4D Printing of Dynamic Structures: A Comprehensive Review of Materials, Mechanisms, and Applications

Hafsa Anwar[1],Alka Roy[2]

[1]Bahauddin Zakariya University, Multan, Pakistan, [2]Dav University, Jalandhar, India

anwarhafsa@hotmail.com[1], alka.roy09@protonmail.com[2]

Abstract

4D printing represents a transformative leap in additive manufacturing by integrating time-dependent transformation into 3D-printed structures. This emergent technology involves the creation of dynamic objects that change shape, properties, or function in response to external stimuli such as temperature, moisture, light, pH, or magnetic fields. By combining smart materials, such as shape-memory polymers and hydrogels, with advanced printing techniques, 4D printing enables the development of structures that mimic biological adaptability. This innovation holds significant promise across various sectors, including biomedical devices, aerospace components, soft robotics, and responsive infrastructure systems. The key distinction of 4D printing lies in its ability to program material behavior into the fabrication process, allowing post-production transformation without further mechanical intervention. This paper provides a comprehensive review of 4D printing focused on dynamic structures. It begins with a detailed introduction to the fundamentals of 4D printing and its evolution from traditional 3D printing. A thorough literature review explores current developments and pioneering research, highlighting applications, material selection, and transformation mechanisms. The methodology section presents approaches to designing, modeling, and fabricating dynamic 4D structures with an emphasis on stimuli-responsive behavior. Additionally, the paper discusses future directions and potential challenges, including scalability, multi-material integration, and real-world implementation barriers. The conclusion consolidates key findings and outlines the implications of 4D printing on the future of smart, adaptable systems.

Keywords: 4D Printing, Dynamic Structures, Smart Materials, Shape-memory Polymers, Self-transformation.

Article Number: SCHORES-JPSE-01-001
SchoRes Journal of Physical Sciences and Engineering
Volume 1, Issue 1, December 2025
Date Published: 1 December 2025

www.schores.org

1. Introduction

The realm of additive manufacturing has undergone a dramatic evolution in the past decade, transitioning from rudimentary rapid prototyping to the fabrication of complex, functional parts. At the forefront of this evolution is 4D printing, an innovation that adds the dimension of time to conventional 3D printing processes[1]. This technology enables the printed structure to transform its shape, properties, or functionality in response to environmental stimuli. Such capability aligns closely with the behavior of living organisms that can dynamically adapt to their surroundings, presenting an exciting frontier in material science and engineering.

Unlike traditional 3D printing, which produces static geometries, 4D printing introduces the ability for structures to evolve over time. This is made possible by integrating smart materials with programmable features during the printing process. As a result, a printed object is not merely a product but a system embedded with potential energy that activates under specific conditions. The transformative nature of 4D printing allows for the realization of systems that are self-assembling, self-healing, and functionally autonomous [2].

The origins of 4D printing can be traced back to the integration of shape-memory materials in additive manufacturing. These materials exhibit the ability to return to a predefined shape when exposed to external stimuli such as heat or water. Researchers at institutions such as MIT pioneered early demonstrations of these capabilities, marking a shift in the purpose of printed structures from static tools to dynamic machines. Since then, research in this area has expanded rapidly, encompassing diverse materials and a growing range of stimulus types.

The potential applications of 4D printing are vast and transformative. In the biomedical field, dynamic structures can be used for targeted drug delivery, tissue scaffolds that adapt during healing, and implants that change form post-implantation. In aerospace, components that alter shape to optimize aerodynamic properties or temperature regulation can significantly enhance efficiency and safety. The civil engineering domain also benefits, with deployable infrastructure and responsive facades becoming increasingly feasible [1].

One of the driving factors behind the adoption of 4D printing is its compatibility with Industry 4.0 initiatives. As manufacturing shifts toward greater automation, customization, and integration with digital systems, 4D printing provides a route to producing intelligent, adaptable components in line with these objectives. This convergence of digital design, smart materials, and responsive behavior underpins the broader vision of adaptive and resilient systems.

