Metamaterial Robotics

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Mechanical metamaterials with customized microstructures are increasingly shaping robotic design and functionality, enabling the integration of sensing, actuation, control, and computation within the robot body. This review outlines how metamaterial design principles—mechanics-inspired architectures, shape-reconfigurable structures, and material-driven functionality—enhance adaptability and distributed intelligence in robotics. We also discuss how artificial intelligence supports metamaterial robotics in design, modeling, and control, advancing systems with complex sensory feedback, learning capability, and adaptive physical interactions. This review paper aims to inspire the community to explore the transformative potential of metamaterial robotics, fostering innovations that bridge the gap between materials engineering and intelligent robotics.

One-sentence summary: This review outlines how metamaterial design principles enable adaptive, multifunctional, and intelligent robotics.

INTRODUCTION

Mechanical metamaterials, known for their periodic building blocks, are architected materials with exceptional properties and functions determined by their microstructures and constituent materials (*1–5*). By tailoring the geometries, connections, and spatial distribution of structural elements, metamaterials can outperform their constituent materials, as demonstrated in lattices (*6, 7*), auxetic metamaterials (*8, 9*), multistable mechanical metamaterials (*10, 11*), origami and kirigami metamaterials (*12, 13*), and stimuli-responsive metamaterials (*2, 14*). Metamaterial designs enable the customization of structural heterogeneity in the distributed body of a robot. The structural versatility of metamaterials enables the design of robotic systems that are not limited to a single predefined function, allowing diverse applications to emerge from a common metamaterial architecture. For example, a modular chiral origami metamaterial has been demonstrated in robotic transformers, thermoregulation, mechanical memories, energy absorption, and information encryption (*15*).ref

One emerging direction in materials research focuses on active and adaptive behaviors, where materials are designed to respond dynamically to their environment and potentially contribute to system-level functions such as sensing or control (*2, 14*). This perspective envisions materials as not merely passive components, but as participants in embedded intelligence within larger systems. To this end, we define metamaterial robotics as robotic systems that leverage metamaterial architectures to physically embed one or more core functions—such as sensing, actuation, control, or computation—within the body of a robot, with the goal of enhancing performance, adaptability, or integration.

Mechanical metamaterials have been utilized in robotics since their emergence in the early 2000s (1). In the initial stage, metamaterials were primarily integrated into the bodies of robots—especially in soft robotics (*16*). Their microstructures offered exceptional mechanical advantages such as lightweight yet high stiffness, large deformability, and nonlinear force transmission, enabling lightweight robotic bodies (*17*), shape-changing origami/kirigami-inspired skins (*18*), and compliant soft robotic components (*19*). In the subsequent phase, robotics leveraging responsive metamaterials achieved stimuli-responsiveness, reconfigurability, and multimodal locomotion and actuation. This led to breakthroughs including environment-responsive robots (*20*), modular and swarm robotic systems (*15, 21*), and mechanical computing with logic gates (*22*). More recently,

artificial intelligence (AI) facilitates the design, modeling, and control of metamaterial robotics. Generative AI enables data-driven and physics-informed design of metamaterials with specific robotic functionalities (*23, 24*). Looking forward, the future vision of metamaterial robotics lies in the convergence of embodied intelligence and reconfigurable matter. Metamaterial robots with real-time adaptivity, on-board learning, and physical intelligence are expected to operate in dynamic, unstructured environments with minimal external computation or human intervention, such as modular reconfigurable robots that can adapt to extreme environments (1E) and humanoid robots integrated with metamaterial-based components (2).

This review presents a comprehensive overview of metamaterial robotics. Initially, we identify key challenges in robotics, concentrating on specific aspects that metamaterials can address. Subsequently, we delineate the metamaterial design principles and illustrate how these principles have been harnessed in robotics to enhance performance in sensing, actuation, control, and computation. Further, we highlight the importance and challenges in design and modeling of metamaterial robots. We conclude by highlighting how integrating AI can advance the intelligence of metamaterial robots.

CHALLENGES IN ROBOTICS

Robotic systems have enabled breakthroughs but accompanied by substantial challenges, including actuation, sensing, control, and computation. Addressing these challenges is critical for the continued evolution of robotic capabilities, especially as robots are deployed in increasingly dynamic and unstructured environments.

Most robotic systems rely on transmission-based actuators, such as motors and gearboxes, providing high force and efficiency across underwater (*25*), granular (*26*), terrestrial (*27, 28*), and aerial (*29, 30*) domains. Although effective, their rigidity and bulk limit use in applications requiring compliance, safety, or miniaturization. Alternative actuators—such as pneumatic and piezoelectric devices—offer improved functionality in wearable robotics and terrain exploration, but still face low power density, limited scalability, and integration challenges for high-degree-of-freedom (DoF) motion (*31–33*).

Sensing is fundamental for robots to perceive their internal states (such as speed, force, po-

sition) and external environments (such as temperature, humidity, gravity) (*34*). Although high-performance sensors provide precise feedback, they are often bulky, power-hungry, and difficult to integrate into compact systems. These challenges intensify in soft robots, which require distributed sensing to capture complex deformations, typically demanding multiple sensors and increasing system complexity and power consumption.

To overcome the limitations of discrete actuators and sensors, research is converging on sensorized actuation, where both functions are integrated within the same material or structure. These self-sensing actuators transduce motion and feedback through changes in electrical, optical, or mechanical properties (*35, 36*), reducing system size, complexity, and energy use—particularly in soft and miniaturized robots. However, challenges remain in material development, fabrication precision, and holistic system design.

Integrating multifunctional materials and increasing system complexity heighten the demands on control and computation. As robots incorporate more coupled and nonlinear elements, control systems must handle high-dimensional, dynamic data. Data-driven and learning-based controllers show promise but require extensive computation and rapid data acquisition (*34, 37–39*), whereas model-based approaches depend on accurate physical models, often impractical for soft or highly compliant systems. Reliance on central processing units and conventional batteries also limits operation in extreme environments, highlighting the need for decentralized and adaptive computation.

The concept of embodied intelligence has emerged as a transformative framework, wherein sensing, actuation, control, and even computation are distributed and embedded within the robot's physical body (*40–43*). Harnessing the body's intrinsic structure enables adaptive, efficient, and robust behaviors, especially when traditional control architectures are insufficient. Metamaterials with programmable mechanical and physical properties enable new forms of embodied intelligence in robotics. Unlike conventional materials, they can be spatially designed at multiple scales to impart behaviors—such as nonlinear stiffness or multistability—directly through their microstructure. This allows robots to achieve complex motions with simple inputs and fewer actuators while providing built-in sensing. By distributing intelligence throughout the body, metamaterials promote adaptive, efficient interactions with the environment and reduce reliance on centralized control.

METAMATERIAL DESIGN PRINCIPLES

A metamaterial typically consists of periodic building blocks, or unit cells, arranged in a specific spatial configuration. In mechanical metamaterials, structural elements deform—through stretching, bending, rotation, buckling, folding, or snapping—under forces, producing collective behaviors and functionalities (*3*). Their constituent materials can be passive (such as polymers, composites, and metals) or active (responsive materials) that respond to stimuli such as temperature, light, or electric and magnetic fields (*2, 14*). Through tailored material composition and their spatial configuration, mechanical metamaterials exhibit enhanced performance and tunable properties.

Metamaterial design principles address key challenges in robotics through three main categories depending on the physics of working principles: mechanics-inspired architectures, shape-reconfigurable structures, and material-driven functionalities (3). Mechanics-inspired architectures exploit deformation modes of structural elements—such as bending, stretching, and buckling—to tune mechanical response, force transmission, and energy landscapes, enabling programmable motion under actuation forces. Shape-reconfigurable structures focus on the deformation of element connections, facilitating dimensional transformations via origami, kirigami, and rotating or interlocking mechanisms (*44, 45*). Material-driven functionality leverages responsive and multimaterial systems to integrate actuation, sensing, and control. Together, these principles provide versatile routes for designing adaptive and multifunctional robotics.

Mechanics-inspired architectures

The body of a robot not only provides structural support but also executes tasks through its motions. Traditional robotic body design primarily emphasizes weight optimization, whereas metamaterial architectures enable the creation of multifunctional robotic bodies. Metamaterial designs utilize diverse deformation mechanisms, including lattices with optimized topologies, auxetics with counter-intuitive deformation behaviors, and structures exploiting instability for snap-through transitions.

