Engineering Science and Military Technologies
Volume (8) - Issue (2) - Sep 2024
ISSN: 2357- 0954
DOI:10.21608/EJMTC.2024.271815.1274

Original Article

Stimuli of 4D technology and its impact on architectural design in the age of artificial intelligence

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Keywords:
Artificial intelligence, biomimicry, 4D four-dimensional, shape-shifting, multi-material.

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Abstract
The paper discusses the advancements in 4D printing applications in architecture; the concept of 4D printing has revolutionized the field of architecture by introducing a new dimension to the construction process. Although it is based on 3D printing technology, more stimulation and stimulus-responsive materials are needed. Depending on specific ways,the stimulus and innovative materials interact, as well as suitable multi. The research explores the concept of the four-dimensional printing system and its impact on the interaction of structures with environmental conditions, aligning with the technological advancements and breaking free from the constraints of three dimensions that have affected the fourth dimension, time. Using innovative materials to integrate 4D technology into the design and implementation process, applying inspiration for design from nature, and taking advantage on rapid advances in artificial intelligence that lead to improve flexibility and environmental adaptation are several methods to benefit from the advantages of this modern technology. It was imperative to seek a more comprehensive framework, introducing the properties of the fourth dimension and understanding quadruple-dimensional biomaterials to produce structures that are more adaptable to the surrounding environment by integrating design stimuliwith advanced technology, innovative materials and artificial intelligence.

I. INTRODUCTION

3D Three-dimensional printing is a process that involves taking the digital model of the three-dimensional design, translating it into a series of horizontal slices in machine language, and then printing it by adding successive, very precise layers of Materials. The 3D model is created using a number of different techniques, or by using a 3D scanner[1] as shown in Figure (1). The history of 4D (four-dimensional) printing starts with the developments and advances in the 3D (three-dimensional) printing technology. In the era of digital printing technology, research endeavors, employing diverse methodologies aim to redefine and advance Additive Manufacturing (AM) processes, commonly known as three-dimensional printing (3DP). This allows unprecedented design freedom for complex structures. This evolution challenges traditional printing processes by utilizing non-traditional materials (such as stimuli-responsive living materials) that bridge the gap between manufacturing processes and growing demand. Traditional three-dimensional printing (3DP) focuses on printing static structures from a single material, thereby being unable to meet all the dynamic functional requirements necessary to keep up with technological advancements. Hence, there is a need for the evolution from three-dimensional printing to four-dimensional printing (4DP). This paper reviews the definition of four-dimensional printing as a symbolic tool for design and the generation of moving shapes, enabling the transformation of geometric configurations in a fully controllable manner. It focuses on the factors of four-dimensional printing, printing methodologies, knowledge of active living materials used in the printing process, their shaping mechanisms, and various stimuli.

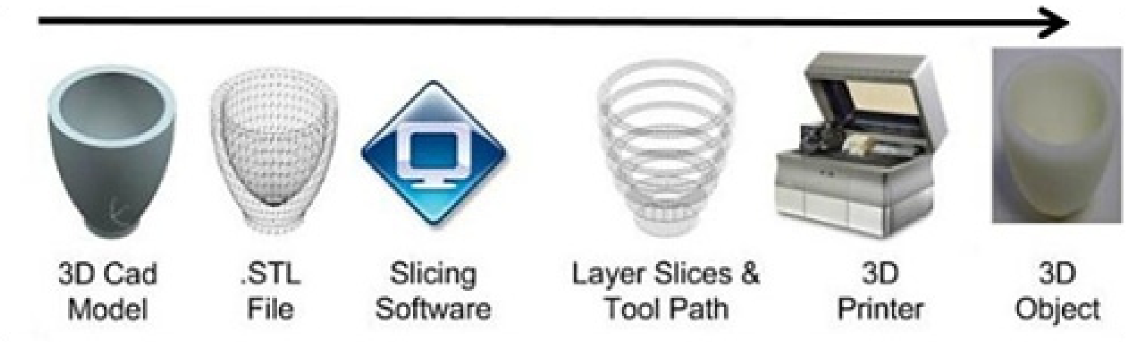


Fig .1: The stages of the 3D printing process[1]

II. 4D PRINTING

Four-dimensional printing can be considered an advanced manufacturing paradigm for scientists, engineers, and designers, representing a highly significant qualitative leap for the success of the industrial revolution. It is utilized in various industries and, most importantly, it inherently transcends spatial and temporal dimensions. Skylar Tibbits defined[2], how transformations occur in a static printed model (three-dimensional) over time. It was observed that a static three-dimensional structure could evolve into a more flexible, dynamic structure over time, as illustrated. This led to a new era in printing that included a new dimension in three-dimensional printing (time), and this innovative technique was termed four-dimensional printing (4DP). In a simplified manner, we can state that four-dimensional printing is three-dimensional printing with the addition of a fourth dimension, time, and the presence of stimuli. 4D printing was initially defined as 4D printing = 3D printing + time[3].

II.1 Factors Basic to 4D printing

The interaction of five key factors significantly influences the efficiency of 4D printing; for this reason, each of these factors must be considered before putting 4D printing into practice in Figure (2). The printing material, stimuli, modeling, interaction mechanism, and Additive Manufacturing (AM) method are some of these essential components. These components, covered in more detail below, allow 4D-printed buildings to evolve in a focused and predictable manner over time[3].

