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3D and 4D Printing as Integrated Manufacturing Methods of Industry 4.0

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Abstract: 3D printing, also known under the term additive manufacturing, is a technology that allows the creation of complex and highly detailed objects using a digital model and a number of materials, such as plastics, metals, and ceramics. 4D printing is an expansion of 3D printing that incorporates time, meaning that the material used in 3D printing can change shape or properties over time. This technology is becoming increasingly important in the context of Industry 4.0, characterized by the Integration of cutting-edge technologies, including artificial intelligence, the internet of things, and advanced robotics into manufacturing processes. In Industry 4.0, 3D and 4D printing is being used to create customized products, improve supply chain efficiency and reduce costs and lead times. Additionally, 3D and 4D printing is also being utilized in sectors like aerospace, regenerative medicine and dental, and automotive to create complex geometries and parts that would be challenging or impossible to create using conventional production techniques. Furthermore, 4D printing opens up new opportunities in emerging, novel, sectors where the ability to create materials that adapt and change over time can be highly beneficial.

Keywords: 3D Printing, 4D Printing, Smart Materials, 4th Industrial Revolution, Industry 4.0

Introduction

3D and 4D printing are considered to be integral manufacturing methods of industry 4.0. Industry 4.0, also known as the fourth industrial revolution, is defined by the use of cutting-edge technology such as the Internet of Things (IoT), Artificial Intelligence (AI), and advanced manufacturing methods to optimize and automate industrial processes (Tsaramirsis *et al*., 2022; Dalenogare *et al*., 2018). Both 3D and 4D printing techniques are considered to be enablers of Industry 4.0, as they allow for the creation of customized products, faster prototyping and product development, and the ability to optimize and automate industrial processes. These technologies can also be integrated with other advanced technologies, such as IoT and AI, to create a more efficient and productive manufacturing process.

Three-Dimensional (3D) printing technology, commonly known as Additive Manufacturing (AM), has lately garnered attention due to its potential for broad usage in applications ranging from consumer electronics to aircraft equipment. 1983 saw the invention of the first 3D printer by Charles W. Hull, co-founder of 3D systems, despite the fact that 3D printing technology has just lately surfaced as a trending topic (Kantaros *et al*., 2022a; Kantaros and Piromalis, 2021a).

With the expiration of several significant 3D printing patents owned by stratasys Inc. and 3D systems Inc., new and expansive applications and markets for 3D printers have emerged swiftly. Users can construct or modify 3D printers on their own, or they can use the rapidly rising availability of inexpensive 3D printers. The recent availability of highly competent 3D design software and 3D design websites (e.g., Shapeway and Thingiverse) enables the sharing of user-created, free 3D digital design files or models, leading to wider access to 3D printers and the expansion of the 3D printing industry. Compared to typical manufacturing methods such as casting, machining, and drilling, this method is more efficient. 3D printing is considered an energy and material-efficient process, using up to 90% of resources and saving up to 50% of energy (Gibson, 2017; Kantaros *et al*., 2021).

3D printing has come to enable a convergence of technologies and applications, including sports equipment, food packaging, and jewelry, as well as items in high tech industries such as aerospace, regenerative medicine, architecture, education, and the automobile industry, among others (O'brien, 2011; Żukowska *et al*., 2023; Han and Chang, 2023; Gregory *et al*., 2023; Jiang *et al*., 2023; Kantaros *et al*., 2016; Kantaros and Diegel, 2018; Kantaros and Piromalis, 2021b; Montusiewicz *et al*., 2022; Kantaros, 2022a-b).

Nevertheless, 3D printing has certain limitations (Kantaros and Karalekas, 2013; 2014; Mazlan *et al*., 2023; Ćwikła *et al*., 2017; Torres *et al*., 2015; Kantaros *et al*., 2013; Stansbury and Idacavage, 2016). It solely takes into account the initial shape of the pre-designed geometry, which is immovable and static and is thus unsuited for dynamic settings. The solution to the emergence of stimuli responsive materials is four-Dimensional (4D) printing in dynamic environments where printed objects must interact in a predetermined manner with them (Chu *et al*., 2020; Mahmood *et al*., 2022; González-Henríquez *et al*., 2022; Tamay *et al*., 2019; Ding *et al*., 2017; Ge *et al*., 2014). It integrates the notion of time with 3D printing. Responding to external environmental stimuli, 4D printed objects gradually alter their appearance or function (physicochemical and biological) In conclusion, 4D printing is the addition of a fourth dimension (time) to 3D printing, which provides tremendous possibilities for fabricating objects with the required properties. Figure 1 depicts a comparison of 3D and 4D printing processes.