Lattices

Lattices, the primary category of metamaterials, comprise periodic networks of beams or shells (*46*). They exhibit ultrahigh stiffness-to-density ratios (*7, 47–49*), resilience (*50, 51*), tunable stiffness (*52–54*), and unusual deformation behaviors (*55*). Mechanical metamaterials comprised of stretch-dominated unit cells demonstrate superior weight efficiency and a higher stiffness-to-weight ratio compared to their bend-dominated counterparts and other foams with disordered microstructures. Conversely, bending-dominated metamaterials offer enhanced compliance and resilience, resulting in superior energy absorption performance (*56*).

An ultrahigh stiffness-to-density ratio enables lightweight yet strong robotic systems (*17, 57–59*). Robots constructed from discrete periodic lattices combine high stiffness with low weight, offering capabilities for swarm assembly, reconfiguration, and versatile locomotion (*17, 57, 58*). A representative example is a carbon fiber-reinforced cuboctahedral lattice system that autonomously assembled a 256-unit shelter in 4.2 days using transport and fastening robots, demonstrating large-scale, self-reconfiguring behavior (4A) (*17*).

Resilience enables robots to undergo large, recoverable deformation with tunable stiffness (*60, 61*). Bending-dominated lattices can be elastically compressed and adjusted for stiffness. A robotic arm composed of X-shaped trimmed helicoids demonstrated controllability, sensitivity, and compliance (*60*). Actuated by tendons, it performed compression, bending, and gripping tasks with variable stiffness, enhancing compliance, workspace, and precision compared to conventional soft robotic arms.

Tunable stiffness in robots can be achieved through predesigned geometric design or in situ modulation via deformation (*52, 62*) or internal pressure (*53, 54*). This capacity is utilized in applications like artificial muscles (*53*), sensing (*54*), and learning (*52*). For instance, a 3D-printed cubic lattice with air-filled channels demonstrated distributed sensing by measuring pressure changes under deformation (*54*). A soft actuator with tunable internal pressure exhibited predictable kinematics. Mechanical neural networks with adjustable beam stiffness demonstrated learning capabilities analogous to weight adaptation in artificial neural networks (*52*) (4B). Tunable edge-localized soft modes and tunable mechanical stability are also found in topological metamaterials (*63, 64*).

Unusual deformation behaviors, such as compression–twist coupling (*55*) and rigid torque trans-

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mission (*65*), can be achieved by strategically designing lattice beam distributions. A chiral-lattice soft robot exemplified this, using a saddle-shaped dielectric elastomer actuator and asymmetric feet—one flat, one chiral—to enable diverse, rapid movements (forward, backward, circular) driven by frequency-dependent voltages (*66*).

Auxetics

Auxetic metamaterials, characterized by a negative Poisson's ratio, exhibit counter-intuitive behaviors such as compression–contraction, stretch–expansion, and convex bending. An auxetic metamaterial contracts in all directions when uniaxially compressed and expands in all directions when uniaxially stretched. In contrast, conventional materials, with Poisson's ratios typically in the range of 0.25–0.5, laterally expand under uniaxial compression and contract under uniaxial tension. Additionally, under a bending load, auxetic plates form convex shapes (positive Gaussian curvature), unlike the saddle shapes of ordinary materials. Typical auxetic designs include re-entrant and chiral microstructures: the former deforms through beam bending and deployment, whereas the latter relies on the rotation of chiral nodes (*67, 68*).

Compression–contraction deformation enables synclastic compressive behavior, enhancing object manipulation and actuation in robotics. This mechanical response facilitates functions such as locomotion with fewer actuators (*69, 70*), conformal grasping (*71*), multi-DoF legs (*72*), flipper-style locomotion (*73*), and rapid, sustained hopping (*74*). Incorporating auxetic metamaterials in a robot's body simplifies control and actuation. For instance, a soft robot with a single actuator and auxetic and conventional clutches demonstrated inchworm motion through a passage (4C) (*69*). The opposing Poisson's ratios of the clutches caused opposite mechanical responses, enabling linear locomotion driven.

Stretch–expansion deformation predominantly occurs in 2D designs, such as highly sensitive and stretchable strain sensors (*75–77*) and multi-DoF hollow-tube actuators (*19*). Integrating chirality into auxetic tubes allows for enhanced force transmission and twisting expansion (*19*). A compliant chiral auxetic actuator with four tubes demonstrated 4 DoFs, enabling movements in multiple directions (4D).

Convex bending deformation enables conformal surface morphing (*78, 79*) and double curvature in flat sheets (*80*). Double curvature allows for seamless shape displays without aliased edges. An

auxetic metamaterial-based shape display demonstrated this by creating a large, continuous surface that responds to hand movements (*80*). The auxetic surface, resistant to easy deformation, provided varying Gaussian curvatures, allowing independent bending in two directions and enhancing the illusion of continuous surface exploration.

Structural instability

Structural instability—such as buckling and crippling—involves sudden failure under minimal force increases. Metamaterials harness such instabilities to create mono-, bi-, and multistable states, as revealed by their elastic energy–force curves (*81, 82*). Monostable systems exhibit reversible nonlinear large deformations, characterized by an initial linear elastic deformation followed by a distinct plateau in the stress–strain curve. Bistable systems snap from a high-energy state to a second stable configuration, releasing stored strain energy as kinetic energy and retaining shape after load release. Multistable systems have three or more stable states, enabling complex, programmable deformations.

Monostable systems exhibit reversible nonlinear compression and switchable buckling modes, useful for pneumatic actuation in artificial muscles (*83*), grippers (*84, 85*), locomotors (*86, 87*), and valves (*88*). For example, a buckling-dominated metafluid gripper enabled crush-free manipulation by exploiting programmable compressibility and viscosity, showing snapping-induced pressure plateaus for effective object handling (4E) (*85*). Tunable buckling modes also enable digital logic gates (*89, 90*) and mechanical information encoding (*91*).

Bistable systems enable rapid transitions between two stable states, providing high-speed, high-force actuation for propulsion (*92*), jumping (*93, 94*), galloping (*95*), and oscillatory loco-motion (*96*). A cheetah-like crawler achieved speeds of 2.68 body lengths per second using a bistable spine actuator that combined springs and pneumatic bending, offering 20 times faster response and three times higher force than conventional actuators (4F) (*95*). Bistable mechanisms also enable mechanical logic (*97–99*), information encoding and storage (*100, 101*), and shape reconfiguration (*102*).

Multistable systems, capable of maintaining multiple stable states, enable multimodal transformations (*103*), ternary logic operation (*104*), and multistate shape morphing (*105*). 3D mesostructures exploiting multistable buckling achieved programmable shape reconfiguration through me-

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chanically guided assembly, accomplished by sequentially releasing prestrained elastomers and stabilizing various buckling modes (*105*).

Shape-reconfigurable structures

Robotic systems often require large shape transformations, constrained by bending, stretching, and buckling of structural elements. Shape-reconfigurable structures—drawing from origami, kirigami, and contact-based coupling—enable transformations between 2D and 3D configurations through deformation at element connections. Origami and kirigami use flexible creases and stiff panels for versatile reconfiguration, whereas contact-based coupling relies on rolling or interlocking blocks for modular adaptability. These principles enhance robotic flexibility, force transmission, and control simplicity.

Origami

Origami metamaterials are created by introducing folding creases into flat sheets, reducing elastic energy and facilitating folding and unfolding (*106, 107*). In rigid origami, elastic energy is localized at creases, yielding predictable kinetics and tunable DoFs. In deformable origami, energy is stored in both the creases and panels, producing more complex mechanical responses. Origami designs allow shape transformations and enhanced force transmission.

Transformations that are 2D-to-2D allow folded sheets to deploy into large flat surfaces, enabling compact structures such as gliders (*108*), programmable matter (*109*), and fluid-driven artificial muscles (*110*). An origami-based glider mimicking ladybird wing veins demonstrated compact folding, rapid deployment (466 ms), and effective aerodynamic support with a 35 g mass and 660 mm wingspan (5A) (*108*).

Transformations that are 2D-to-3D enable flat sheets to bend, twist, and fold under minimal loads, creating untethered robots responsive to external stimuli (*96, 111–115*). Such stimuli-driven designs allow versatile manipulation and locomotion, including soft grippers actuated by external physical fields (*113, 115*) and locomotors with controllable gaits (*111*). Origami millirobots can even operate untethered with minimal electronics (*116*).

Transformations that are 3D-to-3D enable reconfigurable robotic architectures with programmable

functions (*117–120*). Reconfigurability can be achieved through mechanisms such as self-folding chains activated by elastic and magnetic energies (*117*), soft hinges powered by acoustic waves (*118*), pneumatic powder-driven extruded cubes (*119*), transformable wheels with hydraulic actuators (*120*), and origami-based breathable air pouches activated by pneumatic pressure (*121*). For instance, an origami-based transformable wheel switched between large and small configurations with high load capacity (>10 kN), payload-to-weight ratio (>50), and shape variation ratio (~1.7) (5B) (*120*). This wheel, based on a waterbomb tessellation pattern, showed perpendicularity in driving and supporting directions.

