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Programmable responsive metamaterials for mechanical computing and robotics

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Qiguang He[1,2,3], Samuele Ferracin[1,3] & Jordan R. Raney[1]

Unconventional computing based on mechanical metamaterials has been of growing interest, including how such metamaterials might process information via autonomous interactions with their environment. Here we describe recent efforts to combine responsive materials with nonlinear mechanical metamaterials to achieve stimuli-responsive mechanical logic and computation. We also describe some key challenges and opportunities in the design and construction of these devices, including the lack of comprehensive computational tools, and the challenges associated with patterning multi-material mechanisms.

Soft and flexible robots have received great interest in recent years, with their soft, compliant bodies being ideal for safe human–machine interaction and providing resilience in unpredictable, dynamic and possibly hazardous environments[1]. To be more effective, these soft robots must be able to make decisions and execute tasks without frequent human intervention[2]. To achieve such autonomy, state-of-the-art soft robots heavily rely on conventional mechatronics-based architectures, typically consisting of sensors, central processors, and actuators to form feedback loops[3]. While these devices enable autonomy, they bring limitations as well. Conventional electronic subsystems are rigid and bulky and can therefore induce unnecessary fragility when interfaced with soft materials. For example, soft–stiff interfaces can induce delamination. Traditional electronic components may also be incompatible with confined, harsh, and extreme environments (for example, high temperatures, water exposure, radiation, corrosive matter, or environments where metals cannot be used). Moreover, when applications require complex shape changes in response to the environment, sensing, control, and actuation strategies based on conventional electronics usually necessitate many transduction steps, increasing the complexity of the robotic systems. Scalability may also be challenging, as standard electronic form factors may not be compatible with the operational environment (for example, in medical procedures). For the above reasons, innovative strategies are needed that transcend the limitations of centralized mechatronics.

Biological adaptable systems provide an alternative avenue for achieving autonomy. Rather than relying on central processing, biological systems seamlessly integrate autonomous sensing, processing, and actuation functions in their physical bodies[4]. In this paradigm, some degree of intelligence can be embodied in the material–structural combination constituting the body itself. This embodied, distributed intelligence may increase the resilience of autonomous functions, minimize risks of system failure, and allow greater adaptability in complex and dynamic environments. Embodying such physical intelligence in soft robots[5] has the potential to allow the design of systems capable of autonomously changing their morphology and properties in response to a large variety of external stimuli. While numerous responsive materials have been developed in recent decades, which are capable of changing their shape and/or properties in response to external stimuli, such as temperature[6,7], mechanical forces[8], chemical cues[9], and magnetic fields[10,11], these tend to respond monotonically to their environment. For example, a temperature-sensitive composite may change curvature in response to the local temperature, but it does so in a monotonic manner, without logic or intelligence built into the response.

In parallel, mechanical metamaterials have received interest for achieving distinct and exotic behaviors due to their unique internal structure. Mechanical metamaterials are capable of programmable shape changes and tunable mechanical properties[12]. Recently, researchers have been designing metamaterials capable of processing information, sometimes referred to as 'mechanical computing'. The behavior of these mechanical systems can be as simple as that of an individual bit (for example, a bistable mechanism that snaps between two configurations, or a dynamically excited system that shifts from being in phase to being out of phase with an input signal) or more complex integrated networks[13], as reviewed previously[14]. Recent work has shown that stimuli-responsive materials can be combined with these

[1]Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA, USA. [2]Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong SAR, China. [3]These authors contributed equally: Qiguang He, Samuele Ferracin. e-mail: raney@seas.upenn.edu

