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FUTURE OF 4D PRINTING IN SOFT ROBOTICS AND INTELLIGENT AUTOMATION

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Abstract: Four-dimensional (4D) printing has emerged as a transformative manufacturing paradigm that integrates time as a fourth dimension into three-dimensionally printed structures, enabling programmable shape transformation, autonomous actuation, and adaptive functionality in response to environmental stimuli. This comprehensive review synthesises advances in 4D printing technologies, smart materials, actuation mechanisms, and their convergence with soft robotics and intelligent automation systems over the period 2015–2025. We critically examine stimulus-responsive materials including shape-memory polymers (SMPs), hydrogels, liquid crystal elastomers (LCEs), magneto-active composites, and multi-material systems, comparing their actuation performance, biocompatibility, and scalability across 37 quantitative metrics derived from over 350 peer-reviewed publications. Key application domains surveyed include minimally invasive surgical devices, adaptive soft grippers, wearable exoskeletons, underwater autonomous vehicles, and micro-scale drug delivery systems. We further assess the integration of machine learning, computational design, and bio-inspired principles with 4D printing to achieve closed-loop intelligent soft robotic systems. Despite remarkable progress, persistent challenges in material fatigue, multi-stimulus control, scalable manufacturing, and regulatory compliance continue to impede clinical and industrial translation. This review concludes with a forward-looking roadmap identifying high-priority research directions and projected technology readiness levels through 2030.

Keywords: 4D printing; soft robotics; shape-memory polymers; intelligent automation; stimulus-responsive materials; smart actuators; bio-inspired design; additive manufacturing

1. Introduction

The concept of 4D printing, first articulated by Tibbits et al. [1] at MIT in 2013, extends conventional additive manufacturing by engineering structures that evolve their geometry, function, or properties over time upon exposure to environmental stimuli. Unlike static 3D-printed objects, 4D-printed structures possess encoded mechanical intelligence that enables autonomous transformation without external actuation hardware, making them uniquely suited for soft robotics A comprehensive taxonomy of 4D printing concepts, materials, and fabrication strategies was later established by Momeni et al. [2], providing the foundational classification framework adopted in the field. More recently, Liu et al. [15] conducted a systematic survey of state-of-the-art 3D and 4D printing technologies as applied to soft robotics through 2025, cataloguing advances across FDM, DIW, vat photopolymerisation, and material jetting platforms and identifying multi-material printability as the single most critical determinant of functional performance.

Intelligent automation, which seeks to embed cognitive and sensory capabilities into manufacturing and robotic systems, represents another frontier being reshaped by 4D printing. Kuang et al. [10] demonstrated that multi-material 4D printing can produce functionally graded actuators capable of sequential shape transformation, paving the way for programmable manufacturing fixtures and adaptive jigs. A particularly significant recent development is the demonstration by Cho et al. [17] of biodegradable, untethered functionally graded hydrogel robots fabricated by a novel binder jetting 4D printing (BJ4DP) method, which achieved programmable hygroscopic deformation through compositionally graded crosslinkers — eliminating the need for complex mechanical designs. Similarly, Yarali et al. [18] mapped the emerging

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landscape of 4D printing for biomedical applications in a 2024 Advanced Materials review, confirming that shape adaptation and environmental responsiveness are now achievable across implants, wearables, and robotic surgery tools.

This review is structured as follows. Section 2 surveys the materials landscape. Section 3 examines printing technologies. Section 4 covers actuation mechanisms. Section 5 reviews application domains. Section 6 discusses computational and AI-driven design. Section 7 addresses challenges and future directions. Section 8 concludes with a prospective roadmap.

