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Roadmap

Roadmap on embodying mechano-intelligence and computing in functional materials and structures

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Abstract

This is a roadmap article with multiple contributors on different aspects of embodying intelligence and computing in the mechanical domain of functional materials and structures. Overall, an IOP roadmap article is a broad, multi-author review with leaders in the field discussing the latest developments, commissioned by the editorial board. The intention here is to cover various topics of adaptive structural and material systems with mechano-intelligence in the overall roadmap, with twelve sections in total. These sections cover topics from materials to devices to systems, such as computational metamaterials, neuromorphic materials, mechanical and material logic, mechanical memory, soft matter computing, physical reservoir computing, wave-based computing, morphological computing, mechanical neural networks, plant-inspired intelligence, pneumatic logic circuits, intelligent robotics, and embodying mechano-intelligence for engineering functionalities via physical computing. In this paper, we view all the sections with equal contributions to the overall roadmap article and thus list the authorship on the front page via alphabetical order of their last names. On the other hand, for each individual section, the authors decide on their own the order of authorship. (Abstract written by Guest Editors Kon-Well Wang (aka K W Wang) and Suyi Li.)

Keywords: mechanical logic, mechano-intelligence, metamaterials, physical computing, robotics, soft matter

Contents

1. Wave-based analog computing with metamaterials

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Status

Computing and signal processing are ubiquitous operations in modern technologies. Associated with their ever-growing demand, the requirements on speed, memory, data and energy efficiency of computing systems have been rapidly increasing in recent years. All these metrics of performance are fundamentally limited by the common implementations of computers and signal processors, based on digital approaches. In contrast, an all-analog computing platform, which avoids analog to digital conversion and processes the incoming data directly in the analog domain, holds the promise to enable much faster speeds, reduced latency, significantly lower memory needs and energy requirements, leading to an overall enhancement in the amount of data processing per unit of time at a much lower energy cost. At the same time, analog-based computing is not a new topic, it has been explored even before digital approaches to computing have emerged, and over the years its implementations have become marginal due to the superiority of digital computing in terms of noise resilience, robustness, integration and reprogrammability.

The interest in analog computing has been recently revived by the compelling needs mentioned above. In this context, engineered materials (metamaterials) have been opening emerging and unprecedented opportunities for wave manipulation at the nanoscale that may be able to address the previous challenges of analog-based computers. Metamaterials—and their planarized version known as metasurfaces—for computing and signal processing enable ultra-fast speeds, low loss and low noise, deeply sub-wavelength form factors and massively parallel operations, holding the promise for a revival of analog computing based on metamaterials [1–10]. In contrast to conventional analog computers, which were mostly based on electrical or mechanical signals, metamaterials operate based on waves, in particular light and sound, enabling ultrafast speeds and benefitting from tremendous advances in the understanding and implementation of nanostructured materials that can enhance the control over wave propagation. In addition to benefitting from the ultrafast propagation of wave signals, they also leverage the opportunity for integration enabled by nanoscale materials, paving the way for a powerful platform for massively parallel analog-based computing. As examples of the opportunities offered by metamaterials in recent years, figure 1(a) shows the schematic of a layered metamaterial designed to perform mathematical operations on an arbitrary image [1], and figure 1(b) the corresponding implementation in an ultrathin silicon-based metasurface [11]. Finally, figure 1(c) shows an acoustic implementation of the same functionality using sound waves in an acoustic planarized metamaterial [6].

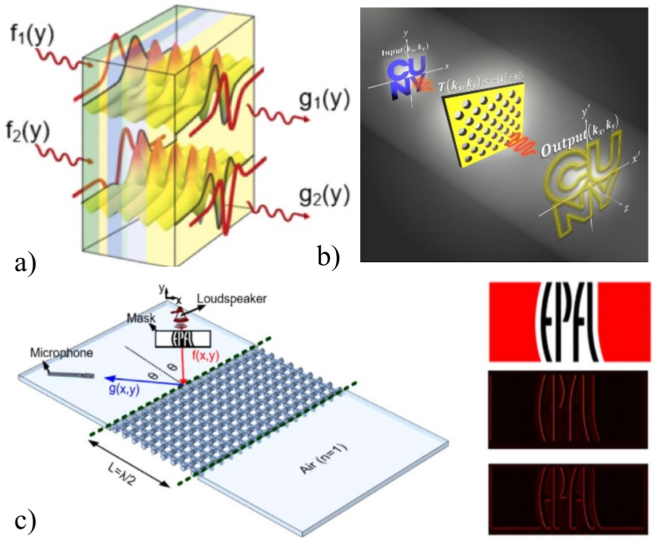

Figure 1. Recent implementations of analog-based computing using metamaterials. (a) Layered metamaterials performing mathematical operations on the incoming signals. From [1]. Reprinted with permission from AAAS. (b) Image processing metasurface performing edge detection; (c) Acoustic metamaterial implementation of an edge detection device. Adapted from [6].

Current and future challenges

Wave-based analog computing with metamaterials offers exciting opportunities given the initial demonstrations, but it also faces important challenges that need to be tackled before this technology can meet the level of maturity required to replace or augment digital computing and signal processing. First, fundamental constraints on what can be achieved stem from symmetry considerations, implying trade-offs between the design parameters, complexity in fabrication and operations to be performed. For instance, a mirror-symmetric metasurface cannot perform odd-symmetric operations with respect to the transverse momentum [12], and complex operations require a minimum thickness associated with the inherent degrees of freedom associated with the underlying operator [13]. Time-reversal symmetry also adds relevant constraints in the conventional implementations.

Another important challenge to be addressed is the limited optical/electromagnetic/mechanical responses available in conventional materials. In the quest for integration, footprint is typically traded with wave–matter interactions, hindering the overall opportunities for analog-based compact computers as compared to the integration density of electronic-based approaches. While light–matter interactions at the nanoscale

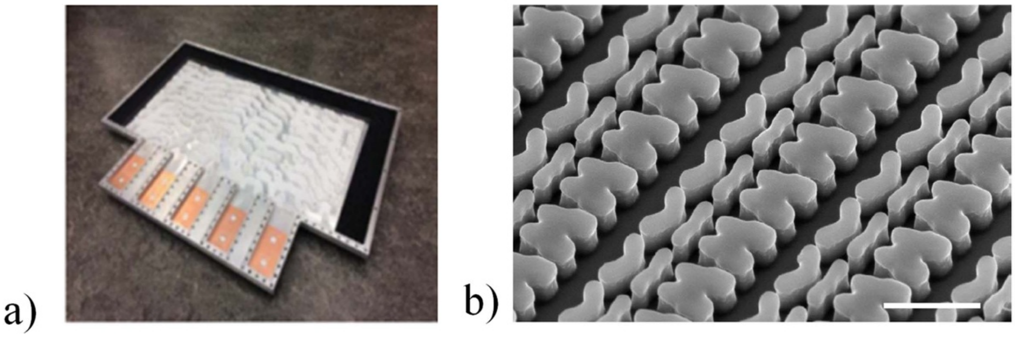

Figure 2. (a) Microwave implementation of an equation-solving metamaterial based on inverse-design. From [7]. Reprinted with permission from AAAS. (b) Photonic implementation with a periodic metasurface backed by a partially-reflecting interface to realize the required feedback. Reproduced from [8], with permission from Springer Nature.

are conventionally limited, polaritonic approaches have been recently pursued to enable stronger light–matter interactions, offering an interesting material platform to compactify the response. At the same time, radio and sound waves offer stronger interactions than light with materials, opening new opportunities. A multi-physics platform leveraging the strengths of different wave phenomena may be an enticing direction for the field, but also opening additional challenges in terms of integrability and fabrication.

To date, most analog computing metamaterials have been limited to perform spatial operations on incoming images and linear responses, compatible with Fourier image processing. Stronger wave–matter interactions may expand these efforts towards nonlinear operations, particularly enticing for various operations of interest that are currently unavailable, including gating, image classification and deep learning. In this context, acoustic and mechanical metamaterials, and/or polaritonic approaches, can offer exciting opportunities to engage strong nonlinearities in compact footprints.

Finally, the biggest shortcoming of current approaches to analog computing with metamaterials is their static response and lack of reconfigurability. While catching up with conventional digital computers may be an uphill battle, some degree of reconfigurability is necessary. Phase change materials or nonlinearities may offer fruitful opportunities in this context [14]. These avenues may open also interesting opportunities to extend the impact of analog computing metamaterials to the temporal domain, envisioning time- and space-time-metamaterials [15]. A highly interdisciplinary progress in material science, photonics, mechanics, electrical engineering and physics is necessary to address these challenges.

Advances in science and technology to meet challenges

Recent progress in the modeling and implementation of metasurfaces and metamaterials has been offering a significant boost to analog-computing wave-based technology. In this context, the field of nonlocal metasurfaces [12] has been rapidly expanding in the past years, demonstrating that an aperture can be nanostructured not only to manipulate the spatial content of an incoming wavefront, as in conventional metasurfaces, but also to engineer its nonlocality in momentum and frequency spaces. These efforts enable rational designs to implement a wide range of mathematical operations in the spatial, and more recently also in the temporal, domain [11]. In the quest for reprogrammability of these wave-based computing metasurfaces, recent progress in material science has been enabling metasurfaces coupled, or even carved into, phase change materials, which can be switched at record speeds, enabling new opportunities for switching operations in real time.

In parallel, topological concepts have been opening interesting opportunities to add robustness and resilience to noise, crucial to compete with digital technologies, and also to further augment the tools available for wave-based computing [16]. Complex topologies and ad-hoc feedback loops have been enabling wave-based equation-solvers [7, 8], as shown in figures 2(a) and (b), with the opportunity of pushing them down to the nanoscale [5]. These efforts open opportunities to design and realize complex wave-based networks of compact computers operating at very fast speeds. In this context, networks of photonic meshes with a high degree of reconfigurability have been recently proposed to realize analog-based machine learning systems in a silicon photonic platform, as shown in figure 2(c) [9]. Similarly, analog Ising machines [10] have been envisioned, which may solve in massively parallel fashion non-deterministic polynomial-time hard mathematical problems. Compactification of these systems with metamaterial topologies is on the horizon, merging these efforts to realize a wave-based computing platform with high speed and low energy consumption.

Exploring acoustic and mechanical-based systems, or hybrid approaches involving opto-mechanical resonators, will introduce stronger nonlinearities and further expand the reach of this technology. Radio-frequency circuitry also offers a natural platform for reconfigurability, through switches, and ad-hoc nonlinearities, which may be used to augment the growing field of *reconfigurable intelligent surfaces* [17]. Opportunities to integrate wave-based analog computing into this radio-wave/mm-wave platform become particularly appealing, offering a natural way to engage the broad community of wireless communications and networks. Opportunities in this context have been recently explored in the area of information metamaterials [3].

Concluding remarks

Wave-based analog computing metamaterials have recently emerged as an interesting platform for ultrafast, compact and energy-efficient computation and signal processing. While the field is still far from being competitive to fully replace digital computers, it appears mature enough for applications in which the same operation, or a few distinct operations, are performed on various inputs in a massively parallel manner, for instance in the case of edge detection, equation-solving, matrix inversion, and even machine learning and Ising machines. The future may bring hybrid platforms in which these analog-based computers pre-process data to be fed to digital technologies. By enhancing their figures of merit and degree of reconfigurability a bright future for wave-based computing metamaterials can be envisioned, encompassing optical, radio-frequency, acoustic and mechanical wave platforms, and their combinations in multi-physics platforms.

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2. Neuromorphic metamaterials for embodied sensing, learning, and physical reconfiguration

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Status

A barrier to implementing truly autonomous robotic systems is the lack of distributed sensing integrated with localized computing. These capabilities are crucial to enabling intuitive proprioception (of position and movement) and exteroception (of external conditions) in complex environments. The desired introduction of proprioception and exteroception in autonomous systems has resulted in substantial research to instrument robotic platforms, smart wearables, and 4.0 industrial sites with arrays of sensors that require sophisticated hardware and software to process and store all the data they generate, often in real time [18]. This grand challenge is further compounded in adaptive systems that require expensive training efforts conducted offline from operation and frequently offsite, i.e. not on the autonomous system's physical embodiment [19]. Offloading data processing and decision-making to remote locations (e.g. data centers) dramatically increases the complexity, total energy consumption, and, crucially, the processing time, a scenario that can ultimately limit operation to controlled settings [20].

Meanwhile, organisms have neuro-mechanical systems that co-evolved with their physical morphologies to locally sense, learn, compute, and react at high speed and minimal energetic cost, e.g. via reflexes and central pattern generators [21]. This co-evolution decentralizes computing and control, freeing higher-level neurobiological regulation for performing other complex functions. For example, insects sense complex wing deformations under load and leverage local neuromechanical functions for adaptive flight planning under changing conditions [22] (figure 3(A)). Even without full neuromuscular control, this level of autonomy results from the intimate morphological coupling between passive anatomical structures that provide load-carrying and lift production functions along with distributed sensing and computation [23]. This example illustrates that successful implementations of autonomous systems for use in unstructured environments can benefit from designing adaptable and controllable physical structures embedding spatially distributed and energy-efficient sensory and signal-processing machinery.

We envision engineered metamaterials consisting of origami or shell-like units to offer a promising approach for realizing bio-inspired structural elements, such as skeletons, wings, and even skins, with reconfigurable shapes and tunable stiffness. Embedding sensors and electrical circuitry in these structures allows binary changes in the N unit cell configurations of the metamaterial to enable electronic storage and Boolean processing of a total of 2^N bits represented by the structure's mechanical configuration. Recently, multistable structures, including an origami arm [24] and discriminative metamaterial [25], demonstrated that sequences of local unit cell reconfigurations can be used to access the structure's unique and stable global configurations of such systems. These preliminary examples illustrate that purely mechanical structures can access higher dimensional state spaces through path-dependent structural transitions.

A separate approach to make sense of unstructured physical environments is to endow engineered structures with *neuro-inspired* sensing and computing functionalities [26] that use histories of physical states (e.g. morphological, electrical) to sense, learn, and calculate. We refer to such systems as *neuromorphic metamaterials* [27] (figures 3(B) and (C)). Despite a growing number of mechanical substrates proposed for conducting mechanologic [28], most do not consider prior inputs in performing computations. This implies that memory of prior events must either reside in another spatial embodiment or be stored elsewhere, such as *in silico*. Even rarer are physical substrates that concurrently show order-dependent responses (i.e. history-dependent strains) and substantial geometrical reconfigurations [29]. These are crucial characteristics in the quest to approximate neuromechanical functionalities.

Current and future challenges

Realizing the potential of neuromorphic metamaterial functionalities requires novel approaches to collocate sensing, computation, and physical reconfiguration, ideally within a single physical embodiment. This requires shifting from integrating different systems and using Boolean logic [30] to instead leveraging direct physical coupling between elements in the system, for example using mechanisms for sensing [31] and memory formation [32] that both intrinsically stem from the embodiment's morphological state.

Fueling this capability requires neuromorphic sensing and computing hardware that emulate activity-dependent synaptic plasticity, memory-formation, and threshold-dependent signaling [33]. This class of hardware includes both artificial synapses (e.g. memristors, transistors), whose history-dependent physical states allow them to be programmed, read, and used in-line for adaptive processing, and artificial neurons, capable of generating threshold-dependent responses for efficient event-based computing [33]. These types of emerging devices enable trainable physical neural networks through supervised or unsupervised updating of the elements' states.

Integrating neuromorphic devices into metamaterials is presently hampered by poorly understood and controlled properties of emerging neuromorphic components, which limit their use, longevity, and training; a lack of available neuromorphic mechanosensors that exhibit in-sensing plasticity, memory, and even threshold-dependence needed to mimic the use-dependent behaviors and energy efficiency of neural computation; and the need for specialized mechanical and electrical circuits that localize learning, computing, and control (e.g. central pattern generation) for responding to stimuli that affect the metamaterial. To further unlock adaptive neuromorphic metamaterials, we anticipate the need

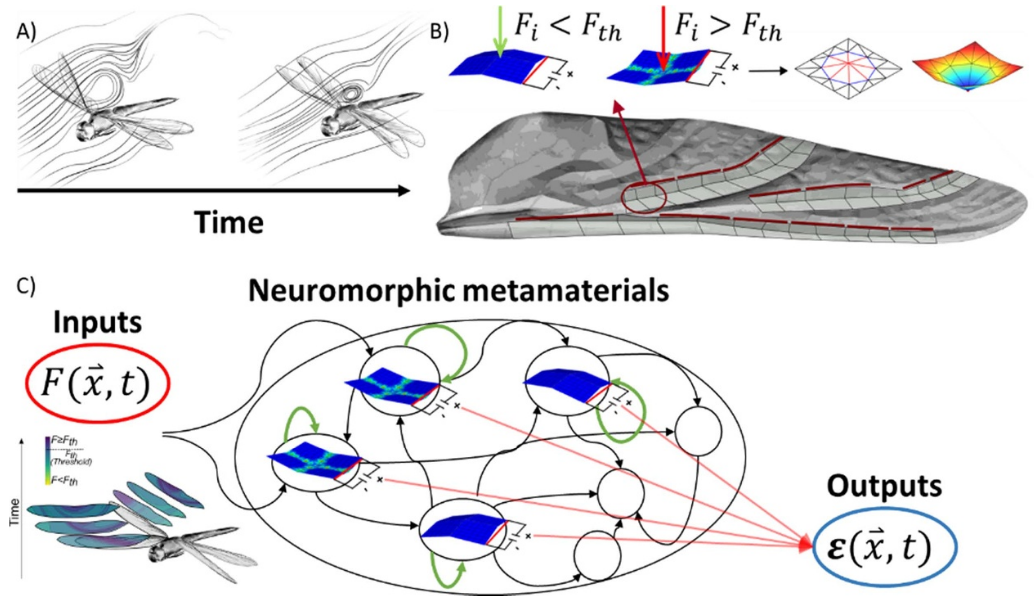

Figure 3. (A) Dragonflies use co-evolved neuromechanical systems and their flexible morphology to identify and control their states, enabling remarkable agility. (B), (C) Neuromorphic metamaterials displaying embodied sensing, computation, and reconfiguration, can enable local and efficient information processing with minimal ancillary systems for data encoding.

for neuromorphic materials that better emulate the diverse behaviors of biological synapses and neurons, including their intrinsic dynamics and memory storage across multiple time domains needed to process multi-modal inputs and different events effectively; the need for co-design and co-manufacturing processes for integrating metamaterials and support electronics that effectively couple them across physical domains (e.g. strain to electrical resistance); and neuroscience-informed understanding of how learning and training can be performed to minimize cost and maximize performance.

