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Technological Evolution in Additive Manufacturing: From Three-Dimensional to Multidimensional Printing Systems

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Abstract:
Though conventional 3-Dimensional (3D) printing or additive manufacturing (AM) has emerged as a disruptive technology, the printed components are functionally limited due to their static nature. Fortunately, the expansion of this technology in multiple dimensions will result in dynamic functional structures. 4-Dimentional (4D) printing adds a temporal dimension to 3D printed components, using technologies such as shape-memory polymers (SMPs) to enable the components to deform over time. 5-Dimentional (5D) printing is similar to 3D printing, but the build plate tilts on two additional axes that can angle the print in such a way that support structures are not needed. 6-Dimentional (6D) printing, in a similar way to 4D printing relative to 3D printing, enables 5D printed components to change over time. 7-Dimentional (7D) printing can produce complex, fine, and intricate products that traditional manufacturing methods cannot achieve. These technologies can be used in medical applications such as organ replacement and bone grafting, as well as in the food industry to achieve ideal colours, flavours, and nutritional components.

Keywords: Additive manufacturing; Bioprinting; Multidimensional printing; Physical and chemical changes; Smart materials.

1. Introduction

Though 3D printing or AM has emerged as a disruptive technology, the printed parts are functionally limited due to their static nature [1-2]. These components can't respond to external stimuli or change over time, thus narrowing their application scope. For example, 3D-printed scaffolds sometimes cannot perfectly fit a bone defect in a patient because of their complex shapes, and implantation is very invasive. Incorporating a temporal dimension during the printing process enables the creation of pre-deformed components that can be heated to expand and perfectly fit the cavities after implantation, ensuring a smoother recovery for the patient. It is applications like this that show the advantages of 4D printing over 3D printing [3-4].

There are two other drawbacks of 3D printing. Al-

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though this technology performs better than subtractive manufacturing in handling waste materials, to minimize the amount of waste, support structures need to be removed. 5D printing completely eliminates the need for support structures by adding 2 axes to the originally fixed build platform, allowing the machine to tilt the model, enabling previously unprintable overhanging sections to be printed as walls. This reduces waste and thus lowers overall cost. Another inherent weakness of 3D printing is their vertical strength. This is due to the layered nature of 3D printed components, and the fact the strength perpendicular to the layers is less than that parallel to the layers. 5D printing can completely eliminate this weakness by printing layers at different angles, thereby achieving isotropic strength [1,5]. 6D printing adds the dimension of time to 5D printing, creating adaptable, responsive structures with strength in all directions and minimal waste [6-7]. 7D printing can achieve more efficient production processes, and costs lower than traditional manufacturing methods (8). This review focuses on the technological evolution process from 3D to multidimensional (4D-7D) printing systems, and emphasizes the far-reaching impact of these technological changes on cross-disciplinary applications.

2. Technological Progression in Multidimensional Printing

2.1 3D Printing: The Foundation of static fabrication

3-Dimensional (3D) printing or additive manufacturing, is a technology that makes 3D models into functional components using a layer-by layer approach. Compared with casting or mechanical processing, this technology has many advantages, such as high degree of customization and the ability to manufacture complex structures [1-2]. There are various forms of 3D printing, including fused deposition modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and material jetting (PolyJet). These processes are briefly explained in Table 1.

Table 1. An overview of the most common 3D printing techniques

Technology	Process	Materials	Characteristics	Applications
FDM	Thermoplastic filament passes through a heated nozzle and is deposited on a heated plate.	PLA, PETG, ABS, PC, PA6, PA12	Lower precision & speed. Lowest cost.	Prototyping, Education, Custom parts
SLA	Uses a UV laser to trace and cure liquid resin into solid layers	Photopolymer resins	High precision, smooth surface. Faster than FDM Requires post processing.	Prototyping, Jewellery, Dental models
SLS	A laser is shone onto a polymer powder bed, which fuses the powder by heat	PA11, PA12, PP	Suitable for high-volume batch production. Good isotropic strength.	Functional prototypes Custom parts Mass production
PolyJet	Jets tiny droplets of liquid photopolymer onto a build platform and instantly cures them with UV light	Photopolymer resins	High Precision Multi-Material & Colour Printing Higher cost	Realistic Prototypes Medical anatomical models

All of these processes implement more dimensions to make printed components less costly, more adaptable and responsive.