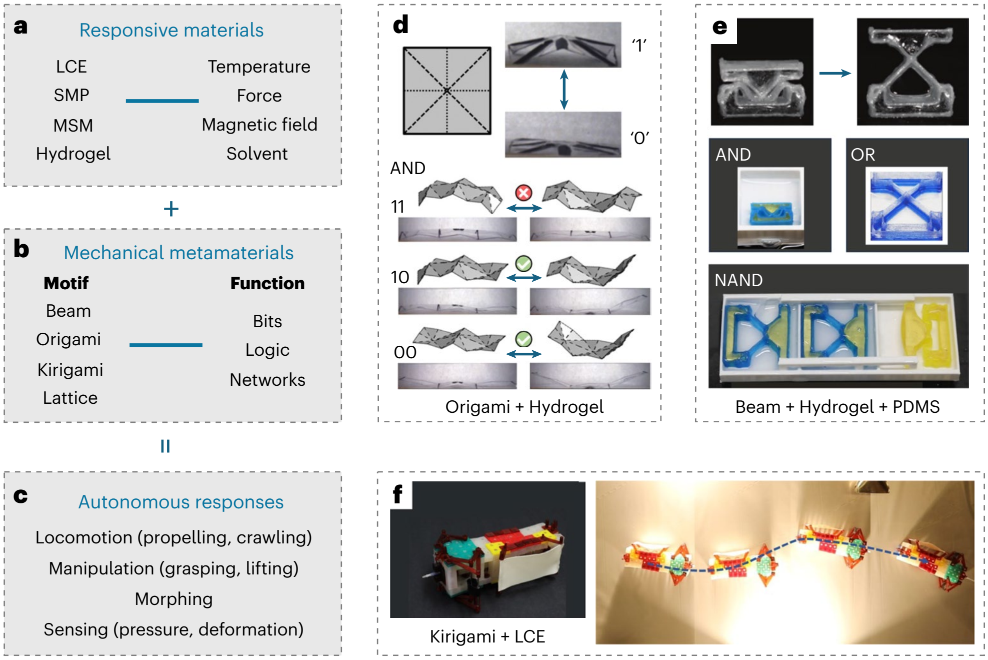

Fig. 1 | Materials and mechanical metamaterials for autonomous mechanical logic. a, Responsive materials, such as SMPs, MSMs, LCEs, and silicone, can change morphology and properties under specific environmental stimuli. **b**, Various structural motifs have been used previously to enable the essential functions of mechanical logic. **c**, Soft robotic autonomy can be achieved by coupling responsive materials and mechanical metamaterials. **d**, Treml et al.[15] demonstrated mechanologic built by combining hydrogels and waterbomb origami, enabling signal storage, logic operations, and transmission. **e**, Jiang et al.[9] developed a beam-based multi-stimuli-responsive system that can achieve digital abstraction and logic operations. **f**, An 'electronics-free' kirigami-inspired soft robot, which can autonomously change trajectory due to the action of stimuli-responsive control modules subjected to environmental stimuli, was presented by He et al.[16]. Panels reproduced with permission from: **d**, ref. 15 under a Creative Commons licence CC BY-NC; **e**, ref. 9 under a Creative Commons licence CC BY 4.0; **f**, ref. 16 under a Creative Commons licence CC BY-NC.

mechanical metamaterials to show simple autonomous responses, including logic gates[9,15] and soft robots with the ability to change their trajectories[16]. This hints at the future potential of autonomous soft robots with distributed intelligence, improved responsiveness, and autonomy. Being able to autonomously sense their environment could allow robotic systems to interact with the environment in manners that are fundamentally distinct from traditional electronics, thereby offering new opportunities to design autonomous electronics-free soft robots.

Here we highlight the current challenges and opportunities in developing advanced metamaterials for mechanical computing and autonomous robots. First, we briefly discuss recent advances in stimuli-responsive materials and programmable metamaterials for applications in soft robotic systems, discussing their potential features and presenting several examples (Fig. 1). Then we summarize the limitations and future opportunities for advancing this field. Three major challenges are identified and possible future directions are discussed (Fig. 2).

State-of-the-art mechanical logic

Conventional mechatronic components have enabled soft robots to perform simple autonomous actions in response to their environment[17], including functions such as grasping, manipulation, locomotion and morphing[1,18]. Can some aspects of this sense–assess–response loop be distributed in the robot's body, as a strategy for avoiding some of the drawbacks of using traditional mechatronic systems?

Regarding the 'sense' and 'respond' functions, researchers have developed numerous stimuli-responsive materials that sense and respond to their environment, for example, changing their shape and properties in response to stimuli such as temperature, mechanical force, light, electricity, and chemical cues (Fig. 1a). In principle, such materials could act as sensors and actuators in soft robots. That is, the 'sensing' function that is typically obtained via solid-state sensors could potentially be achieved solely by including the right set of responsive materials.

