International Journal of Applied Research in Mechanical Engineering

Volume 3 | Issue 2 Article 3

August 2023

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Raja S
Managing Director, Research & Development, Mr.R BUSINESS CORPORATION, Karur, Tamilnadu, India, mr.redu03@gmail.com

Praveenkumar V
Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Amirtapuri, India, shasha.praveen@gmail.com

Rajeswari N
Department of Mechanical Engineering, Surya Engineering College, Erode,Tamilnadu,India, engineerraji0796@gmail.com

Recommended Citation
S, Raja; V, Praveenkumar; and N, Rajeswari (2023) "Challenges and Opportunities in 4D Printing -An Application Perspective," *International Journal of Applied Research in Mechanical Engineering*: Vol. 3: Iss. 2, Article 3.
Available at: https://www.interscience.in/ijarme/vol3/iss2/3

Challenges and Opportunities in 4D Printing -An Application Perspective

Raja.S*[1] , Praveenkumar V[2], N.Rajeswari[3]

[1*]Managing Director, Research & Development, Mr.R BUSINESS CORPORATION, Karur, Tamilnadu, India
[2]Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Amirtapuri, India

[3]Department of Mechanical Engineering, Surya Engineering College, Erode, India

Abstract-

Over the last ten years, 3D printing technology has played a pivotal role in transforming the manufacturing industry. A recent advancement within the realm of 3D printing has introduced time as a fourth dimension, enabling the creation of 4D printing components. While a 3D-printed design remains static, a 4D-printed design has the remarkable ability to change its shape in response to environmental conditions. This paper also examines various applications of 4D printing across diverse fields such as electronics, renewable energy, aerospace, food, healthcare, and fashion. The review addresses research gaps, the current obstacles in 4D printing, and the future prospects of this technology.

Key words- 4D Printing. smart material, application, research gaps, opportunities, future direction

1. INTRODUCTION

Numerous researchers have investigated ways to modify the shapes of objects using various methods, including the use of shape-memory materials [1-3] and shape-morphing systems [4-7]. In 2013, the term "4D printing" was introduced, referring to the creation of 3D-printed objects that can change their shape in response to external stimuli or interactions [8]. This shift from a static to a dynamic state of 4D-printed objects is depicted in Figure 1 and marks a significant advancement in additive manufacturing technology.

To materialize the 4D printing process, three key principles have been established [9]. The first principle involves the development of materials that respond to specific stimuli. The second principle revolves around applying a stimulus to trigger a desired response in the printed material. The third principle is the precise control of the time required for the printed object to respond and change.

An, Chua, and Mironov have proposed three approaches for fabricating 4D objects [10-16]. The first approach focuses on smart materials that adapt their behavior when subjected to stimuli. The second approach involves incorporating polymer-based components into 3D-printed devices to facilitate tissue growth. The third approach entails strategically placing objects in specific patterns to initiate self-organization.

Subsequently, the 4D printing process is influenced by five key factors: the manufacturing method, choice of materials, type of stimulus applied, the interaction between materials and stimuli, and the programming model.

