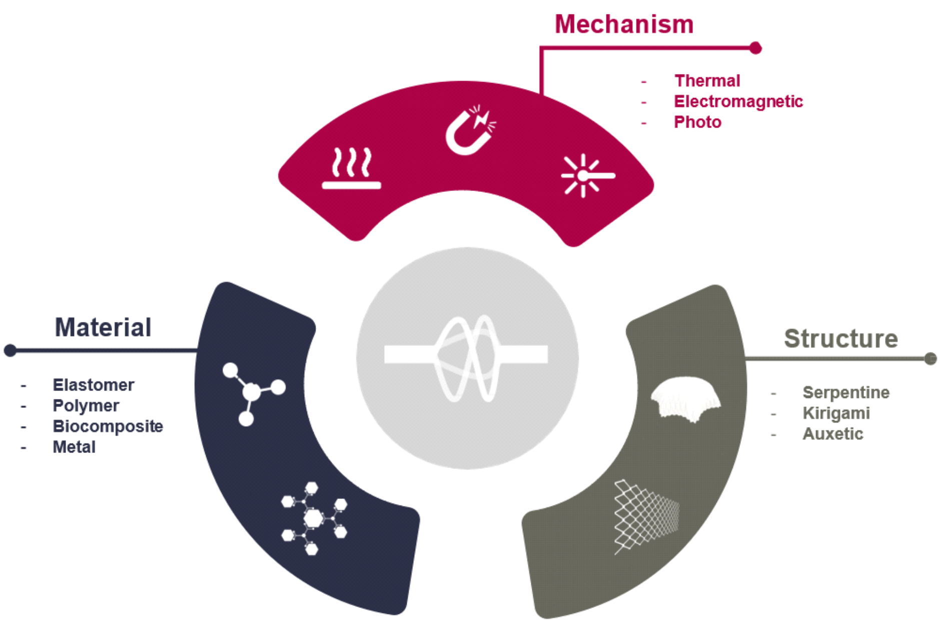
유연인쇄전자학술지, 2025년 6월, 제4권 제1호, pp. 31-54
Journal of Flexible & Printed Electronics, June 2025, Vol. 4, Issue 1, pp. 31-54
Received 2025-05-13, Revised 2025-06-04, Accepted 2025-06-19
https://doi.org/10.56767/jfpe.2025.4.1.31
eISSN: 2951-2174

REVIEW

Recent Advances in Programmable Surface Systems: A Material-Mechanism-Structure Perspective

PiusSoh, HyeinJung, Jin-TaeKim*

Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH), Pohang,Korea



ABSTRACT

Recent advances in programmable surface systems have opened new possibilities in stretchable electronics, where surfaces can actively morph their geometry and functionality in response to external stimuli. This review reports recent developments around three central pillars: functional materials, actuation mechanisms, and geometric design strategies. This framework allows for a unified understanding of how shape-morphing behavior emerges from the interplay between material composition and mechanical design, and it provides insights into how to tailor soft electronic surfaces for reconfigurability, multifunctionality, and robust performance across diverse applications in the fields of biomedical and aerospace engineering.

Key Words: Programmable surface, Programmable material, Soft electronics, Soft actuator

*Correspondence: jimmy516@postech.ac.kr

1. INTRODUCTION

Programmable surface systems are reshaping the landscape of soft electronics by enabling active and reversible control over surface geometry and function in response to external stimuli. Unlike static materials, these systems are capable of undergoing dynamic, on-demand shape transformations, providing surfaces with enhanced adaptability and responsiveness. Their inherent advantages-such as lightweight construction, mechanical flexibility, and the ability to achieve multi-degree-of-freedom motion-make them highly suitable for a broad range of applications. These include biomimetic interfaces, medical devices, and soft robotic systems, where real-time reconfigurability and conformability to complex environments are crucial [1-3].

At the core of programmable surface behavior lies the careful selection of materials whose intrinsic responsiveness determines the overall system performance. Stimuli-responsive materials, including hydrogels [8], liquid crystal elastomers [3,4], biocomposites [9,10], and metals [11-13] enable reversible transformations through physicochemical changes such as swelling, softening, or phase transitions. The material's responsiveness affects not only how deformation occurs but also how reliably and repeatedly it can be executed. As such, material choice directly influences deformability, reconfigurability, and longterm reliability, making it a foundational element in the design of programmable surfaces.

To better understand and design programmable surface systems, materials can be further classified by the type of external stimulus that drives their actuation. These include thermal [19], electrical [20], optical [25-27], and magnetic stimuli [21,22], each offering distinct modes of interaction and control. A stimulus-based classification provides a useful framework for analyzing how different materials convert energy into motion, and it also informs decisions on integration methods, spatial resolution, and energy efficiency. By identifying the mechanisms by which these stimuli interact with materials, researchers can tailor systems for specific functions and environments, from remote actuation to high-speed deformation.

Beyond material responsiveness and actuation input, the geometric structure of programmable devices plays a crucial role in shaping their mechanical behavior. Structural motifs such as serpentine [33], kirigami [34,35], and auxetic [37] architectures are widely employed to enhance stretchability and mechanical resilience. These designs allow surfaces to endure large deformations while maintaining functional stability and uniform stress distribution. Moreover, geometry-driven strategies provide an additional layer of programmability, enabling precise spatial control over deformation without compromising electrical or mechanical performance. As a result, structural design serves as a vital dimension in the creation of programmable surfaces that are both robust and reconfigurable.

To provide a comprehensive understanding of programmable surface systems, this review categorizes recent research across three fundamental dimensions: materials, mechanisms, and structures. Programmable materials are broadly classified into elastomers, polymers and metals. Actuation mechanisms are organized into thermal, electromagnetic, and photo-induced categories. Finally, structural design strategies are examined through the lens of serpentine, kirigami, and auxetic architecture. This framework offers insights into the key design principles guiding current research and lays the foundation for developing next-generation programmable soft systems.

2. PROGRAMMABLE SYSTEMS

2.1. Programmable Materials

2.1.1. Elastomers

Elastomers are materials that can quickly recover their shape after the applied stress is removed and are self-recovering materials that can be explained by changes in conformational entropy [4]. Stimuli-responsive elastomers utilize reversible changes in their physical and chemical properties in response to external stimuli such as temperature, light, electric fields, or magnetic fields.

Polyethylene glycol (PEG) is a polymer primarily used in cosmetics and food products. It functions as a viscosity regulator or, when the number of oxyethylene groups increases, as a moisturizing agent in polymer form. Polyurethane (PU) is a thermosetting resin with the advantage of excellent elasticity.

Muff et al. proposed a semi-crystalline polyurethane bilayer actuator combining a soft segment of PEG with a rigid segment from an HDI/BDO reaction. The crystallization of PEG at the crystal-melt transition achieves large nonlinear thermal expansion properties, and the shape is maintained by the physical crosslinking of the rigid segment. Bilayers fabricated by compression molding can induce large deformations at high refractive indices and low transition temperatures (~65 ℃ or less) by using Joule heating, especially electrothermal control methods. However, due to the highly hygroscopic nature of PEG, it absorbs water and expands upon humidity increase, resulting in curvature relaxation, so humidity management and BDO sum control must control the balance between CLTE/strain and reproducibility. This shows promise for a variety of applications, including drug delivery systems, biomedical devices, soft robots, etc [Fig. 1(a)].

Liquid crystal elastomer (LCE) is a stimulusresponsive material that simultaneously possesses the properties of fluid liquid and an elastic rubber and is primarily manufactured by crosslinking liquid crystal mesogens into a highly deformable elastomer network [6].

Guo et al. conducted research using 4-methoxybenzoic acid and acryloxy-based structural compounds to provide large reversible deformation and recently used independent cubic voxels to assemble complex 3D shapes. Each voxel has a specific directional director field and achieves anisotropic and heterogeneous deformation through thermal and optical stimuli. This overcomes the limitations of existing technologies, which were restricted to 2D to 3D deformation, enabling the realization of various geometric shapes. The LCE-based voxel assembly method uses UV adhesive to bond the voxels, and since these joints may have a subtle influence on shape changes, long-term durability evaluation is necessary. From the perspective of flexible electronic devices, future research should focus on integrating sensors and electronic circuits into LCE, as well as analyzing subtle fluid dynamic phenomena at the joints between voxels and studying the thermal-fluid-structural interactions during shape deformation [Fig. 1(b)].

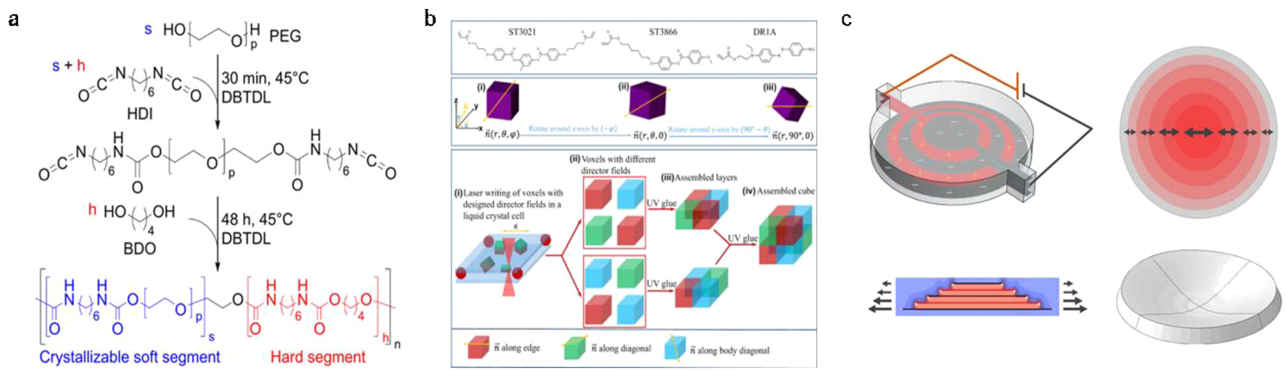


Fig. 1. Elastomer. (a) Synthesis process of the PEG-PUs [5]. (b) Illustration of the fabrication. Chemical structures of liquid crystal (LC) monomers ST3021, ST3866, and dye DR1A (dispersed red 1 acrylate). By rotating the voxel, a director field can be obtained, and the manufacturing process of a single voxel and the 3D assembly using voxels with along the edge, surface diagonal, and body diagonal directions obtained by this method are shown in the schematic diagram [7]. (c) Schematic diagram of the multilayer structure of concentric circular cross-array electrodes. Process of elastic thin sheet deformation driven by voltage applied to the electrodes [8]. Copyright 2023 Wiley, 2021 Springer Nature, 2019 Nature, respectively.