• AM Processes: The printing process used in Additive Manufacturing (AM) is the main thing to consider. Without the need for any intermediary tools, this approach makes it easier to create printing materials from the digital information that the computer provides. [4D] There are numerous AM techniques, such as direct ink writing (DIW), electron beam melting (EBM), jet 3D printing (3DP), stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), and others. As long as the selected material is printer-compatible, nearly all of these procedures may print 4D materials[4].

• Responsive materials: commonly referred to as smart materials, constitute a crucial component in 4D printing. These stimulus-responsive materials can be categorized into various subtypes, as depicted in these characteristics self-sensing, decision-making, responsiveness, shape memory, self-adaptability, multifunctionality, and self-repair delineate the capabilities of this material class. Roy has authored several review papers focusing on materials responsive to stimuli[5].

• Stimulus: To induce alterations in shape, property, or functionality, a 4D-printed structure requires a triggering factor. Researchers have experimented with various stimuli for 4D printing, including water heat, a blend of heat and light, and a combination of water and heat. The choice of innovative materials incorporated into the 4D printed structure is contingent upon the specific application's demands, thereby influencing the stimulus selection.

• Interaction Mechanism: Merely subjecting innovative materials to stimuli may not suffice to achieve the intended form of a 4D printed structure. In this examination, the stimulus must be administered in a specific sequence and for an appropriate duration, a concept referred to as the interaction mechanism. One of the fundamental interaction processes is constrained hydromechanics, where heat acts as the stimulus, and the intelligent material capitalizes on the shape memory effect[6].

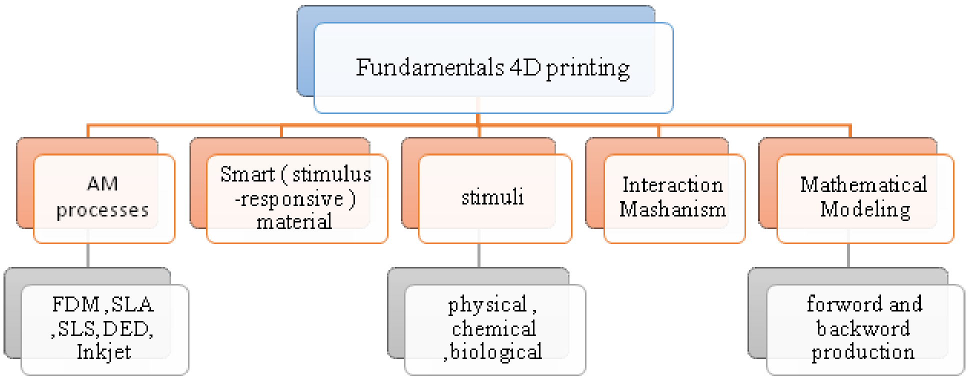


Fig. 2: Fundamentals 4D printing.authors

II.2. Type of materials used in 4D printing.

The innovative materials used in 4D printing are systems or substances containing internal automatic sensors capable of sensing and responding to an external stimulus in a predetermined manner and duration[3]. Essentially, they revert to their original state once the stimulus is removed. These materials possess integrated technological functions involving specific environmental responses, either through changes in their internal physical properties or through the exchange of external energy. They mimic biological processes in living plants and animals, exhibiting enhanced performance after programming. They respond to the surrounding environment and provide an output response. These materials can be categorized into active materials, capable of altering their physical properties when exposed to external stimuli, and passive materials[7] additional substances that reinforce existing materials without changing their properties. The need for active living materials has emerged, demonstrating changes in shape and configuration in response to environmental stimuli such as humidity, temperature, and electricity, as shown in Table (1). The response may involve changes in one or more of these materials:

• Shape Changes: twisting, compression, or dimensional alterations and …others.

• Mechanical Changes: tension, compression, shear, bending and …others.

• Physical Changes: Involving alterations in one or more properties such as color, density, melting point, surface smoothness, electrical and thermal conductivity, heat capacity, reflectivity, transparency, changes in temperature, electric current, or magnetic field and … others.

• Chemical Changes: Involving alterations in chemical properties, structural composition changes, corrosion resistance changes, or emission of specific types of radiation and …others.

Shape Memory Materials (SMMs) can be categorized into unidirectional, bidirectional, and three-directional materials based on the number of shape transformations, as depicted in Figure (3). In unidirectional SMMs, the initial shape cannot be regained after alteration. In contrast, in bidirectional and three-way SMMs, the original shape can be restored after transitioning to a temporary shape. In Shape Change Effect (SCE) materials context, the transformation is proportional to the pre-programmed stimulus[5].