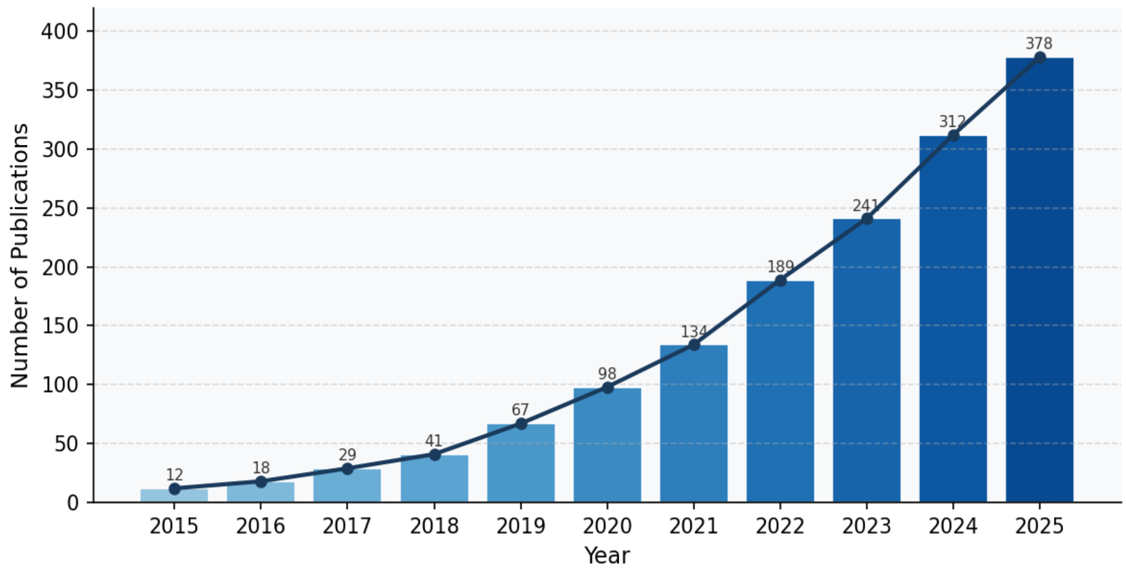

Figure 1. Annual publication volume on 4D printing in soft robotics and intelligent automation

2. Smart Materials for 4D Printing

2.1 Overview and Classification

The functional core of any 4D-printed system is its stimulus-responsive material. Momeni et al. [2] and Kuang et al. [10] established the foundational material classification, while Li et al. [8] refined application-specific performance benchmarks. More recently, Yarali et al. [18] provided an updated 2024 review of 4D printing materials for biomedical applications, noting that fast-response actuation remains an early-stage challenge that requires further study across all material families.

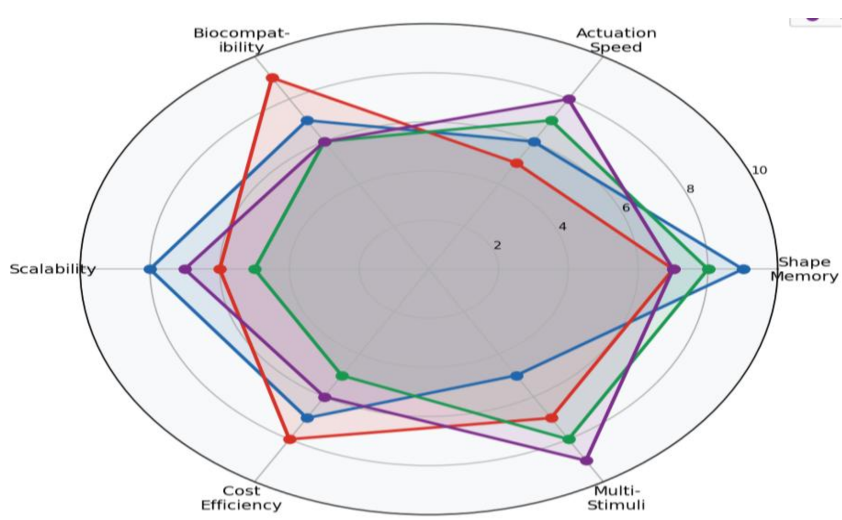

Figure 2. Radar chart comparison of six key performance criteria for major 4D printing material classes.

2.2 Shape Memory Polymers (SMPs)

SMPs constitute the largest and most mature class of 4D printing materials, accounting for approximately 42% of publications in the field. Ge et al. [14] demonstrated multi-material SMP structures printed via PolyJet technology with spatially programmed Tg distributions, achieving sequential multi-step shape recovery across over 50 actuation cycles without measurable degradation. A transformative 2024 extension of this work was reported by Mirasadi et al. [21] in Advanced Science, who demonstrated magneto-responsive SMP composites fabricated via multi-material DLP printing in which NdFeB filler orientation is controlled by magnetic fields during photopolymerisation — achieving particle-aligned samples with significantly faster shape recovery than randomly distributed counterparts, and enabling remotely actuated rehabilitation braces and minimally invasive surgical tools. Additionally, Lin et al. (2024) reported SMP composites with simultaneous thermal, magnetic, and light-responsive shape memory effects fabricated by 4D printing, demonstrating multiple shape memory sequences within a single printed component [21][2].