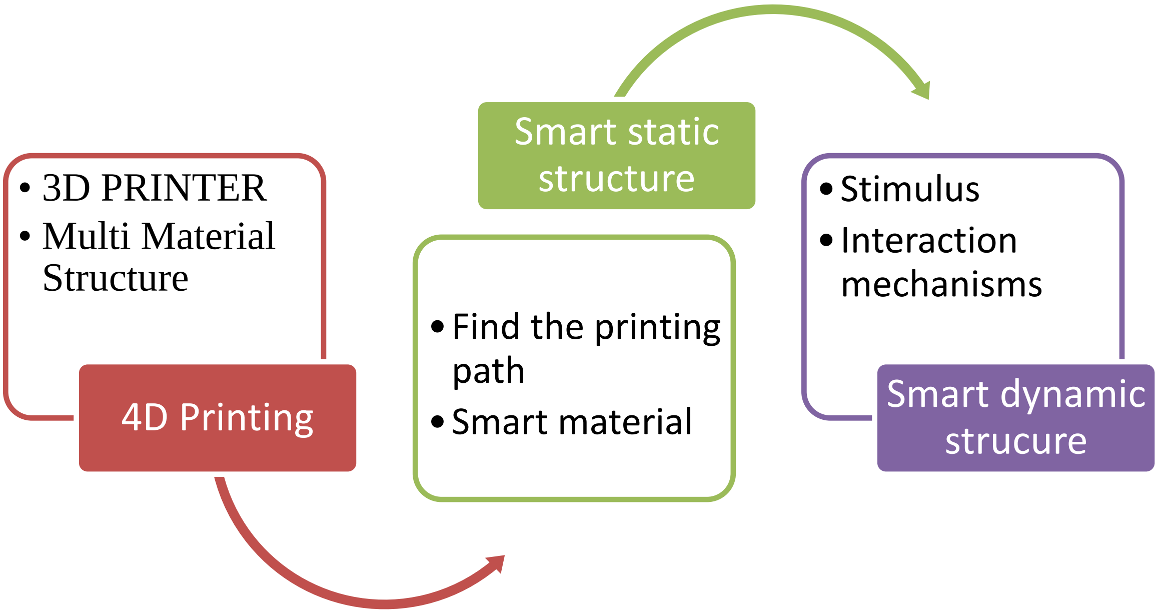

Fig.1 4D printing process

2. DIFFERENT APPLICATIONS OF 4D PRINTING

In the existing body of literature, five distinct techniques have been employed by researchers for the creation of 4D objects. These methods include fused deposition modeling (FDM), direct ink writing (DIW) , stereolithography (SLA), digital light processing (DLP), and selective laser sintering (SLS) [17-28]. The search methodology used in this study to estimate the number of publications associated with each fabrication method for 4D printing varied slightly. It involved using the abbreviation of the manufacturing method as a keyword. For instance, when searching for publications related to the manufacturing process of fused deposition modeling, the search query included the phrase "4D printing" and either "fused deposition modeling" or "FDM," with the "OR" operator ensuring the inclusion of studies using abbreviations. Figure 5 visually presents the publication counts spanning from 2013 to November 2022 based on manufacturing methods, revealing that FDM is the most frequently employed fabrication method for producing 4D components, followed by SLA, SLS, DLP, and DIW. This review summarizes the various manufacturing methods for 4D printing technology addressed in this review paper. Additionally, the manufacturing of 4D-printed objects encompasses other techniques, such as PolyJet printing , powder bed fusion , photolithography , directed energy deposition , and selective laser melting. he primary method employed for creating 4D-printed objects is fused deposition modeling (FDM). FDM has been utilized with various stimuli such as temperature, pH, light, and water. This technique is cost-effective, produces top-notch, high-resolution items, boasts a rapid printing process, and is readily accessible. Originally, FDM was limited to thermoplastic polymers for printing, but research has extended it to composite polymers for enhanced outcomes. However, FDM has drawbacks, including its complexity, fragility, slow printing speed, rough surface finish, and higher material wastage compared to other methods. Despite these limitations, FDM has found applications in industries, biomedical devices, aerospace products, origami structures, drug delivery, and optical devices.

Another method for crafting 4D-printed objects is Stereolithography (SLA). The benefits of SLA include its speed, sophistication, smooth surface finish, and high resolution. It is most effective when used with SMP at lower temperatures. Nevertheless, SLA-printed parts exhibit poor mechanical properties, and the method has a longer response time, necessitating support structures and post-processing. SLA has been widely used in soft robotics, drug delivery, tracheal stents, biomedical scaffolds, and tissue engineering.

Selective laser sintering (SLS) enables component manufacturing without the need for support material and offers high production volume and speed. However, SLS lacks suitable materials for 4D printing and has drawbacks like health risks, high cost, and issues with surface and dimensional accuracy. Applications benefiting from SLS include biomedical devices, drug delivery, magnetism-responsive grippers, and aerospace.

Digital light processing (DLP) is another method for fabricating 4D-printed objects. Developed shortly after SLA, DLP offers rapid production times, high-quality resolution, and the ability to create complex structures. However, it is constrained by material choices, high material costs, and poor mechanical properties. DLP has been explored in various applications, including medication delivery, tissue engineering, and electronic devices.