The table show the major differences concerning 3D and 4D printing processes.

Accordingly, in reaction to stimuli such as heat, water, electricity, or light, 4D printing allows printed objects to alter their form or function over time. The use of intelligent design or responsive materials to produce time dependent deformations of things is the primary distinction when comparing 4D and 3D printing.

Four-dimensional printing adds the time factor contribution to the 3D printed products, hence elevating the significance of the creative process. 4D printed structures must be rigorously pre-programmed using the process of altering controlled smart materials with time dependent material deformations.

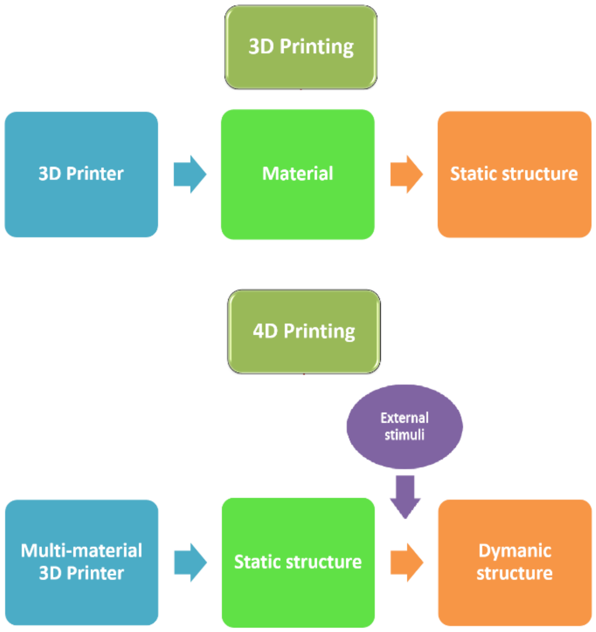

Fig. 1: 3D printing vs. 4D printing process

Nevertheless, the selection of materials for 4D printing is critical, as most 3D printing materials are designed to produce only rigid, static objects. Recently, smart shape alloys and polymer memory materials with self-assembling properties induced by heat, ultraviolet light, or water absorption have been created.

At an MIT symposium, professor Skylar Tibbits first introduced the term "4D printing." He describes 4D printing as "the use of a 3D printer to create objects that can change shape while being simultaneously removed from the 3D printer." In other words, 4D printing is just 3D printing with Shape-Memory Materials (SMM) (Tibbits, 2014). This SMM responds to environmental stimuli and is capable of morphing over time, resulting in the modification of some material properties and the addition of a fourth dimension, time. The vast majority of contemporary research efforts focus on the ability of 4D printed things to change form, such as folding, extending, twisting, and creasing.

For instance, a temperature sensitive Thermal Polyurethane (TPU) filament can contract or expand in reaction to particular temperatures. Additionally, multi-materials with distinct environmental characteristics are useful for 4D printing. Researchers from the Massachusetts institute of technology printed transformable structures using two distinct materials with distinct porosities and water absorption capacities. On one side, on one side, it was made from a porous, water absorbent substance, and on the other, a stiff, water-resistant material. When exposed to water, the water-absorbent side of the material grew while the opposite side stayed unchanged, resulting in form distortion (Siddique *et al*., 2022).

4D printing also features a number of disadvantages that are mostly attributed to its infancy. One of the primary disadvantages of 4D printing is the limited availability of suitable materials. Currently, only a small number of polymers can be used in 4D printing and they feature high cost. Another drawback is the complex process of programming the transformation of the printed object. It requires a detailed understanding of the material properties and the specific manufacturing process used. Additionally, 4D printed objects may not be as strong or durable as those made using traditional manufacturing methods. Owing to its intricacy, 4D printing is still in its infancy and it is probable that further study will be required to overcome these constraints.

Technological Methods Categorization for 3D and 4D Printing

The 3D and 4D printing technologies are subdivided into several printing processes based on the materials used. The selection of materials has an immediate effect on the mechanical or thermal characteristics, as well as the transformation stimuli, of the final products. This section focuses on the three most prominent forms of 3D and 4D printing, as well as the most often used materials for these processes.