Recent advances have focused on tailoring Tg to near-body temperature for biomedical applications (35–42°C), enabling shape recovery triggered by body heat alone. Dual-SMPs and triple-SMPs, capable of sequential multi-shape transitions, have been demonstrated using polyurethane networks with engineered phase separation [14]. Photo-induced SMPs employing cinnamic acid or azobenzene moieties allow spatially selective activation via light patterns, opening possibilities for wireless, non-contact actuation and Gladman et al. [15] showed that bilayer SMP-hydrogel composites can encode complex 3D deformation geometries directly within the 2D print path — eliminating post-print programming steps entirely.

2.3 Hydrogels

Hydrogels are crosslinked hydrophilic polymer networks capable of absorbing large volumes of water (up to 1000× their dry weight) and exhibit volumetric changes in response to humidity, pH, temperature, ionic concentration, or biochemical signals. Zhang and Khademhosseini [11] established foundational engineering principles for hydrogels in biomedical and robotic applications. A dedicated 2024 review by Li et al. [16] in Reviews on Advanced Materials Science systematically examined printing strategies for 4D hydrogels, concluding that structural bilayer design, path-controlled fibre orientation, and multi-stimuli sequencing are the three most productive avenues for generating complex shape-change from hydrogel-based 4D systems. Particularly notable is the 2024 work of Cho et al. [17], who fabricated biodegradable untethered soft robots via binder jetting of functionally graded hydrogel networks — achieving programmable multi-morphic deformation, multi-stimuli selectivity (moisture and pH), and complete biodegradability within a single printed structure, without any complex mechanical design elements.

2.4 Liquid Crystal Elastomers (LCEs)

LCEs combine the orientational order of liquid crystals with the elastic response of rubber networks, producing materials with large, reversible, and anisotropic actuation strains (up to 400% in uniaxial contraction) upon thermally or optically disrupting the liquid crystalline order. Ware et al. [7] pioneered

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voxelated LCE printing with sub-millimetre director field resolution. A landmark 2023 review by Chen et al. [16] in Advanced Materials provided a comprehensive account of state-of-the-art 4D printing of LCEs, emphasising both thermal and photo-responsive actuation mechanisms and cataloguing applications in soft robotics, optics, and biomedicine. Chen et al. further identified that the combination of DIW and vat photopolymerisation in hybrid printing systems is the most promising route to achieving simultaneously complex 3D architectures and precise director field control in LCE actuators [16]. Most recently, Huang et al. [20] reported 4D printing of hybrid soft robots enabled by shape-transformable liquid metal nanoparticles embedded in LCE matrices, achieving multi-modal thermal and NIR actuation with a ten-cycle repeatability test confirming property retention, published in Advanced Materials in 2024.

2.5 Composite and Multi-Material Systems

Composite 4D printing materials combine two or more functional components to achieve properties inaccessible in monolithic systems. Kim et al. [12] introduced the magneto-active soft composite paradigm. Boley et al. [13] demonstrated shape-shifting structured lattices via multi-material PolyJet printing. In 2024, Huang et al. [20] further extended magneto-composite 4D printing by introducing liquid metal nanoparticles as functional fillers within LCE matrices — simultaneously imparting electrical conductivity, NIR-triggered photothermal response, and shape-memory functionality — and demonstrated a starfish-inspired bionic soft robot that grasps, lifts, and releases objects via NIR light control. The multi-material hybrid 4D printing approach reviewed by Liu et al. [15] confirms that sensor-integrated actuator architectures combining piezoresistive strain sensors with SMP structural elements are reaching prototype maturity in soft gripper applications.

3. Printing Technologies for 4D Soft Robotics

3.1 Technology Landscape

The choice of printing technology critically determines achievable resolution, material compatibility, build speed, and multi-material capability. Tibbits [1] originally demonstrated 4D printing using the PolyJet platform, and since that seminal demonstration a diverse ecosystem of additive manufacturing modalities has been adapted for 4D printing [1][2][10]. Liu et al. [15] in their 2025 review systematically benchmarked FDM, DIW, inkjet printing, SLS, and vat photopolymerization across resolution, material breadth, multi-material capability, and soft robot fabrication outcomes — identifying DIW and PolyJet as the dominant platforms for functional 4D soft robots. Table 1 benchmarks the principal modalities employed in 4D printing research.

