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Recent 3D and 4D intelligent printing technologies: A comparative review and future perspective

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Abstract

Additive manufacturing (AM) is generally recognized as three-dimensional (3D) printing or rapid prototyping, which has evolved rapidly in numerous applications. In recent years, a new term has emerged as four-dimensional (4D) printing, which utilizes additive manufacturing methods to print stimulus-responsive products subjected to specific stimuli. 4D printing is generally regarded as the further evolution of 3D printing. In this review paper, recent major fundamentals and technology development between 3D and 4D printing are reviewed, including its features and latest findings. Comparative analysis and rating level are further compared and analyzed using SWOT analysis method. Moreover, some potential applications between 3D and 4D printing are involved, followed by its typical applications, advance trend, and future perspective.

Keywords: Intelligent printing; additive manufacturing; 3D printing; 4D printing; SWOT analysis; comparative analysis.

1. Introduction

Nowadays, manufacturing technology plays a vital role in economic growth, industrial application, scientific and technological progress. As technology rapidly advances, manufacturing technology has developed from the era of

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traditional manufacturing to an era of intelligent, high-efficient, sustainable manufacturing industry[1]. 3D printing technology was invented in the late 1980s, which is generally known as ‘additive manufacturing’ (AM) or ‘rapid prototyping’ (RP). 3D printing has rapidly garnered extensive focus and developed as an emerging manufacturing technology. Therefore, 3D printing has widely adopted in various fields, such as fashion jewelry[2], polymer printed textiles[3], robotics and automation[4], tissue and scaffolds[5,6], electronics[7,8,] and end-use products[9,10]. 3D printing has boosted the application fields according to its several characteristics, such as short-time process, low-cost, customization, and material reduction[11,12]. Furthermore, 3D printing technology is still in the active stage of industrial innovation, which could advance the manufacturing production mode and manufacturing maturity as revolution technology[13]. From a structural design perspective, 3D printing provides a high-efficient and more significant platform for designers to manufacture complex structures using this new technology, which is mainly used for engineering and fashion purposes.

However, the conventional 3D printing technology is used to fabricate static structures from commercial single or more filaments, which cannot meet the needs of dynamic structures and its relevant application such as soft grippers[14], self-assembled space antennae[15,] and self-healing polymers[16]. In order to solve this bottleneck issues, an innovative concept of printing technology has emerged as the term ‘4D printing’. The innovative idea of 4D printing was firstly introduced by Tibbit[17], which involved its definition and potential applications. Although it shows a similar name as 3D printing, 4D printing adds the fourth coordinates of time in addition to the traditional 3D coordinates. Therefore, it can regard 4D printing as giving the printed structure the capability to change its form or function with time under external stimuli, such as temperature, ultraviolet (UV) rays, pressure, or magnetic energy, etc[17-19]. Fig. 1 presents the schematic illustration of the 1D, 2D, 3D, and 4D concepts, which represents 1D as a curve line, 2D as a plane, and 3D as cubic structure. For 4D case, the 3D structure has transformed over time, and arrow points indicate the shape transformation direction[15].

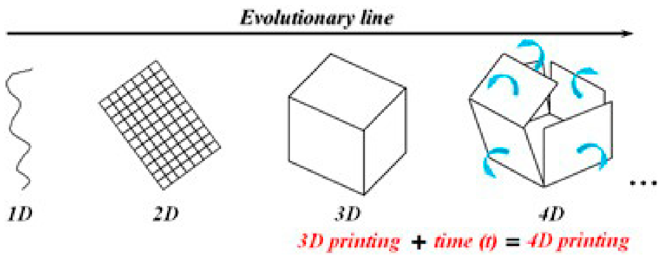

Fig. 1. Schematic illustration of 1D, 2D, 3D, and 4D concepts

In recent years, 4D printing offers advantages over 3D printing in several aspects, which mainly depends on the fast growth of smart materials and multi-material structures[20]. Compared to 3D printing, 4D printing updates the concept of change in the printed configuration over time, which relies on environmental stimuli. Therefore, 4D printed structures should be fully preprogrammed using time-dependent deformations of products[21]. The core element of 4D printing technology is smart material, which provides more flexible, expandable, deformable characteristics of printed product to response specific stimuli. The growing interest in 4D printing has been studied in responsive structures as soft robotics and printed actuators in medical devices[22], smart textile[23,] and aerospace[23]. The idea of 4D printing explores a new research area branch from additive manufacturing, which can provide more potential possibilities for both 3D and 4D printing technologies.