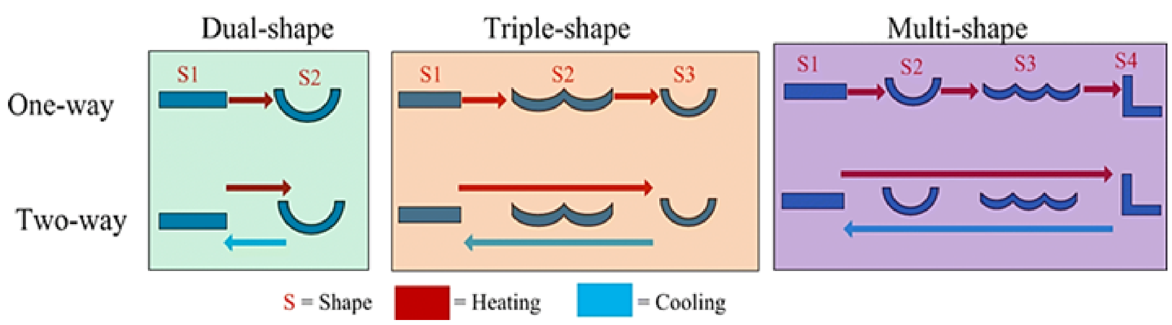
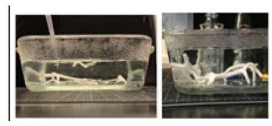
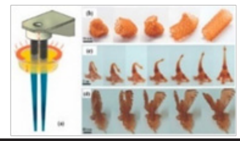
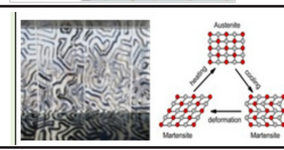
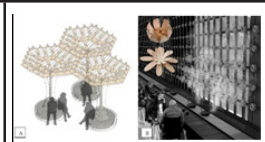
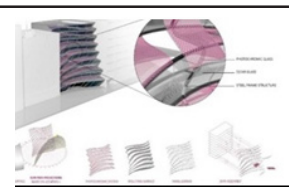
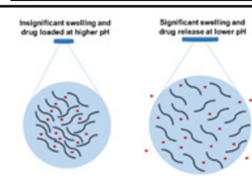
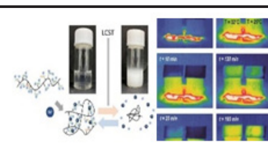
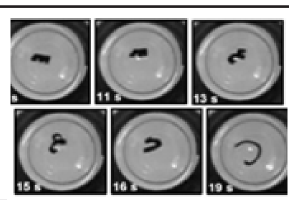
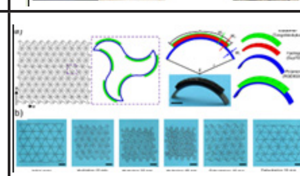


Fig. 3: Condensed description of how SMMs are categorized according to their shape memory functions[8]

Table 1: Summary of materials used in 4D printing. Authors

Matrials	Description	Picture
Hydrogels	These materials absorb water and, when exposed to moisture or water, can alter significantly in size and shape.	 The hydrogel skeleton with biostructural properties in cold water[9]
Shape Memory Polymers (SMPs)	SMPs are able to "remember" and revert to their initial shape in response to certain stimuli, such heat.	 The hydrogel skeleton with bio structural[6].
Shape Memory Alloys (SMAs)	Shape memory alloys, such as nitinol, have the ability to regain its previous shape after undergoingdeformation, usually due to temperature variations.	 Shape memory deformation temperature[10]
Photo-responsive Materials	When exposed to particular light conditions, these materials change their shape in a regulated manner.	 Responsive elements designed to imitate opening and closing [11]
Electro-responsive Materials	These materials are appropriate for applications involving electrical stimulation because they will deform in reaction to an electric current.	 Adaptive building skins to better-optimized forms and material allocation, in response to local environmental[12].
pH-responsive Materials	The pH level of their surroundings determines how these biomaterials alter in size and form.	 Diagrammatic representation of the pH-responsive hydrogel's swelling and drug release pattern[13]
Thermoresponsive Materials	Phase transitions are common ways in which these materials display changes in response to temperature fluctuations.	 Thermo responsiveness can controlled by changing the type ionic species[12].
Magnetically Responsive Materials	Materials that can change their structure or properties under control in response to magnetic fields.	 Thermo responsiveness can controlled by changing the type ionic species[13].
Biodegradable Materials	Materials that are good to the environment and can degrade gradually under supervision.	 Bilayered hydromorphic wood composites with potential shape changes [14]
Combination Materials	Combinations of the aforementioned materials are used in certain 4D printing applications to produce more intricate and customized results.	 Diagrammatic representation of composite design, with an example unit cell indicated in the inset[15]

II.3. Stimulus

Stimuli can alter the shape and functionality of printed structures in response to one or more stimuli. Chemical, biological, and physical stimuli can all be used. Physical stimuli include things like UV light, temperature, humidity, magnetic and electrical energy, and more. in addition to chemical catalysts such substances, pH levels, and oxidizer/reductant usage. together with biological catalysts such as glucose and enzymes. In addition, there are internal indications. For example, the body moves in respect to the surface due to a force called cell traction force, or CTF. Additionally, Figure (4) shows the stimuli that are employed based on the kind of material[16].