Advances in science and technology to meet these challenges

Metamaterial substrates employing intrinsic neuromorphic functionalities must display inherent capabilities to extract critical information from environmental stimuli, exhibit intrinsic memory, and show passive or active geometrical reconfigurations. We and others have contributed recent advances that begin to address these challenges.

An example of a fully mechanical neuromorphic metamaterial is a dome-patterned metasheet [29] that displays order-dependent deflections in response to forces on the domes (figures 4(A) and (B)). The bistable unit cell domes work as mechanosensors that filter out insufficient inputs and also amplify supercritical signals from external stimuli (e.g. pressure or temperature) that push them into an inverted state [27]. Threshold-dependent mechanosensing, combined with their direct effect on the global structure, allows for simultaneously storing memory and large-deformation geometrical morphing as more domes are inverted. Notably, an order-dependent sequence of N transitions accesses a total number of states that scale with $N!$, much stronger than the conventional exponential scaling (2^N) obtained by path-independent configurations of bistable unit cells. In this way, a much larger number of possible deflection patterns, and thus physical memories, can be surveyed and stored by the metamaterial. This type of history-dependent behavior combines memory formation and geometrical reconfiguration in response to external inputs embodied into the substrate.

Building on this response, we developed a dome-patterned metamaterial instrumented with piezoresistive strain sensors and nonvolatile memristors to transduce and remember the deformation states of the domes across successive mechanical inputs [27]. This embodiment represents a significant step toward autonomic neuromorphic metamaterials as it combines the ability of the coupled bistable unit cells to spatially filter and amplify physical inputs and the use of nonvolatile memristors to store histories of dome inversions as readable electrical states (figures 4(C)–(E)). In this fashion, spatially distributed mechanical signals become analog material states within the structure. Moreover, this metamaterial class features analogous behavior to threshold-dependent event cameras augmented with nonvolatile memory that encodes the images directly into the physical network's weights, effectively embodying a Hopfield network in the metamaterial (figures 4(f) and (G)).

Another promising example of linking mechanosensing with neuromorphic signal processing and actuation was recently reported by Sun *et al* [34] who demonstrated reflex-like autonomic responses using synapse-controlled artificial muscle actuators. This work illustrates key ideas of our concept, which, if combined with a reconfigurable structure, could lead to more complex proprioception-like capabilities. Separately, Maraj *et al* [35] demonstrated that artificial synapses exhibiting bio-realistic forms of short-term plasticity, including sensory adaptation, contribute nonlinear signal processing dynamics that specifically benefit pattern

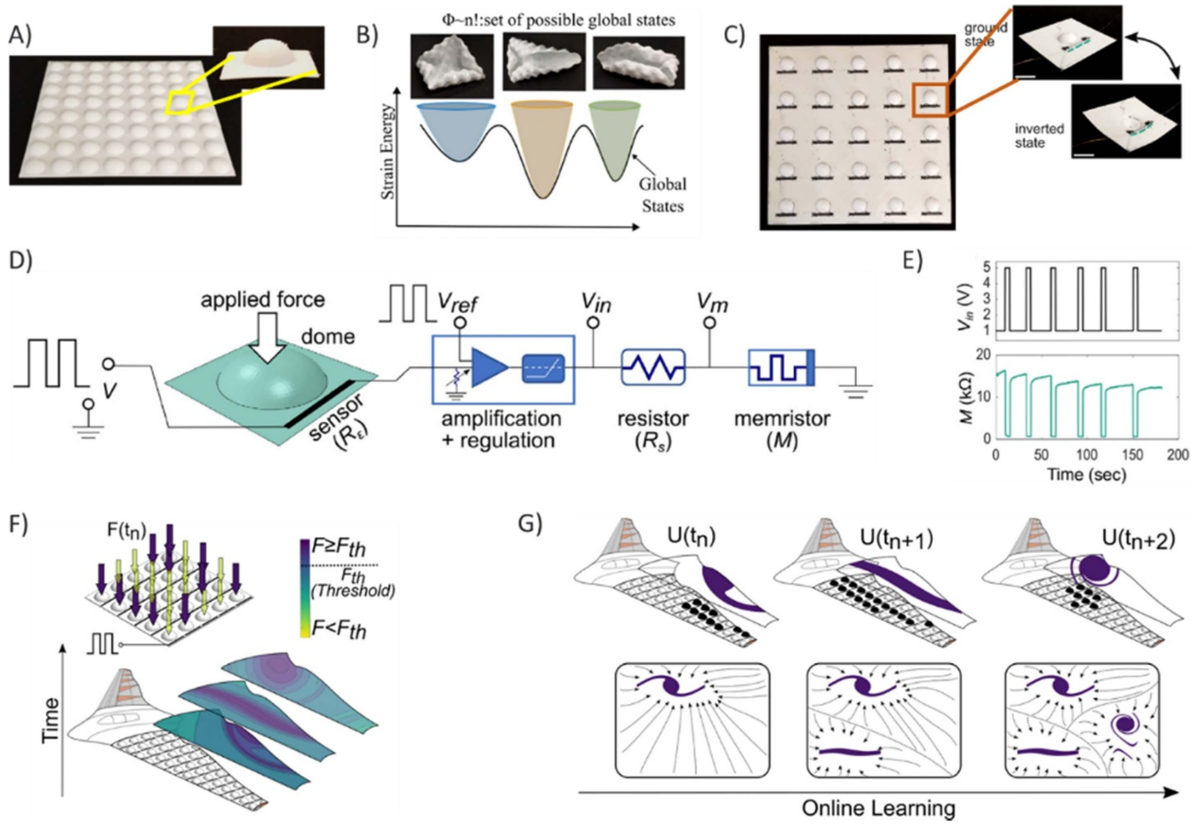

Figure 4. (A) Dome-patterned metasheet formed by locally bistable units. (B) Global coexisting stable shapes of a metasheet, each of which is associated with an energy minimum that can be abstracted as history-dependent state reach via a particular dome inversion order. (C) Metasheet functionalized with piezoresistive sensor. (D) Schematic for 1:1 dome–memristor connection illustrating how the memristor's state changes in response to transducing dome inversions. (E) Incremental reductions in memristance induced by 6 subsequent dome inversions corresponding to when the input voltage is 5 V, following the scheme in (D). (F) Illustration of implementation of metasheet as a wing skin capable of filtering out data, only recording forces when exceeding a desired threshold F_{th}. (G) This class of metasheet embodies a physical Hopfield network capable of learning online important spatiotemporal force patterns $U(t_n)$. (D) and (E) Reproduced from [27]. CC BY 4.0. (F) and (G) Adapted from [27]. CC BY 4.0.

classification. Capabilities like this could improve event detection and support model-free reinforcement learning in robotic systems. More recently, Song *et al* [34] proposed that the brain uses a method called *prospective configuration* to determine the path of error in neural network outputs [36]. This concept is consistent with patterns of neural activity and performs more efficiently and effectively than backpropagation, including in online learning, learning with limited training, and learning in changing environments. Advances in neuroscience of this nature are crucial to devising neuromorphic metamaterials capable of genuine autonomy.

Conclusions

Emulating the morphological intelligence of living creatures remains an aspirational goal for designing autonomous robotic platforms. If successful, we envision a new generation of robotic systems outperforming current approaches for demanding applications such as morphing aircraft, autonomously reconfigurable robotics (e.g. vehicles, soft robots, surgical), human assistive technologies (e.g. exoskeletons), and smart wearables. Satisfying this goal will require multifunctional hardware to process multi-modal sensory information, store memories for later reference, and adaptively compute appropriate responses. In this article, we proposed that introducing history-dependence into a reconfigurable structure and its embedded sensors and computing circuitry will result in a new class of neuromorphic metamaterials capable of far greater sensing, learning, computing, and actuation feats than current systems. Despite recent advances in the field of mechano-intelligence [28, 37], successful future embodiments must rely on the ability for efficient coupling of energy, memory, and stored states across multiple physical domains and leverage a neuroscience-informed co-design of the physical structure and embedded sensory and computing systems.

Acknowledgments

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3. Materials tactile logic

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Status

'Materials tactile logic' is a concept meant to inspire new types of *materials* (e.g. material composites or devices) that can carry out *logic* based on *tactile* input (*i.e.* the way the material is touched or manipulated). Here, the word 'logic' loosely means that the material will respond appropriately to a variety of inputs, similar to the outputs predicted in a logic truth table. Examples of responses could include actuation, stiffening/softening, changing optical properties, warming/cooling, or expanding/contracting. As an illustrative example, consider the famous Venus fly trap [38]. The Venus fly trap is a plant that snaps shut to capture insects when it is touched a certain way. Such plants do not have neurons or transistors to help make decisions on when to close or open. Furthermore, the plant goes beyond being a simple 'responsive material' because it only snaps shut when it is touched in a certain way (multiple touches), which helps to avoid expending energy in response to non-prey. While such a system does not have all the hallmarks of intelligence, it is nevertheless remarkable, especially considering the materials involved are soft. There is growing interest in making soft robotic or electronic devices because they have similar mechanical properties to human tissue and can therefore interact safely and comfortably with humans. It raises the question: is it possible to design soft materials to behave with such sophistication? To date, the answer—in my opinion—is simply 'no', but I hope this short article may inspire future advances.

Current and future challenges

As one modest example from our group, we created a soft tactile logic device consisting of a slab of silicone with embedded soft circuits composed of liquid metal (figure 5) [39–41]. Here, the liquid metal is eutectic gallium indium, a room temperature liquid metal with low toxicity, vapor pressure, and viscosity. The liquid metal traces are like 'veins' that carry energy throughout the material. When touched, local deformation of electrical components (e.g. conductive traces of liquid metal) changes the properties of the circuit. In this simple design, the deformation decreases the cross-sectional area of the liquid metal, thereby increasing the local resistance. With thoughtful design, such changes can be used to divert energy (electrical current) to new places in the slab or to even change potential drops through the circuit. The latter is useful for turning on/off components that have a threshold voltage, such as LEDs. In essence, the slab couples electrical properties with mechanical deformation (shape change) resulting from touch. The

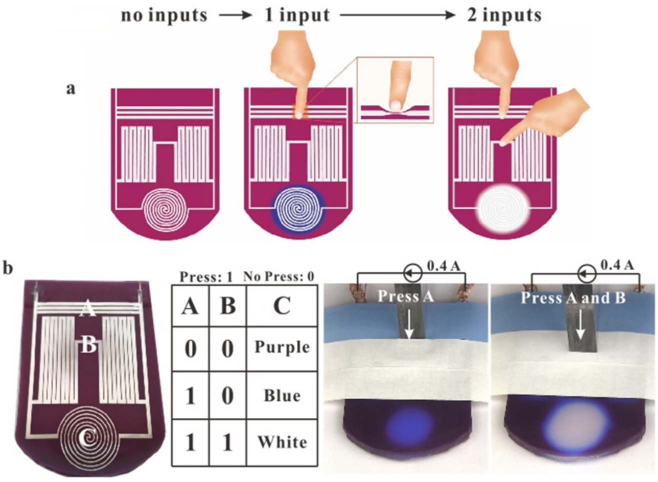

Figure 5. (a). A slab of elastomer containing thermochromic pigments and a circuit consisting of liquid metal. (b). The liquid metal traces are labeled. Touching liquid metal trace (A) increases the local resistance, diverting current to C, triggering a color change by Joule heating. Touching liquid metal wires A & B diverts even more current to C, causing additional color change. The results produce a 'truth table' with outputs depending on how the material is touched. This simple device performs logic in response to touch without any rigid materials, transistors, or neurons. Adapted from [39]. CC-BY 4.0.

electrical energy can be used to do work (power a motor, turn on lights, heat the material) based on the design of the circuit and the mechanics of the material. We demonstrated rudimentary logic by showing 'truth tables' based on the way the material gets touched (figure 5). For example, if we describe a touch as a '1' and the absence of touch in a region as a '0', one can imagine different combinations of 1's and 0's to produce different outputs. While the concept shown in figure 5 is simple, it has several notable features: (1) it is entirely soft, (2) there are no neurons or transistors, yet it can complete rudimentary logic, (3) the response is distal—that is, the output is not in the same point as where it is touched. Perhaps more importantly, it may offer a way to decentralize decision making and offer 'reflex' responses in materials. Although it is simple, this example can perform 'NOR' type operations, which is considered a 'universal gate' because they can be used to implement all other basic logic gates and, by extension, any complex logic circuit [42]. The conclusion discusses other soft components that could be used to make even more complex responsive circuits.

Advances in science and technology to meet challenges

Consider the human body for context. The human body uses neurons to carry out complex tasks by using a 'sense-compute-respond' feedback loop. For example, imagine the seemingly 'simple' task of picking up an apple. You use your senses (touch, typically in combination with sight) to detect the apple.

When you touch the apple, signals go from your hand to your brain, which then effortlessly routes signal to your muscles to properly grasp the apple without crushing it or dropping it. This sort of feedback loop involves information transmitted rapidly back and forth to a centralized location (the brain). What if an artificial gripper could directly know how to grasp the apple by building 'tactile logic' directly into the gripper, thereby avoiding the complexity of communication among multiple sensors? The human body does avoid the 'sense-compute-respond' loop via so-called 'reflex responses' that require faster responses, such as jerking your hand away from an unexpectedly hot object. While perhaps such a sophisticated response is not realistic in man-made systems, it may help inspire 'tactile logic' for new types of wearable devices and soft robotics with reflex-like behavior [43, 44] or multiplexed sensor arrays [45] (see also chapter 6 herein). In essence, materials are needed that can do complex tasks or filter information locally without conventional transistors, neurons or feedback loops, and do so simply based on the materials of construction, communication among the materials, and overall geometry.

Concluding remarks

To achieve the full scope of this 'materials tactile logic' concept, devices may benefit from materials with non-linear responses, threshold behaviors, distal responses, logic, and maybe even memory. The first two concepts imply materials that have an insignificant response to an input until a threshold (e.g. force) is reached, thereby moving away from analog responses. Additional 'responsive' circuit elements may be possible, such as variable capacitors [46], mechanically tunable antennas [47], or liquid inductors [48]. In his book '*Song of the Cell*,' author Siddhartha Mukherjee describes neurons not just as passive 'wires', but as 'active integrators' that only fire based on the integrated total of both excitatory or inhibitory inputs. It seems that such principles could be enabling for dynamic computation in soft materials in response to external stimuli.

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N/A

4. Mechanical logic and autonomous materials

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Status

Fueled by the widespread adoption of new computational design approaches and additive manufacturing techniques, recent decades have seen myriad advances in the understanding and development of mechanical metamaterials and associated mechanisms. These systems have contributed to an ever-expanding design space available to engineers, offering control of properties ranging from stiffness and Poisson's ratio to band gaps and energy localization [49, 50]. Going beyond these traditional targets, researchers have recently begun to explore how mechanical systems could be designed to process information (i.e. mechanical computing). For example, functionally complete mechanical logic has been demonstrated in a variety of static and dynamic mechanical systems [30], often employing multistable mechanisms to enable digital logic or a variety of other unconventional approaches for achieving analog (e.g. neuromorphic) mechanical computation [51–53].