Some of the most common responsive materials are thermally driven: they undergo phase transitions when the temperature changes, causing morphological transformations and changes in properties (for example, stiffness). These include liquid crystal elastomers (LCEs) and shape-memory polymers (SMPs). For example, LCEs change phase from a nematic state to an isotropic state upon heating, causing anisotropic contraction. Versatile deformation modes, such as bending, twisting, elongation, and contraction, can be realized by spatially arranging their microstructure[19]. LCEs have been used in soft robots (for example, LCE tubular actuators that autonomously grasp and manipulate objects in high-temperature environments[20]). Other responsive materials undergo volume changes in response to relevant stimuli. For example, hydrogels swell in the presence of water, and silicones swell in the presence of non-polar solvents. As with the LCEs described above, hydrogels and silicones produce complex shape changes when swelling occurs by controlling the anisotropy of the material (for example, via three-dimensional (3D) printing[21]). Moreover, electrostatic materials (for example, dielectric elastomers) generate reversible actuation under electric fields. They can have a high energy density and rapid response speed due to the electrostatic mechanism[22]. Magnetoactive soft materials (MSMs), which consist of magnetic particles in a polymeric matrix, offer fast, reversible and untethered deformation under external magnetic fields[10]. Robots with such materials can produce versatile locomotion, such as crawling, jumping, rolling, and swimming under external magnetic fields[23]. Finally, soft conductive materials, such as liquid metals and conductive polymer composites, have been used as strain sensors or heating elements for other thermally responsive materials. Liquid metals, such as EGaIn and Gallistan, can create self-healing circuits[24] and can be 3D-printed to create resistive[25] and capacitive[26] pressure and

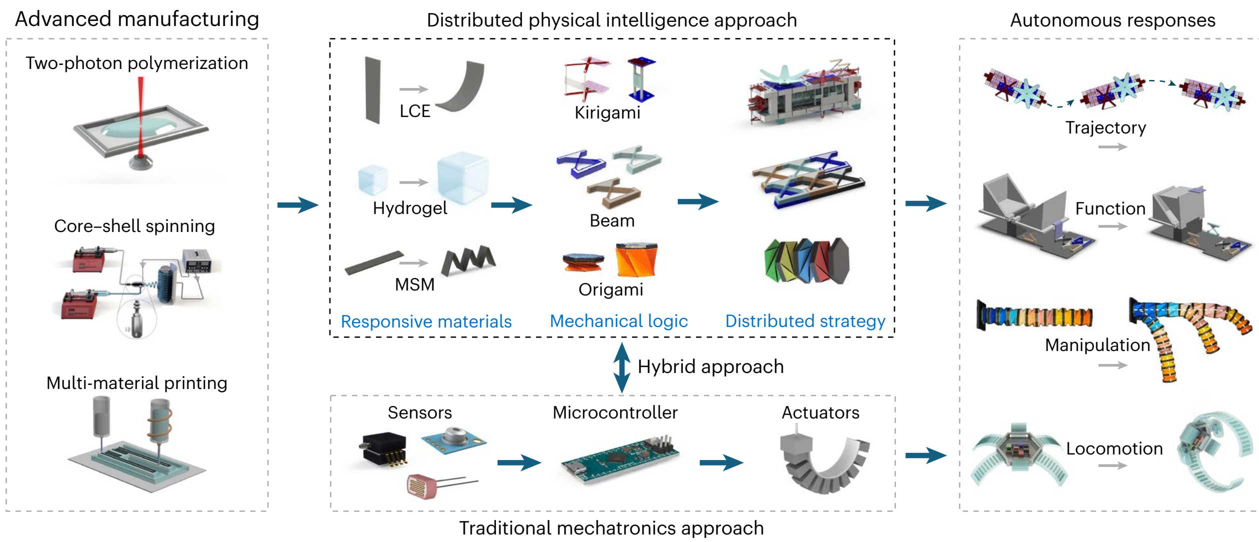

Fig. 2 | Challenges and opportunities in mechanical computing and autonomous robots. Multiple stimuli-responsive materials can be incorporated and distributed in metamaterial networks, allowing the mechanical (robotic) systems to sense their surrounding environment (for example, light, heat, water, magnetic field, solvent, and so on). This can affect the behavior of the robots, such as trajectory (demonstrated by He et al.[16]), function (presented by Jiang et al.[9]), and shape (shown by Wu et al.[51]). To fabricate these systems, advanced manufacturing techniques, such as two-photon polymerization, core–shell spinning (developed by Woo et al.[57]), and multi-material printing, may be necessary. Future autonomous mechanical logic systems may also enable distributed physical intelligence via hybridization with traditional mechatronics. Adapted with permission from: ref. 16 under a Creative Commons licence CC BY-NC; ref. 9 under a Creative Commons licence CC BY 4.0. Reproduced with permission from: ref. 51 under a Creative Commons licence CC BY 4.0; ref. 57 under a Creative Commons licence CC BY 4.0.

strain sensors that can be used to control robots. More comprehensive information regarding the mechanisms, stimuli and performance of responsive materials is available in more exhaustive review articles[27,28].