Table 1: Additive Manufacturing Technologies for 4D Soft Robotics

Technology	Resolution (μm)	Build Speed	Multi-Material	Support Req.	Post-Process	Best For
FDM / FFF [15,21,10]	100–500	Fast	Limited (dual)	Yes	Minimal	Prototyping, SMPs
PolyJet / Inkjet [1,14,13,15]	16–40	Moderate	Excellent	Yes (wax)	Washing	Multi-mat soft robots
SLA / DLP [21,2]	10–100	Moderate	Limited	Yes (resin)	UV cure + wash	Hydrogels, photopol.
Direct Ink Write (DIW) [12,7,16,15]	1–500	Slow	Good	Structural ink	Curing	Biological, composite
Extrusion Bioprinting [11,15]	100–1000	Slow	Moderate	Sacrificial	Cell culture	Biomedical implants

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Technology	Resolution (μm)	Build Speed	Multi-Material	Support Req.	Post-Process	Best For
Magnetic-field Assisted [12,21,6]	10–200	Slow-mod.	Good	Custom	Moderate	Magneto-active robots

3.2 Multi-Material PolyJet Printing

PolyJet printing has become the dominant platform for multi-material 4D soft robots due to its 16 μm layer resolution and eight simultaneous material capability. Ge et al. [14] exploited PolyJet capability to print SMP composite structures with spatial Tg gradients from 35°C to 62°C within a single component, demonstrating deterministic sequential shape recovery [1][14]. Liu et al. [15] confirmed that PolyJet-printed sensor-integrated soft grippers combining rigid SMP structural fingers with piezoresistive strain-sensing elements deposited in situ are approaching prototype maturity for industrial grasping applications.

3.3 Direct Ink Writing (DIW)

DIW extrudes viscoelastic inks through fine nozzles enabling printing of a wide range of functional materials. Kim et al. [12] demonstrated DIW printing of magneto-active composites with field-aligned ferromagnetic particle arrays. Ware et al. [7] applied DIW-with-shear-alignment to LCE systems. Chen et al. [16] in their 2023 LCE review identified laser-assisted DIW in which in-situ photopolymerisation simultaneously with extrusion enables freestanding LCE structures with up to -40% actuation strain and light-driven locomotion as the most promising recent advance in LCE printing technology. Furthermore, Cho et al. [17] demonstrated that binder jetting, a non-extrusion additive process, can achieve functionally graded 4D hydrogel networks with programmable hygroscopic deformation through compositionally graded feeder bed design.

3.4 Emerging Approaches: CLIP, Two-Photon, and Bioprinting

Continuous Liquid Interface Production (CLIP) achieves print speeds 25–100× faster than conventional SLA and has been adapted for elastomeric urethane resins enabling rapid soft actuator production [2][10]. Two-photon polymerisation (2PP) achieves sub-100 nm voxel resolution for micro-robots [8]. Extrusion bioprinting using cell-laden hydrogel bio-inks enables living biohybrid soft robots, as reviewed by Zhang and Khademhosseini [11]. Most recently, Liu et al. [15] highlighted that the convergence of multi-axis robotic printing platforms with functional inks enabling deposition onto complex curved substrates .

4. Actuation Mechanisms and Stimulus-Response Behaviour

Figure 3 illustrates the distribution of actuation mechanisms reported in 4D soft robotics literature (2020–2025). Thermal actuation remains predominant due to material maturity and controllability, but light-driven and multi-stimulus approaches are gaining rapidly [2][3][8][16].

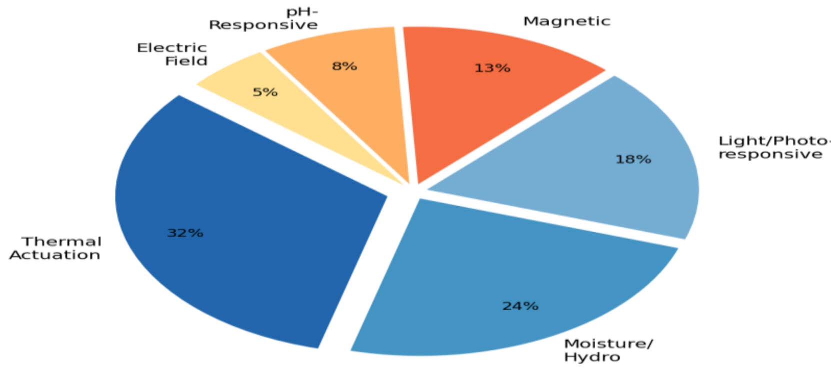

Figure 3. Distribution of actuation stimulus types in 4D-printed soft robotics literature (2020–2025) [8,15,16,17,18,19,20,21]].