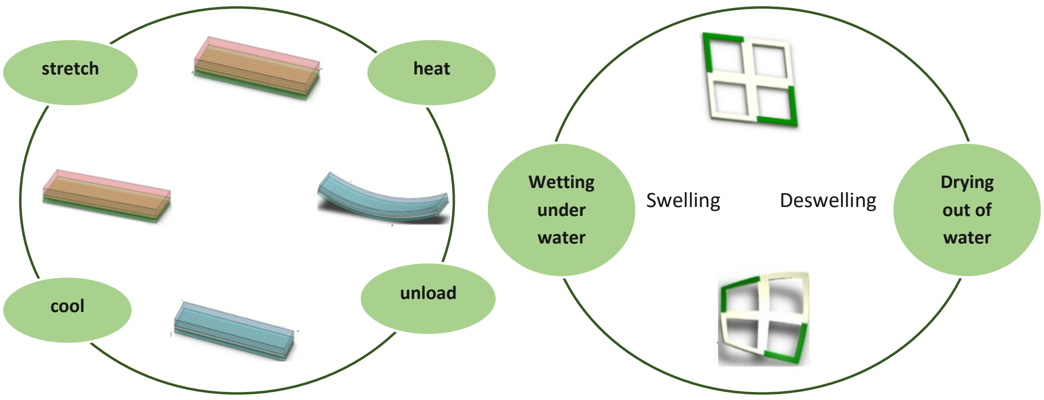


Fig. 4: Diagrammatic representation of the 4D printing process's unrestricted hydromechanical mechanism[16]

III. PROPERTIES OF 4D PRINTED STRUCTURES

The field of 4D printing presents new possibilities in which a structure can be made to self-assemble, self-reconfigure, and self-replicate using ambient energy. This has a number of advantages, such as a large storage capacity reduction and the possibility to create transformations using flat pack 4D printed structures. As an example, these changes can entail switching to three-dimensional structures when necessary for practical uses. Instead of immediately producing a complicated structure through 3D printing, one alternate use entails the first 3D printing of simple components from smart materials, followed by their self-assembly to obtain the ultimate complex shape. Self-assembly, multi-functionality, and self-repair are the three primaries, in Figure (5) categories into which 4D printed structures can be applied[16]

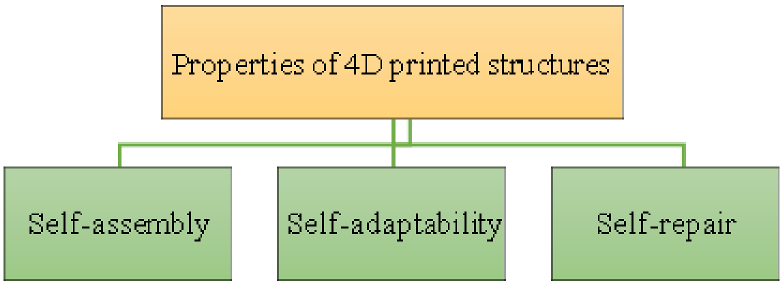


Fig. 5: Schematic of properties of 4D printed materials. Authors

IV. SHAPE-SHIFTING BEHAVIORS, THE STRUCTURES

The range of shape-shifting behaviors covered by 4D printing includes movements like folding, bending, twisting, surface curling, linear or nonlinear expansion[17] contraction, and the production of surface topography features like creases, wrinkles, and buckles. Transitions between 1D and 1D, 1D and 2D, 2D and 2D, 1D and 3D, 2D and 3D, and 3D and 3D are all possible for these shapes in Figure (6). The fact that a structure exhibiting 1D-to-1D shape-shifting over time is likewise identified as a 4D printed structure should be emphasized in Figure (7). Its initial 3D printing and subsequent evolution are to blame for this. Some relevant terminology is presented before exploring the forms and scale of shape-shifting in 4D printing[18].

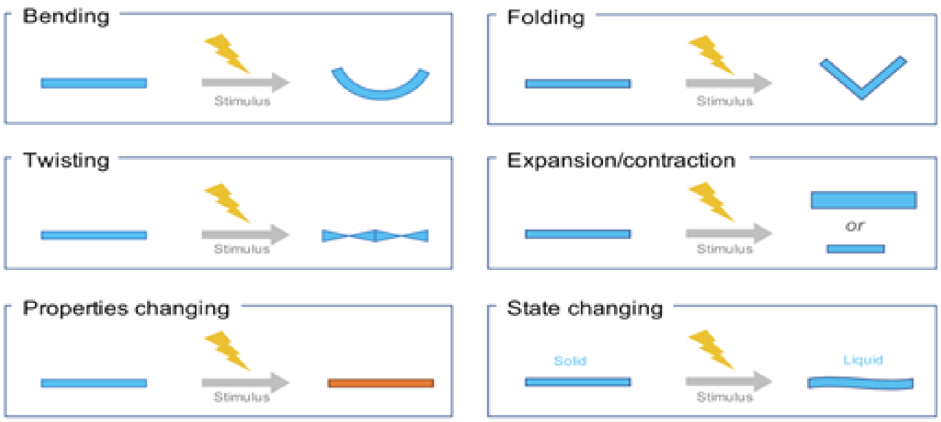


Fig. 6: It shows the transformation of printed materials when exposed to external stimuli[18]