Modularity derived from origami patterns enables reconfigurable and swarm robotics reminiscent of insect behavior (*21, 122, 123*). Compared with fixed-shape modules, origami modules offer greater compactness and deployability. Our group developed the Mori robot, which can move, self-connect, and fold into various 3D configurations (*122, 124*). We later enhanced its versatility using physical polygon meshing, allowing each triangular module to independently extend its edges by up to 7.5%. This supports diverse applications in interaction, manipulation, and multimodal locomotion (5C) (*21*).

Force transmission through origami designs enables programmable kinematics in robotics (*125*). Two notable mechanisms are Kresling origami (*15, 126–130*) and Canfield joint origami (*131–133*). Kresling origami, characterized by its cylindrical shape with triangulated unit cells, features compression–twist coupling motion. Its mechanical properties, ranging from stiff to flexible based on geometric parameters, allow for on-demand deployability and tunable dynamic behaviors, supporting applications like digital logic gates (*129*), robotic arms (*126, 128*), and mechanical memory operation via bistability (*127*). A magnetically controlled Kresling arm demonstrated untethered multimodal deformations—stretching, folding, omnidirectional bending, and twisting—for object grasping and manipulation (5D) (*128*). Canfield joint origami, a compact 3-DoF mechanism, enables haptics, force-feedback, and reconfigurable surfaces (*132, 133*).

Kirigami

Kirigami metamaterials, created by cutting flat sheets to form linkages between panels, enable large shape transformations and nonlinear mechanical responses (*106*). Rigid kirigami, where undeformable panels rotate around small linkages, allows predictable, programmable transfor-

mations (*134*). Deformable kirigami, where both panels and linkages deform under tension or compression, exhibits nonlinear behavior such as buckling (*135*). Depending on the motif, kirigami can deploy into 2D or 3D shapes with high stretchability (*136*) and multistability (*137*).

Transformations that are 2D-to-2D enable kirigami to stretch under tension or contract under compression. Integrating kirigami with auxetic designs enhances flexible electronics for soft robotics, improving perception and autonomy (*138, 139*). Additionally, 2D-to-2D transformations under compressive loads have applications in surface information encoding and storage (*101*), logic operations (*104*), and adaptive locomotion via soft wheels (*140*). A kirigami-wheeled robot, powered by environmental flow, navigated pipelines using soft wheels that provided support and mobility (*140*).

Transformations that are 2D-to-3D in kirigami arise from snap-through buckling under tension or compression, enabling complex 3D surface formation. Two primary transformation modes are stretch-buckling, where tensile loads bend panels out-of-plane to form programmable 3D shapes (*134, 141*), and compression-buckling, where compression induces out-of-plane deformation (*142*). By strategically designing the kirigami's linkages and motifs, stretch-buckling allows programmable control of buckling process, including multiple stages (*143*), buckling direction (*144*), localized mechanical responses (*145*), and the inverse design of desired target shapes (*134*), and supports actuators with diverse linear actuation modes (roll, pitch, yaw, and lift) (*146*) and object grasping (*147*). Compression-buckling can be controlled via prestress (*142*), loading sequence (*148*), substrate properties (*105*), and the presence of defects in the kirigami structure (*149*), and is applied in morphable mesostructures (*135, 142*) and microelectronic devices (*105*). Responsive-material-based kirigami further enables untethered soft millirobots with stimulus-responsive 3D shape changes (*150–153*).

Transformations that are 3D-to-3D involve reconfiguring structures entirely within 3D space, seen in kirigami-based tubes (*18, 143*), lattices (*154*), and baskets (*155*). In tube forms, snap-induced buckling creates textured surfaces that enhance soft actuator locomotion via directional friction (5E) (*18, 156*). Kirigami lattices with Miura folds offer programmable anisotropic bending stiffness for morphing wings and tentacles (*154*). Basket-shaped kirigami grippers use stretch-induced buckling to achieve tendril-like motions, enabling grasping of ultra-soft to ultra-heavy objects—up to 16,000× their own weight (5F) (*155*).

Contact-based coupling

Contact-based coupling in metamaterials involves interactions between building blocks to create two main systems: discretely rolling-contact and continuously interlocking-contact (*157*). Rolling-contact systems use flexure straps (*158*), gears (*44*), hinges (*159*), or magnets (*160–162*) to enable flexible, in situ reconfiguration. This design enables adaptive robot swarms that can be rearranged within their environment, allowing dramatic dimensional transformations from 1D to 2D and 3D. Interlocking-contact systems—built from chainmail, knots, or yarns—achieve tunable mechanics through loosely topological connections like chaining (*163–165*), weaving (*166*), knotting (*167*), or knitting (*168*), offering continuous control over deformation (*166, 167*).

In situ reconfiguration, achieved through the relative rotation and motion of rolling-contact building blocks, enables continuously tuning of elastic properties without substantial increases in strain energy or internal stress (*44, 158*). Incorporating motorized units in place of passive building blocks unlocks possibilities for autonomous locomotion and extreme shape morphing versatility. This approach represents a robust design principle for modular, multi-agent swarm robotics with decentralized control, such as global signals (*160, 169*), mechanical feedback (*160*), spatiotemporal modulation (*161*), and mechanical compression or thermal stimuli (*170*). A compelling example is a self-organizing robotic aggregate with magnetically coupled, motor-driven gear units that switch between solid-like and fluid-like states for adaptable movement (5G) (*160*). This approach highlights the potential for robotic swarms to dynamically adapt their forms in diverse environments through in situ reconfiguration.

Continuously interlocking-contact systems exploit compliance to enable adaptive functionalities. In textiles, interlocking patterns allow fabrics to dynamically adjust softness and shape for wearable adaptability (*163, 168, 171*). These structures also support body-conforming textile electronics for physiological monitoring (*166*). Beyond textiles, integrating stimuli-responsive materials like liquid crystal elastomers (LCEs) enables knotted artificial muscles with rapid thermal actuation (*167*). Interlocking designs also drive microrobotic locomotion, such as corkscrew and tumbling motions via magnetically actuated multimaterial microswimmers (*172*).

Material-driven functionality

Traditionally, robots separate electronics for sensing, actuation, control, and computation from their physical bodies, creating a divide between the "brain" and the "body" (*173*). However, integrating intelligence directly into materials blurs this boundary, enabling robots whose bodies contribute to sensorized actuation and computation in response to external control. Stimuli-responsive (smart) materials can sense and react to external cues—such as temperature, light, moisture, pH, magnetic fields, electric currents, or electromagnetic fields—by generating motions (such as expanding, contracting, bending, twisting, squeezing, and stretching) or altering their physical properties (such as stiffness, phase, and surface texture). This dual sensing–actuation capability allows for direct, material-level control of robotic behavior. However, their use is limited by slow response, low durability, and insufficient mechanical strength in dynamic tasks. Combining responsive and passive materials into metamaterial architectures enables programmable mechanical responses and multifunctional robotic bodies with adaptive, autonomous capabilities. Multimaterial metamaterials further allow spatially distributed functions but face fabrication challenges related to resolution, material compatibility, and process complexity (*2, 14, 174*).

Responsive metamaterials for actuation, sensing, and control

Unlike traditional stimuli-responsive materials that react monotonically to stimuli, responsive metamaterials integrate these materials with mechanical logic networks. In such systems, mechanical logic governs the response of the materials, creating a programmable stimuli-responsive behavior that translates environmental inputs into shape and property changes within the network itself. Such material-based perception embeds sensing functions directly into the robot's body, offering an alternative or complement to conventional sensors. Unlike discrete electronic sensors, this approach enables distributed, structurally integrated mechanical responses to external stimuli, potentially enhancing robustness, spatial resolution, and functional density. Consequently, stimuli-responsiveness enables sensorized actuation, where the same structure both senses and responds, allowing direct control of the robot's behavior using external physical fields.

Thermoresponsive metamaterials, typically based on LCEs and shape memory polymers (SMPs), utilize thermal expansion, phase transitions, and shape memory effect to produce programmable

mechanical responses. Heating can be applied via Joule effect (*175–179*) or enviromental temperature changes (*92, 112, 180–182*). Deformations can be tuned by strain mismatch of bilayered films with different thermal expansion coefficients (*112, 182, 183*), or with active–passive material combinations (*175, 184*). Snap-through instability accelerates actuation speed (*177*), and localized heating enables programmable nonlinear motions (*87, 181*). Beyond polymers, thermostatic metal strips enhance actuation capacity, thermal strain, and bandgap tunability in temperature-responsive metamaterial actuators (6A) (*182*).