This paper aims to briefly review the fundamental aspects of 3D and 4D printing technologies, and it also offers SWOT analysis for both technologies. Moreover, comparative analysis between 3D and 4D printing is compared and summarized, which evaluates its mature level and development prospect, respectively. Also, the relevant application, as well as the future perspective of 3D and 4D printing, is discussed.

2. Technology fundamentals

2.1. 3D printing technology

The 3D printing technology is known as additive manufacturing, which is used for fabricating products in a consecutive layering sequence. 3D printing is mainly classified into solid, liquid, and power-based method, which is based on its input material. The solid-based pattern is comprised of fused deposition modeling (FDM), and the power-based pattern is comprised of selective laser sintering (SLS) and selective laser melting (SLM). The liquid-based pattern is comprised of stereolithography (SLA), digital light processing (DLP), direct ink writing (DIW), and inkjet[24]. Fig. 2 shows three example schematic overviews of 3D printing technology, which typical selected FDM, SLS, and SLA in several methods.

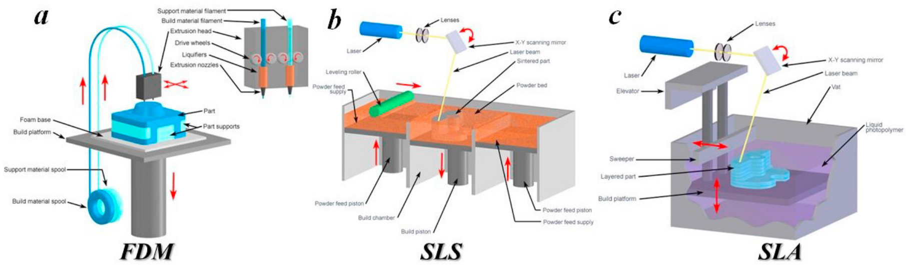

Fig. 2. General schematic overview of 3D printing technology with solid, liquid and power-based patterns (a) FDM; (b) SLS; (c) SLA (Sources: https://www.custompartnet.com)

Currently, there are almost 100 different available 3D printers in the market, which are small and affordable desktop 3D printers, respectively. There are several additive manufacturing methods, which use different input materials and functions. In order to deeply understand its characteristics of relevant methods, a brief overview, and a summary of relevant 3D printing methods are provided in Table 1. Moreover, SWOT analysis of 3D printing technology is briefly shown in Fig. 3(a), which demonstrates strengths, weaknesses, opportunities, and threats of 3D printing technology. It is highlighted that the SWOT analysis of 3D printing with different methods is useful to evaluate and point out its technical characteristics.

Table 1. The brief overview of relevant 3D printing methods

Methods	Status	Layer printing	Key features	Materials	Refs
FDM	Solid	Deposition of solid material	Low cost, clean condition	Thermoplastics (PLA, ABS, PU), composites	[25]
SLS	Power	Layer of powder	Softening particles, sintering	Metals and alloys, ceramics, polymers (PP), composites	[26]
SLM		Layer of metallic powder	Fully melting	Metals and alloys, ceramics, composites	[27]
SLA	Liquid	Liquid layer curing	Ultraviolet curing, high-resolution	Polymers, ceramics, composites	[28]
DLP		Liquid layer curing	No support structure, high-speed	Elastomers, metamaterials	[29]
DIW		Fluid layer curing	Self-supporting, thixotropic ink	Polymers, ceramics, waxes, polyelectrolytes, composites	[30]
Inkjet		Liquid layer solidifying	Multiple print abilities, complex structure, high-resolution	Werowhite, max, visijet M3, crystal, MED620, MED625FLX	[31]

Note: ABS: acrylonitrile butadiene styrene; PLA: polylactic acid; PU: polyurethane; PP: polypropylene

2.2. 4D printing technology

4D printing is an advanced evolution of the 3D printed structure, which can be changeable in terms of shape, property, and its functions over time. 4D printing can achieve self-assembly, self-repair, and multi-functional purposes, which provides time-dependent, predictable, reprogrammable properties. The concept of 4D printing mainly depends on five factors, which are 3D printers or equipment, stimulus-responsive material, stimuli, interaction mechanism, and mathematical modeling[32,33], as shown in Fig. 4(a).