Physically intelligent soft robots have been demonstrated that are able to respond to their environment[29,30]. However, in most cases, the stimuli-responsive materials enabling this capability always respond in the same way when a stimulus appears, regardless of other conditions. For robots to sense, assess and respond to their environment (that is, not merely reacting to it monotonically), stimuli-responsive materials can, in principle, be incorporated with mechanical logic networks, with the mechanical logic regulating the response(s) of the responsive materials to produce a stimuli-responsive system that translates environmental inputs to mechanical outputs in the form of shape and property changes to the network itself. Mechanical logic is often implemented by building a mechanical metamaterial comprising a variety of mechanisms (Fig. 1b), for example, slender beams[31], kirigami[32,33] and origami[34]. Slender elastic beams may buckle when subjected to axial compression, resulting in a monostable–multistable bifurcation, depending on the geometric parameters. Origami can turn sheets of different materials into 3D shapes, which can be predicted and controlled using existing computational design tools[35,36]. Kirigami, similar to origami, but with the addition of cuts, allows for creation of complex two-dimensional structures from a variety of materials, which can be morphed into 3D shapes[37]. These motifs can be repeated in complex arrangements as lattices, chiral metamaterials[38], graded metamaterials[39] or disordered metamaterials[40], any of which could be used to create functional mechanical logic networks. These assembled metamaterial architectures enable mechanical systems to conduct more advanced operations, including information processing and storage[41], in-memory computing[42], logic functions[43], digit recognition[44] and learning[45].

Despite the recent progress in these systems, certain limitations persist. Computation based on metamaterials is still constrained by slow speeds, limited density of computational power and information storage, an absence of 'universal' design tools and architectures, and increased complexity in implementing algorithms, potentially compromising reliability, robustness, and accuracy.

To allow these logic networks to be able to interact with the environment, responsive materials can be incorporated with mechanical systems (Fig. 1c). So far, these systems have been primarily constructed as proofs of principle. While there is not yet a general framework for designing stimuli-responsive mechanical logic, as discussed in 'Challenges and opportunities', there are several recent examples that illustrate possible strategies. We briefly describe some of these below as case studies.

The first example, by Korpas et al.[33], illustrates how responsive materials can be integrated with metamaterials to realize complex responses from environmental stimuli. More specifically, this work describes a kirigami-inspired structure comprising a series of squares connected by hinges that allow rotation. Due to magnets in the squares, the squares can rotate and snap into different configurations. The hinges are LCE-polydimethylsiloxane (PDMS) bilayers, which bend in response to temperature changes in the environment, thereby altering the energy landscape. Interestingly, even though the LCE-PDMS bilayers change curvature monotonically with temperature, the kirigami's geometric parameters (for example, hinge thickness h) allow one to choose a critical temperature T_{Crit} at which the structure suddenly retracts away from a local heat source. Without changing the material properties, one can geometrically choose T_{Crit} over a wide range of temperatures. Moreover, when T_{Crit} is locally exceeded, one can choose whether the structure only locally retracts or whether this retraction should propagate through the rest of the structure. The idea of blending mechanical logic and responsive materials is not constrained to specific mechanisms and materials. Numerous combinations, including SMP origami[46], hydrogel lattices[47], and MSM-buckled beams[48], have been used to demonstrate autonomous morphological changes in response to specific stimuli. Multiple mechanisms like this, if properly arranged together, could create mechanical logic networks activated by environmental stimuli.

Treml et al.[15] developed a mechanical logic capable of memory and signal processing. In this work, hydrogel is integrated with a bistable origami structure based on the 'waterbomb' pattern (Fig. 1d). The hydrogel directly transduces relative humidity from an environmental input into a mechanical signal, transitioning the origami between two equilibrium states, that is, mountain (1), and valley (0) folds. An AND gate can be created by linearly arranging three of these units, with hydrogel present in only the center. Moreover, by organizing logic gates together, a logic circuit can be designed: once a unit harvests energy from the environment and reconfigures, the output of this unit can be transmitted to an adjacent logic gate, propagating via sequential instabilities.