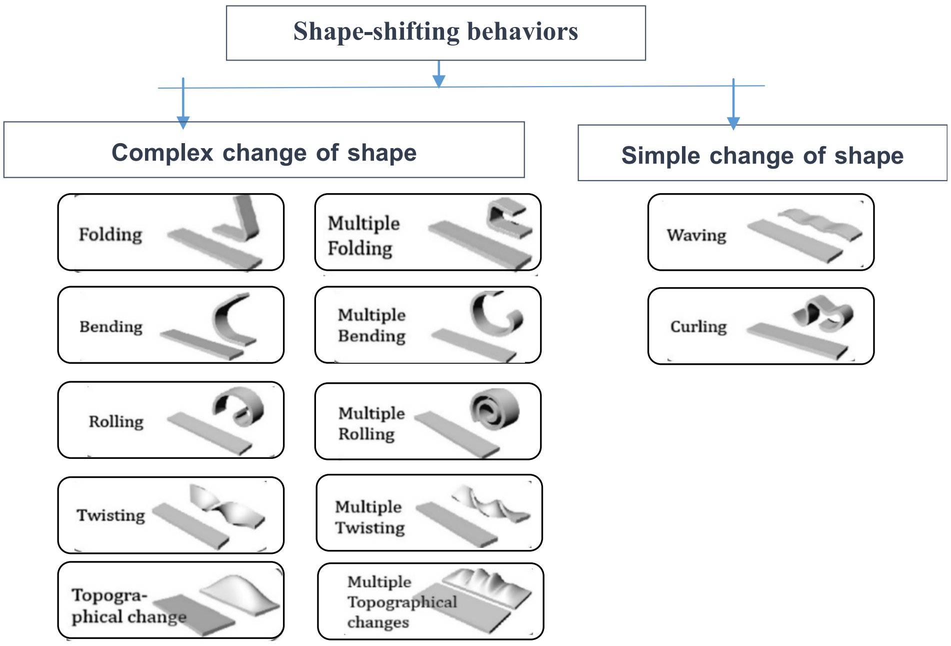


Fig. 7: Classification of 4D shape changing behaviors of printed materials[19]

V. 4D PRINTING AS A TECHNOLOGY BASED ON BIOMIMICRY

Research on applying biomimicry in 4D-printing aims to mimic the organic processes of shape-changing and adaptation present in live things. For instance, scientists have created 4D-printed objects that imitate the motion of plants and animals. Jack Steele was the first doctor and scientist to use the terms biomimetic and bionic One such object is a flat metal structure that is printed using a novel ink made of copper and transformed into a 3D spider. Using 4D-printing in architecture and design can also result in more environmentally friendly and sustainable constructed environments, as it is modeled after the natural processes of adaptation and change that occur in the natural world[19].

V.1. Sensing and reacting

All living things can perceive and react to environmental stimuli, including gravity, light, temperature, water, and chemicals. They can recognize alterations in their surroundings thanks to this talent. Animals have sense organs, such as their eyes, that provide information about the world around them. The neural system of the animal is linked to these sensory organs, which send impulses to the brain that cause actions like movement[20]. Most animals possess five senses: taste, smell, touch, vision, and hearing. In response to light, plants also bend in the direction of the sun and other light sources. Numerous living things display biological phenomena.

V.2 Use of energy

Living organisms must be energy-efficient to survive without wasting energy, operating effectively. These organisms exhibit a tendency to maintain internal stability among interconnected elements, known as homeostasis, through internally regulated mechanisms within certain limits. Among these mechanisms, metabolism is internally controlled to sustain life against environmental changes[21]. Through nutritional representation, organisms absorb energy and transform it into other forms to perform various high-energy-efficient activities.

V.3. Self-Organization

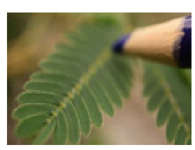
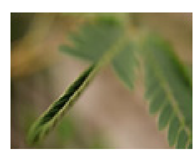
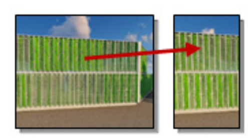
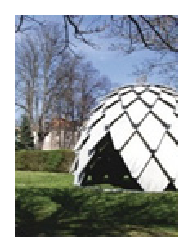
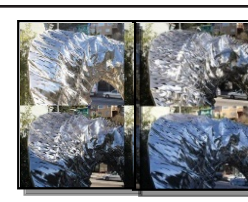
Self-regulation involves the internal adaptation of a system to promote a specific function without external control. In biology, it encompasses processes related to biological growth, genes, and cells, studying the development of living organisms. Genetic control influences cell growth, differentiation, and formation. Cellular growth entails increase in cell number and size[22]. Cellular differentiation is the process by which cells acquire specific types, often involving significant changes in cell shape.