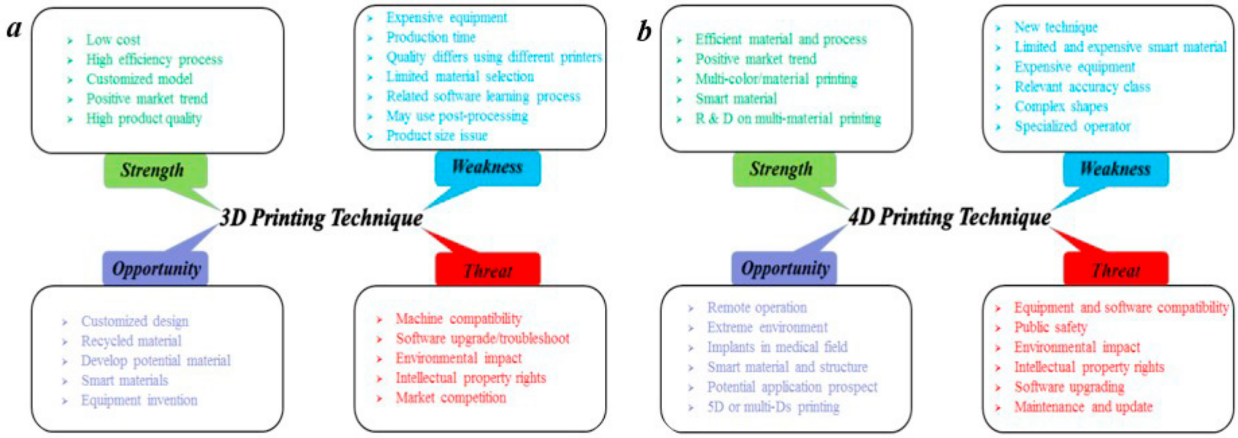

Fig. 3. SWOT analysis of a). 3D printing technology; b). 4D printing technology.

Recently, 4D printing is generally used inkjet, fused deposition modeling[34], stereolithography[35], and selective laser sintering[36]. It is highlighted that the dynamic function of 4D printed products mainly depends on the appropriate combination of smart materials such as smart nanocomposites[37], shape memory alloys, and polymers[9,38]. Smart material is the core technical point to advance 4D printing, which can transform a preprogrammed method to respond to the specific external stimuli. The use of smart materials in 4D printing has been advanced to date. Multi-functionality of shape memory polymers and shape memory composites have been studied, which reported explicitly in the aerospace sector[39].

Table 2. Typical overview and summary of smart materials used in 4D printing[40,41]

Materials	Stimulus	Response	Application
Smart metal alloys	Temperature	Shape	Motor actuators
Ceramics	Current	Resistance	Thermistor/overcurrent
Self-healing materials	Force	Force	Soft robotics, actuators
Polymer	Humidity	Capacity/resistance	Humidity sensors
Pyroelectric material	Temperature	Electric signal	Sensors
Polymeric gal	pH	Swelling / contracting	Artificial muscle
Piezoelectric material	Deformation/strain	Electric signal	Vibration sensors

Moreover, shape memory hybrids and composites are gradually emerging, which has significant potential in industrial applications under the rapid growth in 4D printing. Therefore, a typical overview of smart materials in 4D printing is summarized in Table 2, which refers to response function under the different stimulus and its application areas. Fig. 3(b) presents the SWOT analysis of 4D printing technology, which is used to evaluate its strengths and future outlook in the next several years.

2.3. Comparative analysis

3D printing offers a cost-effective technology to manufacture products, and 4D printing is an advanced technology of 3D printing, which has the capability to achieve multi-functionality, self-assembly, and self-repair. 4D printing applies similar technology to 3D printing, which adds one more dimension of transformation procedure over time. It is a new and advanced technology, which rapidly applied to numerous engineering fields. The main differences between 3D printing and 4D printing are shown in Fig. 4(b), which presents the printing process condition. 4D printing has added mathematics, stimulus, and interaction parts using smart material, which is mainly different compared to 3D printing.