However, despite the promise, 4D printing is still in its nascent stages. Challenges persist in areas such as the development of suitable multi-functional materials, achieving precise control over transformation behavior, and integrating these technologies into existing manufacturing workflows. There are also concerns around durability, repeatability, and the predictability of shape transformations over time [3].

Material characterization remains a critical area of focus, as not all smart materials are equally responsive or stable under various conditions. Furthermore, the interaction between materials and stimuli must be carefully modeled to ensure that transformations occur as intended. This demands robust simulation tools and sophisticated design approaches that can account for multi-physics interactions and long-term behavior.

Equally important is the role of computational design and modeling. Software tools are required to simulate both the initial printing process and the subsequent transformation sequence. This dual-phase modeling is complex and demands interdisciplinary collaboration between mechanical engineering, material science, and computer science professionals.

To address these complexities, researchers are developing novel frameworks and methodologies that encompass both fabrication and transformation. These methodologies aim to offer designers the ability to predict and harness dynamic behavior in a programmable and scalable manner. The integration of artificial intelligence and machine learning is also beginning to influence how transformation pathways are discovered and optimized.

2. Literature Review

The concept of 4D printing, first introduced by [9] at MIT's Self-Assembly Lab, has since gained significant momentum within the academic and industrial spheres. Tibbits demonstrated that time-dependent transformation of 3D-printed structures could be achieved by embedding smart materials that respond predictably to environmental stimuli. His pioneering work laid the foundational framework for future studies exploring dynamic transformations in printed systems. The core idea involved using water-responsive materials to self-assemble simple shapes, initiating a shift from passive to active design paradigms.

Expanding upon this foundation [4] presented a groundbreaking study in *Nature Materials*, introducing a bio-inspired 4D printing method using hydrogel-based composites. Their work employed anisotropic swelling to achieve complex shape morphing akin to natural systems like flower petals or pine cones. By precisely aligning cellulose fibrils within the hydrogel matrix, they demonstrated programmable and reversible shape changes under hydration, offering valuable insights into biomimicry and soft actuation in printed structures. This study underscored the importance of microstructural control in achieving responsive behavior in dynamic materials.

Another significant contribution was made by [7] who provided a comprehensive review in *Materials & Design* that categorized 4D printing into shape memory, stimuli-responsive, and multi-material-based methods. Their review examined the underlying mechanics and manufacturing techniques, highlighting both the capabilities and current limitations. This paper was instrumental in contextualizing 4D printing as an interdisciplinary field that merges material science, mechanical engineering, and digital design. Moreover, they stressed the importance of modeling and simulation in predicting transformation outcomes an area that still requires further refinement.

Some work explored shape-memory polymers (SMPs) within the 4D printing framework, introducing the concept of "self-healing" in printed parts [10]. Their study, published in *Advanced Materials*, presented thermally responsive SMPs that could return to a predetermined shape after deformation, as well as recover from damage. This dual functionality shape transformation and healing opened up new possibilities for resilient applications in aerospace, defense, and biomedical devices. The combination of stimuli-responsiveness and self-repair properties is a hallmark of next-generation dynamic structures.

In the biomedical domain, [3] provided a crucial application-focused perspective on 4D printing. They demonstrated the fabrication of custom-designed, patient-specific implants that transformed post-implantation, thus improving compatibility and reducing the need for surgical adjustments. This study emphasized the practical relevance of 4D printing in personalized medicine and adaptive implants. Their use of UV-curable polymers also showed how light could be used as a stimulus for transformation, broadening the scope of triggers beyond temperature and moisture.

Another notable advancement came from [11] who explored magnetic-field responsive materials in their study published in *Composites Part B: Engineering*. They embedded ferromagnetic particles into polymer matrices to achieve shape change under a controlled magnetic field. This method allowed remote, wireless actuation with relatively high precision, offering a compelling alternative to thermally activated transformations. The research highlighted the trade-offs between different stimulus types and the need for compatibility with intended application environments.