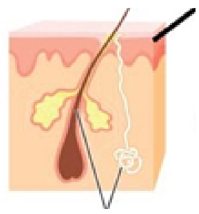
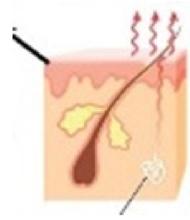
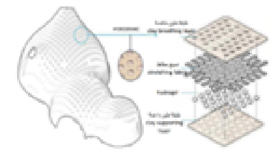
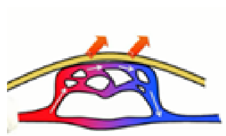
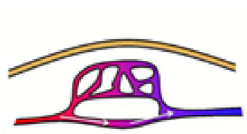
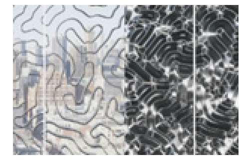
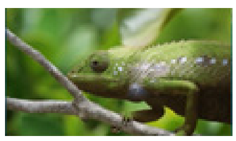
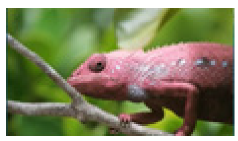
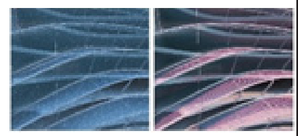
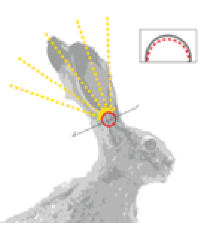
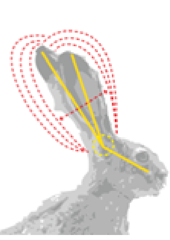
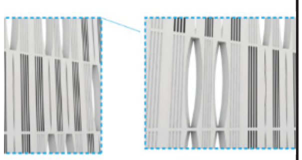
From using 4D smart living materials, new avenues are opened for creating shape-shifting, environmentally-friendly buildings that meet user needs. Inspired by biological processes of plants and living organisms, these materials can be utilized across various fields, including medical devices, robotics, and bioengineering, and can be employed in construction technology to keep pace with the times[23].

VI. METHODOLOGY

Mechanism for utilizing 4D technology by integrating it into the design and implementation processusing smart materials, drawing inspiration from nature in the design stage as shown in Table 2, and benefiting from the rapid progress in artificial intelligence, to which produces more flexibility and more adaptability to the surrounding environment.

Table 2: Conclusion Solutions using 4D printing inspired by nature.Authors

Simulations	Stimuli	The design		Shape changing behaviours	Architectural solutions
		Before Stimulus	After Stimulus		
Mimosa pudica	Touch, heat	 The Mimosa leaf plant before folding its leaves.authors	 The Mimosa leaf plant after folding its leaves. authors	Folding	 Simulation of a mimosa plant to create a building façade[24]
Pinecone	water (humidity)	 Pinecone plant adaptations[22]	 Pinecone plant after folding[22]	Bending	 Simulation of a Pinecone plant to create a building facade[22]
Carlina acaulis flowers	Humidity, temperature or light	 Carlina acaulis flowers plant[22]	 Carlina acaulis flowers plant[22]	Folding	 Simulation of a Carlina acaulis flowers to create a structure building[22]

Human skin	temperature	 Role of sweat glands in human skin[21]	 Role of sweat glands in human skin to control temperature[21]	There is no movement	 Human skin concept to control temperature Applied in the building's outer shell[21]
Muscles of the human	temperature	 The expansion of muscle movement[25]	 The contraction of muscle movement[25]	Contraction and expansion	 Simulation of this movement on the facade of a building[25]
Reptiles and chameleons	light	 Color change and iridophore types in panther chameleons[26]	 Panther chameleons color change[26]	There is no movement	 Change of the building's surface from a dark color to a light color[26]
Jackrabbits	temperature	 Jackrabbits Vaso-constriction in the capillaries[27]	 Jackrabbits vasodilation in the capillaries[27].	Bending	 Response of facade units to air pressure[27].

VII. CONCLUSIONS

The technology of 4D printing provides an option to directly produce complex 3D shapes in many applications. Alternatively, a lower-dimensional object can be printed first, and the additional dimensions can be activated with the necessary functionality in the desired area. Printing a lower-dimensional product in manufacturing is relatively easy, quick, and affordable. Lower-dimensional things are also more convenient to store and move. In terms of investigating 2D-to-3D shape-shifting behavior, adding a third dimension can improve the utility or features of 2D substrates, which can be produced using various standard methods such as roll-to-roll printing, photolithography, and inkjet printing. While many shape-shifting forms and dimensions are demonstrated in the literature, hybrid shape-shifting behavior is still mostly unknown. We may achieve a wide range of alternatives in creative design by integrating contemporary smart technologies, such as stimulation, four-dimensional elements, natural inspiration, and innovative materials, as shown in Table 3-5.

Biomimicry Concept + Stimulus + Innovative materials + 4D Technology = Creative Adaptive Architectural Solutions