However, like any computer, mechanical computers must be able to interact with their environment, accepting information as inputs, and, after performing a computation on those inputs, making the results of computational events available as outputs (figure 6). Obviously, mechanical systems can receive mechanical inputs, and, in fact, interesting 'transformable mechanical metamaterials' have been studied that use one type of mechanical input (e.g. static force) to change a different mechanical property (e.g. band gaps [54], functional logic [55]). However, numerous additional inputs are potentially possible. Many stimuli-responsive materials have been developed in recent decades that transduce physical information in the environment, such as temperature, voltage, humidity, or pH, into mechanical deformation or property changes. For example, liquid crystal elastomer (LCE) architectures can be 3D printed that transduce temperature changes into curvature changes [56]. Similarly, hydrogels can be used to transduce moisture changes to volumetric and/or curvature changes [57]. There are now a few examples that have integrated such materials with mechanical logic, allowing the system of mechanical logic to take environmental signals as inputs and mechanically compute on those inputs [58–62]. The output of the computational event is typically a change in shape and/or properties of the mechanical system. Long-term, these mechanical systems have the potential to lead to autonomous robots for harsh environments and medical applications, and may enable integration of smart metamaterial devices with traditional electronics to provide more efficient hybrid systems in aerospace, environmental monitoring, etc.

Current and future challenges

Just as with the digital electronic computer, mechanical digital logic can perform a variety of abstract computations, including functionally complete logic. However, there are many challenges related to mechanical logic that must be addressed before such systems will be seen as relevant. We highlight two here:

First, early examples of mechanical logic have been larger, slower, and less energy-efficient than digital electronic computers. While miniaturization is possible [63], and can improve these issues, it may be that mechanical logic will never be able to compete directly with digital electronics using these traditional metrics. Instead, are there new conceptual frameworks and metrics under which mechanical computing would prove desirable? For example, unlike transistors in digital electronics, in mechanical computing, a change to the information state is usually associated with significant deformation or motion (e.g. a bistable spring that snaps between two stable configurations). As a result, the shape and mechanical properties of the mechanical system can change significantly as information is processed. Given this, can the system be designed to directly map inputs (environmental stimuli) to outputs (i.e. shape changes, property changes, or direct actions performed on the environment) without taking unnecessary transduction steps outside the relevant physics in which the system finds itself? This could prove advantageous relative to digital electronics, which, to achieve similar results would need to transduce environmental inputs to voltages, process these, then transduce the voltages back to the desired physical changes. If mechanical computing is to be defined in this manner, it necessitates a new conceptual framework along with corresponding design principles. These principles should probe the fundamental mechanisms of information storage, retrieval, processing, time synchronization, computation, and learning based on the interactions among the various components within the mechanical system. Conventional computing frameworks typically assume that the goal is to achieve devices capable of universal computation. However, physical computing taking place in materials or at materials interfaces will often be applied toward applications in which universal computation is not required or desired. Hence, unconventional metrics and alternative computing frameworks are necessary. It is not yet clear how general these frameworks can be, or if they must be predominantly device-specific.

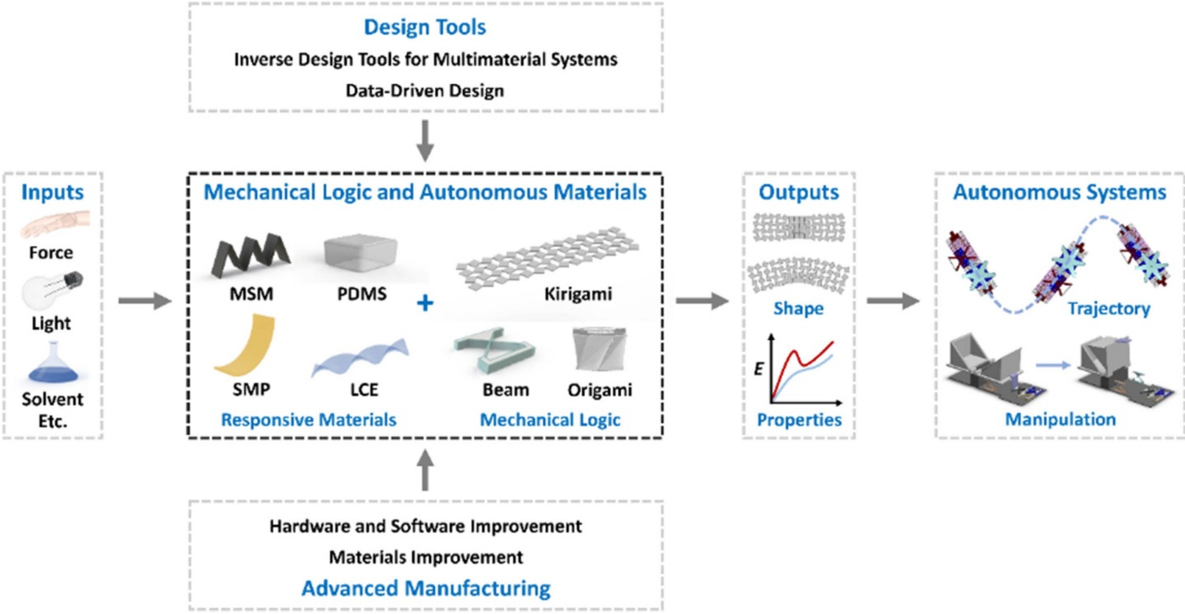

Figure 6. Mechanical logic and autonomous materials. Integration of stimuli-responsive materials with mechanical logic can enable the system to sense multiple inputs simultaneously. The logic can then autonomously compute the output based on those inputs, which typically takes the form of changes in shape and/or mechanical properties. This enables the system to perform autonomous tasks. To achieve this, however, more capable inverse design tools and improvements in multimaterial manufacturing are essential. Adapted from [59]. CC-BY 4.0. From [61]. Adapted with permission from AAAS. Adapted from [66]. CC-BY 4.0.

Second, to what extent is it possible to make mechanical logic 'autonomous' and more 'resilient'? Mechanical metamaterials have been previously designed to exhibit tunable mechanical logic as a function of static deformation [55] (e.g. acting as 'OR' or 'AND' depending on how much static loading is applied). However, transduction from other forms of information into mechanical inputs is also possible, allowing 'metamaterials' to perform some robotic functions autonomously. For example, liquid crystal elastomers can transduce thermal information from the environment into a mechanical signal that can be used as an input in mechanical logic [61]. However, different responsive materials have different characteristic time scales, interfacial characteristics, and material incompatibilities, etc, which currently require case-specific, ad hoc design. This limits the generalizability of the autonomous mechanical logic systems that have been developed to date. In addition to autonomy, mechanical logic based on metamaterials naturally enables systems to perform tasks without relying on a centralized processor. Unlike conventional electronic computing methods, the distributed nature of this mechanical logic is more resilient. Potential advantages include increased redundancy, exceptional adaptability to dynamic environments, and reduced risks of failure. For instance, stimuli-responsive mechanical systems can be designed to autonomously change their shape, and, consequently, their static and dynamic mechanical properties, in response to environmental stimuli [64]. Changes to the properties can then be used as a proxy for determining the configuration of the system, analogous to proprioception in biological systems. The interactions among distributed components govern their collective static and dynamic properties through communication and cooperation. However, in mechanical systems, the components tend to be mechanically coupled; the local deformation induced by one component will significantly influence the adjacent ones. This coupling effect becomes more complicated as the interactions among components intensify.

Advances in science and technology to meet challenges

Perhaps the most critical advances needed to address the challenges described above are significantly more capable design tools. Unlike an ideal transistor, which changes state without changing properties, internal mechanical coupling is intrinsic to mechanical logic, leading to deformation, and potential property changes, as the computation occurs. While judicious use of soft and rigid components can minimize this in some cases, it cannot eliminate it. As a result, there is no direct analogy for mechanical logic available from the compilers and circuit design tools used for the design of digital electronics. Instead, mechanical logic is embodied in the internal mechanical coupling of the system, making it far more challenging to produce a modular circuit of discrete subsystems. Therefore, achieving a specific set of mechanical logic may require that the entire body be designed in one step. This becomes all the more challenging if responsive materials are integrated with the mechanical system. Each material brings its own time scale and set of potential material incompatibilities. These challenges have been a significant roadblock in the design and realization of mechanical logic with meaningful complexity. To overcome this, inverse design tools are needed that can algorithmically construct coupled mechanisms and associated placement of responsive materials, accounting for nonlinearity of the mechanisms, for kinematic incompatibilities, and for materials challenges that arise in multi-material architectures [65] (e.g., different time scales and interfacial incompatibilities). Additionally, topological optimization can be employed to guide the designs of mechanical metamaterials. Given the large number of design parameters inherent in mechanical structures and stimuli-responsive materials, data-driven approaches may be necessary for the design of mechanical computing systems.

Moreover, there still remain practical challenges in manufacturing these multimaterial systems, though available tools have significantly improved in recent years. Integration of responsive materials in mechanical logic is particularly challenging in practice, because these materials are often difficult to pattern with the resolution that is required for the nonlinear mechanisms (e.g., multistable mechanisms) that are often used for mechanical logic. Continued improvements in both multimaterial 3D printing hardware and the chemical formulations of responsive materials are essential for allowing more complex mechanical logic to be constructed and integrated (e.g., in robots) in practice.

Concluding remarks

The combination of mechanical logic and stimuli-responsive materials has the potential to allow engineers to embody some simple decisions in the distributed material/structure of a system or device. In the future, mechanical logic might also be considered to operate synergically with conventional electronic components, thereby establishing a hybrid computational system that leverages the strengths of both. This integration could significantly enhance system performance and form factor, facilitating broader adoption within the robotics community. For example, mechanical computing may be of use as a pre-processing strategy when external stimuli are particularly complex. Mechanical systems could act as information filters, adapting to external forces, or sensing and responding to local stimuli. Subsequently, only key information can be communicated from the mechanical computing system to a more conventional electronic computing system, which would be responsible for higher level functions such as long-term planning. To draw an analogy, it is computationally expensive to safely pick up a delicate object with a traditional robotic gripper made with rigid materials. Using a soft gripper instead can replace a significant amount of this computational cost, simply because the material itself safely conforms to the delicate object. Likewise, autonomous mechanical logic may significantly reduce the centralized computation that is necessary to make some simple decisions (such as trajectory decisions [61] or reflexive actions), or may facilitate simple autonomous behaviors where length scales are not compatible with conventional electronic form factors (e.g., microscale medical robotics). However, research progress in this area, and certainly the practical adoption of these ideas, is inhibited by a dearth of design tools that can automate the design of autonomous mechanical logic, accounting both for the design of coupled nonlinear mechanisms and the behavior of stimuli-responsive materials.

Acknowledgments

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5. Mechanical metamaterials with memory

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Status

Mechanical metamaterials (MMMs) leverage the geometry of their structural layout to embody functionalities beyond those of bulk and classic composite materials. MMMs can be classified depending on (1) the prominence of geometric nonlinearities, (2) the complexity of their design and target function, and (3) the flexibility in tuning or reprogramming functionality post-fabrication.

(1) Initially, the field focused on designing and realizing MMMs with unusual mechanical properties and functions, such as negative Poisson's ratio, extreme stiffness-to-weight ratio, or chirality, described by bulk material parameters within a linear-response framework [67]. However, given the ease of slender structural elements to exhibit geometric nonlinearities (e.g. buckling or snapping), distinct from constitutive nonlinearities (e.g. hyperelasticity, visco-elasticity/plasticity), there has been an upsurge of strongly nonlinear MMMs [67–70].

(2) We distinguish three types of MMMs by their intended function and complexity of design: (i) **Architected materials** feature periodic arrangements of unit cells to achieve continuum-like properties. (ii) **Shapeshifters** are small, aperiodic structures capable of single-step shape morphing in response to external stimuli. (iii) **Machine-like MMMs** blur the boundary between mechanisms and devices, employ multistep and internal reconfigurations, and are specifically designed to exhibit complex functionalities such as memory storage [71], sequential shape-morphing [24], non-reciprocal transmission [72], or signal counting [73].

(3) We further distinguish different levels of post-fabrication versatility: (a) **Pre-programmed MMMs** have layouts that are frozen during fabrication and cannot be modified subsequently. (b) The properties of **tunable MMMs**, related to the wider class of smart materials, can be modified by external stimuli such as orthogonal mechanical driving [68], heat [74], light [75], or magnetic fields [76]. (c) **Re-programmable MMMs with memory** comprise multistable unit cells, leading to distinct and externally accessible internal states, which, ideally, together with the corresponding functionality, can be modified post-fabrication to yield reprogrammable behavior [24, 69, 70, 77]. Figure 7 illustrates the classification of mechanical metamaterials (MMMs) based on their post-fabrication versatility, highlighting an example from each category.

Here, we focus primarily on the emerging confluence of (iii) machine-like and (c) re-programmable MMMs with memory; their multifarious nature and storage of information are at the core of recent exciting developments aimed at realizing unprecedented functionalities, such as physical intelligence, in materia [78].

Current and future challenges

Multistable unit cells are at the core of MMMs with memory, with two broad strategies to realize them: via discrete elastic instabilities (geometric nonlinearities) or plastic flow of the unit cells (constitutive nonlinearities). Either strategy can be followed to devise MMMs whose internal states store memory of past driving conditions.

Discrete memory units can be realized using pre-buckled beams, bistable shells, or non-flat origami elements. Under an imposed transversal load (by contrast to imposed displacement; cf. Maxwell condition), such elements can suddenly and sharply switch, often through snapping, from one stable state to another. As a simple model, one can consider the classic von Mises truss, whose bistability is associated with a bi-well energy landscape. By analogy with bits of information in digital computing, one may label the stable states of bistable units as '0'or'1'. A crucial feature is that the transitions between these states are hysteretic, with a range of external driving parameters where the system can be in either state, depending on its history. These hysteretic bistable elements can then store one mechanical bit. Recent years have seen an upsurge in interest in mechanical hysterons, both to describe memory effects in complex media [79] and as building blocks of MMMs with memory [24, 73]. Evidently, MMMs may feature multiple hysterons to amplify the number of stable states, thereby enhancing their potential for programmability.

We envision four primary challenges in realizing MMMs with memory: (1) designing the bistable units, (2) accessing their internal states, (3) controlling interactions, and (4) leveraging the internal states and their interactions to arrive at functional properties. (1) The first challenge is the design of the underlying bistable elements and optimizing their operational conditions. While most bistable elements facilitate control of the size of the hysteresis loop, independent control of both the $0 \rightarrow 1$ and $1 \rightarrow 0$ transitions often requires a symmetry breaking in the original design. (2) Another challenge is addressing these elements, akin to digital memory. One can straightforwardly access all internal states directly [77], but perhaps surprisingly, for bistable elements with ingeniously designed different switching thresholds, all internal states can also be reached by appropriate global sweeps of the control parameter [80]. (3) A third challenge concerns leveraging intra-element interactions. For arrays of independent bistable elements, given that the switching of one element does not

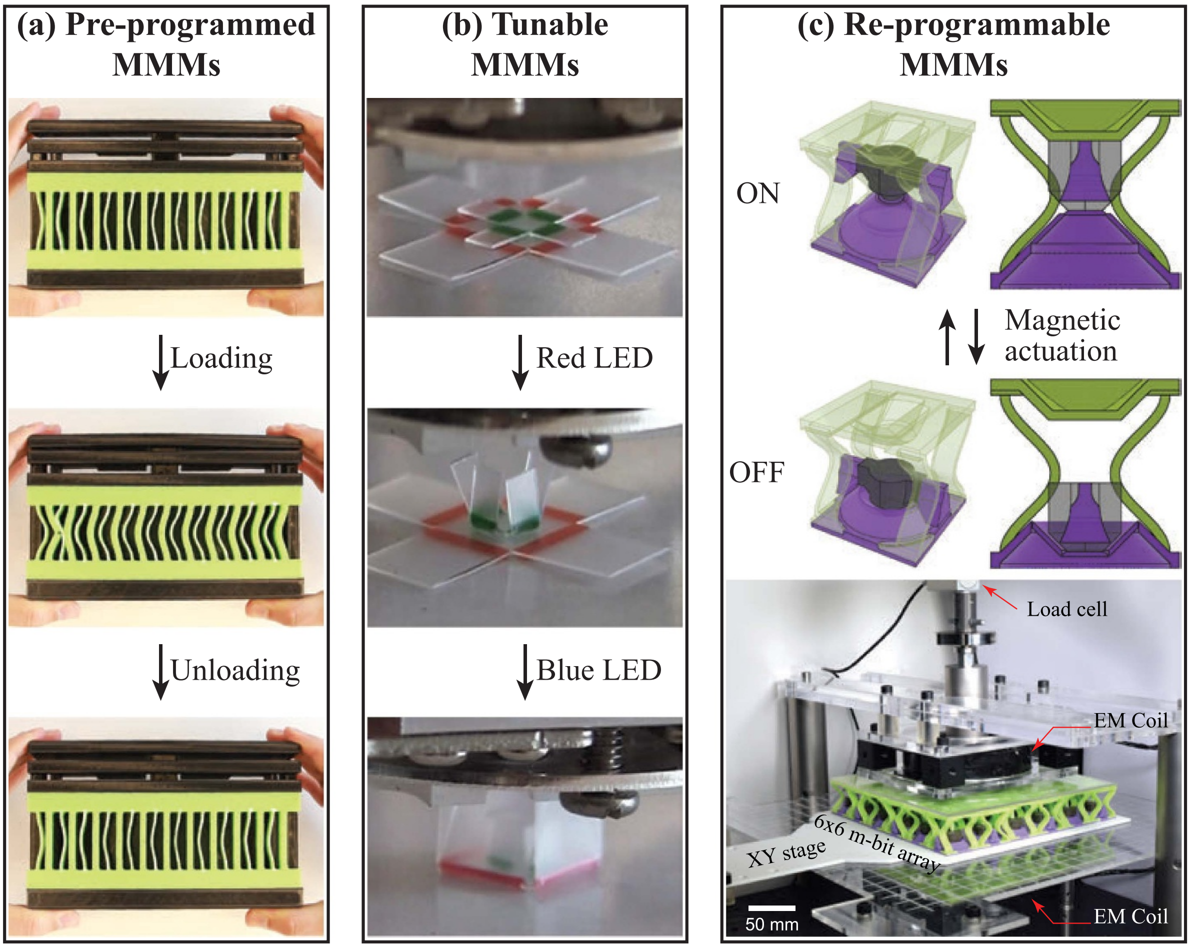

Figure 7. Classification of metamaterials based on post-fabrication versatility, with an example for each category: (a) Pre-programmed metamaterials (MMMs): These have fixed configurations determined during fabrication and cannot be altered afterward. The displayed example is an irreversible metamaterial that counts mechanical driving cycles and encodes the results into interpretable internal states. Adapted (figure) with permission from [73], Copyright (2023) by the American Physical Society. (b) Tunable MMMs: these belong to a broader class of smart materials, where properties can be altered by external stimuli. The shown example demonstrates sequential self-folding of two-dimensional polymer sheets into three-dimensional structures, activated by specific wavelengths of light (red and blue LEDs). Adapted with permission from [75]. CC-BY 4.0. (c) Re-programmable MMMs: These feature multistable unit cells, allowing for distinct internal states that are externally accessible. The functionality can be reprogrammed post-fabrication. The illustrated example is a tileable mechanical metamaterial with bistable memory at the unit-cell level. It can be switched between two stable states using magnetic actuation, each associated with a distinct mechanical response. The system is fully elastic, allowing reversible cycling until reprogrammed. Adapted from [77], with permission from Springer Nature.

depend on the state of the others, the sequencing of state changes is limited. Recent theoretical work indicates that interactions between the bistable elements, where the switching threshold of one element depends on that of others, can provide more complex pathways and advanced memory capabilities [81]; realizing such interactions is an exciting opportunity for future work. (4) A final crucial challenge is coupling these memory elements to a meaningful property of the MMMs. Recent examples include MMMs whose shape [24] or mechanical properties [77] depend on the internal state, and we see considerable potential for the development of novel, reprogrammable functionalities using this internal-state coupling.