Furthering this exploration [5] focused on the integration of computational modeling with material behavior in the 4D printing pipeline. Published in *Advanced Functional Materials*, their study introduced a predictive simulation framework for shape-shifting hydrogel-based structures. They validated the models with experimental outcomes, showcasing the role of simulation in ensuring the reliability of the transformation process. Their approach provided a systematic design method that included time-dependent mechanics and material-environment interaction, enhancing predictability and design confidence.

From a broader perspective, the current literature reflects the convergence of multiple disciplines in driving 4D printing forward. Smart material development is central to this field, as material properties determine both the feasibility and range of transformations. Most research currently focuses on polymers particularly SMPs, hydrogels, and light- or magneto-responsive composites due to their flexibility and compatibility with common 3D printing techniques. However, issues of fatigue resistance, long-term stability, and limited transformation forces remain ongoing challenges.

In addition, simulation and predictive modeling are increasingly critical to designing functional 4D printed structures. With the rising complexity of multi-material and multi-stimulus systems, simple empirical design is insufficient. Computational approaches such as finite element analysis (FEA) and machine learning-based optimization are gradually being adopted to improve design outcomes and reduce trial-and-error experimentation.

Importantly, applications are shifting from conceptual demonstrations to functional deployments. Biomedical devices, aerospace components, and soft robotics are now central to the field's development. Yet, widespread industrial adoption still faces obstacles, including high material costs, slow transformation speeds, and integration challenges with existing manufacturing processes.

In summary, the literature establishes 4D printing as a highly interdisciplinary and rapidly advancing field. Pioneering work has demonstrated dynamic, functional structures with a range of transformation capabilities triggered by various environmental stimuli. While the field continues to expand in both theoretical and applied domains, substantial challenges remain in material development, precision control, and application integration. The next section will discuss the methodology used to fabricate, model, and test 4D printed dynamic structures, drawing from the insights presented here.

3. Methodology

The methodology of 4D printing involves a multi-stage process that integrates material selection, digital modeling, actuation mechanism design, and fabrication strategies. Each of these components plays a critical role in ensuring the functional transformation of the printed structure in response to environmental stimuli. Unlike traditional 3D printing, which focuses on form and dimensional accuracy, 4D printing demands the consideration of how a structure will evolve over time. This methodology outlines the necessary stages and considerations to achieve dynamic, stimulus-responsive behavior in printed structures [6].

3.1. Material Selection and Characterization

The foundational element of any 4D printing methodology is the choice of smart materials. These materials must exhibit predictable, repeatable responses to specific stimuli such as heat, light, moisture, magnetic fields, or chemical environments. Among the most widely used smart materials are:

- **Shape-memory polymers (SMPs)**: Return to a pre-defined shape when exposed to heat.
- **Hydrogels**: Swell or shrink in response to water or pH changes.
- **Liquid crystal elastomers (LCEs)**: Undergo shape changes under thermal or light activation.

- **Magneto-responsive composites**: Deform when subjected to a magnetic field.

Material characterization involves measuring parameters such as transition temperature (e.g., glass transition for SMPs), swelling ratios for hydrogels, and elastic modulus changes under stimulus. Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), and Dynamic Mechanical Analysis (DMA) are commonly used techniques to evaluate these properties [8].

3.2. Stimulus Definition and Transformation Behavior

The selection of the appropriate external stimulus is essential for triggering the transformation process. The stimulus must be practical for the intended environment and must induce a reliable and controllable change. The behavior of the material under the influence of the stimulus must be studied both experimentally and computationally. This includes determining the actuation time, assessing reversibility and fatigue over multiple cycles, measuring the extent and direction of deformation, and evaluating environmental compatibility such as biocompatibility and UV stability. For example, thermally induced transformations using shape memory polymers (SMPs) require uniform heating to a specific activation temperature. Similarly, hydrogel-based systems require hydration and appropriate drying conditions