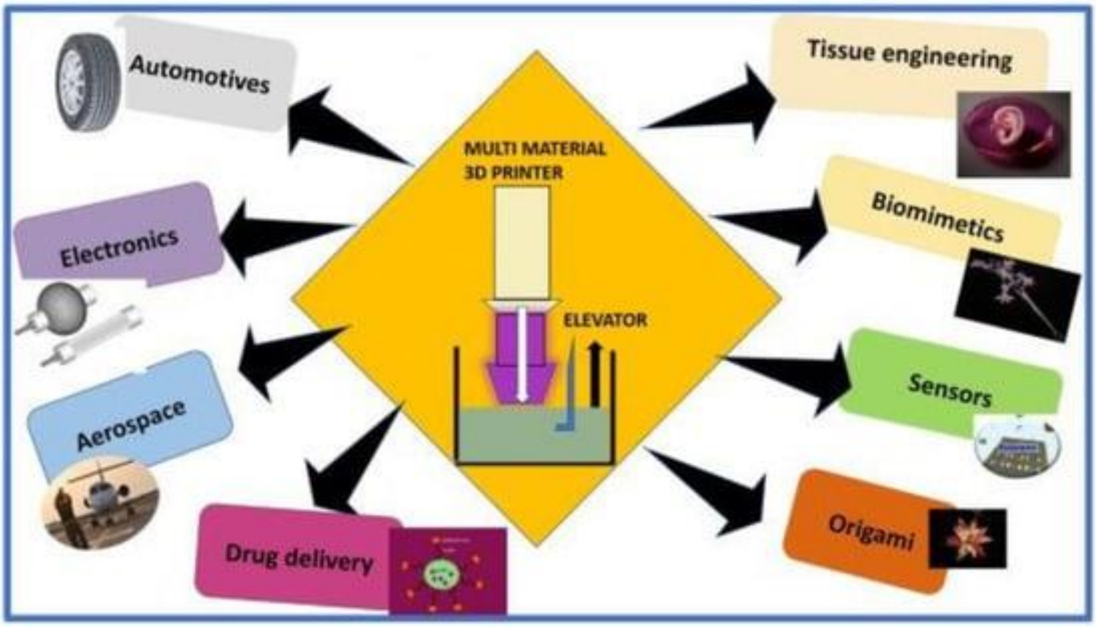

Fig.2 Different application of 4D printing [72]

2.1 Aerospace

The aerospace industry faces various concerns, including the complexity of assembling components and the high costs associated with replacing airplane parts. Additionally, disruptions in the global supply chain are a point of worry. To address these challenges, four-dimensional printing technology offers a solution by producing more manageable assembly parts and reducing assembly time. Numerous researchers have explored the expedited development of aerospace applications like airplanes, wings, and spare parts. Some researchers even designed a bionic butterfly and observed its wing movement under magnetic stimulation. They found that when the magnetic field was distant, the wing-flap process slowed down, and the butterfly returned to its initial position. Li et al. demonstrated the effectiveness of 4D printing in airplane manufacturing by creating a model with exceptional shape-memory performance, suggesting the use of shape-memory polyimides as a material. They evaluated two manufacturing approaches: DLP and extrusion molding, and the 4D-printed model exhibited strong mechanical properties and the ability to revert to its original shape [29-37].

2.2 Catering

Numerous research studies have explored the application of 4D printing technology in food preparation. These investigations have focused on various production methods, including FDM, SLA, DIW, DLP, and SLM, with a wide range of printing materials, such as chocolate, cheese, dough, starch, and potato. Phuhongsung, Zhang, and Bhandari delved were explored into the evolution of flavor changes in 4D-printed materials. They utilized a printing material composed of soybean protein isolate, k carrageenan, and vanilla flavor, applying microwave heating at different power levels. The study revealed that the smell changed after 20 minutes of heating, while the taste remained unaffected. This research suggests that the composite material they used holds promise for 4D printing with careful consideration of heating levels.

Another study by Shanthamma and colleagues investigated color transformation in a 4D-printed product.

They assessed the impact of varying concentrations of turmeric powder and sago flour in a sodium bicarbonate solution. The results demonstrated a time-dependent shift from yellow to orange/red in color, indicating the potential for advancing color transformation through these materials.

In a separate investigation, Tao et al. explored shape alteration in 4D-printed dough through hydration and dehydration triggers. The proposed material exhibited geometric behavior, expanding and contracting when exposed to these stimuli. Participants in this study reported that the manufactured pasta had superior structural qualities, a more savory taste, and cooked differently compared to regular pasta [38-40].

2.3 Defense

Despite receiving significant funding, military-related research in 4D printing remains classified, the leading to a limited presence of studies in the available literature. According to Allied Market Research, the global military 4D printing sector is projected to reach USD 16 million by 2030, with an estimated market size of USD 673 million in 2040, exhibiting a notable CAGR of 45% from 2030 to 2040. Hamel, in his master's thesis, highlighted that investing in the development of military operations using 4D printing technology will ensure the continued supremacy of American airpower in the foreseeable future. This underscores the promising future capabilities and potential of 4D printing technology. Additionally, the U.S. Army Research Office allocated approximately USD 900,000 in funding to support 4D printing technology projects at three universities, including Harvard University [41-45].