Photoresponsive metamaterials operate at both molecular and composite levels. Photoactive molecules like azobenzene undergo light-induced isomerization, enabling reversible bending, folding, contraction, and wave propagation for light-driven functions like light tracking and gripping (*96, 96, 115, 185*). A kirigami-based rolling robot made of photoresponsive LCEs demonstrated light-directed versatile locomotion (6B) (*186*). Localized photoresponses can create strain mismatches, as seen in hydrogel films bending via light-induced hydrophobicity changes (*185*). At the composite level, embedding photoabsorbers into thermoresponsive matrices enables photothermal actuation and reprogrammable soft robotics (*87, 187*). Combining photoresponsive polymers with metamaterial architectures yields non-reciprocal, self-regulated motion, such as LCE microactuators tracking light via opto-chemo-mechanical feedback (*188*).

Chemistry-responsive metamaterials, often based on hydrogels and liquid-crystalline polymers (LCPs), react to liquids, pH, or ion concentration through swelling or shrinking, enabling reversible topological and bending transformations. For instance, LCP microstructures can shift from triangular to hexagonal lattices via liquid-induced swelling (*189*), and layered LCPs bend in response to moisture (*190*). A 3D-printable pH-responsive hydrogel enables 3D-to-3D shape morphing in a single-material-single-step mode (*191*), and xerogels integrating graphene and magnetic elastomers support multifunctional, logic-driven soft robotics (*150*).

Electric-responsive metamaterials—based on electroactive hydrogels (*192, 193*), dielectric elastomers (*66, 194*), LCEs (*178, 195*), and piezoelectric composites (*20, 164, 196*)—deform under applied voltages. Hydrogels bend via ion-induced osmotic pressure, elastomers expand through electrostatic forces, LCEs contract by Joule heating, and piezoelectrics enable two-way conversion between electric and mechanical signals. Integrating these materials into metamaterial architectures enables programing mechanical strains in response to electrical fields, supporting applica-

tions in sensing and feedback-driven actuation (*20, 164, 197*). A robotic metamaterial combining conductive, piezoactive, and structural elements achieved electric-field-driven shape changes and decision-making via self-sensing (6C) (*20*).

Magnetic-responsive metamaterials—typically composites embedded with magnetic particles—enable rapid reconfiguration and actuation in soft robotics (*117, 123, 160, 198*). Though early designs exhibited limited response modes (*147, 152*), recent advances in constitutive material (*113*), structural (*151, 199*), and post-processing design (*153*) have expanded their capabilities. Metamaterial designs can break the undesired chain-like assembly of magnetic dipole-dipole interactions due to the low-energy configurations of dipole symmetry. For example, a lattice design forming magnetic quadrupole modules alters magnetic particle–particle interactions in both symmetry and strength, enabling the formation of stable, frustration-free magnetic assemblies with arbitrary 2D shapes (6D) (*200*). Also, magneto-origami structures allow foldable deployment under magnetic fields (*199*). Programmable magnetization further supports multimodal locomotion and sensing (*151*), although real-time customization via localized magnetization remains challenging (*153*).

Electromagnetic-responsive materials overcome the localized magnetization limit by leveraging Lorentz forces from magnetic fields and electric currents for fast, reprogrammable actuation. Embedding liquid-metal coils in soft enclosures enables highly stretchable, ultrafast actuators (*114, 201*). Configurations like planar spirals and 3D helices allow control of electromagnetic vector orientation and magnitude (*202*). Assembling these modules in parallel permits arbitrary in-plane actuation via magnetic torque and force (6E).

Multimaterial metamaterials for programmable functions

Responsive metamaterials integrate actuation, sensing, and control, but single-material systems constrain design flexibility. Combining responsive with passive or other responsive materials enables versatile architectures—bilayer, multilayer, surface-patterned, doped, interpenetrating, tensegrity, and assembled forms (7A). In these multimaterial metamaterial systems, materials with distinct physical properties are subjected to a load or external stimulus, generating strain mismatch that leads to internal stress and results in intentional deformation behavior. These designs, coupled with metamaterial logic networks, are supported by advanced multimaterial additive manufac-

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turing (*203*). Such multimaterial metamaterials allow decoupled sensing, actuation, and control through various external stimuli, and bring about versatile responses like programmable motion, shape transformation, and variable stiffness.

Metamaterials made from multiple responsive materials can decouple sensing, actuation, and control via diverse external stimuli. Often realized in 2D origami or kirigami architectures (*150, 204, 205*), these systems adapt their shapes or properties through spatially tuned component arrangements. For example, a soft millirobot with a hydrogel–elastomer–magnetic nanoparticle sandwich structure responded to six stimuli, enabling autonomous motion (*204*). Another kirigami-inspired robot used modular materials to sense and react to light, heat, and solvents, adjusting its trajectory autonomously (7B) (*205*).

Metamaterials built from materials with varying stiffness enable programmable motions. Bimaterial systems combining responsive and passive materials allow untethered actuation via magnetic fields (*206*), light (*187*), or heat (*112, 180*). For example, tensegrity structures, consisting of rigid struts and flexible tendons held together by tensile and compressive forces, offer a high stiffness-to-mass ratio, structural flexibility, and broad deployability. Using magnetic-responsive tendons and optimized node configurations enables programmable actuation (7C) (*206*). Bimaterial pneumatic systems use soft components for deformation and stiff ones for guidance, achieving stretch, contraction, twist, and bend (*203, 207, 208*). Multimaterial systems using pre-stretch techniques demonstrated rapid high-energy release in jumping robots (*209*). Modular chiral origami metamaterials consisting of Kresling origami unit cells with different stiffness exhibits programmable information storage/encryption (7D) (*15*).

Multimaterial metamaterials also offer distinct advantages such as reversible shape transformation, variable stiffness, and reduced reliance on actuators. Embedding phase-transition materials—such as SMPs (soft–rigid switching) and low-melting-point alloys (liquid–solid switching)—into passive materials enables shape morphing (*78*), conformal gripping (*210*), shape reconfiguration (*211*), and high-load object manipulation (*175, 184*). These phase-change materials are often arranged in auxetics (*78*), kirigami (*78*), or origami layouts (*211*). For example, a multimaterial auxetic kirigami achieved large deformability and high load capacity, enabling a morphing drone to transition autonomously between ground and aerial configurations (7E) (*78*). Reversible shape transformation can also arise from structural design level, such as through Maxwell lattices—an example

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of topological metamaterials (*11*). Beyond material-level design, unit cell-level strategies—such as locally embedding active units into passive metamaterials—allow for dynamic shape changes and robotic functions (7F) (*212*). This approach minimizes actuator requirements, as passive rigid cells redistribute forces to produce complex motions with fewer active components.

DESIGN AND MODELING OF METAMATERIAL ROBOTS

Achieving integrated functionalities and enhanced performance heavily depends on the design of metamaterial robots. Traditionally, human-guided heuristic design has led to the discovery of a wide range of metamaterials and robotics. However, this approach relies heavily on designers' intuition and inspiration from nature, often involving trial and error. Investigating mechanical properties and responses typically requires laborious experiments or computationally expensive simulations, and design complexity soon exceeds human capacity. Computational methods—such as topology optimization and deep generative models—help overcome these limitations by automating the design process, enabling optimal structure generation (*1, 213*) and inverse design with targeted robotic functionalities (*23, 24*). For a comprehensive overview of recent advancements, challenges, and opportunities in computational models for metamaterial design, see (*214*).

Modeling plays a crucial role in the design and optimization of metamaterial robots. Analytical models, numerical simulations (such as finite element analysis and physics-based simulations (*215*)), and reduced-order models enable the prediction and optimization of metamaterial robots across scales—from unit-cell mechanics to system-level functionality. These approaches support rational mechanical design, physically consistent state estimation, optimal control, and system identification in complex dynamical systems with contact-rich behaviors. Furthermore, AI (such as physics-informed machine learning and data-driven modeling) helps bridge the gap between theoretical predictions and real-world material behavior, accelerating the iterative design process for robotic sensing, actuation, and control (*216*).

Undoubtedly, many challenges remain in the effective design and modeling of metamaterial robots. Physics-based models, although accurate, are often computationally expensive, whereas AI-based models face limitations from data scarcity, low data quality, and physically implausible outputs. In particular, the design and modeling of responsive and multimaterial systems are par-

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ticularly difficult due to their nonlinear and coupled behaviors under multiple stimuli and extreme conditions. Capturing these interactions in real time remains an open problem for control and prediction. A promising direction lies in the integration of AI with high-fidelity physical simulations to bridge data-driven learning and physical accuracy.