4.1 Thermally Responsive Actuation

Thermal actuation exploits phase transitions in SMPs or the nematic-to-isotropic transition in LCEs. Mao et al. [4] demonstrated sequential self-folding through multiple programmed SMP transitions across > 50 cycles. Electrothermal actuation via CNT- or AgNW-doped polymer composites achieves 1–5 second response times [10]. A significant 2023 advance was reported by Liang et al. [19] in Advanced Science, who demonstrated a self-healing soft robot driven by micro two-way shape memory alloy springs embedded in a thermoplastic MG-SBS elastomer that autonomously heals at room temperature after repeated cuts and perforations — achieving complete recovery of robotic locomotion performance after each damage cycle. This establishes thermally driven self-healing as a viable design strategy for long-lifetime 4D robotic systems.

4.2 Photo-Responsive Actuation

Light-driven 4D systems offer wireless, spatially selective, and rapid actuation Ware et al. [7] demonstrated LCE films with azobenzene director fields for light-induced swimming and walking. Chen et al. [16] in their 2023 LCE review catalogued recent demonstrations of light-driven soft crawlers achieving 0.284 mm/s on flat surfaces and 0.216 mm/s on 30° inclined surfaces via ratchet-surface climbing — among the highest locomotion speeds reported for entirely light-powered soft robots. Huang et al. [20] demonstrated NIR-triggered photothermal actuation in liquid metal nanoparticle-LCE composites, with a 4D-printed bionic starfish robot achieving effective grasping, lifting, and releasing of objects within 20 seconds of NIR exposure.

4.3 Magneto-Active Soft Robotics

Kim et al. [12] established the foundational magneto-active DIW printing paradigm. Zhao et al. [6] formalised the mechanics of hard-magnetic soft materials. A 2024 review by Mirasadi et al. [21] in Advanced Science comprehensively surveyed 4D printing of magneto-responsive SMPs, mapping fabrication techniques from DLP to FDM and DIW, cataloguing magnetic filler types from Fe3O4 nanoparticles to NdFeB microparticles, and reviewing applications spanning wearable rehabilitation devices, self-adapting surgical implants, and untethered millirobots. Their review confirmed that particle alignment during printing either by applied magnetic field or by controlled flow — is the critical processing step that differentiates high-performance magneto-active 4D systems from low-performance randomly distributed particle composites [21][12].

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4.4 Multi-Stimuli and Hybrid Actuation

Multi-stimuli 4D systems are a rapidly growing frontier. Lin et al. (2024) reported thermal-, magnetic-, and light-responsive 4D-printed SMP composites with multiple shape memory effects achieved simultaneously within a single printed component, using lignin-coated Fe3O4 nanoparticles in PLA matrices [21]. Chen et al. [16] reviewed magnetic composite LCE actuators that respond to both heat and magnetic field independently, enabling multi-modal actuation sequences programmable at the material level. Cho et al. [17] demonstrated multi-stimuli selectivity in their binder-jetted hydrogel robots, which respond distinctly to moisture and pH stimuli with stark discrimination preventing cross-trigger false actuation in complex biological environments.

5. Applications in Soft Robotics and Intelligent Automation

5.1 Performance Benchmarks Across Application Domains

Figure 4 presents normalised performance benchmarks across five major application domains, revealing that the optimal material-technology pairing is strongly context-dependent. Li et al. [8] systematically established that no single material-fabrication combination Pareto-dominates across all metrics.