2.4 Energy

4D printing technology has the potential to address the challenges associated with low efficiency and high costs in renewable energy. While Momeni and Ni have shown the effectiveness of 4D printing in enhancing energy efficiency, its application in the renewable energy sector remains relatively undeveloped compared to other fields, as depicted in Figure 6. Momeni and Ni have also introduced a novel design aimed at limiting energy consumption through thermodynamic analysis. Furthermore, they have extended their research in this domain by utilizing 4D printing to create a solar concentrator and wind turbine blades [46-54].

2.5 Hardwares

4D printing, known for its promising capabilities, has found application in a diverse range of electronic uses, including circuits, sensors, actuators, magnetics, robotics, energy storage devices, and antennas. Various printing methods, including but not limited to FDM, SLS, SLA, DIW, and DLP, have been employed in these applications. The primary materials commonly associated with electronic 4D printing are shape-memory polymers, shape-memory hydrogels, and shape-memory alloys. To create 4D-printed electronic devices, different stimuli like heating, light, magnetism, and water have been proposed.

Zhang et al. utilized shape-memory polymer materials to craft a 3D electrical circuit. Their study demonstrated the circuit's ability to stretch when exposed to external heat, achieving consistent heating performance. Another study focused on self-folding circuit fabrication using the DIW method and heating stimuli, as described by Deng et al. This technology was found to enable the rapid and straightforward production of customized circuit designs. Chen et al. devised a multi-function sensor/actuator that can self-sense through thermal and mechanical activation.

Mu et al. explored the effects of electromechanical behaviors on soft sensors fabricated through the DIW method, achieving a 45% stretch. Wang and Li introduced a novel approach for manufacturing a reversible actuator based on a bilayer structure that controls voltage to sense strain. Their aim was to create a versatile intelligent actuator. Jeong et al. introduced a rotational multi-stable structure design by adjusting the thickness of the shape-memory polymer beam for various actuators. This design, responsive to external inputs, allows for precise control of activation time. The study concluded that the programmable structure can respond based on material properties without requiring an external power source.

2.6 Medical Applications

Zarek and colleagues utilized the SLA production process along with SMP material to create a tracheal stent [56]. This newly manufactured stent effectively addresses some of the drawbacks associated with existing stent designs, particularly issues related to the positioning of the cartilaginous ring and the risk of injury during deployment. Similarly, Marco et al. introduced an innovative indirect printing technique aimed at surpassing current limitations in soft robotic structure development [57].

Their research involved the design of various microscale stents (at 5 micrometers) using DIW and polymers.

Additionally, Cheng et al. developed 4D-printed vascular stents by employing a genetic algorithm to optimize the stent's structure for the treatment of vascular stenosis [58]. These stents were fabricated using the FDM technique and PLA material. The team conducted comprehensive assessments, including mechanical testing, finite element analysis, and in vitro feasibility tests, to demonstrate the effectiveness of the shape-memory polymer vascular stent in treating vascular stenosis.

Melocchi and colleagues innovated a gastric retention device using 4D printing technology, which relies on shape-memory characteristics [59]. They constructed this device using the Fused Deposition Modeling (FDM) method and subjected it to both aqueous fluids and varying temperatures during their investigation. When exposed to these conditions, the device exhibited favorable mechanical properties suitable for the stomach's unique environment. Additionally, they employed hot-melt extrusion and FDM manufacturing technology, combined with Shape Memory Polymer (SMP) materials, to develop a programmable 4D-printed intravesical drug delivery device [60]. This device could change its shape in response to specific triggers and revert to its original form when exposed to external stimuli. Furthermore, it proves to be a suitable option for delivering drugs effectively in the treatment of bladder diseases. Villar and colleagues devised encapsulated multisomes, characterized by small oil droplets in a water matrix, which are released in response to changes in pH or temperature.

Grinberg and colleagues employed the fused filament technique in their work to produce a knee prosthesis that incorporates an active sensor composed of piezoelectric composites [61]. Various factors were incorporated into their study to initiate the behavior of the printed piezoelectric composite. This research significantly contributed to the advancement of a cost-effective and lightweight, high-performance component. Meanwhile, Hoa utilized 4D printing technology to craft intricate composite springs, distinguishing their study by eliminating the need for intricate curved molds [62]. This innovative approach has the potential to revolutionize spring manufacturing for prosthetics used in the lower leg, ankle, and foot. In a separate effort, Ploszajski and their team created a lightweight chainmail fabric using SLS technology and magnetic stimulation [63].