Many MMMs with memory explored to date rely on bistable elements, and while multistable elements, such as tristable origami and kirigami [82–84] could be used for implementing ternary logic, the tradeoff between capacity and robustness likely favors bistable elements as building blocks for circuits, just as in digital logic. The incorporation of building blocks that leverage cumulative plastic flow however, could potentially lead to a continuous updating of the memory and functionality of the MMM. Whereas work along these directions is scarce, we envision that plasticity [85] or frictional contacts [86] can be exploited to obtain continuously updatable internal degrees of freedom. Self-learning materials are a particularly exciting context to develop such ideas, and there are already a few efforts in this direction [87]. These physics-based 'learning rules,' which we anticipate depending on the continuous and irreversible evolution of properties (e.g. changes in the local length of beam elements, elastoplastic hardening of the material, or sliding frictional contacts), suggest that appropriately designed metamaterials could pave the way for a new class of self-learning matter.

Advances in science and technology to meet challenges

The design space of MMMs with memory is large, and their response may be highly nontrivial. To explore opportunities, and before tackling concrete applications, we should continue emphasizing minimal experimental and theoretical models with a curiosity-driven approach. In addition to elastic instabilities, future efforts should also harness constitutive nonlinearities (e.g. visco-elasto-plasticity of metals and polymers, shape-memory effects, or frictional contacts) and employ advanced/soft materials responsive to diverse stimuli (e.g. light, swelling, temperature, electromagnetic loading) to broaden the scope of potential functionalities of MMMs with memory.

Throughout, one should interpret physical intelligence broadly in the context of information processing. Recent efforts have focused on combinatorial/Boolean logic [30], where the output is a direct, logical function of the input. More ambitiously, one could target MMMs as finite state machines, where the output is dictated by both the internal state and the current input; such devices are computationally far more powerful than combinational logic. Further ahead, exploiting plasticity effects to realize continuously updatable MMMs may lead to mechanical implementations of neural networks [88] or self-learning materials [87]. The hierarchical assembly of unit cells is another important topic for future attention, questioning the optimal architecture for mechanical computing: the choice between centralized control versus a distributed network of minimal mechanical computing elements. The unique benefits and challenges of each strategy remain to be explored and evaluated.

Concluding remarks

In charting a roadmap for a new generation of physical-intelligent systems based on hierarchical assemblies of re-programmable MMMs with memory, one might question whether these efforts simply revisit concepts in classical mechanical computing. However, the shift toward leveraging geometric instabilities and employing soft/smart materials, while coupling these with material nonlinearities, for multistability, logic, and information processing departs significantly from the reliance on traditional mechanical computing on rigid elements and contact-based nonlinearities. Following this path offers many possible advantages. For instance, MMMs with memory may enable 'always-on' computing without external power supplies. Such a direction would significantly enhance efficiency, eliminating the conversion between physical and symbolic domains and circumventing the current over-engineering usage of microprocessors, which, despite their low cost, are often excessive for simple robotic tasks. A new wave of physical intelligence based on MMMs with memory would embrace the inherent complexity of nonlinearities to engineer functionalities that surpass the current state-of-the-art. Potential destinations for this roadmap include embodying physical intelligence into flexible and adaptable mechanical systems for advances in soft robotics, deployable structures, shock absorbers, embedded sensing, MEMS/NEMS electro-mechanical systems, and self-computing microfluidic devices. It will be exciting to see where the road will take us.

6. Soft matter computing and intelligence

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Status

The integration of intelligence into inanimate soft matter represents a transformative shift in materials science and engineering, where the focus extends beyond cultivating unique physical responses to now also giving rise to autonomous and complex behaviors. Intelligence can be defined as the ability of a system to sense an external stimulus, process the incoming information based on current and past conditions, and act accordingly [89, 90]. The fundamental relationship among these requisite elements of intelligence is illustrated as a feedback loop in figure 8(a). In recent years, extensive research has been conducted to develop field responsive materials capable of sensing and responding to a variety of environmental stimulus such as thermal, electrical, optical, or magnetic excitation [91–93]. Yet, these responsive materials lack the inherent ability to process and store information, thus falling short of textbook intelligence.

A compelling method for embedding information processing capabilities into soft matter involves incorporating principles of mechanical computing [30]. Specifically, researchers have drawn inspiration from traditional computers to use digital information processing methods. By abstracting digital states from mechanical configurations, digital mechanical bits can be identified. For example, figure 8(b) shows a single elastomeric mechanism which serves as a mechanical bit. The direction of rotation of the polygonal section indicates the binary value of the unit with clockwise (CW) and counterclockwise (CCW) representing '0' and '1', respectively. Researchers have explored a wide range of kinematic mechanisms and metamaterial designs to represent mechanical bits which can serve as the foundation for all digital logic gates: buffer, NOT, AND, OR, XOR, NAND, NOR, and XNOR [58, 94–97].

With the foundation of digital logic gates, principles of Boolean algebra can be applied to design soft matter systems capable of more complex calculations [98, 99]. El Helou *et al* [37] outlined a method to realize all combinational logic operations in soft mechanical integrated circuits with mechanically reconfigurable electrical circuits that combine buffer and NOT switches, figure 8(b), in series and parallel. In the illustration shown, the light grey conductive network allows electric current to flow between an input voltage and an electrical output based on the configuration or state of the rotated segment.

Building on the established principles of mechanical computing and Boolean algebra, the last component to achieve textbook intelligence within soft matter systems is the introduction of feedback mechanisms with adaptive memory capabilities [100–102]. The integration of feedback and adaptive memory with combinational logic facilitates sequential logic operations. Unlike combinational logic that delivers outputs based only on current inputs, sequential logic incorporates past states to make decisions. Figure 8(c) shows an example of a soft mechanical T flip flop material system that represents a fundamental element of sequential logic. The reconfigurable conductive Ag-TPU network [96] sends an electrical signal based on the current state to an electroactive liquid crystal elastomer (LCE) actuator to switch or toggle the system to the opposite state. In state $Q = 0$, the conductive path on the left connects the input voltage V_{cc} to the red output ΔQ_n. The red output is electrically connected in the back to the electroactive LCE actuator which is shown with the dotted red line in the middle of figure 8(c). The contracting LCE pulls the system to the opposite state, $Q = 1$, where the process repeats for the right LCE actuator. The mechanical flip flop will continue to toggle between configurations while power is applied. Recent work shows how this basis of sequential logic is expanded to design a mechanical material system capable of solving linear algebraic equations with a self-reconfiguring optimization algorithm [103]. Figure 8(d) demonstrates how an intelligent soft material system can be scaled to have increasing information processing density and more memory by combining more fundamental switches in series and parallel. Other examples of sequential logic operations such as shift registers and D flip flops have been explored in microfluidic networks and other mechanical platforms [104–107]. Sequential logic capabilities lay the foundation for more sophisticated tasks such as learning and autonomous operation. The integration of mechanical computing, memory, and adaptive feedback signifies a significant step forward in realizing intelligence in soft matter systems.

Current and future challenges

While soft systems offer unique advantages in terms of flexibility, biocompatibility, and the ability to operate in harsh environments where traditional electronics fail, soft matter computing systems still lag in terms of computational speed and capacity. This disparity highlights the challenge of identifying the appropriate niche or application where the strengths of the soft system outweigh the limitations. Such applications may include areas such as human–machine interfaces, unstructured environmental exploration, or biomedical applications. The pursuit of such applications requires advances in materials science, mechanical design, and computing principles that can leverage the inherent properties of soft matter. Key advancements needed to drive the field forward include the development of faster, higher-capacity responsive materials and improved memory elements. Innovations in microfluidic circuits and electromechanical designs could provide greater precision and scalability in soft matter computing, supporting more complex and dynamic applications.

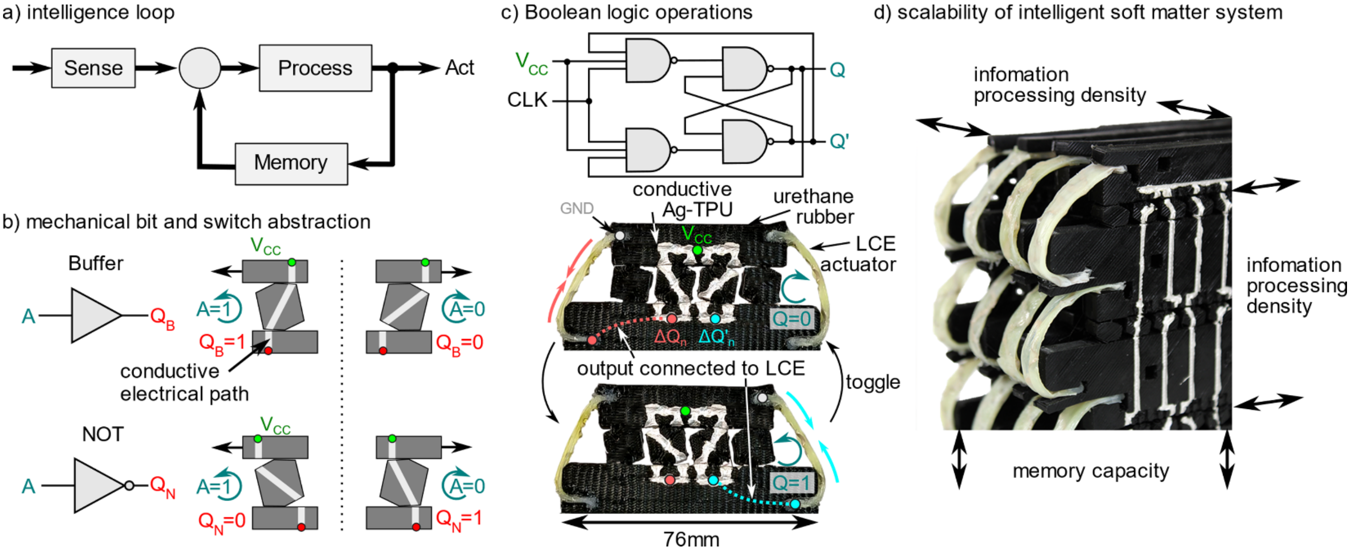

Figure 8. Elements of intelligence in soft matter c omputing systems. (a) Fundamental intelligence feedback loop identifying all requisite components. (b) Example of mechanical bit abstraction and the design of logical gate with integrated mechanical electrical network. CW rotation indicates an input value of '0' and CCW rotation indicates an input of '1'. The mechanical input A (blue) is processed into an electrical output signal Q (red). (c) Example of sequential logic soft material system. The logic diagram is for a T flip flop element. The bottom material represents the two possible stable states. The conductive network sends a signal to the liquid crystal elastomer (LCE) actuators to induce toggling behavior between stable states. The dotted lines represent the electrical connection between the output of the electrical network and the LCE actuator. (d) Representation of the assembly and scalability of soft matter computing material systems. By combining more switches in parallel and series, one can increase the information processing density and memory capacity to perform more complex computations.

Another notable challenge in soft matter computing is the interface of these platforms with other systems that translates the environmental signal from physical stimuli such as mechanical, thermal, optical, or fluidic inputs into a form that's readily usable. Consideration must be taken to convert continuous analog environmental stimulus to digital material configurations or states to be processed using the established combinational and sequential computing principles. Such translation of information also involves converting the often physically encoded outputs of soft matter systems (such as changes in shape, configuration, or material state) into digital signals that can be easily interpreted. Achieving this requires innovative transduction mechanisms that can reliably decode the physical responses of soft matter into precise, digital data, ensuring seamless communication between soft, intelligent materials and external systems. For example, an analog-to-digital converter is presented in [108] which converts an applied force to a soft mechanical metamaterial into a sequence of metastable configurations that correspond to binary states. The binary configurations are then coupled with a mechanical-electrical network using the methods described in [37] to control an electrical light display.

Advances in science and technology to meet challenges

An emerging field of research into the use of biomolecular materials for information processing enables researchers to develop novel soft matter computing systems that can approach and even surpass traditional computing capabilities. Specifically, DNA and RNA offer promising applications in computing due to their highly programmable and ordered behavior [109]. While traditional silicon-based computers typically approach problems sequentially, scientists can use DNA biomolecules to approach problems with parallel processing which exponentially increases the speed of computation [110, 111]. Another attractive property of DNA in computing applications is its potential for information storage. Compared to traditional optical or magnetic storage media, the capacity of DNA is up to a million times denser with 455 exabytes/gram [112]. While still in its early stages, the use of biomolecular materials offers many opportunities to expand the research and applications of soft matter computing.

While many efforts have explored the integration of digital computing principles, exploring alternative computing paradigms like analog computing and reservoir computing opens new avenues to leverage the intrinsic properties of soft matter. These approaches can employ the continuous nature of soft materials for analog computation [2, 113], changing the fundamental approach to processing environmental information. Reservoir computing is a growing topic of interest that utilizes the dynamic response of soft matter to external stimuli as a computational resource, enabling the processing of complex problems involving dynamic systems and high-dimensional data even when such problems can be difficult for traditional computers to solve [114]. These paradigms could offer a more natural exploitation of soft matter's capabilities, potentially leading to computing systems with enhanced efficiency and novel functionalities.

Concluding remarks

Intelligent soft matter offers transformative benefits by enabling materials to sense, process, and respond to their environments. Such functionality can greatly advance research in areas such as wearable technology [115], bio-integrated devices [116], or applications in extreme environments where traditional electronics may not be suitable [117]. Along with establishing foundations for autonomous material technologies, soft matter computing advancements may elucidate understanding of learning and intelligence as fundamental principles and properties of engineered systems. Such understanding opens new avenues in the design of materials that can adapt to varying environments and begin to mimic a broader general intelligence.

7. Morphological computation—leveraging smart materials for smart robots

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Status

Morphological computation (MC) is a design approach in robotics, which proposes to implement intelligence not only in the controller/brain of the robot, but also outsource useful functionality to the robot body [118–120]. MC suggests that we need to exploit smart morphologies to obtain truly intelligent machines. This is inspired by observations in Nature where we can see that biological systems take advantage of their morphologies and corresponding nonlinear dynamics. Complex mechanical structures are exploited to facilitate sensing, controlling, computing and even to accelerate learning. The evolutionary process has found clever ways to leverage body dynamics to make all kinds of biological systems (animals, plants, fungi, bacteria, etc) more energy efficient, robust, resilient and capable of not only surviving but thriving in highly complex environments. Clearly, these properties are also desirable for robotic systems as well.

To fully appreciate the potential of MC, we have to understand the role of the body morphology in a robot. Opposed to an AI system, by definition, a robot has a physical embodiment, which connects the central controller ('brain') to the environment (compare figure 9). It is only through the body that the robot can perceive the world (sensing) and can interact with it (actuation). Information flows in both directions. Therefore, intelligent body morphologies implemented with smart materials can shape and transform this information flow and therefore significantly improve the performance of the robot.