2.2 4D Printing: Introduction of Dynamic Response

By adding the time dimension to 3D printing, it is possible to manufacture components that can adapt to changes. The application of stimuli-responsive materials has enhanced the applicability of such components in applications such as satellite components, smart wound dressings and bone defect scaffolds. This is achieved via materials such as SMPs and hydrogels. These morphological changes have external triggers like heat, moisture, light, and pH). FDM, SLA, SLS, and PolyJet printing technologies were compared in Table 2 to show how they can be utilized for 4D printing [3-4].

Table 2. An overview of the most common 4D Printing techniques

Feature	FDM	SLA	SLS	PolyJet
Method	Extrusion of stimuli-responsive thermoplastic filaments.	Photopolymerization of smart resins that change properties upon stimulation	Laser sintering of polymer powders with shape-changing capabilities.	Jetting and simultaneous curing of multiple photopolymers to create composite, active structures.
Smart Materials Required	• PLA&PU based SMPs. • Hydrogels • Composites with magnetic particles or CNTs	• Shape Memory Photopolymers. • Smart Hydrogels (responsive to water, pH, temperature). • Resins doped with functional nanoparticles (e.g., Fe_3O_4 for magnetic response).	• TPU-based, PCL-based SMPs. • Composite powders with ceramic or magnetic fillers.	• A wide range of photopolymers with different stiffnesses and swelling behaviours. • Emerging electroactive and temperature-responsive resins.
Primary Stimuli	• Thermal • Magnetic	• Thermal • Light • Water/Solvent, • Magnetic.	• Thermal	• Thermal • Water/Solvent • Chemical
Mechanism of 4D Change	1. Print a temporary shape. 2. Deform and "fix" that shape. 3. Apply stimulus (heat) to trigger recovery to the permanent, "remembered" shape.	1. Print a structure with internal stresses or material gradients. 2. Upon immersion in water or application of heat, the structure swells or relaxes, causing predictable bending, twisting, or folding.	1. Print a porous/scaffold structure. 2. Compress it into a temporary shape. 3. Heat application triggers shape recovery, allowing it to self-expand.	1. Print multi-material structures with varying expansion coefficients or stiffnesses. 2. A uniform stimulus (e.g., heat, water) causes differential swelling or contraction, leading to self-folding, bending, or curling.
Advantages	• Low cost and widespread availability. • Easy to create composite filaments. • Good for large, macroscopic shape changes.	• High resolution. • Smooth finish. • High speed.	• No need for support structures. • Parts are durable and have good mechanical properties. • Ideal for porous implants that can expand in situ.	• Unmatched multi-material capability • Can create highly complex, bio-inspired actuation in a single print. • Superior control over material distribution for precise deformation.
Disadvantages	• Low resolution • Anisotropic material properties can lead to unpredictable behaviour. • Limited material choices compared to other methods.	• Smart resin formulations are often proprietary and expensive. • Cured parts can be brittle, limiting their range of motion. • Limited to photopolymer chemistry.	• The porous surface from unsintered powder can affect performance. • Limited by the availability of specialized SMP powders. • It is difficult to create fine, multi-material parts.	• High Cost • Jetted materials can have limited long-term stability and mechanical strength. • The support material removal can be challenging for intricate internal multi-material structures.

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Application	• Self-tightening bone fracture plates. • Simple deployable structures. • Adaptive grippers.	• Vascular stents that expand at body temperature. • Micro-scale drug delivery capsules that open at specific pH. • Tissue engineering scaffolds with dynamic topographies.	• Self-fitting bone defect scaffolds that expand to fill a cavity. • Deployable aerospace components. • Customizable orthopaedic implants with tailored stiffness.	• Programmable self-assembling structures • Soft robotics with “binary” actuators (stiff/soft regions). • Anatomical models that simulate tissue movement.

Most of these methods suffer from support structures that are hard to remove, which is solved by 5D printing.