This research methodology propelled the development of fabric materials for orthotic applications, including an active stiffening wrist brace.

3. Challenges in 4D printing

This paper presented both the advantages and disadvantages of employing 4D printing across diverse applications. It included references to studies proposing different intelligent materials, manufacturing techniques, and triggers for creating 4D-printed components. Nevertheless, it's worth noting that 4D printing technology is still in its early stages, and there remain areas in this field that require further exploration. The following section delves into the future prospects of 4D printing, focusing on aspects such as expanding manufacturing capabilities, predictive modeling, advancements in next-generation technologies, and emerging innovations.

The present manufacturing procedures and the blueprint of 4D printed items closely resemble those employed in 3D printing. As indicated by Sahafnejad-Mohammadi et al., a major challenge in the creation of 4D structures is the scarcity of 3D printers capable of producing 4D components and the absence of dedicated software [64]. To enhance the scalability of 4D production, specialized printers and software will be advantageous for the 4D printing technology.

While numerous studies have explored the creation of 4D parts using various manufacturing methods, stimuli, materials, behaviors, and programmable shapes, there is a noticeable gap in our understanding of the specific design factors that require further investigation. Chen et al. have pointed out that most inverse problems are currently addressed through a trial-and-error approach [65]. Therefore, the implementation of a systematic and well-defined methodology could significantly enhance the efficiency of the 4D printing design process and its resulting structures.

Kantareddy has underscored the continued importance of design guidelines that connect foundational forms to temporary shapes, which are crucial for empowering designers to construct advanced structures based on Shape Memory Polymers (SMPs) [66]. Additionally, the lack of comprehension regarding the design formulation of 4D printing technology poses significant barriers to its progress [67].

Furthermore, Nikkanen has argued that a major hurdle in 4D printing lies in our limited understanding of the behavior of 4D-printed parts. Consequently, there is a pressing need for a mathematical model capable of predicting the behavior of such parts [68]. The introduction of multiple parameters and an exploration of their impacts on 4D printing design would accelerate advancements in this field.

4. RESEARCH OPPORTUNITIES IN 4D PRINTING

The methods for creating 4D objects using the proposed materials have limitations and need more investigation. According to Farid et al., the availability of materials restricts the potential of 4D printing technology [67]. Additionally, the scarcity of research on 4D printing techniques and materials poses a challenge in constructing complex structures with impressive mechanical properties [69]. Ma Quanjin et al. suggest that developing unique smart materials with advanced characteristics will help advance 4D printing technology [70].

Beyond its current characteristics, such as self-assembly and self-expansion, 4D printing could reduce manufacturing and transportation costs, benefiting the logistics sector and enhancing the global supply chain system. Conversely, Ghi and Rossetti contend that 4D printing could be the next generation of lean manufacturing due to its ability to self-repair and self-assemble components from materials [71].

Lastly, newly proposed additive manufacturing technologies like 5D printing and 6D printing have the potential to push the boundaries of 4D printing technology. 5D printing, utilizing the movement of both the print head and the printed object, can create parts with curved surfaces without requiring a support system, thus speeding up the manufacturing process and improving the quality of the printed output. In addition, 6D printing combines 4D printing with the capabilities of 5D printing to produce smart-material structures with features like curved surfaces. These innovations offer new avenues for exploration in this field.

5. CONCLUSION

Compared to alternative techniques like 3D printing, 4D printing is still in its early stages of development and will require more time to advance. Despite the limitations and concerns discussed in this evaluation, there is a promising future for 4D printing technology, particularly in its ability to achieve advanced shape deformation. This review highlights various aspects of 4D printing technology, which has spurred extensive research and studies in the production of 4D-printed items.

The current challenges of this technology encompass its complexity, the necessity for specialized programming, a scarcity of literature, and limited material choices. When subjected to environmental stimuli such as temperature, water, light, humidity, electricity, or magnetic fields, 4D-printed objects undergo changes in their shape, mechanical properties, and physical characteristics. This paper provides an overview of different stimuli, smart materials, and manufacturing techniques.

Several industries, including healthcare, aerospace, renewable energy, and fashion apparel, have benefited from the application of 4D printing technology. Despite the creation of innovative 4D printed products, it is important to note that this technology has not yet reached full maturity. The review also outlines some of the current challenges, ranging from the development of new materials to the creation of mathematical models to improve the predictability of printed components and ultimately scale up the 4D printing production process.

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