Dielectric elastic materials (DEA) are materials that undergo large deformations under an electric field.

Hajiesmaili et al. reported research on achieving precise shape changes by spatially varying the electrode array. The material was manufactured using a centrifugal mixer with an acrylic based precursor, urethane acrylate oligomer, viscosity modifiers, strength enhancers, and controllable crosslinkers and photoinitiators. Subsequently, spin coating was performed to implement flexible electrodes using carbon nanotubes. This method enables precise control of Gaussian curvature by utilizing the multilayer structure and mesoarchitecture of the internal electrodes. This allows for the free implementation of positive and negative curvatures and provides reversibility, returning to its original form when the voltage is removed. However, this method faces practical challenges due to high voltage requirements and a complex manufacturing process. Therefore, the development of materials and bonding technologies that maintain stable electri- cal properties and durability even after repeated deformation is necessary for application in flexible electronic devices [Fig. 1(c)].

2.1.2. Polymers

Polymers are materials that contain physicalchemical conjugated or non-conjugated bonds and exhibit diverse properties through various cross-linking mechanisms. Elastomers are a type of polymer with low crystallinity due to weak cross-linking. In this section, we focus on stimuli-responsive polymers rather than elastomers [9].

Shucong Li et al. have developed a programmable surface based on liquid crystal polymers (LCPs), a technology that exploits mechanical softening due to solvent absorption and geometry rearrangement upon evaporation to enable microstructure control via capillary forces. Unlike LCE, LCP is a material with high strength and alignment due to the liquid crystal mesogen groups linked to the scaffold. The process of softening, evaporation, and curing can be precisely controlled by adjusting the mixing ratio of the liquids. This technology has a wide range of functional applications, including information encryption, particle trapping, and bubble release. However, challenges remain in maintaining uniformity of structural deformation during the liquid evaporation process and ensuring long-term material stability, which depends on the chemical composition of the liquid [Fig. 2(a)].

Hydrogels are polymers with a three-dimensional cross-linked structure that retains moisture due to their hygroscopicity.

Jiang et al. developed a high-strength, self-healing, and recyclable actuator that responds to visible light. By using benzylamine-functionalized anthracene groups, they enabled absorption in the visible light spectrum and achieved high mechanical strength and rapid self-healing properties through a supramolecular network utilizing p-p interactions and hydrogen bonds. This hydrogel exhibits rapid shape transformation in both wet and dry environments and is reprogrammable, enabling reconfiguration into various three-dimensional

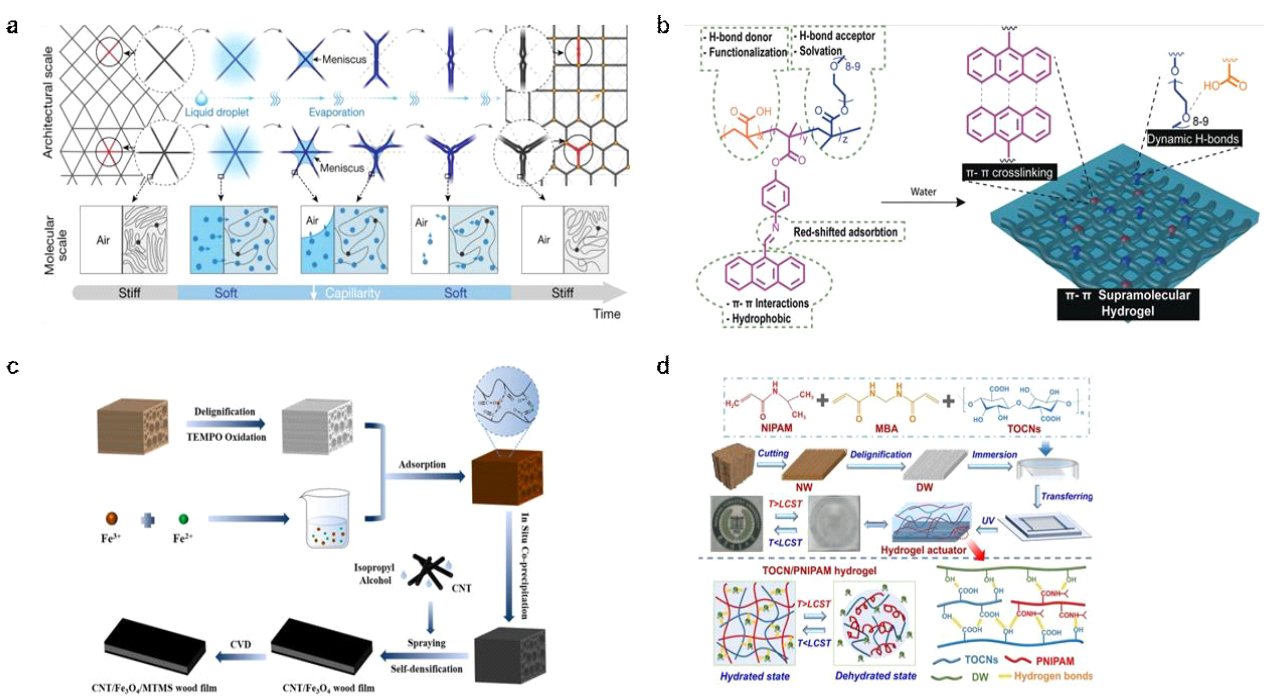


Fig. 2. Polymer. (a) Overview of toplogical transformation of cellular structures. Structural deformation process caused by capillary forces at the air-liquid interface due to changes in polymer networks at the molecular level. Shows the process of node generation and modification [10]. (b) Chemical structure and chemical groups of supramolecular photo-responsive hydrogel, and overview of fabrication process [11]. (c) Schematic diagram of the sandwich structure wood film process through *in-situ* coprecipitation of Fe_3O_4, CNT spraying, self-densification, and chemical vapor deposition of TEMPO wood [12]. (d) Schematic diagram of the synthesis of gradient wood hydrogel through interactions between DW, PNIPAM, and TOCN. Diagram of the temperature response of TOCN/PNIPAM hydrogel [13]. Copyright 2021 Nature, 2020 Wiley, 2022 Elsevier, 2025 Elsevier, respectively.

shapes [Fig. 2(b)].

Chen et al. studied bio-composite materials, primarily wood-based superhydrophobic photodriven films and nanocellulose and wood-bonded hydrogels. The wood film-based actuator utilizes Fe_3O_4, CNT, and MTMS to achieve excellent mechanical strength, superhydrophobicity, and photothermal conversion performance. In particular, the introduction of Fe_3O_4 significantly enhances the photothermal conversion effect, enabling stable and rapid linear motion under NIR light irradiation [Fig. 2 (c)].

Lu et al. combined an anisotropic wood structure with a temperature-sensitive hydrogel to achieve high mechanical strength and rapid thermal responsiveness in a nanocellulose-based actuator. This enabled programmable deformation and information encryption applications. However, managing moisture content changes due to ion concentration and temperature variations, as well as fatigue phenomena during repeated deformation, remain as future research challenges [Fig. 2 (d)].

2.1.3. Metals

Stimuli-responsive metals, such as Ni-Ti (nitinol), which belong to the category of shape memory alloys (SMA), can primarily respond to heat through phase transitions between the austenite phase and the martensite phase. However, these responses are often irreversible or difficult to control [14]. Furthermore, liquid metals or solid metals can be controlled using their electromagnetic properties, such as magnetism and current [15,16].

Zhang et al. developed an MME core-cover fiber based on liquid metal, using a polymer composite containing magnetic particles as the outer coating. The focus is on liquid metals such as gallium-indium (EGaIn). This liquid metal core provides high electrical conductivity (approximately 2.07×10^6 S/m) and excellent mechanical flexibility, enabling continuous deformation without damage. Through coaxial printing processes, it enables the realization of delicate 2D and 3D structures, integrating programmable magnetization, magnetic actuation, and sensing functions, making it a material suitable for various applications such as minimally invasive electrical surgery and remote energy transmission in soft robots and biomedical devices. The printing process itself has limitations in terms of high-precision patterning at the micro scale, and there is room for improvement in the adhesion between liquid metal and composite material interfaces [Fig. 3(a)].

Zhang et al. manufactured a solid metal-based 3D mesostructure that includes conductive metal layers such as copper (Cu) and nickel (Ni). This structure possesses structural stability due to its polyimide (PI) coating. Utilizing electromagnetic forces, this structure enables rapid and precise deformation through the Lorentz force and magnetic force. Specifically, deformation can be precisely controlled based on the thickness and arrangement of the metal layers within the structure, and programmable structural forms can be realized through transitions to multiple stable states. These characteristics enable applications such as thermal conductivity measurement and multimode sensors; however, there is a possibility of issues arising from heat generation caused by currents generated alongside the Lorentz force, necessitating analysis of heat transfer during electromagnetic operation [Fig. 3(b)].