2.3 5D Printing: Multi-Axis and Curvilinear Fabrication

After adding two rotational axes, it is possible to print structures with curved layers and support-free structures with complex geometries. The most significant advantage of 5D printing lies in the fact that the printed components have isotropic strength [1,5]. This is because 5D printing deposits materials along continuous curved, paths, which follow the natural stress lines of the components, making these components up to 3 to 5 times stronger than their 3D-printed counterparts. This means that the component can withstand much higher pressure, shock, and fatigue loads without cracking or failing. This is crucial for applications that require withstanding heavy loads.

The printing head or build plate can be adjusted to an angle, enabling the printer to print the overhanging parts from the optimal position. Usually, a supporting structure can be omitted. The interface between the printing part and the supporting structure is usually rough and inaccurate, requiring additional grinding and subsequent processing. 5D printing does not require these steps.

5D printing can also eliminate the stair-stepping effect of 3D printing, as the nozzle can reach the sides of the print effectively, it can lay down materials parallel to the walls of the part, effectively smoothing the exterior and making the part more accurate.

2.4 6D Printing: Integration of Sensing and Functionality

The integration method of 6D printing and 5D printing is the same as that of 4D printing and 3D printing, enabling 5D printing to change over time [6-7]. To give 5D printing a time dimension, shape-memory polymers (SMPs) are implemented in the 3D printing of filaments, thereby manufacturing complex machines with sensing capabilities obtained from feedback mechanisms composed of multiple materials. This theoretical concept suggests that by using this technology, biomimetic “living systems” with regulatory functions can be created. And this could bring revolutionary changes if applied in organ transplants.

2.5 7D Printing: Integration of Sensing and Functionality

7D printing, a revolutionary technology that enables more efficient production processes, cost reduction, and development of complex, intricate products that traditional methods cannot achieve. Through this technology, it has transformed the manufacturing methods in various industries (e.g., healthcare, aerospace), capable of producing components that conventional techniques cannot achieve, while featuring flexibility, personalized customization, rapid prototyping, and lower resource/material use. This technology is also eco-friendly, minimizing waste in the manufacturing process [3]. In the food industry, it surpasses 3D printing, capable of creating complex edible designs and flavors, thereby achieving customized, nutritious, sustainable meals, remote production, and new entrepreneurial opportunities [8].

3. Cross-Disciplinary Applications

3.1 Biomedical Applications

Multidimensional printing systems have been widely applied in the biomedical field of soft tissues. 4D bioprinting can use intelligent and responsive materials to create deformable scaffolds. These scaffolds are flat when printed and can be accurately inserted into the correct position in a minimally invasive manner. Then, exposed to the correct pH value, they expand into their functional tubular shape, greatly simplifying this process [1]. Specifically, 6D printing combines commercial 6D robotic arms with sterilizable enclosures, such as high-efficiency particulate air (HEPA) filters, ultraviolet radiation (UVC) lamps and temperature control components. Using bioinks like gellan gum, collagen, and GelMA, complex geometries can be printed on uneven surfaces. By automating the production of human adipose-derived stem cell (ASC) constructs, cell survival and adipogenic differentiation can be ensured, demonstrating the potential of 6D printing in personalized and responsive biomedical applications, which can adapt to biological signals in real time [7].

3.2 Vascular Tissue engineering

Multidimensional printing (3D-6D) can precisely fabricate vascularized tissue scaffolds by adjusting mechanical/biological properties. Vascular networks are critical for the delivery of nutrients/oxygen. Current advancements include functional, cell-based, carrier-loaded, and biomimetic vascularized scaffolds. Their applications cover vascular/cardiovascular systems, skeletal muscles, and soft tissues. Challenges remain in achieving intelligent vascular regeneration, which requires progress in materials science, biosensing, and artificial intelligence (AI) integration for real-time adaptation and clinical translation [2].