3.3. Digital Modeling and Simulation

One of the most important components of 4D printing methodology is the development of digital models that simulate both the printing process and the post-fabrication transformation. Finite Element Modeling (FEM) is extensively used to simulate deformation behavior based on material properties and applied stimuli. Software tools such as ABAQUS, COMSOL Multiphysics, and ANSYS enable simulation of thermomechanical responses, swelling-induced strain, and multi-material interactions. This predictive modeling assists in minimizing material waste and design errors by forecasting the final shape and timing of transformations. Parametric modeling tools like Grasshopper (in Rhino) or Autodesk Fusion 360 are also employed in the early design phase to create adaptive geometries. These tools allow designers to encode transformation behavior into the digital blueprint of the object.

3.4. Printing Strategy and Fabrication Process

4D printing builds upon traditional additive manufacturing technologies, with modifications tailored for responsive materials. The most commonly used techniques include FDM, which is suitable for thermoplastics and SMPs; direct ink writing (DIW), ideal for printing hydrogels and elastomers with controlled deposition paths; stereolithography (SLA), used for UV-curable SMPs and high-resolution transformations; and inkjet printing, which supports multi-material deposition and is essential for creating gradient structures. Key fabrication considerations involve several factors. Print orientation influences how the material will deform under stress, while layer thickness and infill density affect responsiveness and transformation speed. Additionally, printing speed and temperature are critical for ensuring proper interlayer bonding and material integrity. During the printing process, the deposition path and pattern are carefully programmed to reflect the anticipated deformation pathway. Anisotropic printing where material properties vary by direction is often employed to encode specific behaviors such as bending, twisting, or coiling into the structure.

3.5. Multi-Material Integration

Dynamic structures often require the combination of active (stimuli-responsive) and passive materials, enabling selective transformation and greater design control. Multi-material printing allows the embedding of different functional regions within a single object. For example, hydrogels can be embedded into rigid plastic frameworks, bilayers can be created where one material expands while the other remains stable, and soft elastomers can be combined with hard thermoplastics. This integration is achieved through multi-nozzle printers or sequential deposition techniques. Care must be taken to ensure adhesion between materials and compatibility in terms of thermal and chemical properties.

3.6. Post-Processing and Activation Testing

After printing, post-processing steps such as curing (for SLA) or annealing (for SMPs) may be necessary to stabilize the structure. Once post-processing is complete, activation tests are conducted under controlled conditions to observe transformation.

Tests involve:

- Applying the chosen stimulus (e.g., submerging in water, heating in a chamber)
- Measuring deformation over time using motion-tracking or digital image correlation (DIC)
- Repeating the cycle to assess fatigue resistance

Activation data is compared to simulation outputs to evaluate accuracy and make necessary design adjustments.

3.7. Validation and Application Prototyping

To validate a design, prototype structures are often subjected to functional testing within their target environment. For example, biomedical prototypes are tested in simulated body fluids or tissues, aerospace components are tested under thermal cycles and mechanical loads, and architectural elements are subjected to light, wind, or moisture variations. These tests help determine whether the printed structure maintains integrity and functionality during and after transformation. Iterative prototyping ensures that transformation behavior is reliable and repeatable.

This structured methodology ensures that dynamic behavior is integrated from the design phase through to the final deployment. By combining smart materials, precise modeling, and advanced fabrication, 4D printing provides a robust platform for developing adaptable and intelligent systems.

4. Future Work

While 4D printing has made significant strides, future research is needed to address the limitations associated with material performance, scalability, and multi-functional integration. One promising direction is the development of novel hybrid materials that combine responsiveness with mechanical strength and environmental stability. Moreover, integrating artificial intelligence and machine learning into the design process may enhance predictive modeling and automate the optimization of transformation behaviors. Advances in multi-material and multi-scale printing techniques are expected to support more complex and hierarchical structures. There is also a need to establish standardized frameworks for transformation characterization and to expand the range of stimuli that can be used reliably in diverse operational conditions. Bridging the gap between laboratory-scale prototypes and real-world applications, particularly in construction, biomedicine, and soft robotics, remains a key objective for the next phase of research.