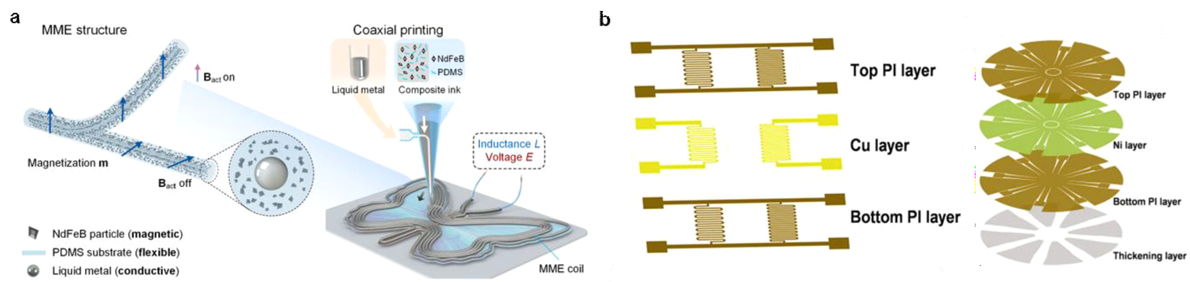


Fig. 3. Metal. (a) Illustration of hybrid magnetic-mechanical-electrical (MME) structure. It shows the external driving magnetic field and internal residual magnetization magnetic field, as well as the coil geometry structure. Coaxial printing method, which is the coil structure that forms the skeleton of the butterfly robot [15]. (b) A schematic diagram showing the layer structure based on a two-dimensional precursor decomposition diagram. A nickel layer is inserted between two polyimide (PI) layers, showing a sandwich structure [16]. Copyright 2023 Springer Nature, 2021 PNAS, respectively.

Table 1. Summary of representative studies on programmable materials

Material		Authors	Title	Source	Majorthemes
Elasto-mer	PEG	Muff et al.	Bilayer Bending Actuators Based on Semicrystalline Polyure-thanes with Large Thermal-Expan-sion Coefficients	Adv. Intell. Syst. 2023	High CTE PEG soft segments and HDI/BDO cross-linking with a PEG/BDO ratio that tunes crystallinity for humidity-sensitive performance while enabling 50°C thermal bending, using a semi-crystalline PU bilayer.
	LCE	Guo et al.	Shape-programmable liquid crystal elastomer structures with arbit-rary three-dimensional director fields and geometries	Nat. Commun. 2021	Acrylate-based LCE voxels (≈60−100 μm) printed by two-photon lithography from LC mono-/diacrylates, azo-dye dopant, and photoinitiator, enabling fully pro-grammable 3D director fields and reversible optical morphing.
	DEA	Hajiesmaili et al.	Reconfigurable shape-morphing die-lectric elastomers using spatially varying electric fields	Soft Matter 2021	Dielectric-elastomeric laminates: Stacked UV-cured acrylic layers separated by CNT electrodes with overlap tapers with height, creating an internal E-field gradient for fast and fully reversible bidirectional morphing with purely electrical drive.
Poly-mer	LCP	Li et al.	Liquid-induced topological trans-formations of cellular microstru-ctures	Nature 2021	Solvent plasticized LCP/SU-8/PDMS micro-lattices: Acetone lowers modulus by up to 300× and forces the zipper walls by capillary evaporation, enabling reversible to-pology rewiring.
	Hydrogel	Jiang et al.	Strong, self-healable, and recycl-able visible-light-responsive hydrogel actuators	Angew. Chem. 2020	BIFA-functionalized poly(MAA-co-OEGMA) hydrogels combine π-π stacking with visible light-induced anth-racene photodimer cross-linking, while sacrificial acid-ether H-bonds co-release energy to enable rapid self-healing and fully reversible operation.

Table 1. Continued

Material		Authors	Title	Source	Majorthemes
Poly-mer	Biocom-posite	Chen et al.	Superhydrophobic light-driven actuator based on self-densified wood film with a sandwich-like structure	Compos. Sci. Technol. 2022	A self-contained high-density cellulose film composed of an Fe_3O_4 core, CNT inter-layer, and MTMS silanized skin forms an ultra-hydrophobic, photothermal wood-based actuator.
	Biocom-posite	Lu et al.	Gradient wood-derived hydrogel actuators constructed by an isotropic-anisotropic stru-cture strategy with rapid thermal-response, high strength and programmable defor-mation	Chem. Eng. 2025	Injection of TOCN-PNIPAM hydrogels (gradient isotropic/anisotropic) into delig-nified wood channels provides robust and ultrafast programmable actuation in the vicinity of LCSTs.
Metal	Liquid	Zhang et al.	Coaxially printed magnetic-mechanical-ele-ctrical hybrid structures with actuation and sensing functionalities	Nat. Commun. 2023	Remote field actuation and magnetic induction sensing with EGaIn core, PDMS/NdFeB magnetic sheath, and optional PDMS skin over coaxial DIW.
	Solid	Zhang et al.	Rapidlydeployableandmor-phable 3D meso-structures with applications in multi-modal biomedical devices	PNAS2021	Litho-patterned, spin-coated PI/Cu/Ni sand-wich precursors buckled in millimeter-scale 3D integrate Cu Lorentz and Ni magnetic drives for multiple stable mor-phologies.

Table 2. Advantages and Limitations of programmable materials

Material		Advantages	Limitations
Elastomer	PEG	- Large thermal expansion via crystalmelt transition - Low transition temperature - Excellent biocompatibility	- Highly hygroscopic; Sensitive to humidity, leading to curvature relaxation - Needs precise humidity and formulation control
	LCE	- Reversible anisotropic deformation - Thermal and optical responsiveness - Create complex 3D shapes via voxel assemblies	- Requires high actuation temperature - Optical stimulus has shallow penetration - Low-through put for large builds
	DEA	- Large reversible deformations under electric fields - Precision shape control with internal electrode architecture	- Requires high voltage - Complex fabrication - Needs improvement in durability and electric stability under repeated use
Polymer	LCP	- Mesogen alignment gives high strength - Programmable microstructures via capillary force control - Useful for particle trapping	- Uniform structural control during solvent evapo-ration is difficult - Long-term material stability depends on solvent composition

Table 2. Continued

Material		Advantages	Limitations
Polymer	Hydrogel	- High strength, fast visible light responsiveness - Self-healing and recyclable	- Sensitive to moisture, ion, temperature - Fatigue during repeated deformation is a concern
	Biocomposite (wood-based)	- Strong mechanical performance - Photothermal response under NIR light - Superhydrophobic / light-driven motion	- Structural degradation due to moisture or temperature changes - Requires fatigue resistance for longterm use
	Biocomposite (nanocellulose +hydrogel)	- Fast thermal responsiveness - Programmable shape change - High mechanical integrity	- Ion concentration / moisture-sensitive - Potential fatigue over repeated cycles
Metal	Liquid	- Excellent electrical conductivity - Printable into complex structures - Integrates magnetics and sensors (MME)	- Limited micro-patterning precision - Interface adhesion between core and polymer requires improvement
	Solid	- High structural and electrical stability - Precisely controllable via Lorentz and magnetic forces - Multi-stable programmable states	- Heat generation during operation may cause instability - Requires thermal management under current-driven deformation

2.2. Programmable Mechanisms

In this section, we classify and examine programmable mechanisms based on the type of external input, specifically focusing on three representative categories: thermal, electromagnetic, and photo-induced actuation.

2.2.1. Thermal Actuator

Thermal actuators operate by absorbing heat and converting the resulting temperature change into mechanical deformation. The thermal energy required for actuation can originate from various sources. Actuation is most commonly driven by either electrical input (electrothermal actuation) or light exposure (photothermal actuation), depending on the system's design and energy delivery strategy [17,18]. Regardless of the heat source, the fundamental mechanism involves localized heating that induces internal stress or softening, enabling the surface to change its shape in a controlled and reversible manner.

Babakhanova et al. demonstrated a thermally responsive programmable surface using liquid crystal elastomers (LCEs). By employing photoalignment techniques, they inscribed precise molecular orientation patterns into the LCE, enabling the surface to deform into concave or con-vex shapes in response to temperature changes. Specifically, radial (splay) alignment induced depressions, while circular (bend) alignment produced elevations, both driven by an "activation force" arising from spatial variations in molecular orientation [Fig. 4(a)].

Cao and Dong developed a soft electrothermal actuator capable of complex programmable surface deformations by leveraging the free-form design of embedded heaters. Using electrohydrodynamic (EHD) printing, they directly patterned low-melting-point Bi/Sn alloy heaters within a PDMS/PI bilayer structure. This approach enabled precise spatial control

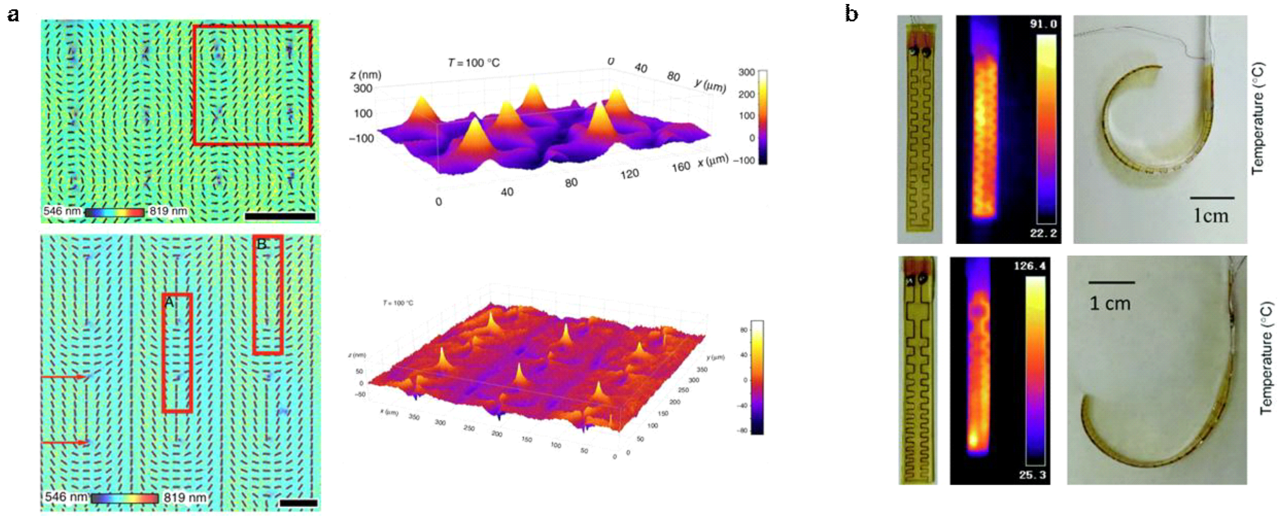


Fig. 4. Thermal stimuli-based actuator. (a) Surface depression and elevations caused by various defect patterns [19]. (b) The fabricated actuator and heating pattern [20]. Copyright 2018 The Authors, 2021 The Royal Society of Chemistry, respectively.

of heat distribution, allowing deformation modes such as uniform bending, graded bending, localized folding, and twisting depending on the heater geometry. By varying line spacing, orientation, and location of the printed heaters, they achieved diverse and reconfigurable 3D shape changes. This method surpasses traditional uniform heating-based actuators and offers a versatile platform for soft robotics and adaptive structures through shape programmability at the surface level [Fig. 4(b)].