It is significant to analyze and compare between the 3D printing and 4D printing technologies, which obtains characteristics of two technologies and market future. Table 3 exhibits the comparative analysis between 3D and 4D printing technologies, which involves printing method, material, design concept, equipment costs, related equipment, market trends, and its applications. On the other hand, it is also shown the evolution trend of 4D printing from 3D printing. 3D printing has significantly grown in recent years that could indirectly increase the market demands of 4D printing in the next decade. With the emergence of 4D printing and smart materials, it will have a significant impact on industrial sectors.

Table 3. Comparative analysis between 3D and 4D printing technology

Category	3D printing technology	4D printing technology
Printing method	Printing repeats a 2D structure lay by lay from bottom to top	Printing is the extension of 3D printing
Printer type	3D printer	Smart/multi-material 4D printer
Materials	Thermoplastics, ceramics, metals, paper, food, polymers, nanomaterial and biomaterials	Smart material, multi-material, self-assembled, self-actuating, and self-sensing material, shape memory polymers magnetostrictive and advanced material
Design concept	The 3D digital object (drawing or scanning)	3D digital object with deformation feature
Related equipment	Apparatus, material extrusion, and selective laser sintering	Modified nozzle, binder, and selective laser
Product flexibility	No	Yes, after printing in shape, color, various functions, and other conditions
Product state	Static structure	Smart, dynamic structure
Equipment cost	Low	High
Market outlook	Medium	Medium-High
Applications	Engineering and design, consumer products, education, aerospace, medical, robotics, military and defense, industrial goods, fashion, and others	Construction, medical, furniture, transportation, aviation, aerospace, biomedical device, soft robotics, and others

Table 4 exhibits the rating comparison of 3D and 4D printing technology, which compares with strength, weakness, opportunity, and threat rating level on both technologies. Considering four factors, 3D printing obtains a higher overall rating value, which depends on its available and mature process with reliable 3D printer companies, and it improves the market prospect in 3D printing industrials. Furthermore, it is significant to show that 4D printing as innovative technology will have numerous opportunities and potential market space, which should improve its existing weakness and threat factors.

Table .4 Rating comparison of 3D and 4D printing technology (Data source: [17])

SWOT factors	3D printing technology	4D printing technology
Strength	9	7
Weakness	7	6
Opportunity	8	9
Threat	7	7
Overall rating value	31	29

Note: 10 is the maximum rating value, and 1 is the minimum rating value

Based on the market analysis report from Marketsandmarkets, 3D printing market is increased with a compound annual growth of 28.5 %, and it is expected to obtain 30.19 million $ in 2022, as shown in Fig. 5. Considering future trends and scopes of the 4D printing market, it is expected to become commercialized in 2019. As the 4D printing technology is still in its initial stage, the global market of 4D printing is targeted to increase with compound annual growth of 42.5 %. It may reach $ 537.8 million, as shown in Fig. 5, which presents that 4D printing will have a better market trend and space compared to 3D printing.

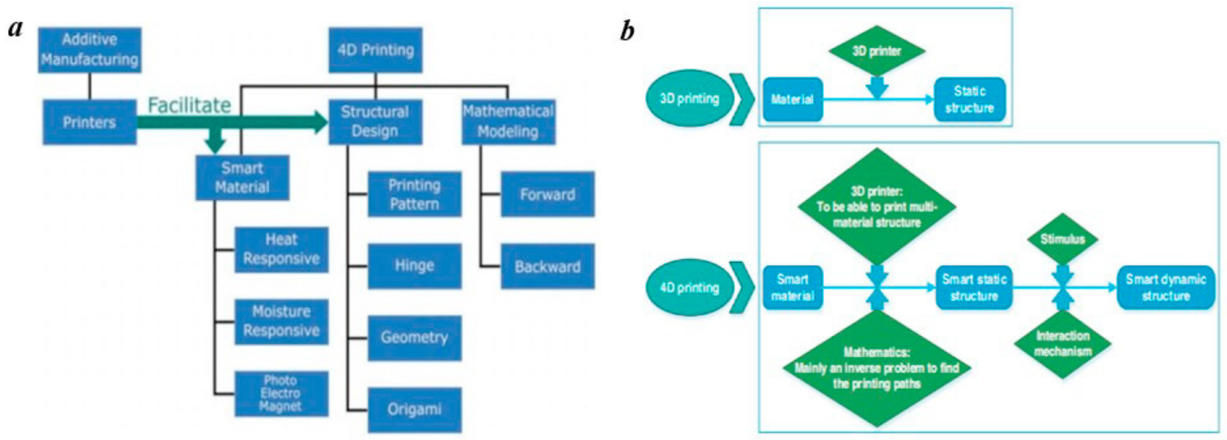

Fig. 4. (a). Research concept in 4D printing with five factors[33]; (b). The differences between 3D printing and 4D printing technology[15]