OUTLOOK

Although metamaterial design principles have substantially enhanced robotic designs, current state-of-the-art metamaterial robots still lack full integration of sensing, actuation, computation, communication, locomotion, and manipulation. Some prototypes demonstrate partial integration—such as piezoelectric metamaterial robots capable of movement, sensing, and feedback control (*20*), and non-reciprocity metamaterial robots incorporating local sensing, computation, communication, and actuation (*217*). Achieving fully functional integration in metamaterial robotics can be pursued through various strategies, including the partial or full combination of responsive materials, metamaterial designs, embodied intelligence, advanced fabrication techniques, and high-fidelity simulation and control techniques.

Looking ahead, there remains critical research gaps in achieving the full potential of metamaterial robotics. First, unified design frameworks are needed to seamlessly integrate material properties, geometry, and functionality across scales; progress is hindered by the lack of standardized datasets and benchmarks. Second, achieving robust, scalable manufacturing remains an open challenge, particularly in fabricating structures with spatially varying heterogeneity and properties. Third, the modeling of dynamic interactions between metamaterial robots and environments—especially in unstructured, real-world settings—requires more efficient hybrid modeling tools. Finally, such a long-term vision requires having a platform of metamaterial robots that go beyond online models: robotic systems capable of autonomous learning, adaptation, and reconfiguration through the co-evolution of material, morphology, and control. Advancing toward this goal will require interdisciplinary collaboration across robotics, materials science, computer science, and manufacturing, alongside a sustained effort to develop open-access tools and shared platforms for community-wide innovation.

Recent advances in AI have expanded the capabilities of metamaterial robotics. Beyond design

and modeling, AI such as reinforcement learning supports autonomous control (*39, 218, 219*), real-world humanoid locomotion (*220*), dynamic robotic tracking (*221*), and agile soccer skills (*222*). Embedding these AI models into metamaterial robotic systems can improve robotic control, enabling robots to perform complex tasks, adapt to changing environments, and learn over time (*223*). With hierarchical architectures inspired by biological systems, metamaterial robotics holds the potential to achieve embodied intelligence across scales–from individual robotics with embedded intelligence to swarm robotics with the ability of communication and collaboration.

We define the intelligence in the context of metamaterial robotics as the capacity to autonomously sense, process, and respond to environmental stimuli, and to learn, adapt, and update behavior based on memory. To move beyond subjective interpretation, intelligence can be evaluated using six objective criteria: sensorimotor responsiveness, the ability to detect external stimuli and generate a physical response within defined latency thresholds; adaptability, the capacity to modify behavior or performance in response to varying environmental or task conditions; task generalization, the ability to perform multiple tasks or operate across different conditions without manual intervention; energy efficiency, the amount of energy required for perception, actuation, or decision-making relative to task complexity; autonomy, the degree to which the system operates without external control, including local feedback control loops or embedded computational decision-making; on-board learning, the capacity to store past experiences or states and use them to guide future decisions.

Individual metamaterial robotics

Integrating metamaterials into robotic components can address key challenges in actuation, sensing, control, and computation, advancing toward embodied intelligence. At a lower level of intelligence, metamaterial robots resemble simple organisms such as Western Pacific hexactinellid sponges, which thrive in extreme deep-sea environments through hierarchical cylindrical lattice structures that provide mechanical robustness across scales (*224*). This hierarchical architecture inspires mechanical computing systems, where information processing and storage emerge as inherent material properties (*22*). Such mechanical computing systems have been realized in logic computing (*89, 97*), information storage (*100, 101*), and mechanical neural network (*52*). By leveraging hierarchical

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architecture and mechanical computing, metamaterial robots could blur the boundary between "body" and "brain", potentially enabling autonomous adaptation to extreme environments (*225*).

At a higher level of intelligence, metamaterial robotics may mirror complex organisms such as humans. Drawing inspiration from biological systems, vertebrates possess sophisticated sensory systems that enable them to perceive their environment through vision, touch, and other senses. They also have brains that learn, compute, reason, and make decisions, muscle systems that contract and relax to generate forces, and compliant bones and soft tissues that achieve dynamic gaits by storing elastic energy. Embodied AI follows this principle, enabling robots to interact with the physical world with agility, dexterity, and understanding. Furthermore, Emerging technologies—including quantum machine learning (*226*), quantum materials (*227*), nanoelectromechanical systems (*228*), and neuromorphic computing (*229*)—further promise miniaturized "brains" within robotic bodies. We envision metamaterial robots that integrate such computing units with decentralized sensing networks, artificial muscles, and compliant skeletal structures (*2*). This system-level intelligence emerges from a combination of centralized computing system (for higher-order learning, decision-making, and control) and distributed, material-embedded sensing and actuation units (for local responsiveness and adaptation). In this sense, the "brain" captures the collective functionality of mechanical responses and embedded sensing networks, enabling the robot to perceive, interpret, and interact with its environment.

Swarm metamaterial robotics

Beyond individual robotics, swarm robotics involves groups of robots that coordinate and cooperate to solve problems or perform tasks collectively. Self-organized swarms of simple robots can function as a robotic society that is more robust to individual failures, more resilient to environmental changes, and capable of performing complex tasks and constructing sophisticated structures (*230*). Traditional robot swarms are typically homogeneous in physical designs and control algorithms, limiting emergent diversity and task flexibility. Metamaterials offer a pathway toward heterogeneous swarms composed of robots with specialized perception, actuation, and control capabilities, adaptable to varied environments. For example, metamaterial robots based on multistable structures can reconfigure their shapes (*82*), whereas those incorporating multiple smart materials can sense

and respond to various external stimuli (*2*). Crucially, the contact-based coupling of metamaterial building blocks provides a mechanism for physical interaction and coordination across robots of different sizes and forms, enabling the creation of robotic aggregates and collectives (*160,161,169*).

Looking ahead, for robotic systems to perform increasingly complex tasks, they must—like many organisms on Earth—evolve from operating as isolated individuals or under centralized control to functioning as self-organizing, loosely coupled teams. Inspired by natural collectives—such as insect colonies or fish schools—swarm metamaterial robotics aims to generate emergent collective behaviors through simple local interaction rules. With the integration of embodied AI, these swarms could achieve higher levels of intelligence, enabling learning, communication, and collaboration across scales. Such systems could range from microscale robot swarms for biomedical applications like targeted drug delivery, to meter-scale robot swarms for space exploration missions (1E).

CONCLUSION

Metamaterial robotics represents a rapidly emerging frontier that unites materials, mechanics, and robotics to create systems capable of integrated sensing, actuation, control, and computation. Design principles—mechanics-inspired architectures, shape- reconfigurable structures, and material-driven functionality—enable tunable mechanical responses that underpin embodied intelligence, fostering adaptive, reconfigurable, and functionally distributed robotic systems. Modeling and simulation—ranging from physics-based to AI-driven and hybrid approaches—are key to predicting performance, optimizing structure, and bridging the gap between material behavior and robotic function.