With the rise of Soft Robotics [121] and Additive Manufacturing [122], MC has gained additional momentum. The idea of Soft Robotics is to go beyond standard building blocks of classical robotics (i.e. rigid struts and high-torque servo motors) by using also soft materials to develop new robotic solutions. Employed materials include silicones, polymers, hydrogels and many forms of smart materials. Interestingly, most of them exhibit complex and nonlinear dynamics. This poses a challenge in the context of traditional robotics frameworks, especially when it comes to modeling and controlling these bodies. However, from the perspective of MC these nonlinear dynamics provide a wealth of opportunities to build intelligent bodies [123]. Simply put, the more complex the materials are, potentially, the more complex functionalities can be outsourced to the body morphology.

Most of MC-based robotic systems are individual proof-of-concepts that demonstrate impressively the potential of the approach. However, MC being a relative new concept has still a long way to go and a number of challenges need to be addressed.

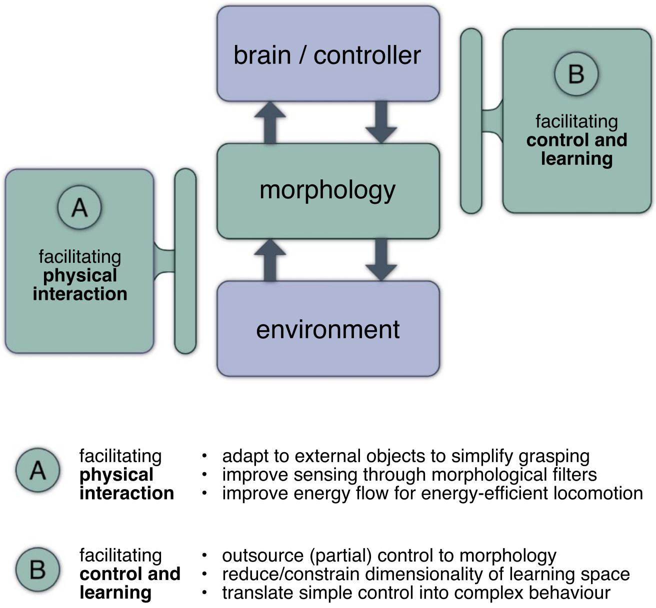

Figure 9. The morphology of a robot is the central piece that connects the controller ('brain') with the environment. It defines how the robot perceives and interacts with the real world. Information flows in both direction through the body morphology. Therefore, the body plays a crucial role in the overall behavior and performance of the machine. (A) It can help to couple the robot body with the environment. For example, it can improve energy flow and make locomotion more energy-efficient, outsource the problem how to grasp objects to the morphology through its compliance, or use morphology to improve sensing. (B). The morphology can also be used to improve the coupling between the controller/brain and the body. For example, control can be (partly) outsourced to material properties (dynamics), translate simple inputs from the brain into complex behavior, and morphologies can help to reduce the learning time.

Current and future challenges

One challenge is the lack of a general understanding how we can map a desired functionality onto a corresponding morphology (see figure 10). There have been a few attempts to provide more rigorous theoretical frameworks, e.g. [124–126],, which have also been demonstrated to work in real robotics systems, e.g. [127, 128] but these models are quite generic. This is due to the fact that MC is a rather broad concept (compare figure 9). We need more specific solutions, maybe connected to concrete physical building blocks that implement fundamental functionalities, and which can be combined arbitrarily.

Another set of innovations are needed with respect to new materials. Most of the currently available smart materials are responding only to one input and react quite slowly. Also, to allow the emergence of more complex morphologies, we need materials that can communicate locally. This

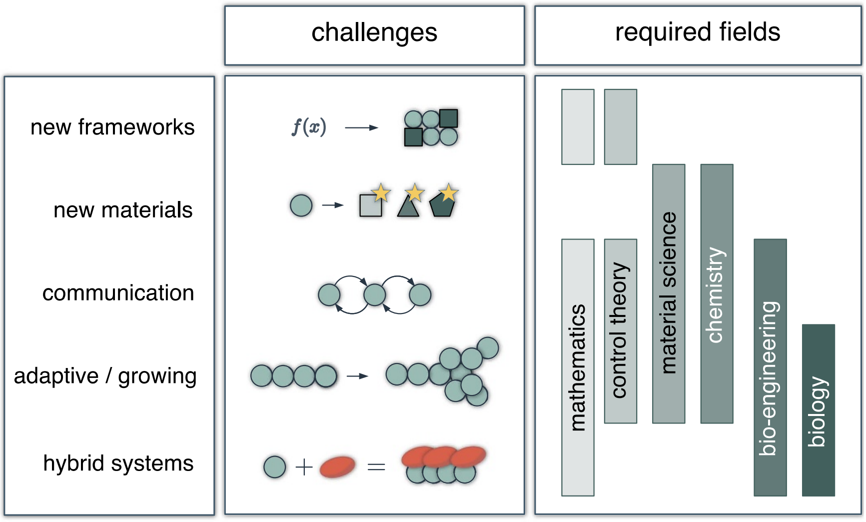

Figure 10. The challenges for leveraging smart materials for morphological computation needs to be addressed by a highly interdisciplinary approach that goes beyond robotics. We need to include experts from mathematics, control theory, material science, (bio)chemistry, bioengineering, and biology.

morphological communication ideally will go beyond mechanical transmission of forces, e.g. by exploring chemical and (non-conventional) electro-magnetic ways to share information. This will also enable us to implement distributed intelligence throughout the body further increasing robustness and resilience in those systems.

Besides intelligent materials, clever structures need to be developed as well to build up a hierarchy loosely resembling the way biological bodies are layered. This hierarchy could potentially go over orders of magnitude from molecular interaction to full robotics systems, which comes with its own technological challenges.

To obtain highly autonomous systems, we also need materials that can adapt radically. From the viewpoint of morphological computation, changeable morphology means we can (re)programme the underlying functionality in the body. This means we need to which parts of the body should change and when. This radically changes the approach we design robots. Instead of building one fixed body for one solution, we have to design a morphology that provides the best possible solution space to solve all relevant problems the robot might encounter. Connected to that we require morphologies that can translate experience (e.g. obtained through physical interaction) into sensible morphological changes which can be leveraged into in-materio, online learning. Ultimately, we want to have robots that can grow and heal their bodies and, consequently, their underlying functionalities.

Interestingly, a lot of the properties discussed here can already be found in biological tissues. Therefore, a possible approach is to leverage biology by integrating natural cells and structures into hybrid robotics systems. This requires novel technologies that can keep these cells alive and steer them to grow into the right morphological structures.

Advances in science and technology to meet challenges

The challenges described in the previous section require a highly multidisciplinary effort (see figure 10) and it is therefore crucial to actively reach out to the corresponding research communities and engage them. In addition, morphological computation provides a radically new perspective of how to design robots. This also means for all envisioned advances we have to re-think the way we understand how functionality should be implemented. Smart materials work for the most part in an analogue domain, i.e. their dynamics can be best described by nonlinear dynamical systems. Therefore, the implementable functionalities should be understood as analogue computations instead of digital ones. This means we have to consider computational approaches that go beyond Turing machines or logic gates.

To address the lack of theoretical models we need input from Mathematicians, especially complexity researchers, to understand how local morphological communication can lead to emergent solutions. Control theorists can provide useful input as well, as their community has developed excellent tools to understand dynamical systems and how to combine them. Furthermore, the development of quantification tools to measure morphological computation, like [129], is needed to enable a design-driven optimization.

To obtain better smart materials we have to go beyond considering only mechanical properties to implement functionality. Materials that work on chemical and/or electro-magnetic principles can open new possibilities. This requires Material Scientists, Chemists and even Biochemists. They are also needed for overcoming the challenges related to in-materio communication. In addition, good mathematical models are required to leverage this communication into morphological solutions.

To design intelligent structures, metamaterials has emerged as an exciting new paradigm [67, 130] especially when connected to modern additive manufacturing approaches. Techniques like Origami and Kirigami have already demonstrated their value to build intelligent structures and could be developed more [131].

To address the challenge of highly adaptive morphological structures novel approaches need to be developed that go beyond changing stiffness. Protocells could be a path forward to obtain other exciting modalities [132]. Adaptive morphologies could be used to translate machine learning approaches into morphologically implemented weights and nonlinear transfer functions. For example, the first layer of a deep learning network could be physically (morphologically) implemented to extract features.

As mentioned before biological cells are the ultimate smart material. Recently, major steps have been achieved to control the growth of muscle tissues [133, 134], and the work on Xenobots have shown new ways to leverage the inherent intelligence of cells [135, 136]. However, there is still a need for technological advances to keep biological cells alive and function over a long enough period of time and to integrated them with other living systems.

Concluding remarks

Morphological computation has started to demonstrate its potential to serve as a framework for designing smart bodies for smart robots. However, there is still more to do. The development of better materials, innovative structures, powerful generalized frameworks, and novel technologies, especially to build hybrid systems, will all contribute to a novel generation of robots. They will be highly adaptive, robust, resilient and capable of learning with and through their bodies. As a result, morphological computation will not only change the way we build individual parts of robots (e.g. sensors or actuators), but it will radically change the way we think about robots in general. It will allow us to design systems that can become truly ubiquitous and fully embedded in the real world to a radical level. Intelligent materials will allow us to build robots that work on, in, and with biological bodies. It will provide us with the technology to obtain biodegradable intelligent artifacts and to build robots at all scales from molecular machines to networks of robots embedded in nature.

The promise of morphological computation is a promise to leverage smart materials and structures to build the next generation of intelligent machines.

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8. Mechanical neural networks

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Status

A mechanical neural network (MNN) [137] is a mechanical version of an artificial neural network (ANN) [138–140] (figure 11). Whereas ANNs are mathematical equations that learn to map input data to output date by tuning their interconnected scalar weights, MNNs are physical lattices that learn to map input forces or displacements to output forces or displacements by tuning the stiffness of their interconnected beams. Thus, MNNs are a kind of metamaterial that can learn to achieve multiple desired behaviors (e.g. shape morphing, acoustic wave propagation, and mechanical computation) and/or properties (e.g. Poisson's ratio, shear and Young's modulus, and density) with persistent exposure to unanticipated and changing external mechanical stimuli.

Although a variety of ANN-inspired physical systems have been proposed in the last decade [141–145], Lee *et al* [137] was the first to propose and experimentally demonstrate a MNN (figure 12) as described here. Although the MNN demonstrated by Lee *et al* [137] was a macro-sized lattice consisting of only 21 6 inch tuneable beams arranged within a planar repeating triangular pattern, the concept is intended to be extended to micro-sized lattices consisting of millions of micron-sized tuneable beams arranged within three-dimensional (3D) volumes of any shape and tessellation pattern. Since the envisioned MNNs would inherently possess numerous layers of nodes, which are analogous to the neurons within ANNs, such MNNs would behave as deep neural networks [146] that can learn many complex behaviors simultaneously. Moreover, if such MNNs are fixtured differently, damaged, or cut to occupy an alternate volume, they can relearn previously mastered behaviors and acquire new behaviors as needed with exposure to changing ambient conditions.

Once practical versions of such micro-sized 3D MNNs are a reality, a new age of artificial-intelligent (AI) materials that autonomously learn desired behaviors and properties will emerge. Example applications that would be enabled by such MNNs include: *(i)* aircraft wings that learn to adapt their shape as they accrue flight experience over time so that the craft achieves optimal fuel efficiency and maneuverability in response to changing wind loading conditions, *(ii)* the frame of a building that learns to remain stationary as the building is shaken in different directions and with random frequencies by an earthquake simulator, and *(iii)* body armor that learns to optimally redirect shock waves away from vital organs after being shot at many times and from many different directions.

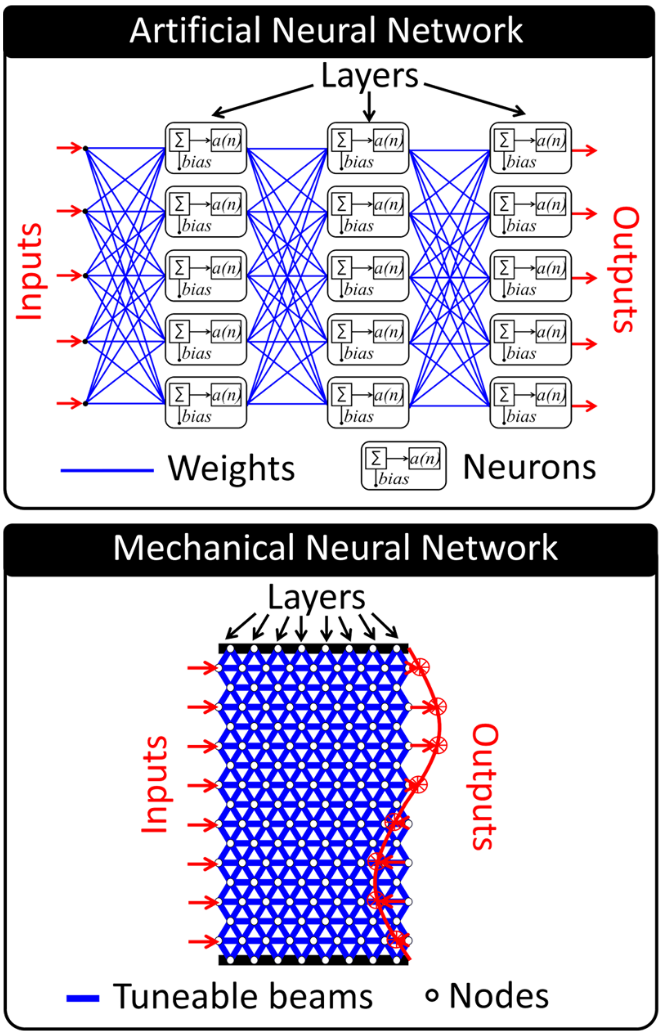

Figure 11. Artificial neural networks (ANNs), which adjust interconnected scalar weights within an equation to learn, are analogous to mechanical neural networks (MNNs), which adjust interconnected tuneable beams within physical lattices to learn.

Current and future challenges

There are many challenging research areas that should be studied to advance the field of MNNs beyond its current state. Studying how the accuracy and speed of MNN learning is affected by arranging the tuneable beams within 3D configurations instead of planar, i.e. two-dimensional, configurations (e.g. the MNN of figure 12) is one such area. Determining what packing tessellation (e.g. regular space-filling tessellations such as rhombic dodecahedrons or random aperiodic tessellations) is optimal for arranging the beams within such 3D MNN lattices is another challenging area of research. Understanding the effect of lattice size (i.e. number of beams, layers, and

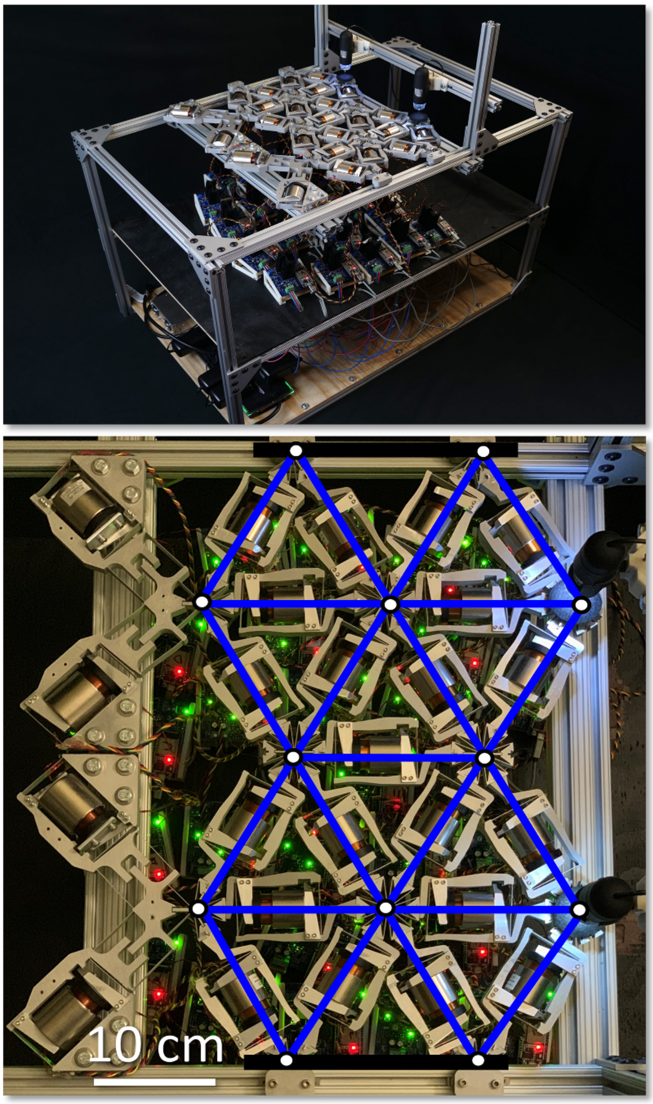

Figure 12. The first mechanical neural network (MNN) [137] to be fabricated and used to experimentally demonstrate the ability to learn desired behaviors by adjusting the stiffness of its 21 tuneable beams, shown simplified as blue lines embedded on top of the photo. From [137]. Reprinted with permission from AAAS.

output nodes) and scale (i.e. whether the lattice's beams are macro-, meso-, or micro-sized) on the learning abilities of such 3D lattices is also important. Moreover, determining how many behaviors and properties such MNNs could learn given the kind of behaviors and properties that are desired is also of value. Currently, only quasi-static shape-morphing behaviors have been learned by MNNs, but many of the most exciting applications require dynamic or thermal behaviors such as the ability to focus or redirect acoustic waves, or exhibit zero thermal expansion amid fluctuating ambient temperature. Thus, studying how MNNs learn a large variety of behaviors and properties is an important but challenging task. It is also important to understand how MNNs consisting of beams that can tune their stiffness in multiple directions, instead of just along their axes, affect the learning process. Additionally, it is important to understand how MNNs consisting of beams that achieve discrete stiffness values only (as opposed to those that achieve a range of continuous stiffness values) influence the learning process. Although MNNs consisting of beams that achieve binary states of stiffness along their axes have already been studied [147], MNNs consisting of beams that achieve more than two states of stiffness along multiple directions should be studied. Comparing the learning performance of MNNs consisting of beams that are controlled to exhibit linear or nonlinear force–displacement profiles of many kinds during the learning process could significantly help improve the process by identifying the most promising one. Lastly, determining what optimization algorithm would be most effective in training a MNN is also a challenging area of study that should be further pursued in addition to what has already been studied in the area [148].