Table 3: The bio-inspiration of Homeostatic Building Facade.Authors

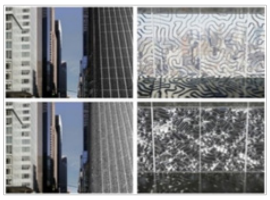
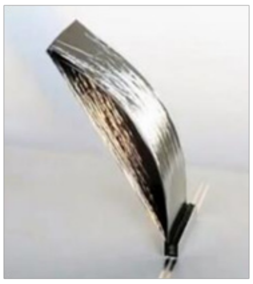
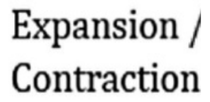
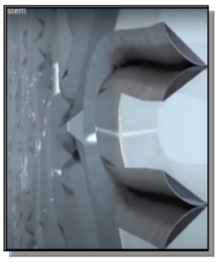
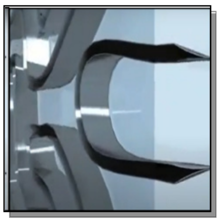
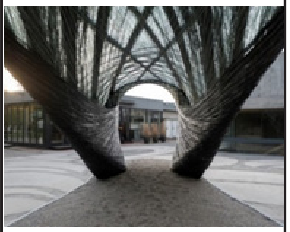
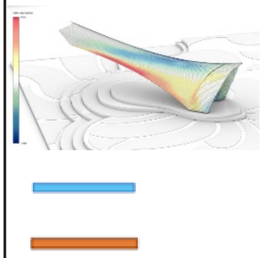
Project Name	Bio-inspiration	4DP intelligent material	Stimulus	Shape-Shifting behaviors
Homeostatic Building Façade, New York	The bio-inspiration model is the homeostasis of biological organisms.  Shape of coral reefs[28].  Homeostatic façade system[28]	1-A Rubber-like polymer 2-Flexible polymer that responds to electrical charges   Demonstrates the movement of a flexible polymer in response to electrical charges[29].	1-Temperature: The elastomeric stretches as a result of heat from the sun warming the building's interior during the day, casting shadows inside the structure. 2-Electric field.	   Demonstrates the elastomeric stretches as a result of heat from the sun warming[30]. AM Process Direct ink printing (DIW).

Table 4: The bio-inspiration model is the homeostasis of biological organisms.Authors

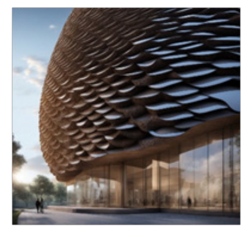
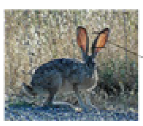
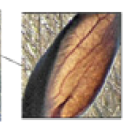
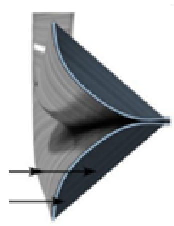
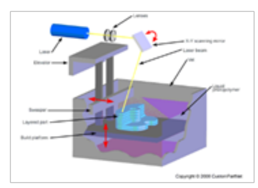
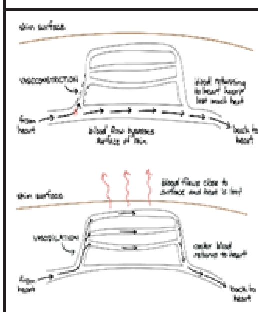
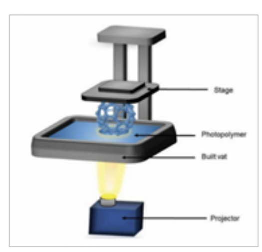
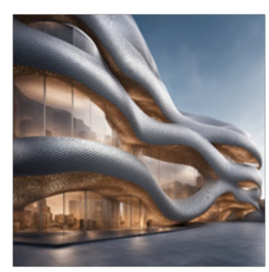
Project Name	Bio-inspiration	4DP intelligent material	Stimulus	Shape-Shifting behaviors
ICD-ITKE Research Pavilion 2016-17 / ICD/ITKE University Stuttgart, Germany	 Species of leaf miner moths[31].  Light weight, Long Span Fibrous Construction[32].	1- Fiber composite materials. 2- Bicarbonate compounds.  Fiber composite materials structure[32].	Light: works as an indirect catalyst, as the carbon fibers absorb light and store it throughout the day, then the light energy is discharged during the night to illuminate the structure.	Change in the properties of material.  Explains the change in the properties of optical carbon fibers when exposed to light[31]. AM Process 1-Industrial robots 2-Fused Filament Fabrication (FFF).  Explains the use of industrial robots in creating optical fiber composites[33]

