stretchable conductors mainly composed of elastomeric matrices infused with conductive particulate, liquid metal, or ionic liquid additives [29–31]. By measuring the resistance change induced by the length and cross-section area change of the elastomeric resistor, mechanical deformation could be determined with consideration of the sensor arrangement. [Fig. 3(a)] This approach, however, is highly dependent on the conductivity of the material. Therefore, if the conductivity is affected by factors such as strain (e.g. carbon nanotubes) or environmental instability (e.g. ionic gels), then the sensor would suffer from hysteresis and drift. Liquid metal based stretchable sensors exhibit little hysteresis to strain but are susceptible to leakage [Fig. 3(b)] [32]. Intrinsically conducting conjugated polymers could overcome some of the issues introduced by conductive fillers, but their conductivity and stretchability need to be further improved for integration in highly stretchable systems [33]. Capacitive sensors have less restrictive requirements on the stretchable conducting elastomer. Capacitance change is driven by the cross-section area and thickness changes of the dielectric layer and is dependent on the electrical permittivity of the elastomeric dielectric rather than conductivity of the electrodes [Fig. 3(c)]. Both resistive and capacitive stretchable sensors have achieved good mechanical compliance and demonstrated excellent sensitivity to mechanical deformations. They are limited, however, in the amount of information they can provide for the mechanical stimuli (i.e. mode, location) and thus requires geometric patterning and, in some cases, machine learning to detect complex mechanical stimulus. To this end, sensing through the optical approach provides a promising direction, as light carries rich information from wavelength spectrum, to intensity and polarization, which could reflect various disturbances in the propagating medium. By measuring the intensity variations introduced by mechanical deformations, a stretchable sensor made of an elastomeric optical fiber has demonstrated low hysteresis, high precision, and high repeatability measurements with highly stretchable elastomers [Fig. 3(d)] [34]. Further incorporating chromaticity in the sensing scheme has revealed more aspects of the mechanical stimuli (e.g. location) [35]. Recently, a stretchable Distributed Fiber Optic Sensor (DFOS) achieves simultaneous measurement of the mode (i.e., press, stretch and bend), location and magnitude of mechanical deformations with only one sensor by exploiting wavelength-specific absorption and frustrated total internal reflection with a broad-wavelength spectrum input. Composed of a dual-core elastomeric waveguide and deposited with absorbing chromatic dye patterns, stretchable DFOS uses the intensity and the chromaticity outputs from the two cores to extract rich information through a single sensor. It further decouples multimodal and multi-location deformations by mapping the outputs to the color space [Fig. 3e] [48]. Finally, the optical sensing approach has fewer requirements on the synthetic material—it needs to be an elastomer which

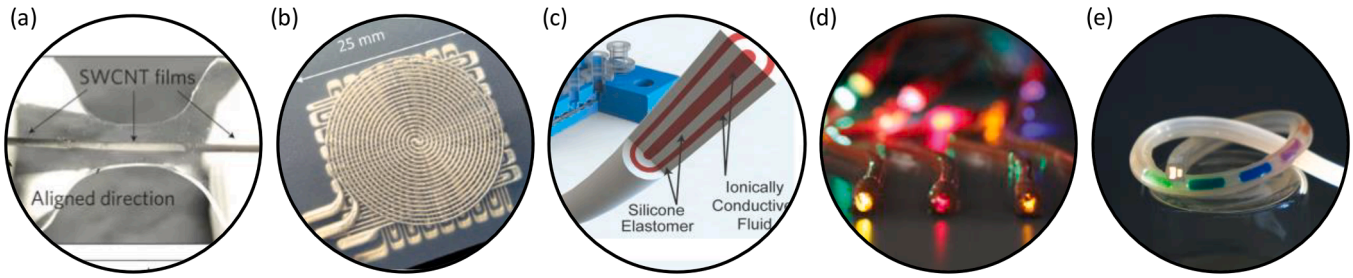

Fig. 3. Mechanosensing with stretchable material composites. (a) Stretchable resistive strain sensor based on thin films of aligned single-walled carbon nanotubes (SWCNT). Upon stretching, the microcracks of SWCNT enlarge, increasing the electrical resistance. (Reprinted from [29], Copyright (2011), with permission from Springer Nature). (b) Stretchable resistive strain sensor based on liquid metal eutectic gallium-indium (EGaIn). (Reprinted from [32], Copyright (2012), with permission from IEEE). (c) Soft capacitive strain sensor based on multicore–shell fiber printing. (Reprinted from [31], Copyright (2015), with permission from John Wiley and Sons). (d) Stretchable optical sensor based on intensity variation in a waveguide. The waveguide sensor is composed of a transparent elastomeric core with a higher refractive index than the elastomeric cladding. Upon stretching, the output light intensity diminishes due to increase in optical path length, as explained by Beer-Lambert Law. (Reprinted from [34], Copyright (2016), with permission from The American Association for the Advancement of Science).

is transparent in a wavelength range and has higher refractive index than the cladding material or air.

The adoption of synthetic soft materials as sensors has enabled robots to acquire some of the rich mechanosensation experienced by mammals and allowed them to perform useful tasks [34,36]. Building active functions in the sensing materials could provide robots with sensing capabilities beyond passive proprioception and exteroception. For example, by incorporating self-healing materials in the construction, a damage-resilient robot could detect the onset of damages and evaluate recovery methods, such as gait adjustments, leading to a more intelligent robotic system empowered by materials.