3. Application fields

3.1. 3D printing application

3D printing technology has widely applied in various areas due to it is low-cost, short processing time, highly efficient, customization and personalization characteristics, which refers to infrastructure, military & defence, building & construction, etc.[42] According to its applied fields, it is directly indicated that 3D printing technology and its products have commonly used in our daily life. Some typical examples are introduced as follows. For example, high-quality 3D printed replicas of cadaveric material were printed for teaching resources in education[43]. Recently, several findings have studied the use of 3D printing to produce bones, stem cells, blood vessels, tissues, organs, and drug delivery devices in the medical area[44-46].

Furthermore, the 3D printing technology has significant application potential in the military and defense sector, such as arms and weaponry parts, which provides much more self-dependent[47]. A brief description of the typical application in building and construction has been carried out by Skanska company and WinSun company[48]. Currently, 3D printing is being applied in the food areas such as military and space food, sweet food, which was firstly introduced in the food sector by researchers from Cornell University[49]. 3D printing is also used for sensor packaging, which is designed for infrastructure health monitoring as a new piezoelectric sensor[50]. Fig. 6 presents the 3D printed products used in the medical area, which creates a patient-specific model as a human-made implant organ. 3D printing technology could expand its contribution from medical research into practical application.

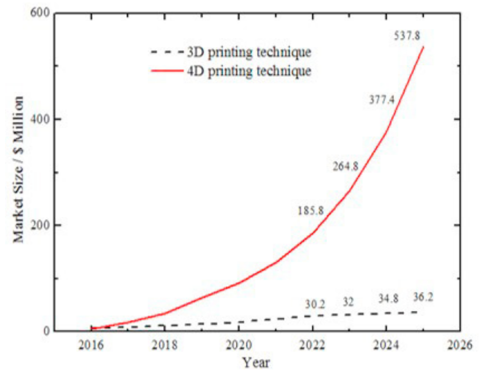

Fig. 5. Market size ($ million) analysis between 3D and 4D printing technologies (Data source: www.marketsandmarkets.com)

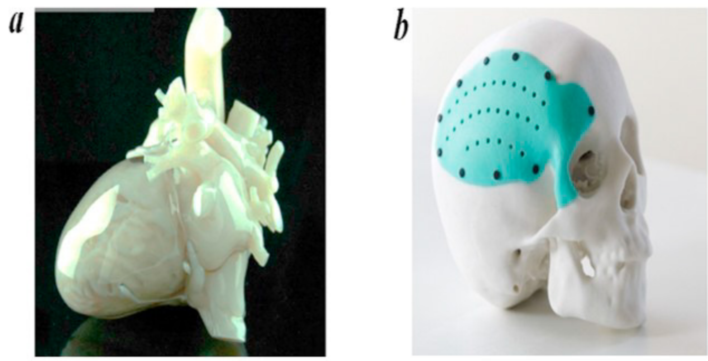

Fig. 6. 3D printed models in the medical area (a) 3D printed heart; (b) 3D printed skull (Source: https://3dprintingindustry.com/news; sketchucation.com)

3.2. 4D printing application

4D printing opens the door of new fields with potential applications, which depends on its structure, can be activated from one state to another under the relevant stimulus. It involves soft robotics, self-repair device, responsive structure, etc. Some typical examples are mentioned as follows. For example, the soft material structure is an essential element to implement new actuators in soft robotics, which can reversibly change its shape as programmed style to response the external stimulus[51]. 4D printed structures are also used and designed to self-repair purpose. Some relevant applications involve flexible self-healing pipes[52], self-healing hydrogels, which shows numerous advantages about recoverability, reusability, and recycling[53].

The use of 4D printing technology has widely applied in many different sectors. For instance, sensitive materials such as light-responsive it can also serve as 4D printing materials, which can be deformed under UV rays or sunlight[54]. The light-responsive materials can use in packing, aerospace structures, photovoltaic, and biomedical devices[17,55]. Furthermore, shape memory polymer (SMP) is mainly selected as the deformation of thermo-respective materials, which used to produce smart structures with self-assembly and self-folding functions[56,57]. Fig. 7 presents two examples of 4D printed objects, which are preprogrammed to subject to water condition and transform into other shapes, which shows the shape-shifting behaviors in 4D printing.