However, in each of the examples above, only a single stimulus (heat and humidity, respectively) was used as an input. In principle, as the stimuli-responsive materials serve the role of sensors for the mechanical logic networks, multiple responsive materials could be incorporated to allow the network to respond to multiple types of physics in the environment simultaneously. Sun et al. recently developed a multi-responsive multistable mechanical metastructure by integrating a printed ferromagnetic LCE (magLCE) with the structure[49]. This responsive metamaterial switches between three different stable states in response to temperature and magnetic field, showing the capability of information processing and storage. Apart from LCEs and MSMs, other responsive materials, along with nonlinear mechanisms, enable the logic functions in response to the environments containing multiple stimuli. Jiang et al.[9] demonstrated functionally complete mechanical logic gates that can compute based on multiple stimuli simultaneously (Fig. 1e). This logic was enabled by constructing beam-based bistable structures from 3D-printed, anisotropic materials. The bistable beams were made from either fiber-reinforced hydrogel or fiber-reinforced PDMS. When exposed to, respectively, water and non-polar solvents (for example, toluene), these materials undergo anisotropic swelling. This can cause a bistable beam in a buckled configuration to suddenly become monostable as the nonlinear geometry passes through a geometrically defined bifurcation. The monostable state supports only an unbuckled beam configuration, causing rapid snapping of the beam into an elongated state. By combining hydrogel-based and PDMS-based beams, multi-stimuli-responsive logic gates such as AND, OR and NAND can be realized (Fig. 1e).

An example of how it is possible to utilize the previously presented strategies to translate abstract information processing and external signals into associated physical changes was demonstrated in a recent work by He et al.[16], in which an autonomous kirigami-inspired soft robot was designed. This robot can autonomously navigate through an environment with multiple stimuli (heat, light, solvents and so on) based on stimuli-responsive modules that can produce mechanical constraints in the kirigami[16] (Fig. 1f). A pneumatic actuator is integrated with the kirigami, which cyclically inflates and deflates, causing the kirigami squares to open and close. Responsive materials (for example, LCEs, hydrogels and so on) in the control modules enable the modules to sense stimuli in the environment. When this occurs, the module can be reversibly activated (or deactivated), producing (or removing) a mechanical constraint in the kirigami. The collective interaction among multiple modular units throughout the kirigami body induces changes to the curvature of the robot, and consequently alters the trajectory of the robot. While this work only maps mechanical logic outputs to trajectory changes, in principle the outputs of mechanical logic could be used to control other functions of robots, such as their locomotion[50], manipulation[51], and sensing[52] functions. While the focus of this Perspective is on mechanical computing as applied to soft robotics, other applications of mechanical logic can be envisioned, including applications related to energy harvesting[53] and information security[41].

Challenges and opportunities

Although recent studies have demonstrated the feasibility of some simple aspects of decentralized mechanical intelligence in soft systems and soft robots (Fig. 1), substantial challenges and associated opportunities still exist. Here we briefly describe some key challenges and future possible directions for the field, following Fig. 2. Each of these challenges shares a common problem: the lack of a general framework for the design of distributed intelligent systems and their components. Electronic computing systems have predominantly relied on well-established architectures (for example, von Neumann), describing the overall structure of the computing system, defining the tasks of each component and its interaction with other subsystems. An architecture for distributed mechanical computing should take into consideration the various needs and advantages of these systems. For example, it should define the roles of each component, how data are stored locally, and how other components can access these data. Moreover, it should describe how parallel processes are managed and synchronized and address scalability. Additional properties are presented throughout this section.

Integration of inputs from multiple environmental stimuli

Stimuli-responsive materials enable mechanical metamaterials to actively sense and respond to distinct environmental inputs[54]. In principle, one can incorporate multiple such materials into a metamaterial or robot to enable responses to multiple stimuli. However, this leads to technical difficulties.