Despite substantial progress, challenges remain in scalable manufacturing, accurate modeling of nonlinear and stimuli-responsive behaviors, and seamless integration of decentralized sensing and control. Addressing these gaps will require interdisciplinary collaboration across materials science, mechanical engineering, robotics, and computer science. Looking forward, metamaterial robotics has the potential to reshape how robotic systems interact with their environments—evolving from rigid, centralized machines to adaptive, intelligent collectives capable of self-organization, learning, and autonomous evolution, embedding intelligence not only in algorithms but within their
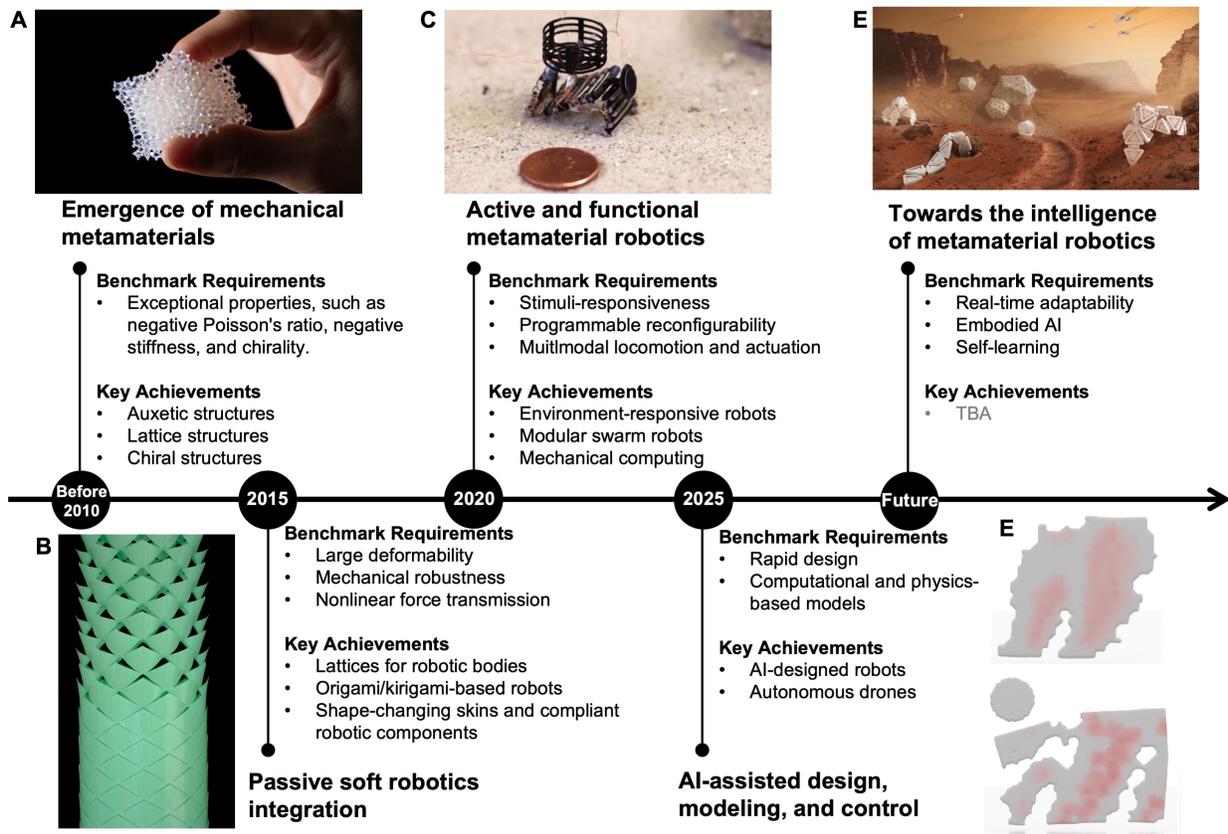
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very materials and microstructures.

Figure 1: **Development timeline of metamaterials for robotics.** (**A**) Auxetic metamaterial (Credit: Ikumu Watanabe, NIMS) (*8*). (**B**) Soft actuator capable of crawling with kirigami skins (*143*) . (**C**) Proprioceptive architected robotic metamaterial (Credit: Rayne Research Group/UC Berkeley) (*20*). (**D**) AI-designed robots for locomotion and object manipulation (*24*). (**E**) Illustration of a modular, reconfigurable robot swarm transforming into various forms for space missions (*21*).

Central nervous system (Brain)
based on <u>embodied AI</u> or <u>mechanical computing</u> for higher-order learning, decision-making, and control.

Artificial skeleton
based on <u>auxetics</u> and <u>lattices</u> with lightweight, resilience, compliance, stress-shielding, and self-healing ability.

Robotic arm
based on <u>multimaterial lattices</u> with multipe DoF and on-demand actuation.

Artificial muscle
based on <u>lattices</u> with high stroke and high-output force.

Electronic skin
based on <u>Kirigami</u> and <u>smart materials</u> for sensing.

Robot joints
based on <u>contact-based coupling</u> with high compliance and continuously *in situ* shape reconfiguration.

Robotic hand
based on <u>origami</u> for dexterity and flexibility.

Artificial legs
based on <u>structural instability</u> with enhanced agility and acceleration.

Figure 2: **Concept of a humanoid metamaterial robotics.** It leverages metamaterial designs for core robotic components, with a central nervous system governing high-level functions such as learning, decision-making, and control.

Mechanics-Inspired Architectures
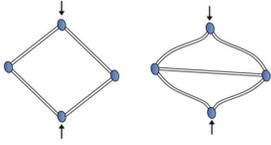
Lattices

Design Variables	Working Principle	Functional Features	Robotic Applications
Unit cell type; geometric type, size, and spatial arrangement of structural elements	Deformation of structural elements	Ultrahigh stiffness-to-density ratio; resilience; tunable stiffness; unusual deformation behaviors	Lightweight robotic bodies; distributed pressure sensing; artificial-muscle-like actuation
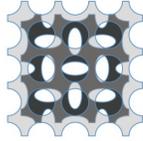
Auxetics

Design Variables	Working Principle	Functional Features	Robotic Applications
Unit cell type; curvature, angles, and size of structural elements	Deformation resulting in global synclastic behavior	Compression-contraction, stretch-expansion, and convex bending deformation	Enhanced strain sensors; conformal surface morphing; programmable motions
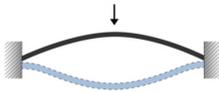
Structural Instability

Design Variables	Working Principle	Functional Features	Robotic Applications
Unit cell type; curvature and aspect ratio of structural elements; initial imperfections	Snap-through transition of structural elements	Monostable, bistable, and multistable states; fast transition	Crush-free manipulation; high-speed actuation; mechanical computing; shape reconfiguration

Shape-Reconfigurable Structures
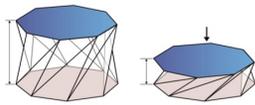
Origami

Design Variables	Working Principle	Functional Features	Robotic Applications
Crease pattern; mountain and valley fold assignments; panel shape and size	Folding/unfolding of element connections	2D/3D to 2D/3D transformation; modularity; force transmission	Compact deployable package; modular swarm robots; controllable kinematics
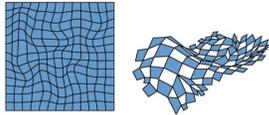
Kirigami

Design Variables	Working Principle	Functional Features	Robotic Applications
Cut pattern, length, and width; linkage size	Deformation of element connections	2D/3D to 2D/3D transformation; out-of-plane deformation	Stretchable sensors; multimodal actuators; crawling locomotion; tendril-like grippers
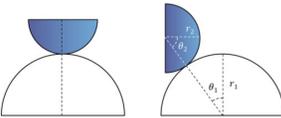
Contact-Based Coupling

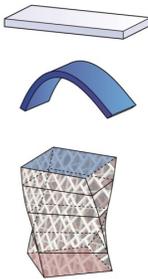| Design Variables	Working Principle	Functional Features	Robotic Applications
Unit cell geometry; contact interface; connectivity and topology	Rolling- and interlocking-contact between adjacent unit cells	Transformation from 1D to 2D and 3D; continuously in situ shape reconfiguration; compliance	Multi-agent swarm robotics; adaptive wearable electronics; super compliant robots

Material-Driven Functionality

Responsive Metamaterials

Design Variables	Working Principle	Functional Features	Robotic Applications
Type of responsive material	Mechanical logic governs the stimuli-responsive behavior	Generate motions or change physical properties in response to external stimuli	Motor-free actuation; environmental sensing robots; untethered magnetic control

Multimaterials

Design Variables	Working Principle	Functional Features	Robotic Applications
Type, number, and spatial arrangement of material components	Multimaterials designed in different spatial layouts with mechanical logic	Programmable motion; multimodal sensing and actuation; variable stiffness	Decoupled control; programmable locomotion; logic memory