Computation. In the control aspect, robots with animal-like adaptive behavior requires adaptive controllers that could accommodate parameter variations due to damage, and potentially the adjustment of control objectives based on severity of the damage. Refs. [37–39] provide detailed reviews on the state of art soft robotic control strategies. Thus far, researchers have explored various material libraries for use as robotic actuators and sensors, unleashing exciting functions. Computation, on the other hand, is still mainly performed by silicon-based digital schemes. Therefore, challenges arise at the integration of a robotic system composed of materials with drastically different properties. Biology provides abundant inspirations for tackling this challenge with the approaches such as gradient moduli of elasticity [25]. Opportunities lie in novel structures that mimic the integration of local mineralization and soft tissues in organisms, multifunctional materials and composites, and advanced materials for both distributed computation and communication for centralized computation. In a more fundamental materials approach, oscillatory chemical systems such as the Belousov-Zhabotinsky reaction offer the ability to perform signal processing without a silicon based computers at all. [Fig. 4(a)] [40,41]. Scientists have made great advancements in understanding the interesting phenomena (oscillations, waves and chaos) arising from nonlinear chemical dynamics in the past three decades [42]. Applying logics generated in the materials with nonlinear chemical dynamics could create a material-centric computation scheme that unveils novel biomimetic functions with complex logics, such as hemostasis and morphogenesis, for robotic applications. [Fig. 4(b),(c)] [43,44].

Summary and Future. Overall, when selecting the right materials for robots, designers should be equipped to evaluate the efficacy of the novel material for robotic integration. This requires uniting the higher-level goal of the specific robotic application with a fundamental understanding of the novel material candidates, including the working principle, material synthesis complexity and repeatability, product reliability and scalability, ease of integration, operating condition, fabrication, and cost.

The new material science of robots explores possibilities of robotics from the fundamental level of material constitution. Rooted deeply in basic science, this approach allows innovations in robotics on all scales from micromachines to extensive systems and breaks new ground in robotic function from self-healing to camouflage [7,9,13,21,45–47]. Robotic design based on novel materials, however, is still in its infancy. At the current stage, work in the field has only demonstrated proof-of-concept machines with highlighted function enabled by a new material. To build autonomous robots that could perform useful tasks, the

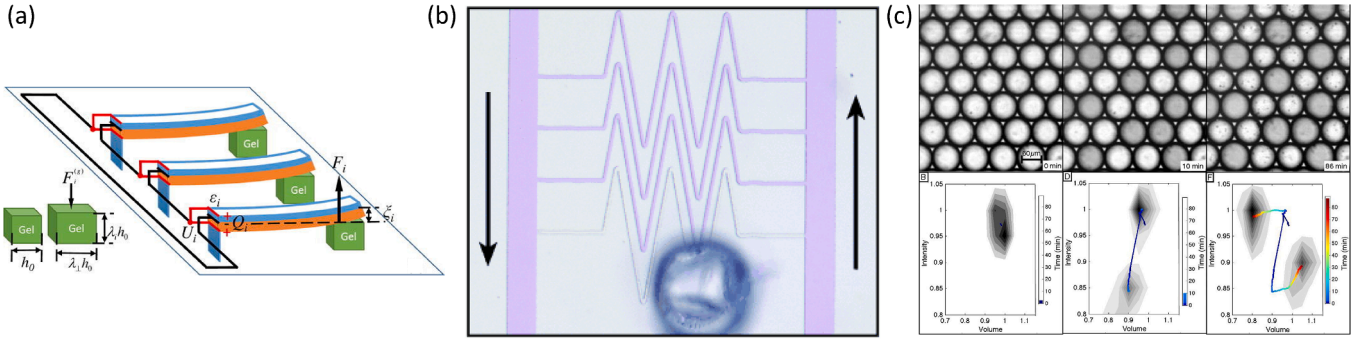

Fig. 4. Computation through the materials approach of nonlinear chemical dynamics. (a) Schematic of coupled oscillator network composed of self-oscillating polymer gels undergoing the Belousov–Zhabotinsky (BZ) reaction and overlaying piezoelectric (PZ) bimorph cantilevers. (Reprinted from [40], Copyright (2018), with permission from AIP Publishing). (b) A self-repairing biomimetic microfluidic system as the minimal model of hemostasis built with three reactions controlled by microfluidics. This shows functional system reactions can be built with microfluidics that controls interactions between individual reactions and maintains them away from equilibrium. (Reprinted from [43], Copyright (2004), with permission from John Wiley and Sons). (c) A cellular chemical system that quantitatively tests Turing's theory of the reaction-diffusion driven morphogenesis via an emulsion of aqueous droplets containing the Belousov–Zhabotinsky oscillatory chemical reactants dispersed in oil. Reproduced from Ref. [44].

integration of actuation, sensing and computation is required.

We have yet to see emergence of autonomous robotic systems that achieve unprecedented tasks by leveraging advantages of the new materials. One reason is likely due to the complexity of the tight integration of these systems. Innovation in fabrication methods, most notably, 3D printing, has become an increasingly useful tool to address this challenge and have yielded promising results. In a larger context, however, this challenge transcends disciplines and requires collaboration between material scientists and entrenched roboticists. The future of generally adaptive robotics requires the participation of biologists, chemists, material scientists, and chemical engineers. The participation of excellent researchers in these fields will lead to a paradigm shift in the field of robotics towards the prominence of autonomous materials.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The optical sensors reviewed in this work have been filed under international patent applications, no. 62/642,407 for Waveguide and Sensor Based on Same and patent application no. 62/382,484 for Waveguides for use in sensors or displays. The listed inventors for the former are Robert Shepherd, Hedan Bai, Shuo Li, and Yaqi Tu and listed inventors for the latter are Robert Shepherd, Huichan Zhao, Rukang Huang, Hedan Bai, and Shuo Li. The intellectual properties are being licensed by Organic Robotics Corporation which is partially owned by Robert Shepherd.

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