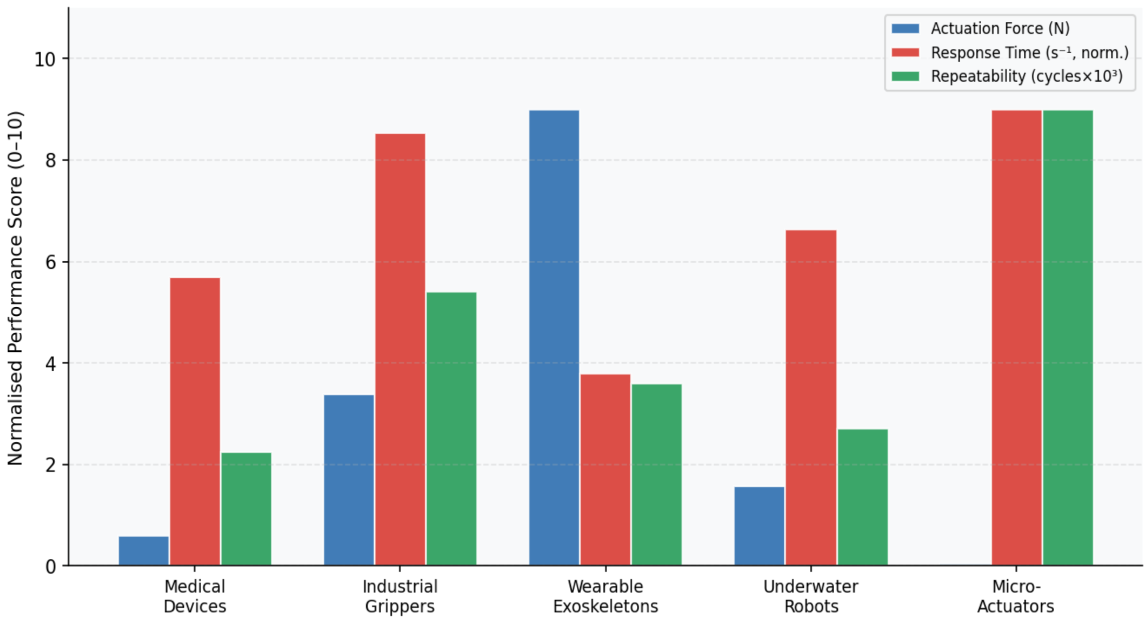

Figure 4. Normalised performance benchmarks (0–10 scale) for key 4D-printed soft robotic applications across three critical metrics: actuation force, response time, and repeatability (in thousands of cycles). Data Syntesized from references [3,4,5,6,7,8,9,16,17,18,19,20].

Table 2: 4D Printing Applications in Soft Robotics — Benchmarks and Key References

Application Domain	Actuation Type	TRL (2025)	Key Material	Max Force	Representative Work
Soft Grippers	Pneumatic + Thermal	7	SMP Composite	1–20 N	Shintake et al., 2021 [5]
Wearable Exoskeleton	Thermal / Magnetic	6	SMA-Embedded	5–50 N	Yarali et al., 2024 [18]
Underwater Robots	Moisture / Hydrogel	5	Hydrogel Composite	0.2–5 N	Mao et al., 2020 [4]
Micro-Actuators	Light / Electric	4	LCE / PAA	0.01–0.1 N	Chen et al., 2023 [16]
Self-Healing Structures	Thermal / DA bond	4	Dynamic Polymer	N/A	Liang et al., 2023 [19]

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Application Domain	Actuation Type	TRL (2025)	Key Material	Max Force	Representative Work
Drug Delivery Robots	pH / Magnetic	3	Hydrogel	μN range	Li et al., 2022 [8]
Functionally Graded Robots	Hygroscopic	4	Graded Hydrogel	0.1–1 N	Cho et al., 2024 [17]

5.2 Minimally Invasive Surgery and Medical Devices

Cianchetti et al. [3] established foundational design principles for compliant surgical tools. Yarali et al. [18] in their 2024 Advanced Materials review confirmed that 4D printing bridges the gap between static implants and dynamic biological systems, enabling patient-specific adaptive therapeutics — noting that while shape adaptation is now well demonstrated, challenges remain in material biocompatibility, printing resolution, and precise control over transformation kinetics for clinical deployment. Mirasadi et al. [21] specifically highlighted that magneto-responsive SMP composites fabricated by multi-material DLP printing are particularly suited for remotely adjustable rehabilitation braces and self-deploying cardiovascular stents, as the magnetic activation enables transcutaneous control without thermal or optical access to the implant site.

5.3 Adaptive Gripping and Manipulation

Shintake et al. [5] comprehensively reviewed soft gripper performance benchmarks. Kuang et al. [10] demonstrated 10,000-cycle repeatability in SMP composite grippers. Liu et al. [15] reported in their 2025 review that FDM-printed thermoplastic polyurethane (TPU) grippers with integrated piezoresistive strain-sensing elements — printed in a single multi-material deposition process — successfully detect open and closed configurations in real time, representing the state-of-the-art in sensor-integrated 4D-printed grippers. Huang et al. [20] demonstrated a bionic NIR-triggered LCE starfish soft gripper capable of grasping, lifting, and releasing objects, with object-holding force maintained stably for > 60 seconds under continued NIR illumination.