Figure 3: **Metamaterial design principles for robotics.**
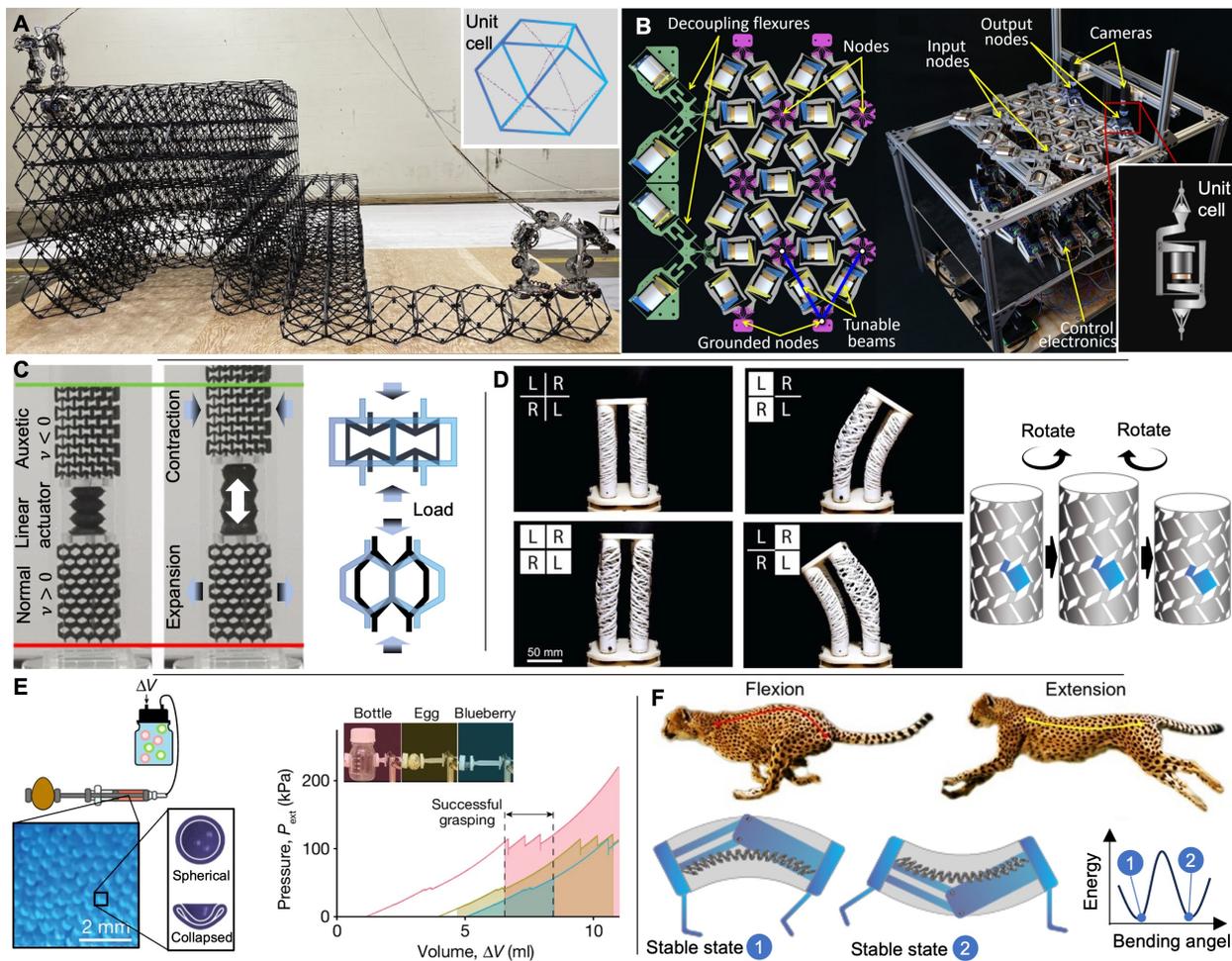
Figure 4: **Metamaterial robotics based on mechanics-inspired architectures.** (**A**) Ultralight, strong lattice metamaterial (inset) forms the body of a self-reprogrammable robotic structural system that is assembled and reconfigured by mobile robots (*17*). (**B**) Lattice-based mechanical neural network capable of learning multiple mechanical behaviors by adjusting beam stiffness (*52*). (**C**) Auxetic metamaterials simplifying robot control and reduce actuator requirements in a soft robot. The soft metamaterial robot composed of auxetic and conventional clutches achieves inchworm-like motion using a single actuator. The actuator triggers intrinsic synchronization of the two passive clutches: the auxetic clutch contracts laterally, whereas the normal clutch expands under compression (*69*). (**D**) Auxetic chiral tubes with twist–expansion deformation enhancing a four-degree-of-freedom actuator. By controlling the twist of each tube, the system achieves programmable motion (*19*). (**E**) Shell buckling creating a programmable metafluid composed of micrometer-scale capsules. Nonlinear behavior arising from shell buckling enables an adaptive two-jaw gripper to grasp objects with widely varying sizes and compressive strengths (*85*). (**F**) Snap-through bistability amplifying actuation speed and force in a locomotive soft robot, enabling rapid energy storage and release within tens of milliseconds between two stable states (*95*).
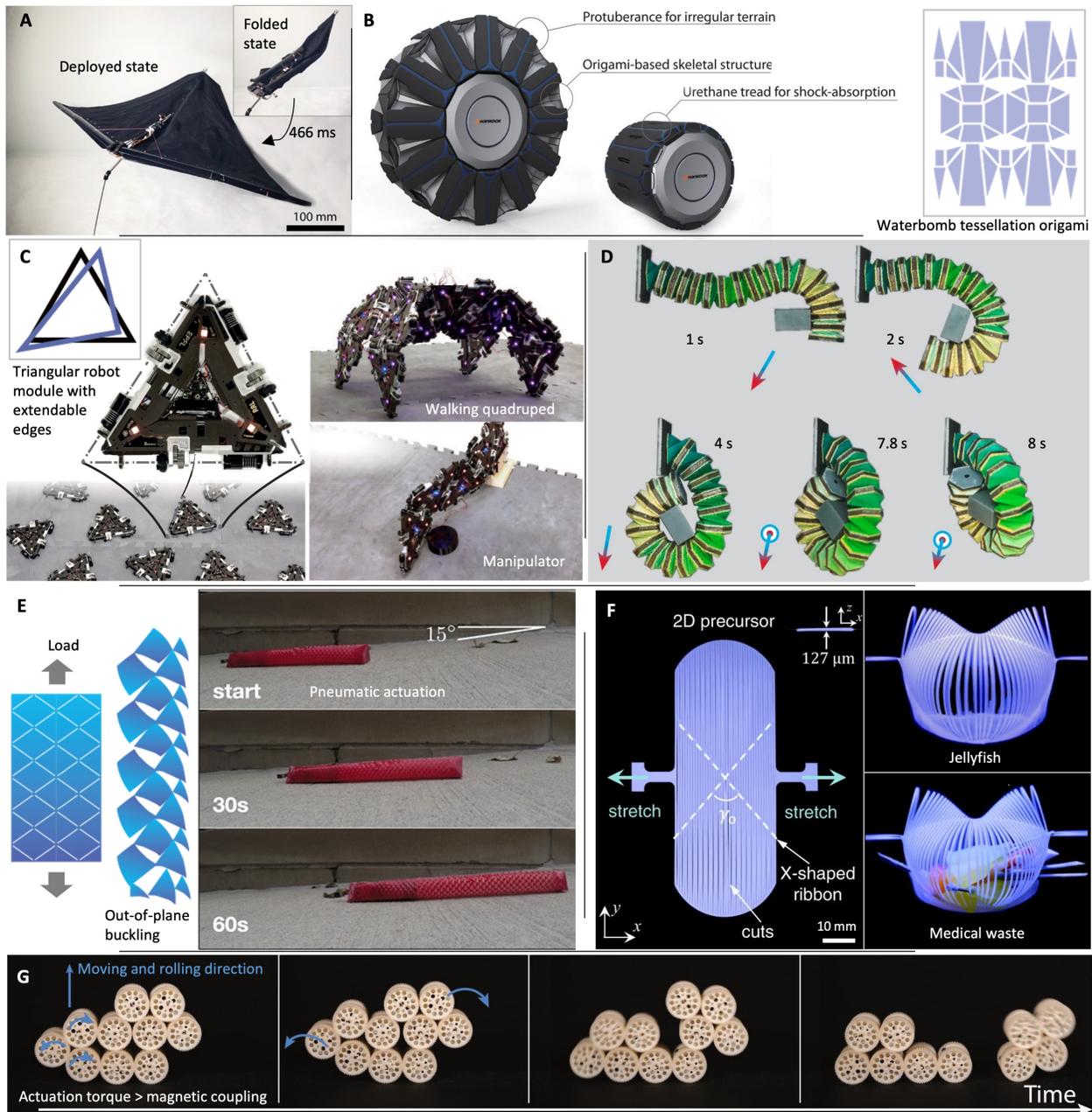
Figure 5: **Metamaterial robotics based on shape-reconfigurable structures.** (**A**) Compliant origami frame forming a deployable glider that expands by releasing stored energy (*108*). (**B**) Waterbomb tessellation origami forming a transformable wheel capable of switching between two configurations (*120*). (**C**) Modular origami robot made of triangular shape-changing modules, reconfigurable into diverse 3D configurations (*21*). (**D**) Kresling origami modules forming an octopus-like robotic arm with omnidirectional bending and object-grasping functionality (*128*). (**E**) Kirigami skin enhancing the crawling capability of a soft crawler through buckling-induced pop-up textures (*18*). (**F**) Kirigami-based gripper enabling angle-programmed, tendril-like grasping trajectories for handling diverse objects (*155*). (**G**) Magnetic rolling-contact coupling enabling a self-organizing robotic aggregate capable of autonomously splitting and forming (*160*).