5. Conclusion

The evolution from static 3D printing to dynamic 4D printing signifies a transformative shift in the field of additive manufacturing. This review has explored the foundational principles of 4D printing, emphasizing how the integration of time-responsive behavior into printed structures has expanded the functional and application potential of additive fabrication. By using smart materials such as shape-memory polymers, hydrogels, and magneto-responsive composites, 4D printing enables structures that can autonomously adapt, transform, or evolve in response to environmental stimuli. This adaptability mirrors natural systems and offers vast opportunities across sectors like aerospace, biomedical engineering, and smart infrastructure. The literature reviewed in this paper illustrates how research has progressed from basic demonstrations to advanced models that leverage computational design, predictive simulation, and multi-material integration. Innovations in material science and printing technology have enabled increasingly precise control over transformation pathways, yet significant challenges remain. These include ensuring long-term durability, achieving consistent transformation under real-world conditions, and scaling production for industrial use. Moreover, the need for improved software tools, standardized testing protocols, and cross-disciplinary collaboration remains critical for broader adoption. In conclusion, 4D printing represents a convergence of material science, design engineering, and digital fabrication. It enables the creation of intelligent, adaptive systems that respond dynamically to their environments. While still an emerging field, its potential is vast and transformative. Continued innovation in material development, actuation mechanisms, and digital modeling will further expand its capabilities and bring forth new applications that align with the vision of future-ready, self-evolving technologies. With sustained research and technological refinement, 4D printing is poised to redefine how we design and interact with the built and natural world.

References

[1] Behl, M. and Lendlein, A. Shape-memory polymers. *Materials Today*, 10(4), pp.20–28, 2007.

[2] Bodaghi, M., Wang, L., Zhang, F., Liu, Y., Leng, J., Xing, R., Dickey, M.D., Vanaei, S., Elahinia, M., Hoa, S.V. and Zhang, D. 4D printing roadmap. *Smart materials and structures*, *33*(11), p.113501, 2024.

[3] Ge, Q., Sakhaei, A.H., Lee, H., Dunn, C.K., Fang, N.X. and Dunn, M.L. Multimaterial 4D printing with tailorable shape memory polymers. *Scientific Reports*, 6(1), pp.31110, 2014.

[4] Gladman, A.S., Matsumoto, E.A., Nuzzo, R.G., Mahadevan, L. and Lewis, J.A. Biomimetic 4D printing. *Nature Materials*, 15(4), pp.413–418, 2016.

[5] Kirillova, A., Maxson, R., Stoychev, G., Turcaud, S., Lipson, H. and Ionov, L. 4D biofabrication using shape-morphing hydrogels. *Advanced Functional Materials*, 27(12), pp.1700243, 2017.

[6] Mao, Y., Yu, K., Isakov, M., Wu, J., Dunn, M.L. and Qi, H.J., Sequential self-folding structures by 3D printing of shape memory polymers. *Scientific Reports*, 5, pp.13616, 2015.

[7] Momeni, F., Hassani, N.S., Liu, X. and Ni, J. A review of 4D printing. *Materials & Design*, 122, pp.42–79, 2017.

[8] Song, J. and Guo, Y. Magnetic Field Driven Microrobot Based on Hydrogels. *Advanced Robotics Research*, p.202500103, 2025.

[9] Tibbits, S. 4D printing: multi-material shape change. *Architectural Design*, 83(1), pp.116–121, 2013.

[10] Zarek, M., Layani, M., Cooperstein, I., Sachyani, E., Cohn, D. and Magdassi, S. 3D printing of shape memory polymers for flexible electronic devices. *Advanced Materials*, 28(22), pp.4449–4454, 2016.

[11] Zhang, F., Wang, L., Zheng, Z., Liu, Y. and Leng, J. Magnetic programming of 4D printed shape memory composite structures. *Composites Science and Technology*, 184, pp.107866, 2019.