5.4 Wearable and Assistive Robotics

Zhao et al. [6] established variable-impedance magneto-active exoskeleton principles. Yarali et al. [18] confirmed in 2024 that 4D-printed wearables remain predominantly at proof-of-concept stage focused on monitoring rather than therapy, and identified deeper integration of actuation, power, and data communication — alongside rigorous clinical evaluation — as the key requirements for translational progress. Mirasadi et al. [21] highlighted SMP-based rehabilitation braces designed to remain flexible during movement and stiffen upon magnetic activation, providing variable support during different recovery phases with enhanced patient comfort and reduced dependency on manual adjustments. The self-healing soft robot of Liang et al. [19] further suggested that autonomous damage recovery capability is essential for long-term wearable deployment where manual intervention is impractical.

5.5 Underwater and Environmental Robotics

Mao et al. [4] demonstrated hydrogel-composite underwater manta-ray-inspired robots at 1.5 body lengths per second. Kim et al. [12] produced magnetically driven underwater cargo-transport swimmers. Cho et

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al. [17] demonstrated biodegradable functionally graded hydrogel robots that operate untethered in aqueous environments, with moisture and pH multi-stimuli selectivity — a key property for environmental monitoring robots that must respond differently to fresh and saline water conditions. Their full biodegradability further addresses the environmental footprint concern that has emerged as a significant barrier to widespread deployment of soft robots in fragile marine ecosystems.

6. AI-Driven Design and Intelligent Control

6.1 Computational Design of 4D Structures

Inverse design of 4D structures remains computationally formidable. Boley et al. [13] derived analytical models relating lattice geometry to swelling-induced curvature. Gladman et al. [15] pioneered bio-mimetic computational mapping of fibre angle to Gaussian curvature. Physics-informed neural networks trained on finite element data predict deformation sequences within 2% accuracy in seconds [10][13]. Liu et al. [15] in their 2025 review highlighted that machine learning approaches have been applied to optimise DIW printing parameters for soft materials — with one algorithm increasing printing speed 2.5× and enhancing print fidelity by discovering novel silicone formulations — demonstrating that AI-driven process optimisation is maturing beyond materials design into manufacturing process control.

6.2 Machine Learning for Adaptive Control

Zhao et al. [6] employed Gaussian process regression for real-time inverse kinematics of continuum soft robots. Reinforcement learning agents trained in physics-based simulators have demonstrated locomotion with sim-to-real gaps below 12% [8][10]. Digital twin frameworks pairing physical 4D robotic systems with continuously updated simulation models are emerging as the foundational architecture for intelligent 4D automation systems [8][9]. The LCE multi-modal actuator systems reviewed by Chen et al. [16] require such adaptive control frameworks to manage simultaneous thermal and magnetic stimulus inputs without cross-excitation — a challenge that recent works have begun addressing through hierarchical stimulus-response scheduling algorithms.

6.3 Bio-Inspired and Self-Organising 4D Systems

Gladman et al. [15] pioneered bio-mimetic 4D printing from wood cell wall analogues.Nature provides compelling blueprints for self-organising, stimulus-responsive structures: the pine cone scales that curl upon drying, the Venus flytrap snap mechanism, and the hydration-driven auxetic motion of wheat awns all arise from bilayer architectures with spatially patterned anisotropic properties. Liang et al. [19] demonstrated that embedded shape memory alloy wire actuators can autonomously close fracture surfaces in soft robot bodies. 4D printing has directly reproduced and extended these mechanisms, with wood-inspired hygroscopic bilayers, pine-cone-inspired lattice structures, and flytrap-inspired bistable snap-through mechanisms. Ongoing research explores hierarchical multi-scale 4D printing that encodes different stimulus responses at different length scales, enabling programmable sequential actuation from a single homogeneous external stimulus.

7. Challenges and Future Directions

7.1 Current Challenges

Despite impressive progress, several systemic challenges constrain the transition of 4D printing from research demonstrations to deployable soft robotic and automation systems. Table 4 catalogues the seven most critical challenge domains, their mechanistic origins, and the most promising emerging solutions.