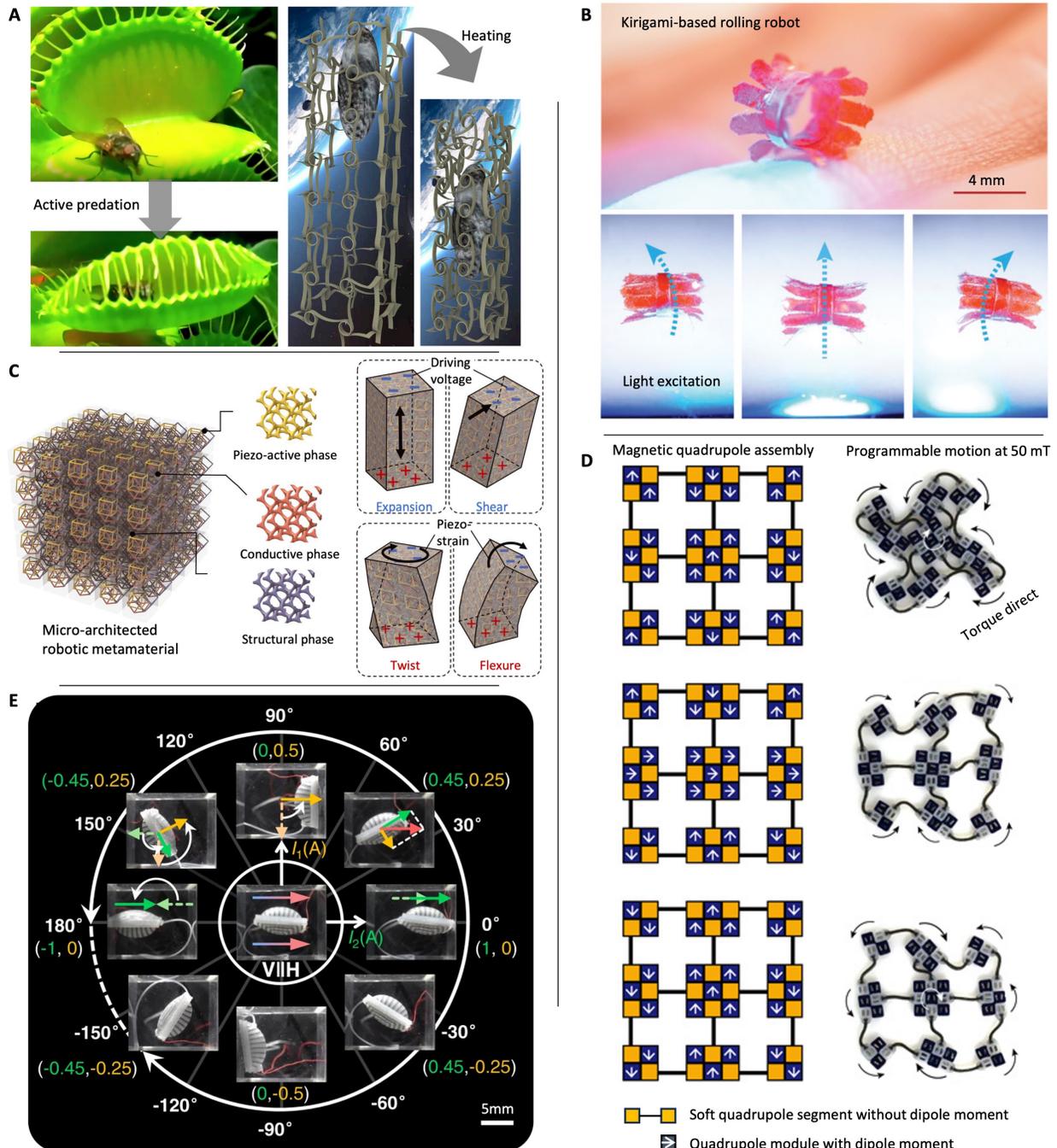
Figure 6: **Metamaterial robotics based on responsive metamaterials.** (**A**) Temperature-responsive metamaterials composed of thermostatic metal strips, demonstrating active predation behavior in extreme temperature environments (*182*). (**B**) Photoresponsive kirigami forming a millimeter-scale rolling robot, with locomotion controlled by light excitation direction (*186*). (**C**) Piezoelectric metamaterial with various strain modes and a piezoelectric strain matrix (*20*). (**D**) Magnetically responsive lattice forming programmable actuators composed of passive and active (with dipole moment) quadrupoles, with programmable motions controlled by magnetization direction (*200*). (**E**) Electromagnetic soft actuator module with self-vectoring control and high-dimensional operation, capable of forming modular robots with multimodal locomotion (*202*).
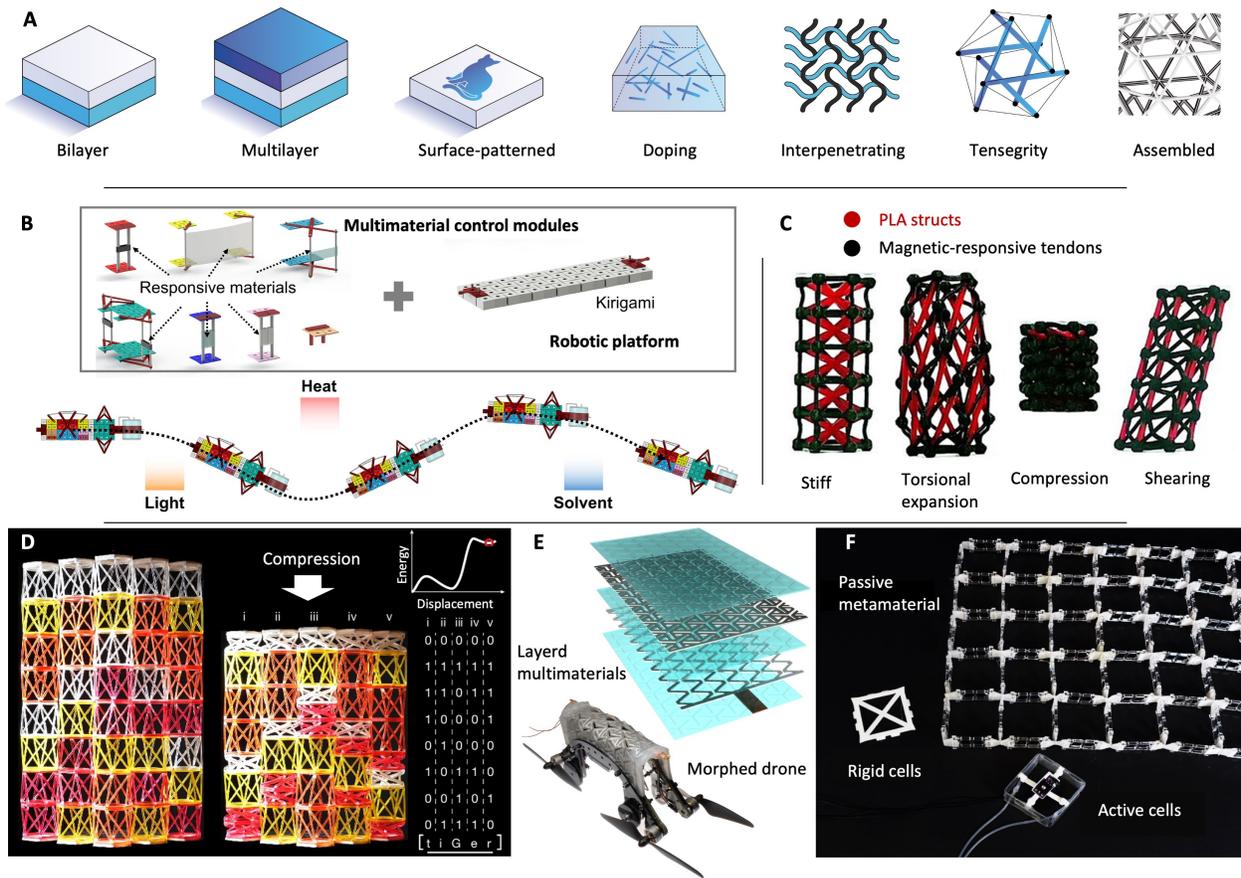
Figure 7: **Metamaterials robotics based on multimaterial metamaterials.** (**A**) Various multimaterial layouts that can be integrated with metamaterial designs. (**B**) Multimaterials with diverse stimulus responsiveness, creating a modular robot actuated by decoupled multiple stimuli (*205*). (**C**) Bimaterials composed of magnetic-responsive tendons and passive struts architected in a tensegrity structure, creating magnetically controlled programmable actuation (*206*). (**D**) Multimaterials with varying stiffness assembled into a modular metamaterial, allowing programmable information storage/encryption based on the folding and deploying sequence of origami cells (*15*). (**E**) Multilayered multimaterial metamaterial with a phase-transition auxetic endoskeleton used to construct an autonomously morphing drone (*78*). (**F**) Unit cell-level multimaterial system composed of a passive metamaterial framework and locally inserted passive and active unit cells, enabling pneumatically actuated, reconfigurable robotic function (*212*).

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