2.2.2. Electromagnetic Actuator

Electromagnetic actuators utilize the Lorentz force to achieve programmable deformation in soft surface systems. By embedding conductive liquid metal ribbons within an elastomeric matrix and applying a static magnetic field, localized currents can be precisely controlled to generate distributed Lorentz forces. This configuration enables rapid and reversible shape morphing with low power consumption, as demonstrated in recent studies.

Bai et al. developed a dynamically reprogrammable metasurface that enables high-speed, high-precision shape morphing through Lorentz-forcedriven actuation. The system consists of a serpentine gold-polyimide conductive mesh embedded in a soft substrate, where programmable electrical currents interact with an external magnetic field to induce localized out-of-plane deformations. By varying the current distribution via independent voltage control, the surface can morph into diverse 3D shapes within 0.1 seconds.

A key innovation lies in the hybrid control scheme: a model-driven inverse design enables rapid approximation, while a feedback-based experimental loop using real-time 3D stereo imaging corrects for nonlinearity and environmental perturbations. This approach allows the surface to self-evolve into target shapes and even achieve multifunctionality, such as simultaneous optical alignment and structural displacement. The platform demonstrates a data-driven strategy for programmable soft matter with potential applications in soft robotics, adaptive optics, and intelligent surfaces [Fig. 5(a), Fig. 5(b)].

Ni et al. introduced a soft, shape-programmable surface that integrates liquid metal microfluidic networks into an elastomer membrane, enabling rapid and reversible 3D morphing under electromagnetic actuation. By injecting currents into crossbar arrays of liquid metal ribbons placed in a magnetic field, Lorentz forces induce localized deformations with sub-second response time. A key innovation lies in the use of 3D digital image correlation (3D-DIC) to build a large database that maps surface deformations to specific current distributions, allowing for near-instant retrieval (within milliseconds) of actuation patterns for desired target shapes-significantly faster than finite element analysis (FEA). Furthermore, by solidifying the liquid metal, the system can fix shapes without continuous power and reprogram them upon reheating [Fig. 5(c), Fig. 5(d)].

2.2.3. Photo-Responsive Actuator

Light enables contactless and spatially targeted actuation, offering distinct advantages over conventional electrical stimulation [23,24].

Ford et al. developed photoresponsive soft actuators by integrating gold nanorods (AuNRs) into liquid crystal elastomer (LCE) matrices, enabling localized photothermal actuation under near-infrared light. Using direct ink writing (DIW), complex 3D architectures were

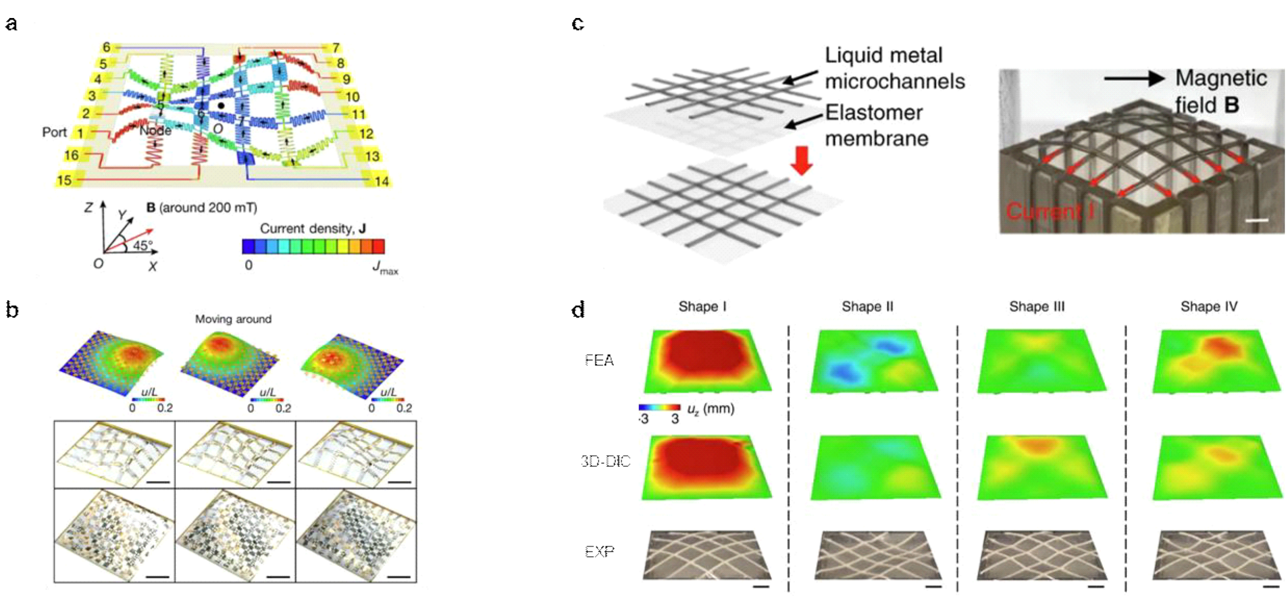


Fig. 5. Electromagnetic stimuli-based actuator. (a) Schematic illustration (enlarged view) of a representative square mesh sample constructed from the serpentine beams. (b) FEA and experimental results of a 4×4 and 8×8 sample morphing into target abstract shape-shifting processes. Scale bars, 5 mm [21]. (c) Schematic illustration of the fabrication process and action of Lorentz forces. (d) FEA predictions and experimental results (3D DIC and optical images) of four representative 3D shapes transformed from the programmable surface featuring a non-orthogonal and asymmetric ribbon layout (0°/45°) [22]. Copyright 2022 Springer Nature, 2022 The Authors, respectively.

printed with shear-aligned mesogens, allowing precise control over deformation in response to light. The AuNRs generate localized heating, triggering ne- matic-to-isotropic transitions that result in various programmable shape changes such as bending, crawling, rolling, and lifting. By combining structural design, controlled printing, and selective optical stimulation, the actuators demonstrated multiple modes of motion and even physically intelligent behaviors like damage avoidance. The inclusion of computer vision-based laser tracking further enabled closed-loop control of rolling motion, highlighting a powerful strategy for constructing next-generation soft machines using light as both a power source and controller [Fig. 6(a)].

Peng et al. developed a reprogrammable shape-morphing hydrogel system by synergistically integrating photochromism and photothermal actuation using surface-functionalized CdS quantum dots. Upon UV irradiation, the CdS QDs undergo a reversible color change from white to black, modulating their photo-