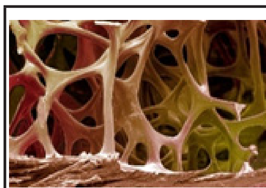
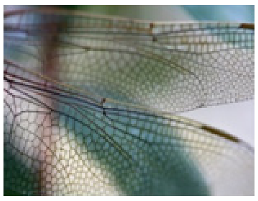
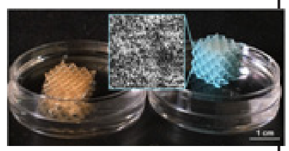
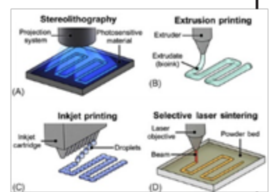
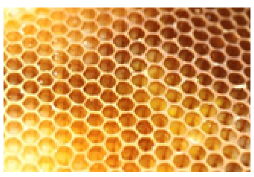
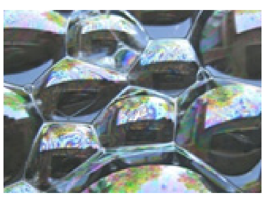
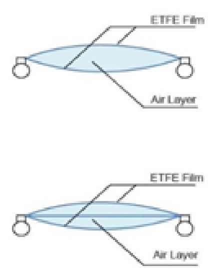
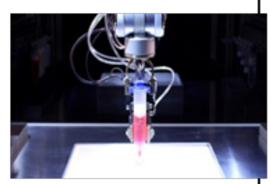
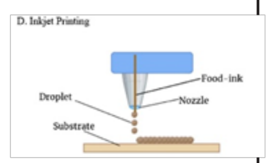
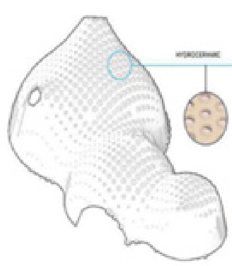
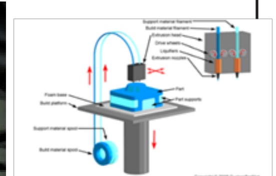
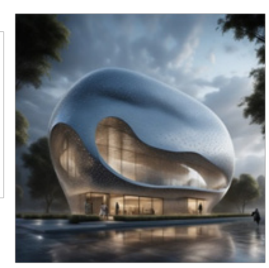
• Adaptive architecture:Using 4D printing, architects may design architectural interventions that adjust to the light, temperature, and humidity in their surroundings. To optimize solar gain and minimize energy usage, a facade that is 4D printed can alter its shape in reaction to temperature fluctuations. Materials that are self-assembly, self-sensitive, and self-healing: 4D printing combines conventional additive methods with intelligent materials and outside stimuli to create materials that can change over time. These materials have the potential to be self-assembly, self-sensitive, or self-healing, which might be quite useful for contemporary buildings given the increasing demand for autonomystructures with low energy consumption and environmental impacts.

• Multi-material technology: By combining 4D printing with multi-material technology, we may create buildings that are dynamic, flexible, and adjustable for on-demand performance, potentially revolutionizing our ability to govern building performance. Thanks to this technology, structures with different material properties may be designed and built to react to their surroundings and change with the times.

• Applications in infrastructure: 4D printing might be used to create drainage pipes that expand or contract in response to water flow or sewer systems that move waste by contracting and relaxing like how they traverse topographical slopes.

Table 5: Creative Adaptive Architectural Solutions using biomimicry, 4D Technology and AI.Authors

Biomimicry Concept	Stimulus	Innovative Material	4D Technology	CreativeAdaptive Architectural Solutions
 The concept of plant accumulation[34].	Humidity	 Wood polymer composite[35].	 FDM (fused deposition modeling)[36].	 The concept of Building accumulation Generated by AI.authors[37].
  Vasoconstriction and vasodilation in the capillaries[38].	Temperature	 Acrylic polymer polylactic acid (PLA)[39].	 Stereolithography (SLA)[40]	 Concept of Vasoconstriction and vasodilation in building Generated by AI.authors[37].
 Muscle Movement[38].	Temperature	 Rubber Elastomer (MDPI)[41].	 Digital Light Process (DLP)[42].	 Concept of muscle movement Generated by AI.authors[37].

 Bird skeleton structure[43].  Dragonfly wing[44].	Humidity	 Thermo polymer poly -lactic-acid Tessellation[45].	 4D Bioprinting[46].	 Voronoi Self-folding tessellation Generated by AI.authors[37].
 Hexagonal honeycomb pattern[47].  Soap Bubbles pattern[48].	Temperature	  ETFE Material[49].	  Inkjet printing[50].	 Voronoi pattern Generated by AI.authors[37].
 Like human skin to control temperature[21].	Temperature	 4D biomaterial "Hydroceramic"[51].	 FDM (fused deposition modeling)[52].	 Concept of human skin Generated by AI.authors[37].

VIII. CHALLENGES AND FUTURE DIRECTIONS USING 4D PRINTING IN ARCHITECTURE

There are advantages and disadvantages of using 4D printing in architecture. The following are some of the main obstacles to overcome and potential directions for 4D printing in architecture:

• Material Restrictions: A major obstacle is the scarcity of materials appropriate for 4D printing. Expanding the uses of 4D printing in architecture requires creating a greater variety of materials that can react to external stimuli.

• Production Scalability: One of the biggest challenges in using 4D printing for large-scale architecture projects is to increase the production process's scale. Technological and material advances in printing will be necessary to overcome this obstacle.

• Standardized Procedures: Another difficulty with 4D printing is the requirement for standardized procedures. Industry standards for this technology must be established to guarantee the dependability and quality of 4D printed architectural elements.

• Computational Algorithms: Resilient computational algorithms are necessary to integrate complex data streams for 4D printing. Enhancements in simulation and computational design technologies are required to maximize the functionality of architectural features that are 4D printed.

• Growth and Adoption of the Market: Despite the enormous potential that 4D printing offers, the industry is still in its infancy. The development of new applications and the advancement of technology will determine whether or not 4D printing is used in the architectural field.

Meeting these challenges will take cross-disciplinary cooperation, ongoing research and development, and inventive materials and production techniques. Despite these difficulties, 4D printing in architecture offers many opportunities, and the field is seen as promising one for developing dynamic, flexible, and sustainable constructed environments.

Even though 4D printing is still in its infancy, it has exciting possibilities for the development of buildings and architecture. We may anticipate seeing more ground-breaking and inventive uses of this technology in the built environment as research and development continue.

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