Advances in science and technology to meet challenges

The most significant technological advances that are required to enable practical 3D micro-sized MNNs are in the field of additive manufacturing. To fabricate useful volumes of such lattices with micron-sized beams in reasonable build times, a dramatic increase in print speed, resolution, and build volume would need to be achieved. Moreover, additive technologies would need to achieve these advances while also being able to simultaneously print multiple materials including conductive and nonconductive materials for enabling embedded circuitry as well as actuator and sensing materials such as piezo electric materials. Designs that require delicate overhanging features would also need to be accommodated. Technologies that could achieve these demanding requirements would also need to perform their job in reasonable amounts of time, at competitive costs, and while consuming sufficiently low amounts of energy. Tiny integrated circuit (IC) chips may also need to be periodically inserted within the MNNs using robotic manipulators as their lattices are being additively fabricated to facilitate their complex control during learning.

Advances in micro/nano-sized actuators and sensors would also facilitate the creation of practical MNNs. Bi-directional actuators are needed that can impart larger loads over longer ranges. Micro/nano-sensors are needed that can more accurately sense displacements over larger ranges with higher resolutions and at faster sampling speeds. These actuators and sensors should be able to be additively fabricated within the MNN's lattice.

Disruptive advances in computation, such as quantum computing, would also dramatically increase the speed at which MNNs could learn multiple behaviors simultaneously. With greater computational capabilities, MNNs could start the learning process with more promising combinations of tuneable beam stiffness values since those values could be rapidly determined via simulation instead of using random stiffness combinations to begin the learning process. Thus, advances in computation would facilitate substantially faster learning in part because MNNs would simply refine rapidly simulated solutions instead of learning from an uninformed starting point. Note that MNNs will always learn behaviors with greater accuracy than simulated solutions, since physical systems take all factors of reality into account immediately according to natural law. Advances in computation would also increase the speed of the physical learning process itself since faster computation would increase the speed of the optimization algorithms employed.

Concluding remarks

Mechanical neural networks (MNNs) show promise for enabling AI materials that can autonomously learn desired behaviors and properties. They are physical versions of artificial neural networks (ANNs) in that MNNs learn by tuning the stiffness of their beams, which interconnect their nodes, similarly to how ANNs learn by tuning their scalar weights, which interconnect their neurons. The field is currently in its infancy and thus, much needs to be studied to determine how to design beams that can be fabricated on the micro-scale, and packed within practical 3D lattices that fill space while being able to achieve large ranges of variable stiffness in multiple directions and with high efficiencies. Significant advances in the fields of additive fabrication, micro/nano-actuation and sensing, and computation are necessary before the field of MNNs can itself advance to the point where practical AI materials are ubiquitous in society.

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9. Plant-inspired intelligence in engineering systems

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Status

Nature has engineered living beings with materials capable of computing purposeful movements during interactions with their environment, featuring morphological and behavioral adaptation. Lacking a nervous system, plants represent a peculiar natural model of embodied intelligence. They manifest intelligent behaviors triggered by a multitude of stimuli, chemical and physical, aiming to comply and survive in challenging and mutable environments. Computation is delegated to their tissues, having both sensing and actuation capabilities, with a wide range of architectures and evolved mechanical properties. For this reason, plant-inspired intelligence has been a great source of inspiration for engineering and robotic systems. In this roadmap, we provide a snapshot of how plant intelligence manifests, and we report the most significant and groundbreaking examples of engineering and robotic systems equipped with plant-inspired intelligence that appeared in the scientific literature in the past decade. In particular, we focus the roadmap on selected plant-inspired movement enabler principles: passive hygromorphic, bistability, and growth.

Because of the diversity of challenges offered by their environments, plants have evolved the ability to shape and morph their bodies through active, metabolically expensive, and passive metabolic-free movements. Many active movements rely on apical growth. Examples are tropisms, meaning directional growth responses used to reach critical resources [149], like light in shoots or nutrients in roots. Considering its relevance in shaping plant phenotype, apical growth has been explored as a new motion paradigm in robotics [150] (figures 13(A)–(D)). In particular, additive manufacturing technologies have been employed as enablers of robot-embedded apical growth by miniaturizing a 3D printer-like mechanism that pulls a thermoplastic filament, heats it, and plots it circularly to build the robot's body and layer-by-layer increasing the structure from the moving head. Such a mechanism has allowed the realization of root-inspired soil explorers [151–153] and the mimicking of plant perception-action loops [154], fostering recent perspectives on a plant computational power [155, 156] employable for robot navigation. The engineering translation of apical growth through additive manufacturing and the integration of plant-inspired control strategies led to the realization of a fault-tolerant system capable of dynamically adjusting its growth direction, disregarding disturbances [154], and mechanically computing the low-resistance path upon physical interactions with the environment by exploiting the malleability of the material extruded during growth [152]. This approach largely differs from animal-like locomoting strategies, more widely implemented in robotics, since it encloses the unprecedented functionality of 'morphing while moving.' The robot has no predefined morphology; it constructs its body in real time according to external environmental signals, displaying plant-like phenotyping while accomplishing environment navigation.

The morphological adaptation in plants also occurs along different growth stages. For example, the cactus *Selenicereus setaceus* adapts its stem geometry, transitioning from a star-like shape to a circular form when aging. This transformation enhances flexural rigidity, allowing the cactus to explore complex three-dimensional environments. A soft, 3D-printed multi-material system has been developed inspired by this adaptive trait that uses hydrogel as an actuator [158]. The hydrogel-elastomer system adjusts its shape through anisotropic swelling, enabling controlled movements. Despite being growth an energetically costly process in nature, the artificial system demonstrates the possibility of reaching a morphological change merged with body stiffening without energy input, prompting the integration of energy-saving actuation into robot material.

Different kinds of movements are those with metabolic-free activation. Passive movements are typically nastic, invariant to the direction of the stimulus, and performed thanks to a pre-design and specific material arrangement that facilitates a desired deformation upon an environmental trigger. Examples of such systems in the plant domain are the opening and closure of pine cones [159], the coiling in the tail of Geraniaceae seed (e.g. *Erodium* and *Pelargonium*) [160], or in the wheat awns [161]. In these examples, motion is obtained by the reversible adsorption and desorption of environmental humidity. In the last 10 years, several devices based on hygromorphic actuation have been reported. Shin *et al* reported a bilayer structure that harnesses the environmental humidity energy and transforms this into motion (called Hygrobot). The system was based on a hygroscopically responsive film consisting of aligned fibers through electrospinning, which swelled and shrunk in response to the humidity change, generating locomotion [162]. More recently (2023), a biodegradable soft device was developed to model and mimic the inner bilayered hygroscopic structure of *Pelargonium* and the biomechanics of the hygroscopic seeds (figures 13(E) and (F)). The artificial seed was realized through 4D printing by coupling the 3D printing of polycaprolactone (inactive layer) and electrospinning of artificial microfibrils of polyethylene oxide (PEO) and cellulose nanocrystals (CNC) oriented at different angles. The artificial seed explored randomly and autonomously a sample soil with roughness and cracks only driven by environmental humidity changes [157]. Inspired by *Erodium* seeds, a self-drilling seed carrier was designed and fabricated by turning wood veneer, which was delignified and manually molded into strips, and obtaining a hygromorphic bending or coiling actuation. Thanks to the artificial seed design based on a three-tailed carrier and a resting angle (25°–30°), the drilling success after two humidity cycles was 80% with perspective applications in aerial seed [163].

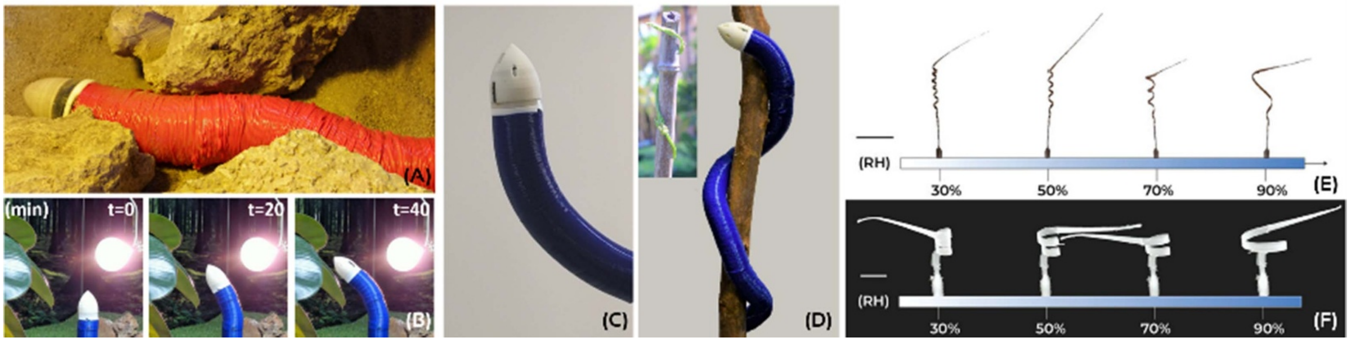

Figure 13. Plant-inspired intelligent systems. (A–D) Growing robots based on additive manufacturing showcasing different phenotyping achieved upon interaction with the environment. In (A) the robot navigates on a sand terrain and passively adapts its growth to the mechanical interactions with rocks (see [152]). In (B) a sequence of three successive frames (every 20 min) of the robot growth while performing skototropism, a directed growth towards shaded areas induced by a neighboring plant (see [154]). In (C) the robot grows against gravity like in the shoots of plants (negative gravitropism). In (D), the robot twins around a branch like in twining plants (an example in the inset, up-left corner). (E) Example of nastic movements in the natural seed of *Pelargonium appendiculatum* at different humidity percentages (RH). The tail uncoils with increasing humidity and coils with water desorption. Adapted from [157]. CC BY 4.0. (F) The morphological, compositional, and biomechanical characteristics of the awn in *P. appendiculatum* have been imitated with biodegradable materials in an artificial seed that showcases analogous behaviors to the natural one in response to increasing and decreasing levels of humidity (see [157]). The scale bar in (E) and (F) corresponds to 1 cm. Adapted from [157]. CC BY 4.0.

Fiorello *et al* showcased a biohybrid self-dispersing miniature machine using wild oat fruit awns combined with a biodegradable flour capsule fabricated through a mold realized by two-photon polymerization (2PP). The capsule carried tomato seeds, showing potential applications in reforestation and precision agriculture [164]. Compared to the current literature on crawlers and explorers powered by anthropic energy sources (e.g. electronic or pneumatic), the reported devices can move, explore, adapt their morphology, or drill the soil wirelessly, only driven by environmental humidity changes and hygromorphicity with a consequent low energy impact on the environment, paving the way for sustainable robotics.

However, relying on purely diffusive processes, such systems tend to be slow and possibly difficult to apply when real-time motion is desired. To counteract this limit, plants, often underestimated in their potential for fast movements, have evolved ingenious strategies to fasten their responses, exploiting various physical phenomena in actuation systems, like bistability or explosive mechanisms. The fast-closing mechanism (∼50 ms) of the *Dionaea muscipula* offers a brilliant example. This plant seems to exploit the release of elastic energy stored in the leaf structure to achieve rapid closer. The leaves are characterized by two inverted curvatures underling the bistable mechanism, allowing the leaf to bend and stretch [38, 165]. Based on this principle, a hygroscopic bistable structure (HBS) was obtained by bonding pre-stretched PDMS layers prior to depositing electrospun polyethylene oxide (PEO) nanofibers [166]. The use of bistability coupled with the hygromorphicity of electrospun material demonstrates a sensible advantage in the response time (≈1 s) of the HBS with respect to a purely diffusive bilayer structure (≈10 s). Alternatively, the snapping of an artificial flytrap was also proved using light stimulation and photothermal effect through the development of anisotropic poly(N-isopropylacrylamide) hydrogel nanosheets loaded with gold nanoparticle [167]. Li *et al* reported a biohybrid electrical plant-based actuator that uses a conformable electrical interface as an electrical modulating unit and a real Venus flytrap as an actuator [168].

Challenges and perspectives

Many challenges must be addressed to fulfill the potential of engineering systems or robots equipped with plant-inspired intelligence. Below are the main challenges we believe must be solved, accompanied by possible solutions:

(i) *Performance*: responsiveness and sensitivity. Plants adapt and respond to environmental stimuli such as light, water, gravity, and chemicals, but their processes are slow compared to animals' reactions. The response of the materials should be fast, accurate, and reliable. Engineering and the development of multifunctional composite materials could help increase response times through the design of new fillers and composites.

(ii) *Adaptability*. The systems should work in complex, structured, and evolving environments rather than more controlled conditions like in laboratory settings. Soft robotics has brought attention to the importance of demanding the computation of environmental uncertainties to bodies and materials. Embodied compliance, as well as the possibility to reconfigure, reshape bodies, or construct them on demand, are features already implemented by plants with potentialities to increase even artificial systems adaptability.

(iii) *Sustainability*. The engineered systems should rely on sustainable materials (renewable, biocompatible, biodegradable) to avoid leaving 'e-waste' behind and realize a substantial reduction of CO_2 footprint [169]. Researchers are designing and developing advanced composites based on different polymeric matrices (also bioderived, recyclable, and renewable) [170]. The family of printable and renewable biodegradable materials has expanded in the last 10 years (e.g. polyhydroxyalkanoates (PHA), cellulose-based polymers, hydrogel) coupled with bioprinting techniques.

(iv) *Degradation and durability after repeated mechanical stresses*. This point is connected with point (iii). The addition of reinforcement fillers (particulate or fibers) [171] in biodegradable materials could allow the tuning of degradation times under mechanical stresses. Alternatively, bioinspired metamaterials with unprecedented properties (i.e. high strength, tunability, and versatility or resilience to deformations) could also be designed and fabricated to increase durability against mechanical stresses [172, 173].

(v) *Energy*. Plants are self-producers of energy and adapt their physiological processes when resources are scarce or under stress to prolong their survival. An ideal functional smart material should find its (renewable) energy source directly from the environment and harvest it to reduce its impact on Earth's energy balance.

(vi) *Scalability and manufacturing*. Scaling up the production of prototypes from laboratory to mass production could be a bottleneck. Advanced manufacturing techniques (fused deposition molding, direct ink writing, electrospinning, injection mold, or casting) [174] should be employed, which also can make industrial transfer easy. Moreover, greater effort should be made to pay attention to a system's cost in terms of manufacturing (materials and process) and its energy balance.

Many of the challenges may have a possible solution in the development of new nano(composite) materials, accompanied by new designs and manufacturing processes. The complex design of multi-material and micro-nano structures inspired by plants poses a significant challenge in emulating nature's finely tuned biomaterials, where the interplay between an organism's body and its environment plays a pivotal role in determining system actions. Unraveling and mimicking such motions and structures require sophisticated tools like image analysis, biomechanical analysis, dynamic modeling, and 3D reconstruction. This process is followed by artificial reproduction using advanced micro-fabrication techniques: two-photon lithography has revolutionized the replication of micro-scaled natural structures [175]; electrospinning emerges as a promising technology, producing biocompatible, biodegradable materials [176]; extrusion-based fabrication techniques, successful in biomedical applications, offer alternatives for developing the next generation of biocompatible robots [177]. Techniques like 3D bio-plotters and fused deposition modeling have been harnessed for creating shape-morphing botanical-like structures [57] and growing robot [154]. The emphasis on these advanced techniques underscores the challenge of realizing multi-material structures and micro-nano structures while pushing the boundaries of fabricating and functionalizing components and systems based on multi-functional biomaterials. The infinite range of combinations and the high flexibility could lead to breakthroughs in durability, stainability, performance, and adaptability.