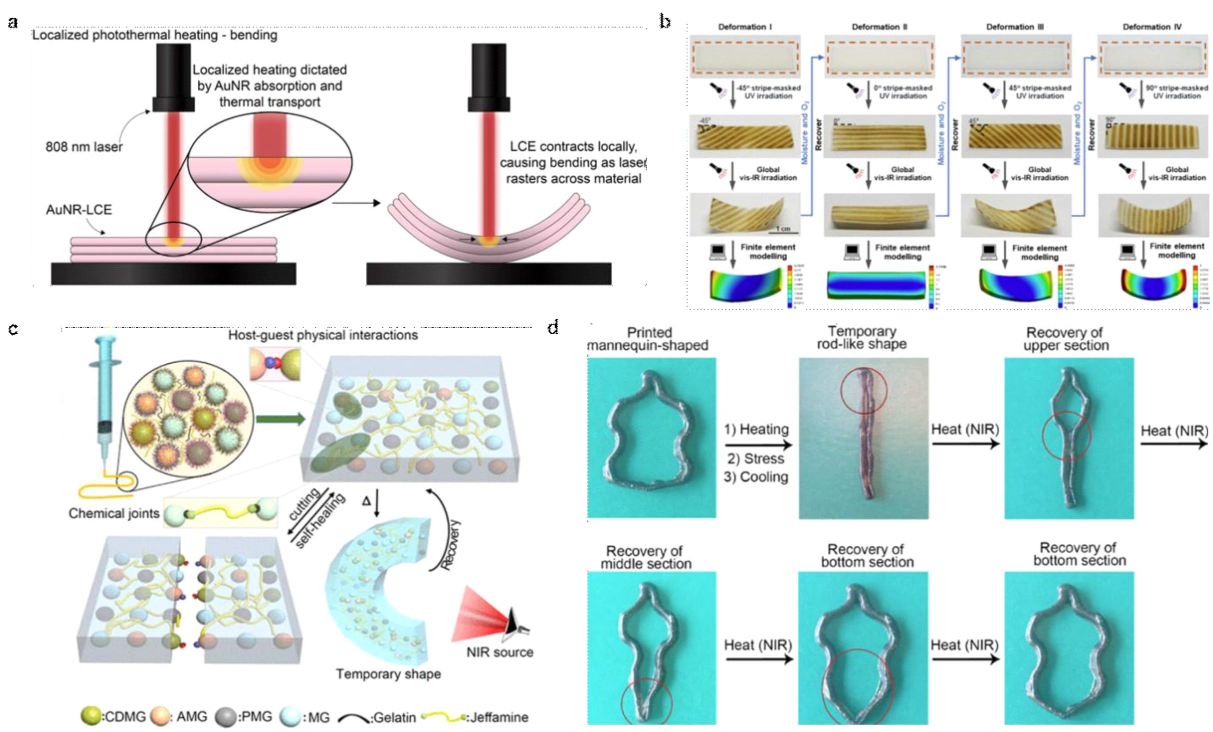


Fig. 6. Photo-responsive actuator. (a) Illustration of how localized heating could result in modes of actuation [25]. (b) 4 cycles of reversibly programmable shape morphing of the hydrogel modulated by synergistic photochromic and photothermal deformation. The programming was achieved by using photomasks featuring stripe patterns with orientation angles ranged from − 45° to 90° relative to the horizontal axis, at intervals of 45° [26]. (c) Scheme of printing methodology for the creation of SLSH hydrogels, their extrusion, and physical and chemical interactions. (d) Segmental shape recovery of a temporary rodlike structure of SLSH70 to its mannequin-like permanent shape upon illumination of NIR beam. Each segment could deform separately and independently [27]. Copyright 2024 Elsevier Inc., 2025 Elsevier B.V., 2025 American Chemical Society, respectively.

thermal conversion efficiency under subsequent vis-IR exposure. This enables programmable, stressfree deformation of 3D-printed bilayer hydrogels through light-controlled internal water loss gradients. The deformation direction and magnitude can be precisely tuned by designing UV-induced stripe patterns at specific angles. Beyond simple morphing, the system supports dual-mode 3D/4D shape memory, and polydopamine-modified microgels for efficient photothermal conversion under NIR light. These components were extruded via extrusion printing and chemically cross-linked post-printing to form a robust, shape-memory network. The actuator operated through segmental NIR-induced heating: localized laser irradiation triggered polydopamine-based heating, softening the hydrogel and recovering the pre-programmed permanent shape without affecting adjacent regions. This modular material strategy enabled programmable, spatially selective actuation with reusability and self-healing, making it a powerful platform for advanced soft robotics [Fig. 6(b)].

Sheikhi et al. developed a 4D-printed soft actuator based on multifunctional granular hydrogels, engineered by combining four types of microgels with

Table 3. Summary of representative studies on programmable actuation mechanisms

Mechanism	Authors	Title	Source	Majorthemes
Thermal responsive	Babakhanova et al.	Liquid crystal elastomer coating with programmed response of surface profile	Nat. Commun. 2018	Thermally induced surface morphing via photoaligned liquid crystal elastomers, enabling reversible elevation and depression through spatially programmed molecular orientation.
	Cao and Dong	Programmable soft electrothermal actuators based on free-form printing of the embedded heater	Soft Matter 2021	Spatially programmable surface deformation using EHD-printed embedded Bi/Sn heaters, enabling localized bending, folding, and twisting via electrothermal actuation.
Electromagnetic responsive	Bai et al.	Dynamically reprogrammable surface with selfevolving shape morphing	Nature 2022	Electromagnetic shape morphing via serpentine gold-polyimide mesh with programmable current control, enabling sub-second reconfiguration through Lorentz-force actuation and real-time feedback optimization.
	Ni et al.	Soft shape-programmable surfaces by fast electromagnetic actuation of liquid metal networks	Nat. Commun. 2022	Fast, reconfigurable surfacem orphing via Lorentz-force actuation of liquid metal networks, with data-driven shape control enabled by 3D-DIC- based actuation mapping and shape fixation through metal solidification.
	Kim et al.	Shape morphing programmable systems for enhanced control in low-velocity flow applications	Adv. Intel. Sys. 2025	An electromagnetically programmable surface based on Lorentz force actuation was developed and applied for flow control. PIV experiments were conducted in a small-scale wind tunnel, and the wake flow field was quantitatively analyzed through PSD and POD modes in response to real-time surface morphing.

Table 3. Continued

Mechanism	Authors	Title	Source	Majorthemes
Photo responsive	Ford et al.	Movement with light: Photoresponsive shape morphing of printed liquid crystal	Matter 2024	Light-driven programmable actuation via AuNR–LCE composites, enabling multi-modal shape morphing through localized photothermal transitions and DIW-printed anisotropic architectures with closed-loop laser control.
	Pent et al.	Reprogrammable shape morphing hydrogel modulated by synergistic photochromism and photoactuation	Chem. Eng. J. 2025	Light-programmed hydrogel actuation via CdS QD-mediated photochromism and photothermal conversion, enabling spatially selective, reversible shape morphing and logic-level functions without mechanical reprogramming.
	Sheikhi et al.	4D Printing of self-healing, thermally, and near-infrared light-responsive granular hydrogels with segmental directed movement for soft robotic	ACS Appl. Polym. Mater. 2025	4D-printed modular hydrogel actuator combining NIR-triggered shape memory and self-healing via multifunctional microgels, enabling segmental, spatially selective actuation through localized photothermal conversion.

distinct roles. The actuator ink incorporated β-cyclodextrin and adamantylamine- functionalized microgels to enable host-guest interactions for self-healing and shear-thinning behavior, epoxy-bearing microgels for covalent crosslinking with Jeffamine to achieve thermal information encryption, light-guided object manipulation, and even logic gate control in soft electronics. This approach introduces a novel material-level mechanism for light-driven soft actuators, enabling on-demand, reversible, and spatially selective reconfiguration without mechanical reprogramming [Fig. 6(c), Fig. 6(d)].

2.3. Programmable Structures

A growing number of researchers have aimed to develop fully stretchable electronic systems to meet the demands of next-generation wearable devices [28]. To achieve this, significant efforts have been directed to-

Table 4. Advantages and Limitations of programmable actuation mechanisms

Mechanism	Advantages	Limitations
Thermal responsive	- Simple actuation mechanism - Easily integrated with SMP,LCE - Large strain eneration possible	- Slow response time - High power consumption - Thermal inertia and heat dissipation issues
Electromagnetic responsive	- Fastres response speed - Precise and programmable control - Wireless actuation possible	- Requires external coils/magnets - Limited force per volume - Potential electromagnetic interference
Photo responsive	- Remote and localized control - Non-contact operation - High spatial resolution possible	- Limited penetration depth - Light source dependency - Often low mechanical output or slow response

ward imparting stretchability not only to individual components but to the entire integrated system.

One of the most effective strategies has been the use of geometrically engineered structures, which enable materials with inherently low stretchability to withstand large deformations. In particular, these structural designs have been instrumental in enhancing tolerance to tensile strain in the horizontal direction, thereby expanding the mechanical limits of soft electronic devices.

In this section, programmable structures are classified into three representative geometric strategies-serpentine, kirigami, and auxetic designs.

2.3.1. Serpentine

Serpentine interconnects, particularly those with noncoplanar geometries in either their fabricated or deformed states, offer enhanced stretchability and mechanical adaptability. Their deformation behavior is well understood through experimental and theoretical studies. When fabricated in ultra-thin forms and integrated with soft elastomeric substrates like PDMS or Ecoflex, these structures achieve effective moduli comparable to human skin (~100 kPa), enabling conformal integration for wearable applications [29,30].

Zhang et al. conducted a systematic study on the mechanical behavior of serpentine interconnects in elastomer-supported stretchable electronics, emphasizing their ability to achieve both high stretchability and areal coverage. Through a combination of analytical modeling, finite element simulations, and experiments, they identified critical buckling modes-symmetric and anti-symmetric-and derived scaling laws that predict elastic and total stretchability based on geometric parameters such as length-to-spacing ratio, unit cell number, and cross-sectional dimensions. Their optimized serpentine design achieved up to 172% total stretchability and 81% areal coverage, while maintaining electrical performance under extreme deformation, demonstrating serpentine geometry as a key strategy for highly deformable and mechanically programmable soft electronic systems [Fig. 7(a)].

2.3.2. Kirigami

Kirigami-inspired structures, formed by strategically introducing patterned cuts into solid membranes, facilitate large deformations in stretchable electronics through bending and twisting motions. Their high stretchability and ability to conform to complex 3D surfaces make them particularly well-suited for wearable human-machine interfaces [31,32].