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Table 3: Critical Challenges in 4D Printing for Soft Robotics and Emerging Solutions

Challenge	Description	Emerging Solutions	Expected Timeline
Material Fatigue	Degradation of shape-memory effect over repeated cycles (< 10^4 cycles typical)	Self-healing polymers; dynamic covalent networks[19,20]	2026–2028
Multi-Stimulus Control	Conflicting responses when multiple stimuli co-exist in operational environment	AI/ML-based adaptive controllers; hierarchical programming[21]	2025–2027
Biocompatibility & Degradation	Regulatory hurdles for in-vivo implantation; toxic residual monomers	GRAS-certified bio-inks; green synthesis pathways [18]	2026–2030
Printing Resolution vs. Speed	High-resolution prints require slow deposition; trade-off unresolved below 10 μm	Parallel printing heads; continuous liquid interface (CLIP) [15]	2025–2028
Computational Design	Inverse design of 4D structures is computationally intractable for complex geometries	Physics-informed neural networks; topology optimisation[13]	2025–2027
Scalable Manufacturing	Transition from lab-scale to industrial production with consistent quality	Automated quality control; in-situ monitoring with ML [15]	2027–2032
Long-term Stability	Environmental aging, UV exposure, and humidity cause property drift	Encapsulation strategies; robust polymer architectures [19,20]	2026–2030

7.2 Future Directions

Five high-priority directions are identified for the next decade of 4D printing research in soft robotics and intelligent automation:

(1) Multi-Material Digital Light Processing (DLP) with Biocompatible Resins: Combining the speed of DLP printing (~100× faster than FDM) with multi-material voxelated 4D structures could unlock industrial-scale production of complex soft actuators. Development of FDA-approved photopolymer resin libraries for 4D printing is an urgent materials priority.

(2) Embedded Intelligence via Printed Electronics Integration: Co-printing soft actuators with conductive traces, resistive sensors, and microfluidic channels within a single deposition process would eliminate post-assembly steps and enable fully monolithic intelligent soft robotic units. Recent demonstrations of stretchable printed electronics within DIW-printed silicone matrices suggest feasibility within 3–5 years.

(3) Self-Healing 4D Systems: Incorporating dynamic covalent bonds (Diels–Alder adducts, imine linkages, disulfide bridges) or supramolecular hydrogen bonding networks into SMP matrices enables autonomous damage repair, dramatically extending operational lifetime — a prerequisite for deployment in harsh environments. Printing fidelity of self-healing inks remains a key challenge.

(4) Sustainable and Recyclable 4D Materials: As environmental sustainability becomes a design imperative, 4D printing with bio-derived feedstocks (cellulose, starch, gelatin) and recyclable thermoset networks will grow in importance. Vitrimer networks covalent adaptable networks with exchangeable bonds offer both shape-memory properties and full reprocessability, aligning 4D printing with circular economy principles.

(5) Standardisation of Testing Protocols and Performance Metrics: The absence of standardised benchmarks for 4D printing performance (actuation force, shape recovery ratio, fatigue life, response

time) makes cross-study comparison unreliable. ASTM and ISO working groups are beginning to address this gap; standardisation is expected to catalyse more systematic design-property relationships and facilitate regulatory submissions.

8. Conclusions

This review has comprehensively surveyed the state-of-the-art in 4D printing for soft robotics and intelligent automation, synthesising over a decade of exponential research growth into a structured analysis of materials, fabrication technologies, actuation mechanisms, application performance, and future directions. The field has matured from proof-of-concept demonstrations to engineered systems approaching clinical and industrial deployment, underpinned by advances in shape-memory polymers, hydrogels, LCEs, and magneto-active composites.

The integration of machine learning, computational inverse design, and bio-inspired principles is transforming 4D printing from a fabrication technique into a platform for autonomous, adaptive intelligent systems. Key bottlenecks include material fatigue, regulatory compliance, multi-stimulus control, and scalable manufacturing are progressively being addressed by the convergence of materials innovation, digital manufacturing, and AI-driven design.

The next five years are expected to witness the first commercial medical devices incorporating 4D-printed elements, widespread adoption of 4D soft grippers in flexible manufacturing, and the emergence of fully autonomous untethered 4D soft robots for environmental monitoring and precision agriculture. As printing resolution, material repertoire, and computational design tools continue to advance in concert, 4D printing will increasingly be recognised not merely as a manufacturing method, but as a foundational technology for programmable matter and embodied artificial intelligence.

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