Conclusions

In this roadmap, we have shown and reviewed the recent and groundbreaking examples of engineering and robotic systems inspired by selected plant intelligent mechanisms of movement, which include growth, hygromorphic-, and bistable-based mechanisms. To extend the current development of robots, the bodyware in future robots will be able to grow, regenerate, repair (self-healing), and morph shapes to accommodate physical constraints or evolve to comply with the task. Smart multifunctional materials play a crucial role in this perspective, accompanied by biohybrid solutions to ensure both multifunctionality and biocompatibility. Going beyond current power sources, robots will harvest their energy from the environment, and intelligence will evolve concurrently with a shape-shifting body. Extracting the principles where the numerous plant tissue functionalities are grounded can guide the design and implementation of such functionalities for exploiting better sensing, stability, stiffness, toughness, adhesion, and growth, among other properties, to be adopted in more efficient and compliant robotic systems. Thanks to versatility, low-energy consumption, multifunctionality, autonomy in movements, and flexibility in design, the plant-inspired systems and robots could find application in several fields, such as precision agriculture (e.g. seeding and soil monitoring), reforestation, environmental monitoring, space exploration and the construction and/or maintenance of smart-building.

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10. Physical intelligence in small-scale magnetic soft robots

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Status

Observing from nature, we can see that a lot of organisms often delegate several functions and low-level decision making to their physical body and reduce the load from their central nervous system or *Neural Intelligence*. This phenomenon of encoding intelligence in the physical body is termed as *Physical Intelligence* [78]. In nature, we observe physical intelligence across all length scales; from the chemotaxis of fungi to the sensing and capturing of insects by Venus flytraps. The prevalence of physical intelligence in nature can be explained by noticing that for the first ∼3 billion years, life on Earth did not evolve to have neurons, which means all intelligent behaviors were decentralized and realized in the organisms' physical body. Plants have not evolved to have brains even nowadays, and yet they make continuous, complex decisions purely based on physical intelligence.

In recent times, researchers have been able to realize physical intelligence in artificial agents (robots, actuators, etc), which serves to complement and increase the capability of their *Computational Intelligence* (a central decision-making unit, such as a CPU). The field of soft robotics has access to a large variety of stimuli-responsive soft materials or active polymers, which allows us to encode multiple functionalities—actuation, sensing, control, computation, adaptation, learning, etc—in the physical structure of a soft robot body. Magnetically actuated soft robots lend themselves particularly well to utilizing the benefits of physical intelligence with the advantages of their wireless control and actuation, high spatiotemporal control, on-board energy source free actuation, etc. It is possible to design magnetic, completely soft robots without any on-board electronics, sensors, powering, computation, memory, and actuators.

Soft robots

At millimeter size scales, access to on-board computational intelligence becomes limited and physical intelligence becomes an attractive option. For some designs, a changing external magnetic field itself can provide multiple functionalities like multimodal locomotion (figure 14(A)) [178], while in other cases the robots are only powered by an external magnetic field and other functions, such as adaptive locomotion based on environment conditions [179], self-propulsion [180], shape-adaptation [181], self-healing [182], usually come from various functional materials. At the micron scale, where the size is comparable to single cells, we are entirely dependent on physical intelligence for all functions including decision-making. Microrobots can utilize chemical energy by interacting with its environment to propel themselves autonomously. Due to their small size, they are ideal for *in-vivo* applications like targeted delivery of drugs, biologics or inorganic agents, local surgical tasks (e.g. tissue penetration, biopsy collection), diagnostics, and imaging; all of which are achieved though functional and responsive materials embedded in the body of the microrobot [183].

Biohybrid robots

Integrating synthetic robots with living cells or organisms (e.g. cardiomyocytes, bacteria, algae, immune cells), to create a biohybrid soft robot, provides an attractive approach to harness the physical intelligence already found in nature. In such biohybrid robots, the organism provides not only motility, but also physically intelligent capabilities (e.g. various taxis movements of bacteria [186], algae (figure 14(B)) [184]; target specificity of immune cells [187]). A weak external magnetic field can also be used to orient the propulsion direction of the biohybrid robot.

Flexible mechanical metamaterials

Apart from robots or actuators, mechanical metamaterials with magnetic interaction provides a potential design approach for physical intelligence. Magnetic fields have been used to dynamically tune mechanical properties—stiffness [188], Poisson's ratio [189], etc—in truss-based metamaterials. The fundamentals of computation (e.g. memory [77] and binary logical operations (figure 14(C)) [185]) can be not only encoded in a physical system, but also tuned using magnetic fields, providing a high degree of computational capability without the need for a central processing unit.

Current and future challenges

Magnetic field

There are two methods of magnetic actuation: gradient field-based force and uniform field-based torque generation. For both cases it is difficult to localize magnetic fields, specially over any useful distances, which prevents individual control of multiple robots located nearby or in a swarm. Furthermore, generating high fields/gradients with electromagnets lead to high energy consumption, heating issues, and bulky coil systems. While using permanent magnets solves some of these issues, they come with their own set of challenges, such that, a complex arrangement of magnets may be needed to create a desired magnetic field distribution, requirement of additional robotic systems to manipulate the magnets, and safety issues due to the inability to 'switch off' the magnetic fields.

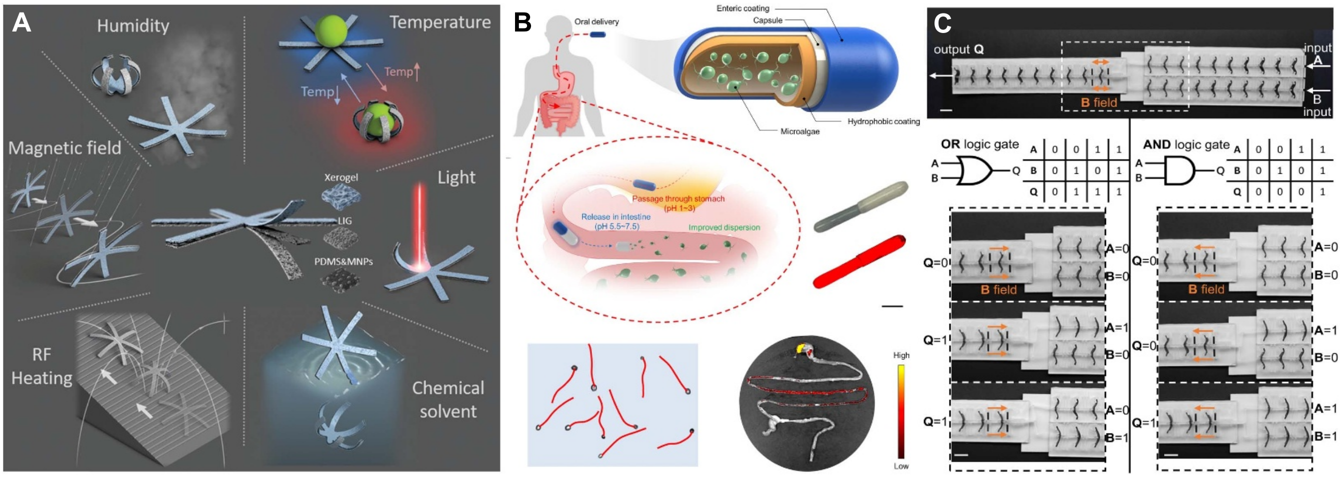

Figure 14. Physically intelligent miniature magnetic soft robots. (A) A multimodal soft robot, which while having a primary magnetic actuation mechanism, change their locomotion gait autonomously based on the environmental stimuli and conditions. Reproduced from [179]. CC BY 4.0. (B) Working principle of an algae-based biohybrid motor for drug delivery in the gastrointestinal tract with the biodistribution in the GI tract shown by fluorescence imaging. From [184]. Reprinted with permission from AAAS. (C) A magnetically programmable flexible mechanical metamaterial, capable of performing different binary logical operations under the influence of varying external magnetic field (scale bar 10 mm). Reproduced from [185]. CC BY 4.0.

Fabrication

Fabrication of and assigning magnetic domains to magnetic soft robots presents a major challenge in manufacturing. While recent progress has been made towards more streamlined and efficient manufacturing (compared to the traditional molding followed by template assisted magnetization approach [190]), these methods cannot provide the complexity in form and magnetization profile necessary for many applications. For example, a roll-to-roll method greatly simplifies and scales up the fabrication process, but it still requires a separate, manual template-based magnetization step [191]. Additive manufacturing is attractive as it is possible to assign magnetic domains in the robot while it is being printed, however, challenges like low magnetic particle loading, distortion of the printed structure due the magnetic gradients of the coils, and limitation to 2D or quasi-2D structures remain [192]. For magnetic soft robots at the sub-millimeter scale, however, we are still restricted to molding techniques as methods like two-photon polymerization are incompatible with soft elastomers mixed with magnetic particles [193].

Biocompatibility

A major application of magnetically actuated soft robots is in biomedical systems, where apart from the evident advantages like wireless, electronics-free actuation and control, physical intelligence plays a big role in allowing these robots to navigate in complex environments, e.g. inside the human body. Fabricating such robots from materials that have simultaneously bio- and hemocompatibility are difficult [194]. One of the major reasons being the most commonly used hard magnetic materials, NdFeB, is cytotoxic and not biocompatible due to its corrosive nature. While the current strategy is to coat both the magnetic materials and the soft robots with a biocompatible coating, there remains the possibility of safety hazards due to the corrosion and leaching of cytotoxic species. Furthermore, at the end of the planned deployment period, it would be necessary to retrieve the miniature soft robots from inside the human body, which presents an additional level of complexity.

Advances in science and technology to meet challenges

Systematic design

Physical intelligence is still a very new field of study and at the same time has a quite broad definition and scope. Even in the case of magnetic actuation, other responsive materials are often used to add functionality [195]. This broadness of scope implies a huge design space, which limits the applicability of systematic design, and has caused the development of physically intelligent soft robots be dependent on the intuition and experience of researchers. While this intuitive, ad-hoc approach had been sufficient in the exploratory phase of the field where new methods of encoding physical intelligence are being surveyed; in the current stage of utilizing physically intelligent soft robots in real-world applications, a more structured route for systematic design needed.

'Green' magnets

Advancement in material science for the development of magnetic materials that are biocompatible, bioresorbable, and are not composed of cytotoxic elements like heavy metals, are required for any *in-vivo* biomedical applications. While there has been some preliminary work in developing completely polymeric, metal-free magnets; they are limited to low-strength soft magnets [196], and not yet suitable to be actuated from cm-scale distances (which is required for *in-vivo* control). Parallelly, continuing the theme of using biocompatible coatings on traditional magnetic materials, there needs to be a systematic study of the efficacy of coatings in different environments as well as testing according to regulatory requirements. This strategy, however, retains the disadvantage of having to retrieve the robots, as coatings can help with only the biocompatibility aspect and not with bioresorbability.

Simulation
The capability of fast, computationally inexpensive simulations is key for developing any data-driven learning systems for automatized designing of magnetic soft robots. Current commercial numerical (finite element analysis) software are not adept at multiphysics, dynamic simulations combining structural deformation, magnetic actuation, fluid–structure-interaction, etc. Simulation capabilities important for magnetic soft robots (e.g. uniform field based torque) is either unavailable [185] or do not match experimentally observed behavior [197]. Although researchers have developed custom finite elements codes to simulate magnetic deformation and actuation [76], they are very limited in scope, computationally quite expensive, not yet at the level to produce the large amount of numerical results to be useful for data-driven models.

Concluding remarks

Researchers continue to be inspired by the many examples in nature while finding new ways to encode physical intelligence in synthetic soft robots. Physical Intelligence is no doubt essential in advancing the field of autonomous soft robots, by both complementing computational intelligence where possible and substituting it where necessary (e.g. sub-millimeter scales or harsh environments). Meanwhile, magnetic field has turned out to be one the most appealing methods of soft robot actuation; it is inevitable that researchers will look to focus at the intersection of these two strategies while designing the robots of the future: harnessing the advantages of physical intelligence in magnetic soft robots.

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11. Pneumatic logic circuits for intelligent wearables

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Status

Wearable robotic devices play a vital role in assisting people with disabilities and functional limitations. In addition to motion assistance, modern wearables support a range of applications including therapeutic compression, rehabilitation, and haptic communication. Wearables that apply forces on the user's body often utilize pneumatic actuators to do so; pneumatic muscles and pouch motors developed in the 1960s are widely deployed today as soft assistive actuators in prostheses and orthotic devices. Arrayed elastomeric actuators (pneu-nets) appeared in the early 2010s and have become ubiquitous as end effectors in soft robots and wearables [198]. Recently, researchers have developed new soft actuators that leverage mechanical anisotropy in elastic or textile materials to achieve preprogrammed actuation profiles and sequences [199, 200].

Although mechanical and electric actuators may be used to drive wearable robots, soft pneumatic actuators remain the preferred choice in assistive wearables because of their unique ability to safely and comfortably exert large, sustained forces to move the user's body. Intelligent operation of pneumatic wearables is mainly realized using electronically controlled electromechanical valves, mirroring the proven, decades-old approach used in industrial robotics and automation (figure 15a). However, recent efforts have increasingly focused on designing electronics-free, fully pneumatic logic circuits that can interface directly with wearable pneumatic actuators. Minimizing the dependence on electronic components reduces cost, complexity, and failure points, improves comfort and reliability, and confers additional benefits such as washability and unobtrusive integration with the user's clothing. Miniaturized fluidic logic circuits first appeared in microfluidic devices in the 2000s, enabled by the introduction of soft valves ('Quake valves') actuated by fluid pressure (figure 15b) [201, 202]; subsequent developments led to fluidic circuits that closely emulate the capabilities of electronic circuits, such as analog and digital logic, sequential operations, signal amplification, and memory storage [203]. Microfluidic logic was leveraged to build the first entirely soft, self-powered robot—the 'Octobot'—in 2016 [204]. Growing beyond microfluidics, macroscale pneumatic circuits constructed from compliant materials for practical use with soft robots emerged in the 2020s with the development of bistable elastomeric valves which, analogous to the Quake valve, can be combined into logic and memory units (figure 15c) [205, 206]; these valves were subsequently configured for control and programming of pneumatic robots, including an untethered soft-legged walking robot capable of navigating obstacles in its environment [207]. Soft pneumatic logic gates were adapted from three to two dimensions with the introduction of sheet-based valves in 2022 [115, 208]; by leveraging the kinking of soft channels embedded in sheetlike materials such as textiles and polymer films, these valves enabled the seamless integration of lightweight logic circuits into wearables and the creation of textile computers for electronics-free digital control (figure 15d). With further progress in textile-based fluidic circuits, we may expect future wearables to feature advanced computing capabilities such integrated sensing, analog signal processing, and enhanced memory storage.

Current and future challenges

Even as soft actuators provide an inherent level of comfort and safety that must be deliberately engineered into their rigid counterparts, the current generation of wearable devices that use soft actuators remains limited by reliance on rigid accessory components—gas tanks, compressors, battery packs, electronic controllers, and electromechanical valves—for achieving untethered and intelligent operation. These components add weight and bulk to the overall system, reducing comfort and ultimately burdening the user. The development of textile-based pneumatic sensors, controllers, and power sources can help replace these rigid onboard components with soft and lightweight alternatives that also reduce cost, improve comfort and durability, and offer unique advantages such as washability and resistance to electromagnetic interference that are currently lacking in wearables based on electronic circuits. For applications requiring high computational speeds or complexity, or capabilities such as wireless communication that cannot currently be implemented fluidically, pneumatic circuits can be designed to work alongside electronic or microfluidic circuits through suitable interfacing components (electronically actuated fluidic valves or microfluidic signal amplifiers), performing low-level logic functions while delegating high-level tasks to electronic or microfluidic controllers that can accommodate a much higher density of miniaturized logic elements.