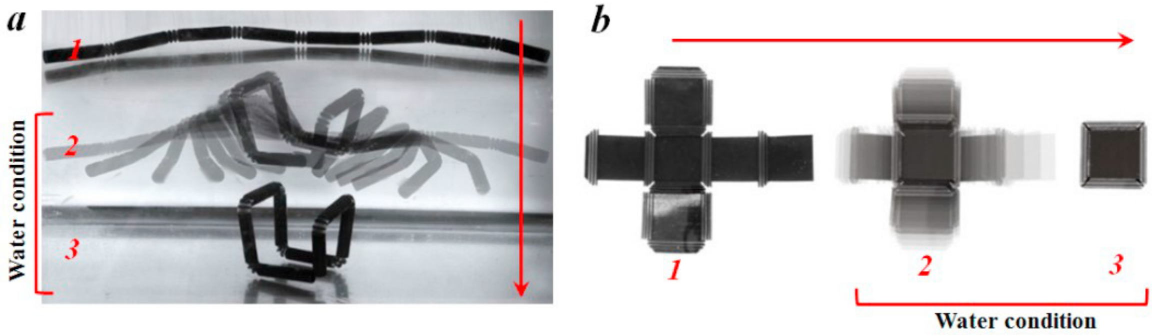

Fig. 7. The illustration of shapeshifting by self-folding using water absorption materials: (a) 1D to 3D[41]; (b) 2D to 3D[41]

4. Future perspective

Intelligent printing, although as a novel technology, has the potential to use in many potential areas. For 3D printing technology, it is limited in terms of materials for specific applications under extreme external conditions or environment such as biomaterials in medical application, which is still required further development of novel materials. Currently, available 3D printers of novel materials have challenged with the limited industrial application using single material.

Therefore, there are several challenges to advance the next generation of 3D printing technology, which is mainly listed as follows:

- Advance printing speed and resolution and reduce energy consumption and costs.
- Improve the printed product dimension accuracy, and scale size (e.g., nanoscale)
- Develop new 3D printing materials with superior properties
- Integrated 3D printing with other traditional process or multi-process technology (e.g., additive + subtractive technology) as hybrid or triple technology

For 4D printing technology, it is used smart materials to design and transform structural function. The used of 4D printing is increasing in the medical areas to fulfill the potential requirements. Smart materials have regarded as the cornerstone of 4D printing. However, it is still a challenging task in 4D printed structures, which could overcome in the future. In upcoming years, it could make tremendous contributions in medical, engineering, and other potential areas. It is a superior technology compared to traditional manufacturing process concerning with product quality and performance. Future perspective of 4D printing technology with some blank or insufficient areas is briefly listed as follows. In the future, additive manufacturing could make contributions to discover endless possibilities in unknown areas.

- Develop novel smart materials with advanced properties
- Apply to the implantable medical application as a mature technology
- Enhance its stimulus-responsive performance
- Research on self-controllable function such as self-growing and self-reacting
- Improve printed product lifespan, recycle cycle times and preprogrammed cycle capability
- Explore printed product structural complexity

5. Conclusion

Intelligent printing manufacturing is developed as an advanced technology compared to conventional manufacturing technology, which is known as 3D and 4D printing technologies. 3D printing technology has used to produce static structure in 3D coordinates, and 4D printing is regarded as a state-of-art technology of combing smart material and 3D printing technology. In recent years, 4D printing has emerged and gained attention according to its structural response over time under environmental stimuli. This review paper provides a basic understanding of the fundamentals of 3D and 4D printing technologies, which involves its concept, development trend, and recent research findings. 3D and 4D printing technologies are comparatively analyzed using SWOT method, which presents its strength, weakness, opportunity, and threat.

Furthermore, comparative analysis between 3D and 4D technologies has been compared and summarized, which refers to the processing method, material, equipment costs, related components, and market trends. In this paper, it is also reviewed the relevant applications on 3D and 4D technology, which shows commercial and industrial development in the current situation. Future perspective of two technologies has been discussed, which indicates that the 4D printing technology can be utilized in various potential applications such as medical treatments, soft robotics, and other unknown fields in engineering fields.

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