Liu et al. developed a kirigami-based soft electronic platform by integrating a tough, porous composite nanofiber framework (CNFF) composed of aramid nanofibers and polyvinyl alcohol, designed for conformal and stretchable skin mounted devices. The CNFF substrate, fabricated via blade coating and critical point drying, offers high toughness and breathability, making it ideal for wearable applications. Electronic functionality was introduced using two complementary strategies: microfabricated inorganic circuits were transfer-printed onto the CNFF for high-performance sensing, while conducting polymers such as PEDOT were electrochemically deposited within the porous network to form stretchable interconnects. Laser-cut kirigami patterns imparted exceptional mechanical deformability, enabling devices to stretch over 130% strain and endure over 5,000 cycles without

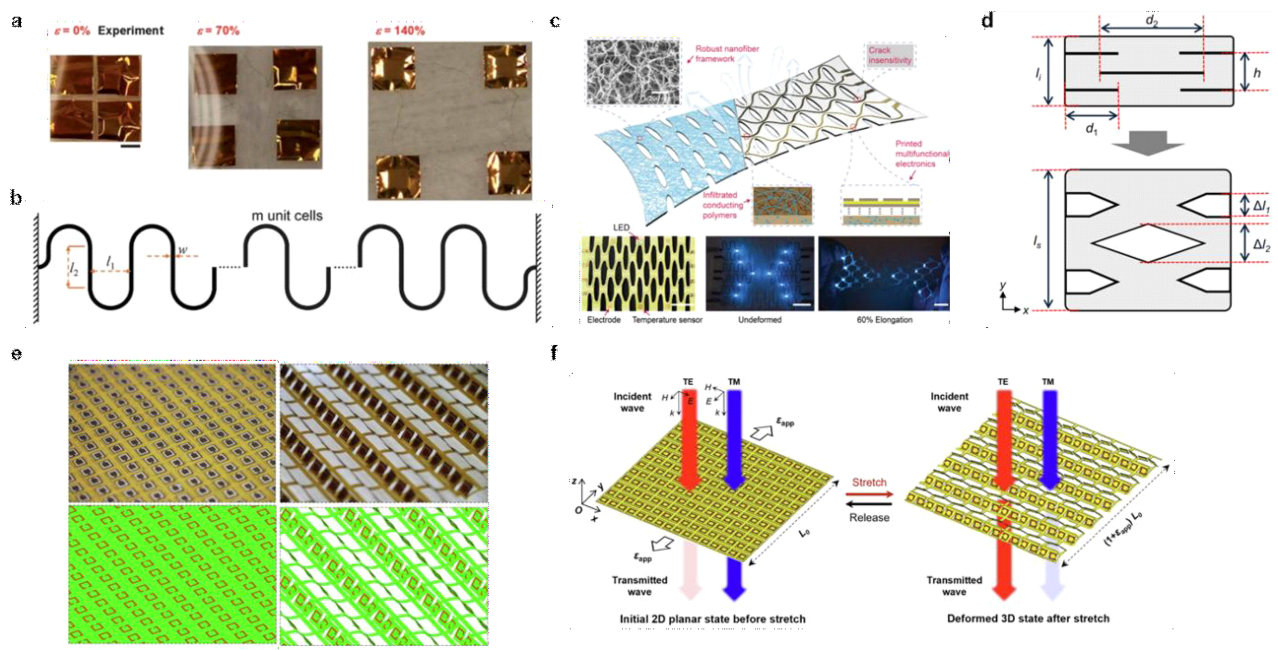


Fig. 7. Serpentine and kirigami structure based actuator. (a) Experiments on the buckling mechanisms of the serpentine interconnect with strain from 0% to 70% and 140% with different design. (b) Schematic of the serpentine structure [33]. (c) CNFF-based kirigami membrane with transfer-printed microelectronics and infiltrated conducting polymers showing a stretchable LED array powered with serpentine interconnects from conducting polymers. Scale bars, 10 mm. [34]. (d) Illustration of the geometry layout of a kirigami structure [38]. (e) Experimental and simulated results on the periodic deformations of the metasurface under various strain levels. (f) Upon stretch, the 2D planar SRRs will be transformed into the periodically arranged 3D configuration, which is capable to manipulate the transmissivity of the TE and TM linearly polarized wave [35]. Copyright 2013 The Royal Society of Chemistry, 2025 Willy-VCH GmBH, 2024 The Authors, respectively.

electrical failure. These devices conformed seamlessly to dynamic 3D skin surfaces and maintained stable electrical outputs for physiological sensing, including ECG, EMG, and skin temperature. This fabrication approach demonstrates a robust and scalable path for multifunctional, breathable, and stretchable bioelectronics [Fig. 7(b)].

He et al. developed a mechanically reconfigurable soft metasurface by integrating kirigami design with copper split-ring resonators (SRRs) patterned on a thin polyimide (PI) substrate. By introducing strategically placed laser-cut slits, the initially planar metasurface transforms into a three-dimensional configuration when uniaxial strain is applied, causing the SRRs to rotate out of plane. This structural reconfiguration enables selective modulation of electromagnetic wave transmission, enhancing or suppressing the passage of linearly and circularly polarized waveswithout significantly shifting the resonant frequency. Notably, deformation relies solely on mechanical stretching, eliminating the need for active materials or external circuitry. This kirigami-based approach offers a lightweight, ultrathin, and tunable platform for adaptive electromagnetic devices, particularly suited for wearable RF systems, satellite communications, and deployable antennas [Fig. 7(c), Fig. 7(d)].

2.3.3. Auxetic

Auxetic structures, characterized by a negative Poisson's ratio, expand laterally when stretched, offering unique mechanical properties such as enhanced energy absorption, shear resistance, and conformability. These attributes make them particularly suitable for applications in stretchable electronics and wearable devices. Recent studies have demonstrated the integration of auxetic geometries into various substrates to improve mechanical performance and functionality [36].

Loh et al. developed a 3D-printed soft electronic surface by integrating a capacitive sensing array into an auxetic mechanical metamaterial framework. The sensor array consists of 6×6 capacitive sensors embedded at the vertices of an auxetic lattice, which expands laterally under tensile strain due to its negative Poisson's ratio. This unique geometry fabricated using multimaterial FDM 3D printing with carbon-loaded PI-ETPU electrodes and TPU dielectric layers, allows the sensor array to conform closely to curved and deforming surfaces without altering capacitance during stretching (up to 21.6% strain). As a result, the sensor accurately detects normal contact forces while remaining insensitive to geometric deformation, enabling decoupled sensing of force and strain. Demonstrations on soft robotic grippers showed real-time force mapping and object shape recognition, while wearables on human joints achieved personalized conformability and

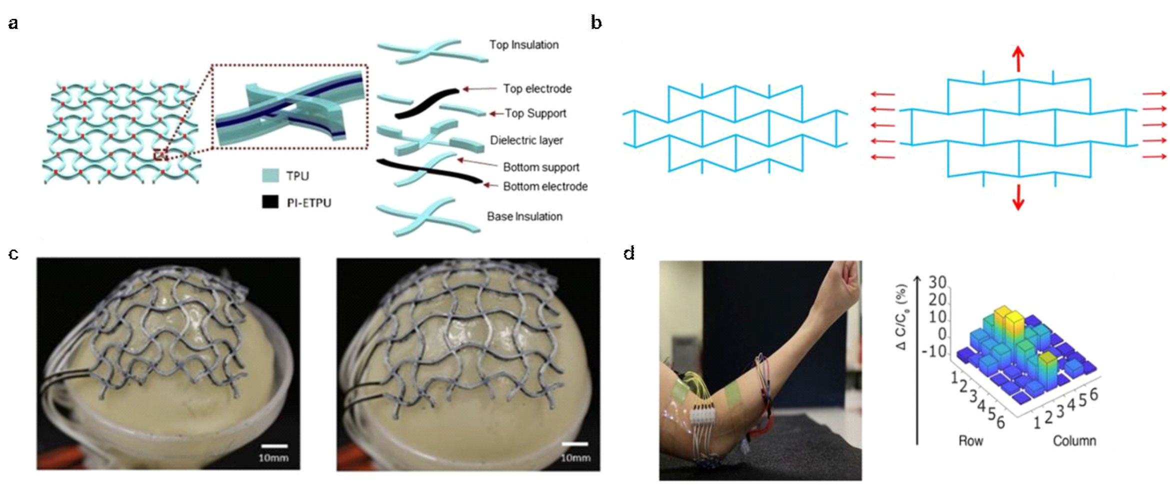


Fig. 8. Auxetic Structure based actuator. (a) Schematic illustration of the 6×6 soft capacitive auxetic sensor array, with capacitive sensors embedded at the vertices (inset), a blown-up view reveals air gaps within the dielectric layer. Red dots highlight the locations corresponding to pixels on the capacitance change map. (b) Illustration of the auxetic structure [39]. (c) Sensor array adhered on a minimally inflated balloon surface (scale bar 10 mm). (d) Elbow with sensor array is vertically pressed onto table to demonstrate force-sensing capabilities of wearable sensor array. Capacitance change map shows a force distribution profile concentrated at the bony tip of the elbow in contact with table [37]. Copyright 2005 Academic Journals, 2021 Wiley-VCH GmBH, respectively.

Table 5. Summary of representative studies on programmable structures

Structure	Authors	Title	Source	Majorthemes
Serpentine	Zhang et al.	Buckling in serpentine microstructures and applications in elastomer-supported ultra-stretchable electronics with high areal coverage	Soft Matter 2013	Mechanically programmed deformation using serpentine interconnects with out of-plane buckling, achieving up to 172% stretchability and stable conductivity under extremes train for soft electronic surfaces.
Kirigami	Lie et al.	Robust and multifunctional kirigami electronics with a tough and permeable aramid nanofiber framework	Adv. Mater. 2022	Kirigami-patterned nanofiber composite platform enabling>130% stretchability and robust physiological sensing via transferprinted circuits and PEDOT-in-fused porous networks for breathable, skin- conformal soft electronics.
	He et al.	A kirigami-based reconfigurable meta surface for selective electromagnetic transmission modulation	npj Flex. Electron. 2024	Kirigami-enabled mechanical reconfiguration of SRR metasurfaces on PI sub-strates, allowing polarization-selective EM wave modulation through strain-in-duced 3D transformation without active components.
Auxetic	Loh et al.	3D printed metamaterial capacitive sensing array for universal jamming gripper and human joint wearables	Adv. Eng. Mater. 20221	Auxetic 3D-printed capacitive sensor array enabling decoupled force sensing on deformable surfaces, with stable performance under strain and personalized conformability for soft robotics and wearables

Table 6. Advantages and Limitations of programmable structures

Structure	Advantages	Limitations
Serpentine	- Simple layout enables high stretchability - Effectively relieves strain in rigid components - Compatible with conventional fabrication	- Localized strain concentration at high deformation - Limited for high-density integration - Difficult to form complex 3D shapes
Kirigami	- Allows large geometric transformations (2D to 3D) - Programmable directional deformation via cut patterns - Suitable for deployable/foldablesystems	- Reduced mechanical durability due to cuts - Limited strain directionality - Lower precision in fast dynamic motion
Auxetic	- Negative Poisson's ratio enables expansion in all directions - Effective for impact mitigation and energy dissipation - Adds function through geometry alone	- Requires precision fabrication - Integration with soft circuits is challenging - Complicated scal ability for large areas

contact force detection (Fig. 8).