First, each responsive material serves as a sensor for environmental signals. Ideally, the materials would each respond to orthogonal, independent stimuli in the environment. In practice, however, responsive materials may respond to multiple stimuli, and may do so by varying degrees to each stimulus. For example, LCEs can be designed to actuate to thermal changes, but they also swell in response to some solvents. Thus, to incorporate multiple responsive materials into a given system, it is essential to first determine an operational range for each material, with respect to multiple stimuli (for example, light intensity, magnetic flux density, and solvent compatibility). In addition, each of these materials has its own characteristic response time. The disparities can, in part, be attributed to different operational mechanisms (for example, swelling, phase transitions, or electrostatic interactions) or to features of different sizes (that is, the different surface-to-volume ratios result in different diffusion times). As a result of these challenges, metamaterials and/or robots that can respond to multiple stimuli simultaneously are typically designed in an ad hoc manner. The development of a more general framework and practical design tools is essential for mechanical computing to gain more widespread adoption.

Although recent progress in additive manufacturing has provided effective approaches for fabricating responsive materials and tunable metamaterials[55], integrating many stimuli-responsive materials with the often intricate geometries used in mechanical metamaterials still constitutes a manufacturing challenge. Mechanical metamaterials derive their unique properties specifically from their subtle internal geometric features. Even slight geometric errors can lead to substantial variations of the properties. To avoid this, it is critical to meticulously optimize relevant manufacturing parameters (for example, temperature, nozzle size) and procedures (for example, curing time). This is not only a hardware or software problem, but also a materials-specific challenge in which every material of interest may need to be chemically optimized and/or reformulated. Second, interfacial incompatibilities in multi-material systems severely limit the robustness and function of these systems. Chemical and topological modifications, adjustments to printing and/or post-processing parameters, and the application of adhesives can all help. However, these mitigation approaches are all highly specific to the interfaces in question. Finally, many existing active mechanical metamaterials are predominantly confined to millimeter sizes, potentially limiting their applications in fields of biomedical engineering and other areas where reduced physical size is required. Nonetheless, in principle, scalable advanced manufacturing techniques can enable the realization of micro- and nanoscale systems. For example, microscale metamaterials and responsive materials have been fabricated using techniques such as two-photon polymerization and core–shell spinning methods[56,57]. However, these methods are time-consuming and often restricted to specific materials (for example, photo-sensitive material)[56]. Therefore, future research should focus on improving manufacturing efficiency and diversifying material options to facilitate the miniaturization of these mechanical systems.

Resilience in uncertain or harsh environments

Soft robots have the potential to operate in extreme environments where traditional electronics cannot. Recent work has demonstrated the feasibility of mechanical strategies to tolerate unusual or harsh conditions, such as particular chemical compositions[9], extreme temperatures[58], high radiation levels[59], and frequent mechanical impacts[60]. The mechanical compliance of the materials is, in part, responsible for this resilience. In addition to this, however, mechanical logic is intrinsically distributed due to its 'embodied' nature. Decentralized physical intelligence is inherently more resilient than centralized intelligence. Catastrophic failures are less likely to occur in decentralized systems, due to the ability for one entity to take over from another failing entity[61]. Moreover, distributed systems can incorporate simple redundant components more seamlessly than complex centralized units. It is also possible that materials can specifically be selected for self-healing capabilities, allowing partial recovery of function after damage occurs[62].

However, designing distributed systems to take advantage of these properties is challenging. Unlike centralized systems, there is a dearth of design tools for constructing distributed architectures. In part, this is due to the fact that digital electronics are sufficiently advanced that almost all such systems are capable of universal computation. As distributed computing systems, systems of mechanical logic are typically bespoke for one or perhaps a few specific tasks. As a result, approaches used for the design of one type of mechanical logic may not translate to the design of another mechanical logic system. In this context, there are few examples of algorithmically generated mechanical logic, limiting their broader relevance. Moreover, the components in a mechanical system are intrinsically mechanically coupled to one another. Traditional digital electronics rely on independent subsystems and components (for example, transistors), where a state change in one component does not produce physical changes in other components. In contrast, when components in a mechanical computer (for example, a bistable membrane) change states during a computational event, it produces local, and perhaps global, deformation, that, by its nature, influences adjacent components. While this fact is certainly a challenge, which must be accounted for in the design process, it may also be an opportunity. For example, the result of a computational event in a mechanical computer may be a shape change that leads to a desired set of property changes, including the static and dynamic mechanical properties[63,64]. If this can be taken advantage of in the design, exciting new capabilities may become possible in engineering and robotics.