3.3 Bone Tissue Engineering

In bone tissue engineering, multi-dimensional printing can be used to customize implants for patients to repair bone defects. Current methods have drawbacks. Autologous transplantation requires more surgical procedures and damages the donor site; Allografts always suffer from supply shortages and faces the risk of rejection; synthetic grafts lack bioactivity and strength. 3D/4D printing supports antibacterial scaffolds and bioinks (e.g., collagen, chitosan) [9-10]. 4D bioprinting can produce functional bone grafts, which can be printed in deformed states, expand after heating to fit its cavity, and have vascularization capabilities, thus enabling a rapid and painless healing process [2]. 5D/6D enhances the complexity of structure, responsiveness, dynamic scaffolds for infective bone defects in regenerative medicine [11]. capabilities, Antimicrobial peptides (AMPs) optimized by AI and smart materials improve infection control and personalized treatment [9]. Future research directions include hybrid bioprinting, real-time adaptive systems, and clinical translation in orthopedics to address current challenges in scaffold design and functional integration.

3.4 Cancer Research

In cancer research, 3D/4D printing technology can provide tumor microenvironment models that are consistent with physiological conditions, which are used to study disease progression, drug responses, and tissue interactions. The 4D temporal dynamics enable the tracking of changes over time [1]. Emerging 5D/6D printing and AI may be able to overcome current limitations and promote the development of more precise cancer diagnosis and treatment strategies [5].

3.5 Brain Disorders

Nanotechnology can improve drug delivery for brain disorders, including including tumors, stroke, Parkinson's Disease (PD), and Alzheimer's disease (AD). By using nanocarriers (NCs) for precise targeting, nanotechnology overcomes the problem of blood-brain barrier (BBB). Multifunctional nanotherapies reduce side effects and improve treatment outcomes. In this field, 3D to 6D printing technology has gradually been explored for improving treatment efficacy of brain disorders [1,12].

3.6 Drug delivery

6D printing combines 3D/4D structuring, AI, biosensing, and adaptive feedback to achieve dynamic and patient-specific drug delivery. Although it is still in the experimental and clinical validation stage, it can adapt in real time to physiological signals (such as pH value, temperature, biomarkers, etc.). The challenges include integration of biosensing and AI, material standardization, large-scale manufacturing, and regulatory barriers. Its transformative potential lies in promoting the development of personalized medicine through responsive and self-regulating systems, but practical application requires overcoming technical and clinical signals [6].

3.7 Foods and Supplements

Multi-dimensional printing (3D-7D) has revolutionized food technology, enabling the creation of personalized, complex edible structures and the control of the release of functional ingredients. 3D/4D printing technology can change shape/property over time. For example, boiled flat noodles can transform into a 3-Dimentional structure when stimulated by heat and water. This will make foods more convenient for transportation [3-4]. 5D-7D printing technology improves efficiency and reduces costs by minimizing support materials and optimizing processes. However, there are still challenges in commercialization regarding printability, scalability, and cost-effectiveness. Future development directions include intelligent, adaptive systems for real-time adjustments, extending shelf life through protective coatings, and the scalable production of sustainable, nutritious food systems. Additives like cyanidin and curcumin can react to microwaves, thereby visualizing the acidity or alkalinity of the food [8].

4. Trends, Challenges, and Future Prospects

Looking forward, smart materials library will encompass biocompatible polymers, recyclable plastics and high-strength composite materials, making material selection

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process in application scenarios intuitive and efficient. AI and machine learning algorithms can monitor the material selection and printing process in real time, thereby optimizing the 3D model of the multidimensionally printed prototype. A hybrid manufacturing mode will emerge where FDM and SLA technologies work together to manufacture functional components [13].

To achieve such a future, many obstacles still need to be overcome. Our current materials are unable to perform any operations beyond basic 4D printing, so we need many breakthroughs in the field of material science. The existing machines cannot achieve a smooth workflow, and the reliability issues also need to be resolved through extensive experimentation [13].

One of the main reasons why we can only print basic bone scaffolds at present is that biocompatible intelligent materials are also in short supply. Due to low demand and intense competition, the costs of biological materials and intelligent materials are persistently high, but with the commercialization of 4D bioprinting, this problem should be solved on its own [9].

5. Conclusion

The continuous development of additive manufacturing has led to the birth of numerous innovative technologies, and a paradigm shift in this field is necessary to adapt to these new technologies. These new tools will change fields such as healthcare, aerospace, electronics, food science, materials science, robotics, computer science, and life sciences. To see the impact of these new technologies, more collaboration and future breakthroughs are needed to transform this concept into technology.

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