The architecture of fluidic logic circuits in microfluidic devices and soft robots has traditionally mirrored that of electronic circuits, wherein discrete components such as relays (valves), resistors, and capacitors are interlinked through fluidic connections. Although this traditional paradigm for embodying fluidic logic has proven quite successful in contemporary soft robots and wearables, recent efforts have targeted a deeper integration between fluidic components and the soft materials from which they are built [30, 209]. Leveraging the innate mechanical and fluidic properties of soft materials—such as their elasticity, porosity, and response to internal or external fluidic pressure—to aid or execute fluidic signal processing can lead to new embodiments of soft sensors and controllers that achieve tight integration between material, form,

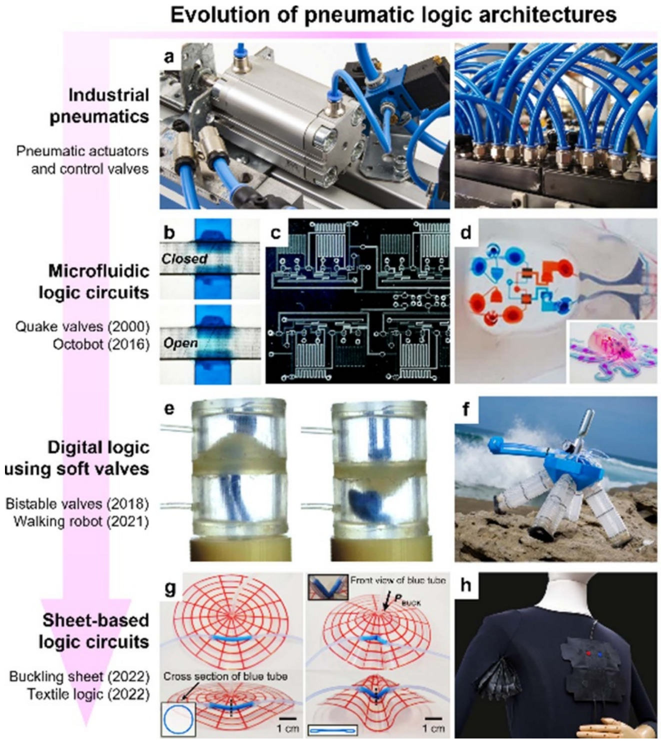

Figure 15. Milestones in the evolution of wearable pneumatic logic, beginning with industrial pneumatic systems and progressing through microfluidic computing, soft pneumatic valves, and sheet-based logic circuits. (Panels (b), (c), (e) and (g) Reproduced with permission from [202]. Reproduced from [203] with permission from the Royal Society of Chemistry. Reproduced from [206], with permission from Springer Nature. From [208]. Reprinted with permission from AAAS. Credit for panel (d): Lori Sanders/Harvard University. Credit for panel (f): David Baillot/UC San Diego.).

and function. For example, the deformation of wire-wound soft tubes under tension was recently utilized to devise a fully pneumatic strain sensor that outputs an analog pressure signal in response to elongational strain; the output of the sensor may be coupled directly to pneumatic muscles to provide controlled assistive forces in response to user movement [210]. Future developments of such 'mechanofluidic materials' can lead to a new generation of wearables that fully leverage the inherent fluidic computing and information processing capabilities of their constituent materials.

Advances in science and technology to meet challenges

Portable power sources: Pneumatic wearables today rely on gas tanks or tethers to offboard compressors, necessitating periodic replenishment or restricting the user's range of motion. Onboard systems that generate pressurized gas from energy-dense chemical fuels or by harvesting energy from the user's movement can mitigate these limitations, enabling truly portable and self-contained wearables (figure 16-1). Promising approaches have been devised recently that utilize combustion [211], chemical reactions [212], or mechanical energy harvested from the user's footfalls [213].

Logic circuit miniaturization: Achieving intelligent control using onboard pneumatic circuits requires miniaturization of existing circuit components so that circuits of increasing complexity can fit within the available device footprint to meet the growing requirements for computing power and memory (figure 16-2). However, scaling down the size of fluidic components begets new challenges; insofar as the size of actuators is fixed by their intended function, innovative strategies are required to interface high-volume actuators with miniaturized controllers so that response and actuation times can be maintained. For example, recently developed fluidic transistors and amplifiers may help impart sufficient gain to small-throughput logic signals to generate high-flow-rate pneumatic signals for driving large-volume actuators [214, 215].

Pneumatic sensing: Wearables today rely on electronic transducers (resistive and capacitive sensors) and allied sensing technologies (thermo-, piezo-, and triboelectric elements) to translate physical inputs to voltage signals, which require conversion to pressure signals before interfacing with pneumatic controllers and actuators. Soft sensors capable of directly transducing environmental and physiological variables (e.g. temperature, humidity, force, and displacement) to pressure signals can eliminate the need for such intermediate conversion steps, reducing complexity and facilitating tighter integration between sensors, controllers, and actuators (figure 16-3).

Diversified applications: Even as motion assistance and rehabilitation remain core strengths of wearable pneumatic actuators, there is considerable scope for exploration of new application spaces for intelligent, pneumatically controlled

Figure 16. Focus areas for future research and development in soft pneumatic wearable systems. We highlight five enabling technologies whose future development will overcome critical challenges facing pneumatic wearables today. (Panels 1 and 3 Reproduced from [212]. CC BY 4.0. Reproduced from [210]. CC BY 4.0. respectively under the Creative Commons Attribution license: https://creativecommons.org/licenses/by/4.0/. Panel 2 was Reproduced from [203] with permission from the Royal Society of Chemistry).

wearable robots: therapeutic compression, haptic communication and navigation, thermoregulation, impact protection, capacity augmentation through mechanical assistance or supernumerary appendages, and wearable suits for extraterrestrial and space applications (figure 16-4).

Sustainability: Anticipating the increase in the number and diversity of smart wearables in the future, researchers and designers must look ahead to ensure the sustainability of materials and processes involved in the manufacturing, use, and disposal of wearable pneumatic devices (figure 16-5). Conducting life-cycle assessments of future wearable products, developing effective repair, recycling, and reuse strategies, and incorporating natural and biodegradable fabrics and structural materials can help ensure sustainable production and commercialization of wearables [216, 217]. New materials developed for use in pneumatic wearables and assistive products must be safe, sustainable, and biocompatible.

Concluding remarks

More than 2.5 billion people today require one or more assistive products, a number that is projected to grow to 3.5 billion by 2050 [218]. Meanwhile, access to assistive technology remains low in many parts of the world, with 'the most common barriers to accessing assistive products (being) high costs, low availability, and lack of support.' [218] Recent developments in pneumatic wearable technology point to its future promise and potential in realizing equitable access to safe, comfortable, and affordable assistive devices to underserved communities across the globe. With sustained research efforts at addressing existing roadblocks in the path to independent, untethered, and electronics-free operation, we are optimistic that soft pneumatic logic, sensing, and actuation systems will mature to support future generations of safe, comfortable, washable, and durable pneumatic wearables.

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12. Embodying mechano-intelligence for engineering functions via physical computing

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Status

We are witnessing an emerging demand for the next generation of adaptive structures and materials to be even more intelligent due to societal needs for high-performance autonomous systems, such as automated vehicles, personal monitoring devices, smart robotics, adaptable manufacturing processes, and tunable infrastructures. Such structures and materials must respond—autonomously, efficiently, and in real-time—to mission needs and working conditions. For example, they should *acquire information* from the surrounding environment, *memorize* it, and *decide* on the action plan, all in a highly integrated manner. Traditionally, these intelligent behaviors are achieved by using, for example, centralized computers and massive electronics, which are becoming overwhelmingly cumbersome and inefficient as the demand for autonomy rapidly increases. Moreover, with more reliance on add-on electronics, there is a serious concern in cybersecurity and resiliency. As a result, one has sought to fundamentally advance system performance, efficiency, and security by creating intelligence in the physical domain and outsourcing parts of the intelligent tasks to mechanical components [78, 89]. Similar strategies are often observed in plants and animals. For example, the octopus' hydrostat-muscular arm has an intricate muscular layout with a sensory-neural network to accomplish remarkably complex locomotion and manipulations without solely relying on its brain [219]. Engineering case studies have emerged to achieve or mimic some intelligent behaviors mechanically [77, 207, 220–223]. While promising, these efforts mostly aimed at developing clever designs to achieve focused tasks. *Overall, there is a critical need for a systematic and broad foundation for creating and integrating the different elements of intelligence in the mechanical domain*, such as the perception of information from sensory data, memorization, decision-making, and command outputs. Such a foundation is a prerequisite to systematically realizing robust and truly intelligent adaptive structures and materials.

Current and future challenges

Recent studies have shown that the rich dynamics of well-designed mechanical systems may be harnessed to pursue computing in the mechanical domain, the so-called physical computing. Such computing power could be utilized to develop the abovementioned foundation required for mechano-intelligence. An ideal mechanically intelligent structure should be capable of harnessing its embedded computing power to perceive and learn information and make decisions while memorizing, and interfacing with sensing and actuation with minimal electronics. While promising, most physical computing studies to date have focused on computation only. That is, systematically harnessing physical computing to achieve engineering functions with mechano-intelligence has yet to be extensively explored. Below are some challenges and questions to be addressed:

(a) What physical computing methods are effective in achieving mechano-intelligence, and how? Pursuing reservoir computing in a physical body-based neural network, the *Physical Reservoir Computing* (PRC) [25, 114, 224, 225] is promising due to its simplicity and robustness. At the same time, because of the wave propagation features in architected materials, it would be powerful to realize *Wave-Based Computing* (WBC) [226–231] at the materials level, building on wave dynamics. With these tools, how do we best select and harness computing mechanically to achieve engineering-relevant intelligence? Can we develop elastic wave networks with topologically protected waveguides in architected materials for robust WBC? Moreover, can we design WBC together with PRC synergistically to best bridge computing with intelligent engineering functions?

(b) What are the correlations between the physical system's design and its computing and intelligent performance? To achieve better mechano-intelligence, we want to understand how the mechanical system's computing power correlates to the underpinning design parameters, including geometry, mechanics, dynamics, and material properties, as well as placement and number of sensory readouts.

(c) How can we design for intelligence and other mechanical functions concurrently? Computing and intelligence are rarely the sole functions of a mechanical system. Practical implementations require us to consider other performance metrics, like mechanical strength, kinematics and dynamics. Therefore, a systematic methodology needs to be established to optimize the system.

Advances in science and technology to meet challenges

In recent years, we have seen exciting new research efforts to advance the field. While the outcomes of these works do not directly answer all the above-mentioned questions, they are creating the knowledge that will address the challenges and enable the potential.

(a) Mechanical metamaterial for information perception and decision-making. In recent studies, researchers explored mechano-intelligence for wave and vibration control

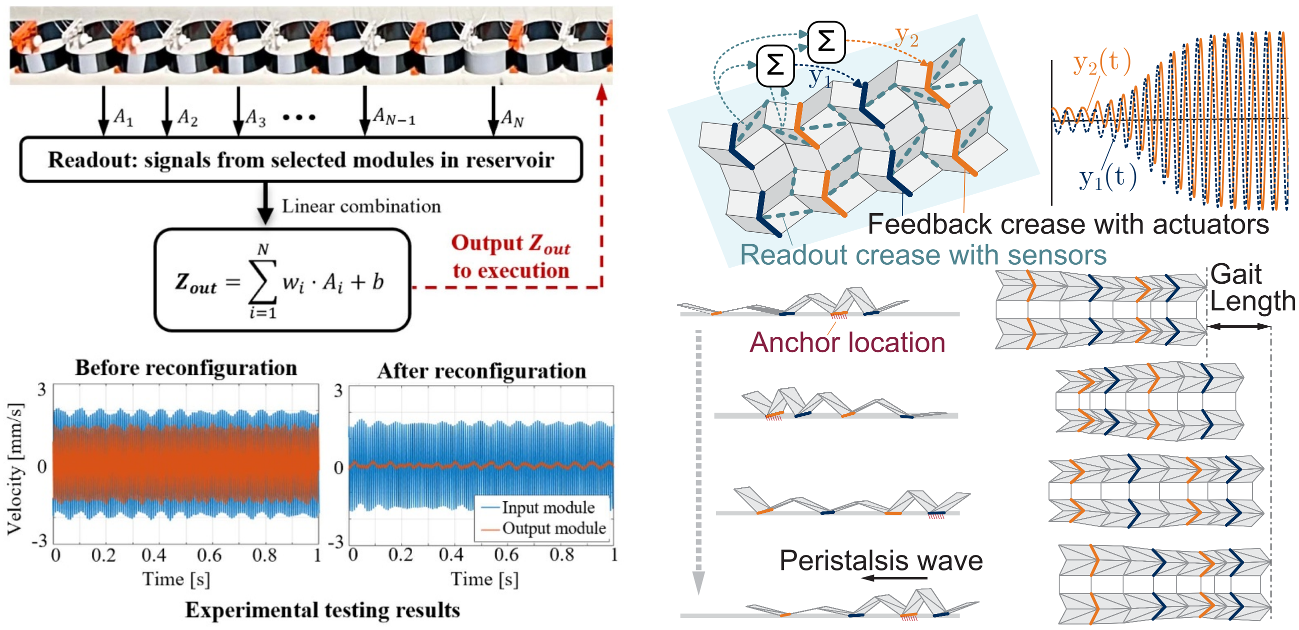

Figure 17. Recent advances in using physical reservoir computing (PRC) to achieve mechano-intelligence tasks. Left: Intelligent wave control harnessing physical computing in self-learning-self-tuning phononic metamaterial—perceives changes and self-reconfigures to isolate vibration. Adapted from [232]. CC BY 4.0 Right: Origami reservoir that can compute limit cycle to achieve peristaltic locomotion and perceive abstract information, like payload weight, from its body dynamics. Adapted from [225]. CC BY 4.0.

[232]. (figure 17, left). It is shown that a 1D mechanical metamaterial can harness its nonlinear dynamics as a reservoir to learn and perceive different excitations and make decisions to self-reconfigure and tune its own bandgaps via physical reservoir computing. This way, it can isolate (or pass) elastic waves when the excitation frequency (or amplitude) changes, i.e. achieve and integrate elements of intelligence in the mechanical domain for engineering functions, such as vibration and noise controls, and phononic information processing and logic designs. In addition, the LASSO regression algorithm was employed to design the most informative readouts (number and location); it further reduced electronics and overfitting by eliminating redundant or irrelevant readouts.

(b) Dynamic origami for robotic locomotion and exteroception. Recent studies have elucidated that origami structures are also ideal platforms for achieving mechano-intelligence because they are inherently nonlinear and high-dimensional—two of the most critical requirements for effective reservoir computing. In addition, origami is versatile and can be adapted for different applications, such as shape morphing, robotics, and mechanical property programming. Here, physically intelligent robots with origami reservoirs are particularly exciting (figure 17, right). For example, one can strategically distribute sensors and actuators to a Miura-based robot. This robot harbors sufficient reservoir computing power to compute limit cycles, generating a peristalsis crawling gait without centralized computers [225]. Moreover, the origami reservoir can accomplish exteroception tasks by estimating the weight and position of external payloads on its body [233]. Finally, by carefully designing the underlying crease pattern and folding the origami into different configurations, one can achieve different levels of computing performance [234]. This allows us to concurrently design for mechano-intelligence and other mechanical properties (e.g. stiffness).

(c) Cellular automata inspired multistable origami metamaterials for mechanical learning. Recent advances in multistable metamaterials reveal a link between structural configuration transition and Boolean logic, heralding a new generation of computationally capable intelligent materials. To enable higher-level computing, existing computational frameworks require large-scale networked logic gates, which places high demands on the fabrication of materials counterparts and the propagation of signals. Inspired by cellular automata, a novel computational framework was developed based on multistable origami metamaterials by incorporating reservoir computing [235], which can accomplish high-level computation tasks without the need to construct a large-scale logic gate network, eliminating the demanding requirements in conventional mechano-logic.

(d) Topological metamaterials for elastic wave control and WBC. Recent research uncovered an approach that harnesses 2D multimodal higher-order topological states to achieve robust and frequency-selective mechanical logic for WBC [236]. Moreover, a 3D topological metamaterial was created to harness multimodal local resonance, unlocking multiband and low-frequency elastic wave control [237]. This work, for the first time, produced unequivocal experimental evidence of planar and

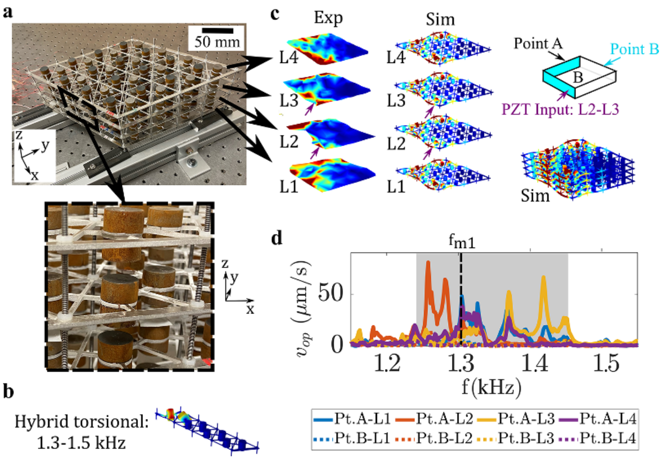

Figure 18. An experimental investigation of 3D topological metamaterial with protected waveguides. Outcomes useful for robust wave-based physical computing. Adapted from [237]. CC BY 4.0.

multi-polarized elastic waveguides (figure 18), which paved the way for future 3D and fractal mechanical materials and devices to robustly process information via protected wave networks for physical computing.

Concluding remarks

Embodying intelligence in engineering systems via harnessing physical computing will provide the basis for addressing the emerging societal needs for highly effective, efficient, safe, and secured autonomous systems, greatly surpassing current technology with more efficient and sustainable performance, lower power consumption, more direct interactions with surroundings, and better resilience against harsh environment and cyberattack. The intelligent functionalities empowered are essential to revolutionize adaptive structures to have broad impacts on future smart robotics, personal wearable monitoring devices, adaptable manufacturing systems, tunable infrastructures, and automated vehicles, etc, which could widely benefit the aerospace, automotive, biomedical, manufacturing, and robotics industries, and our society. The long-term success of this field will continue to hinge upon the synergy of broad convergent research collaborations. In addition, discovering new functionalities will continue to energize this field.

Acknowledgments

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Data availability statement

No new data were created or analyzed in this study.

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