3. PERSPECTIVE AND FUTURE PROSPECTS

Programmable surface systems have shown remarkable progress in recent years, yet several challenges and opportunities remain for future exploration. To date, the application of these actuators has been largely confined to areas such as biomimetic interfaces, medical devices, and soft robotic systems. To fully realize their potential, future efforts should explore broader applications across diverse fields, expanding beyond the currently established domains.

Chen et al. demonstrated a wireless, ultra-thin, and ultra-light programmable surface based on electro-hydraulic actuation, designed as a haptic electronic skin for on-body applications. The system was fabricated using microcircuit printing and microfluidic injection techniques to create individual electro-hydraulic actuators, each consisting of a dielectric oil encapsulated between printed electrodes and elastic membranes. Upon applying high-voltage electric fields, Maxwell stress compresses the oil, causing localized surface protrusions that form programmable tactile patterns. The actuators, only 199 μm thick and 23 mg in weight, can be individually controlled to generate up to 150 mN of force and 0.58 mm of displacement. This programmable surface was integrated into wearable devices for various practical applications, including real-time Braille displays with 98% recognition accuracy, tactilebased navigation for visually impaired users, and immersive haptic feedback during gaming scenarios. The system exemplifies a scalable and functional approach to shape-morphing soft electronics for interactive human-machine interfaces (Fig. 9).

Kim et al. developed a gallium-based programmable surface to actively control and quantitatively analyze flow fields in real time through wind tunnel PIV experiments. Furthermore, they presented a dynamically reconfigurable surface using liquid metal-based soft microfluidics and electromagnetic actuation, enabling rapid 3D shape morphing from a flat 2D state. By synchronizing the surface deformation with projected content, the system allows applications such as adaptive projection screens with vibration cancellation and interactive 3D displays simulating physical interactions, supported by real-time 3D imaging and computational modeling (Fig. 10).

Given their ability to undergo flexible deformation, these systems hold promise for integration into a wider range of applications. Beyond skin-attachable haptic interfaces, they could be extended to domains such as fluid manipulation, thermal regulation, and structural adaptation.

Achieving such versatility will require overcoming key challenges, particularly in miniaturization and wireless operation. For broader applicability, it will be essential to develop programmable surface platforms

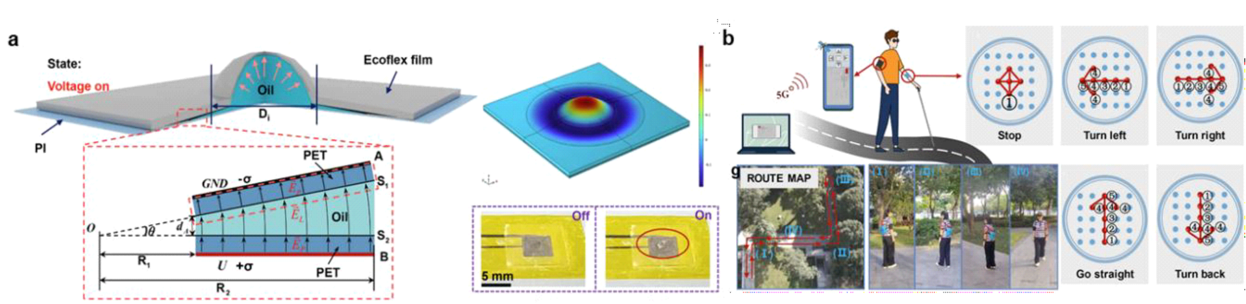


Fig. 9. Haptic applications of programmable surface in electronic skin systems. (a) Structure, simulation cloud map, and optical photo of EH-actuator. (b) Schematic diagram of road navigation process and tactile modes of the navigation arrows: "stop", "turn left", "turn right", "go straight" and "turn back" [40]. Copyright 2024 Elsevier B.V.

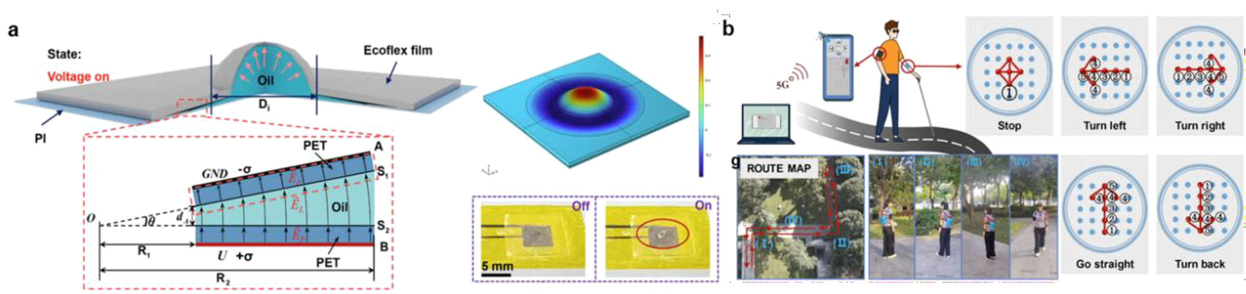


Fig. 10. Applications of programmable surface. (a) Experimental setup for the PIV measurements. (b) Mean streamwise velocity distributions for the null cases, f_0=0 Hz, (left) and modulated cases (right) operated at the natural frequency, f_c=50 Hz. Top, middle and bottom contours indicate different incoming velocities at U = [0.65,1.06,1.49] m/s, respectively. (c) Velocity profile comparisons between f_0 and f_c cases at χ=100 mm downstream [41]. (d) Optical (top) and 3D-DIC images (bottom) of the programmable surface with the letter "N" projected onto it (left) and bulging upwards due to external vibrational noise (right). (e) Optical (top) and 3D-DIC images (bottom) of the programmable surface actuated with different current intensities to find the optima to cancel the noise effect. (f) The maximum displacement on the surface as a function of time at different phases of noise cancellation [22]. Copyright 2022 The Authors, 2025 The Authors, respectively.

that are both compact and lightweight while supporting wireless communication capabilities. This remains a significant challenge for the field moving forward.

ABBREVIATIONS

PEG: Polyethylene glycol
HDI: Hexamethylene diisocyanate
BDO: 1,4-Butanediol
CLTE: Coefficient of linear thermal expansion
LCE: Liquid crystal elastomer
CNT: Carbon nano tube
TEMPO: 2,2,6,6-Tetramethylpiperidine-1-oxyl
DW: Delignified wood
PNIPAM: Poly (N-isopropylacrylamide)
TOCN: TEMPO-oxidized cellulose nanofibers
DEA: Dielectric elastic material
LCP: Liquid crystal polymer
MTMS: Methyltrimethoxysilane
NIR: Near-infrared radiation
SMA: Shape memory alloy
MME: Magnetic mechanical electrical
EHD: Electrohydrodynamic
FEA: Finite element analysis
DIW: Direct ink writing
DIC: Digital image correlation
PDMS: Polydimethylsiloxane
CNFF: Composite nanofiber framework
SRRs: Split-ring resonators
PEDOT: Poly(3,4-ethylenedioxythiophene)
ECG: Electrocardiography
EMG: Electromyography
FDM: Fused deposition modeling
TPU: Thermoplastic polyurethane
PIV: Particle image velocimetry
PSD: Power spectral density
POD: Proper orthogonal decomposition

ACKNOWLEDGMENTS

Author Contributions

Pius Soh drafted the Abstract, Introduction, Programmable Mechanisms and Structures, and Perspective and Prospects sections. Hyein Jung drafted the Programmable Materials section. All authors read and approved the final manuscript.

Funding

J. T. Kim acknowledges that part of this work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT)(RS-2024-00342270).

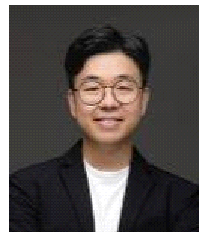
Declarations of Competing Interests

The authors declare that they have no competing interests.

AUTHORS

Pius Soh
2019～2025: B. S. Department of Aero-space and Mechanical Engineering, Korea Aerospace University
2025～Current: M. S. Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH)

Hyein Jung
2020～2025: B. S. Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH)
2025～Current: M. S., Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH)



Jin-Tae Kim
2009～2013: B. S. Cum Laude, Mechanical Engineering (Minor in Mathematics), School of Mechanical and Aerospace Engineering, Oklahoma State University
2013～2015: M. S., Theoretical and Applied Mechanics, School of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign
2015～2020: Ph. D. Theoretical and Applied Mechanics, School of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign (Advisor: Leonardo P. Chamorro)
2020～2023: Postdoctoral Researcher, Northwestern University (Advisor: John A. Rogers)
2024～Current: Adjunct Professor, Institute for Convergence Research and Education in Advanced Technology, Yonsei University
2024～Current: Assistant Professor, Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH)

REFERENCES

[1] Feinberg, A. W.; Feigel, A.; Shevkoplyas, S. S.; Sheehy, S.; Whitesides, G. M.; Parker, K. K. Muscular Thin Films for Building Actuators and Powering Devices. Science 2007, 317 (5843), 1366-1370.

[2] Mura, S.; Nicolas, J.; Couvreur, P. Stimuli-Responsive Nanocarriers for Drug Delivery. Nat. Mater. 2013, 12 (11), 991-1003.

[3] Zheng, W. J.; An, N.; Yang, J. H.; Zhou, J.; Chen, Y. M. Tough Al-Alginate/Poly(N-Isopropylacrylamide) Hydrogel with Tunable LCST for Soft Robotics. ACS Appl. Mater. Interfaces 2015, 7 (3),

1758-1764.