Another challenge lies in understanding how distributed components can efficiently cooperate and communicate. This task is complicated by the varying degrees of coupling between distributed components. In some applications, distributed components can sense, compute, and act completely locally and independently, while in others, increased interaction may be necessary. Different computing abilities may require the use of entirely different materials and metamaterials, further complicating the interaction between components. Moreover, hybrid systems can be designed where centralized and decentralized components coexist and interact (this concept will be further explored in the next section). In digital computation, such challenges are addressed by defining precise communication protocols for each subsystem. It is possible that analogous definitions could be developed for distributed mechanical computation systems. For example, the method for exchanging data should be defined (via mechanical stress or displacement, electromagnetic signals, temperature, and so on). Another important aspect is time synchronization, which is fundamental when coupled subsystems operate at different timescales. However, the customized and ad hoc designs of many distributed systems may limit the general applicability of such definitions.

Preprocessor for electronic computation

Biological systems integrate distributed physical intelligence within their bodies to perform specialized and simple tasks[5]. This enables even the simplest creatures to sense and compute basic responses. By embedding part of the sensing, computing, memory, and actuating functions into the physical structure of the body, distributed intelligence can decrease the workload of a centralized processor. Distributed processes can contribute to overall system resilience in more than one way. First, they can independently manage specific functions, analogous to reflexes that locally respond due to a sudden change in the environment (for example, inducing morphological changes to move the robot away from harmful stimuli). Second, they can pre-process or filter information to accelerate central computation or to minimize the amount of information that the central process uses. For example, consider how challenging it is for a rigid robotic hand to pick a piece of ripe fruit without destroying it. This is because it is computationally intensive to sense the geometric subtleties of the fruit, compute the requisite contacts, and actuate the hand precisely into a suitable configuration. By making the gripper soft instead of rigid, picking the fruit becomes easy: the soft material itself pre-processes the contacts via its own compliance, thus obviating the need for the computationally intensive sensing, processing, and contact calculations. Analogously, hybrid systems that incorporate mechanical logic with conventional digital electronics may be able to use the mechanical system to locally sense and respond to the immediate environment, saving computational effort for other tasks that require centralized processing (for example, long-term planning, machine vision and so on).

The broad range of possible ways to integrate different functions makes it challenging to efficiently design these hybrid systems, as understanding which tasks can be handled by the distributed components and which must be handled by the centralized processor is crucial. The metrics to optimize this variable can be multiple: the required resilience of the system, the reaction speed, manufacturing constraints, and so on. As mentioned earlier, a framework that can generalize these concepts, allowing for a better understanding of how to implement this balance, does not exist at present. Instead, engineers must rely on their experience to build candidate architectures. Inverse design tools capable of algorithmically generating these architectures are needed. While topological optimization has become very powerful, and has been applied to metamaterial design[65], it is still challenging to account both for the complex nonlinear effects in these mechanical systems and the integration of stimuli-responsive materials. Deep-learning approaches have grown in popularity[66], and could become important in the design of mechanical computers. However, it is still challenging to obtain a sufficient amount of data for these and similar data-driven approaches, given the large number of parameters in stimuli-responsive mechanical systems. General tools that can design complex distributed or hybrid systems starting from the environmental stimuli and the required robotic response have yet to be developed.

Recent advances in programmable responsive metamaterials have created new interest in mechanical computing. In this Perspective, we have discussed the state of the art of mechanical computing strategies for the design of intelligent systems that can autonomously interact with their environments in a manner distinct from that of conventional mechatronics, namely, via the coupling of stimuli-responsive materials and computing mechanical metamaterials. We presented key works that exploit this interaction in different ways. In addition, we have identified three major challenges and outlined future opportunities for advancing this field. One foundational challenge is the lack of a formalized architecture and practical rules to enable more efficient design of intelligent mechanical systems and their components and subsystems.

Programmable responsive metamaterials for mechanical computing and robots is intrinsically multidisciplinary, requiring expertise spanning various domains, including mechanical metamaterials, applied mechanics, responsive materials, soft robotics, mechanical computing, and bio-inspired controls. We hope that our Perspective will inspire the exploration of novel mechanical systems for computing and robotics.

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Author contributions

All authors conceptualized the work. J.R.R. acquired funding and supervised the project. All authors wrote, reviewed and edited the paper.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Jordan R. Raney.

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