[4] Tolvanen, J.; Nelo, M.; Hannu, J.; Juuti, J.; Jantunen, H. All-Around Universal and Photoelastic Self-Healing Elastomer with High Toughness and Resilience. Adv. Sci. 2021, 8 (24), 2103235.

[5] Muff, L. F.; Weder, C. Bilayer Bending Actuators Based on Semicrystalline Polyurethanes with Large Thermal-Expansion Coefficients. Adv. Intell. Syst. 2023, 5 (2), 2200265.

[6] Morris, B. The Components of the Wired Spanning Forest Are Recurrent. Probab. Theory Relat. Fields 2003, 125 (2), 259-265.

[7] Guo, Y.; Zhang, J.; Hu, W.; Khan, M. T. A.; Sitti, M. Shape-Programmable Liquid Crystal Elastomer Structures with Arbitrary Three-Dimensional Director Fields and Geometries. Nat. Commun. 2021, 12 (1), 5936.

[8] Hajiesmaili, E.; Clarke, D. R. Reconfigurable Shape-Morphing Dielectric Elastomers Using Spatially Varying Electric Fields. Nat. Commun. 2019, 10 (1), 183.

[9] Young, R. J.; Lovell, P. A. Introduction to Polymers; 3rd ed.; CRC Press: Boca Raton, FL, 2011; pp 383-530.

[10] Li, S.; Deng, B.; Grinthal, A.; Schneider-Yamamura, A.; Kang, J.; Martens, R. S. et al. Liquid-Induced Topological Transformations of Cellular Microstructures. Nature 2021, 592 (7854), 386-391.

[11] Jiang, Z.; Tan, M. L.; Taheri, M.; Yan, Q.; Tsuzuki, T.; Gardiner, M. G. et al. Strong, Self-Healable, and Recyclable Visible-Light-Responsive Hydrogel Actuators. Angew. Chem., Int. Ed. 2020, 59 (18), 7049-7056.

[12] Chen, J.; Zhu, Z.; Zhang, H.; Fu, S. Superhydrophobic Light-Driven Actuator Based on Self-Densified Wood Film with a Sandwich-Like Structure. Compos. Sci. Technol. 2022, 220, 109278.

[13] Lu, Y.; Ma, Y.; Deng, F.; Yue, Y.; Jiang, S.; Wu, Q. et al. Gradient Wood-Derived Hydrogel Actuators Constructed by an Iso-tropic-Anisotropic Structure Strategy with Rapid Thermal-Re-sponse, High Strength and Programmable Deformation. Chem. Eng. J. 2025, 504, 158903.

[14] Catal, A. A.; Bedir, E.; Yilmaz, R.; Canadinc, D. Design of a NiTiHf Shape Memory Alloy with an Austenite Finish Temperature beyond 400℃ Utilizing Artificial Intelligence. J. Alloys Compd. 2022, 904, 164135.

[15] Zhang, Y.; Pan, C.; Liu, P.; Peng, L.; Liu, Z.; Li, Y. et al. Coaxially Printed Magnetic-Mechanical-Electrical Hybrid Structures with Actuation and Sensing Functionalities. Nat. Commun. 2023, 14 (1), 4428.

[16] Zhang, F.; Li, S.; Shen, Z.; Cheng, X.; Xue, Z.; Zhang, H. et al. Rapidly Deployable and Morphable 3D Mesostructures with Applications in Multimodal Biomedical Devices. Proc. Natl. Acad. Sci. U.S.A. 2021, 118 (11), e2026414118.

[17] Yao, S.; Cui, J.; Cui, Z.; Zhu, Y. Soft Electrothermal Actuators using Silver Nanowire Heaters. Nanoscale 2017, 9 (11), 3797-3805.

[18] Raturi, P.; Kumar, A.; Singh, J. P. Graphene-Polydimethylsilox-Ane/Chromium Bilayer-Based Flexible, Reversible, and Large Bendable Photomechanical Actuators. Smart Mater. Struct. 2017, 26 (9), 095030.

[19] Babakhanova, G.; Turiv, T.; Guo, Y.; Hendrikx, M.; Wei, Q. H.; Schenning, A. P. H. J. et al. Liquid Crystal Elastomer Coatings with Programmed Response of Surface Profile. Nat. Commun. 2018, 9 (1), 456.

[20] Cao, Y.; Dong, J. Programmable Soft Electrothermal Actuators based on Free-Form Printing of the Embedded Heater. Soft Matter 2021, 17 (9), 2577-2586.

[21] Bai, Y.; Wang, H.; Xue, Y.; Pan, Y.; Kim, J. T.; Ni, X. et al. A Dynamically Reprogrammable Surface with Self-Evolving Shape Morphing. Nature 2022, 609 (7928), 701-708.

[22] Ni, X.; Luan, H.; Kim, J. T.; Rogge, S. I.; Bai, Y.; Kwak, J. W. et al. Soft Shape-Programmable Surfaces by Fast Electromagnetic Actuation of Liquid Metal Networks. Nat. Commun. 2022, 13 (1), 5576.

[23] Jiang, H. Y.; Kelch, S.; Lendlein, A. Polymers Move in Response to Light. Adv. Mater. 2006, 18 (11), 1471-1475.

[24] Zeng, H.; Wasylczyk, P.; Wiersma, D. S.; Priimagi, A. Light Robots: Bridging the Gap Between Microrobotics and Photomechanics in Soft Materials. Adv. Mater. 2018, 30 (24), 1703554.

[25] Ford, M. J.; Porcincula, D. H.; Telles, R.; Mancini, J. A.; Wang, Y.; Rizvi, M. H. et al. Movement with Light: Photoresponsive Shape Morphing of Printed Liquid Crystal Elastomers. Matter 2024, 7 (3), 1207-1229.

[26] Peng, X.; Li, H.; Xu, J.; Lan, C.; Liu, J.; Wu, B. et al. Reprogrammable Shape Morphing Hydrogel Modulated by Synergistic Photochromism and Photoactuation. Chem. Eng. J. 2025, 511, 162103.

[27] Sheikhi, M.; Vakili, S.; Karimi, N.; Rafiemanzelat, F.; Maleki, A.; Taheri, A. et al. 4D Printing of Self-Healing, Thermally, and Near-Infrared Light-Responsive Granular Hydrogels with Segmental Directed Movement for Soft Robotic. ACS Appl. Polym. Mater. 2025, 7 (1), 123-134.

[28] Lee, S.; Yang, J. C.; Park, S. Geometrical Engineering for Implementing Stretchable Electronics. J. Flex. Print. Electron. 2022, 1 (2), 125-136.

[29] Kim, D. H.; Lu, N.; Ma, R.; Kim, Y. S.; Kim, R. H.; Wang, S. et al. Epidermal Electronics. Science 2011, 333 (6044), 838-843.

[30] Jiang, H.; Sun, Y.; Rogers, J. A.; Huang, Y. Post-Buckling Analysis for the Precisely Controlled Buckling of Thin Film Encapsulated by Elastomeric Substrates. Int. J. Solids Struct. 2008, 45 (7-8), 2014-2023.

[31] Blees, M. K.; Barnard, A. W.; Rose, P. A.; Roberts, S. P.; McGill, K. L.; Huang, P. Y. et al. Graphene Kirigami. Nature 2015, 524 (7564), 204-207.

[32] Li, H.; Liu, H.; Sun, M.; Huang, Y. A.; Xu, L. 3D Interfacing between Soft Electronic Tools and Complex Biological Tissues. Adv. Mater. 2021, 33 (3), 2004425.

[33] Zhang, Y.; Xu, S.; Fu, H.; Lee, J.; Su, J.; Hwang, K. C. et al. Buckling in Serpentine Microstructures and Applications in Elastomer-Supported Ultra-Stretchable Electronics with High Areal Coverage. Soft Matter 2013, 9 (33), 8062-8070.

[34] Liu, H.; Li, H.; Wang, Z.; Wei, X.; Zhu, H.; Sun, M. et al. Robust and Multifunctional Kirigami

Electronics with a Tough and Per-Meable Aramid Nanofiber Framework. Adv. Mater. 2022, 34 (50), 2207350.

[35] He, S.; Wang, Y.; Li, H.; Chen, Z.; Zhang, Y.; Xu, L. et al. A kiri-Gami-Based Reconfigurable Metasurface for Selective ElectroMagnetic Transmission Modulation. npj Flex. Electron. 2024, 8 (1), 48.

[36] Curtis, S. M.; Saini, N.; Hsu, J. W. P.; Doolittle, L. R.; Hsu, J. W. P. Auxetic Superelastic TiNiCuCo Sputtered Thin-Films for strEtchable Electronics. SMST2022 2022, 11-13.

[37] Loh, L. Y. W.; Wang, Z.; Sun, M.; Liu, H.; Xu, L. 3D Printed Metamaterial Capacitive Sensing Array for Universal Jamming Grip-Per and Human Joint Wearables. Adv. Eng. Mater. 2021, 23 (5), 2001082.

[38] Lee, D. W.; Park, D. H.; Choi, J. C.; Chung, S. Strain-Engineered Stretchable Substrates for Free-Form Display Applications. Soft Sci. 2024, 4 (1), 10.20517/ss.2024.36.

[39] Liu, Y.; Hu, H. A Review on Auxetic Structures and Polymeric Materials. Sci. Res. Essays 2010, 5 (10), 1052-1063.

[40] Chen, Y.; Wu, H.; Wang, X.; Qiu, P. Wireless Programmable Patterns of Electro-Hydraulic Haptic Electronic Skins Able to Create Surface Morphology. Chem. Eng. J. 2024, 500, 156612.

[41] Kim, J. T.; Kim, T.; Jung, H.; Haung, Y. T.; Chamorro, L. P. Shape Morphing Programmable Systems for Enhanced Control in Low-Velocity Flow Applications. Adv. Intell. Syst. in press.