Stereolithography (SLA)

SLA operates under the working principle of a UV or visible laser light that is guided onto liquid photopolymer resins. In order to manufacture each layer, a laser beam solidifies resin by illuminating a 2D cross section of the item in a vat of resin. The item has then lifted a distance equal to the layer thickness in order to maintain contact with the object's base and fill it with resin. This process is repeated until the complete model is created, at which point the platform is taken from the vat and excess resin is drained. After cleaning and curing under UV light, the SLA object is complete. Due to the use of liquid photopolymers, SLA generates a smoother surface on the end product compared to other 3D printing methods.

Although SLA can manufacture a wide variety of shapes, it has a number of drawbacks, including the necessity for extensive cleaning after manufacturing and the production of significant amounts of resin waste. In addition, the method is confined to epoxy or acrylic based resins, the majority of which shrink following polymerization. SLA printers can achieve greater resolution and a more complicated structure for photo cross-linkable materials (Li *et al*., 2022; Valencia *et al*., 2022; Karatza *et al*., 2022). Figure 2 depicts a schematic of the SLA 3D printing method.

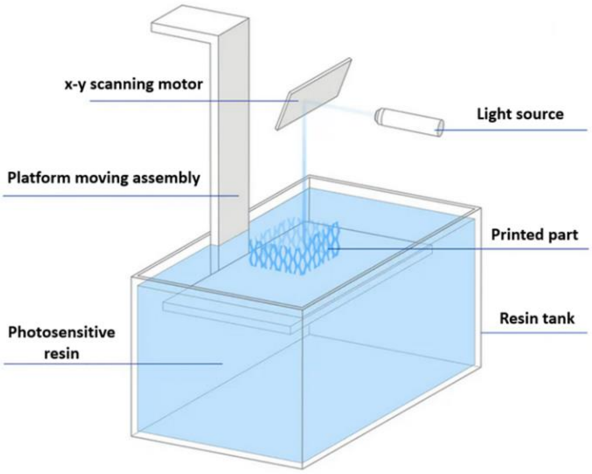

Fig. 2: SLA 3D printer schematic

Fused-Deposition Modeling (FDM)

The FDM process creates three dimensional structures by extruding thermoplastic materials and depositing the semi-molten materials layer by layer onto a platform. The thermoplastic filament is introduced to an extruder that feeds and retracts it in precise quantities. Two rollers force the molten filament into the extrusion nozzle tip, which is heated to the melting point by a heater block. As the print head attributes the design of each cross-sectional layer of the intended structure, a digitally positioned mechanism deposits the extruded filament. The platform is then moved to the Z location based on the setting for layer thickness. These processes are repeated until the 3D structure is constructed (Hassanien *et al*., 2023; Bandinelli *et al*., 2023; Buzko *et al*., 2023; del Barrio Cortés *et al*., 2022).

Figure 3, a major advantage of FDM is the range of filament materials that are available. Acrylonitrile Butadiene Styrene (ABS), nylon, Polyethylene Terephthalate (PET), Thermal Polyurethane (TPU), Polyoxymethylene (POM), Polycarbonate (PC), High Impact Polystyrene (HIPS) and Polyvinyl Acetate (PVA), among others, are among the commercially available FDM filaments with varying strength and temperature properties. In addition, some materials can be utilized as source material for blending with other functional materials to enhance particular functions. As demonstrated in Fig. 3, the Polylactic Acid (PLA) filament is a popular option due to its wide range of possible qualities. Several FDM filaments can be utilized as 4D materials when the temperature is applied to them because of their thermoplastic properties. Figure 3 depicts a schematic of the FDM 3D printing method.

Powder Bed and Inkjet Head 3D Printing (PBP)

PBP is a modification of the inkjet printing method. First, a layer of powder is put and rolled to ensure uniform thickness. Next, the inkjet print head drips the binder in a specified pattern as it travels across the bed of powder to create a single layer of a printed object. The process is repeated until the powder binds to the layer beneath it. Due to the ease of removing unbound powder with an air pistol after solidification, PBP does not require support structures. Several print heads combined with colored binders provide full-color printing (Ameddah and Mazouz, 2021; Xu *et al*., 2021).

Due to its capacity to react with water-based binders, Calcium Sulfate ($CaSO_4$) is among the most commonly used powders. It can rapidly react with solutions containing water and solidify into gypsum ($CaSO_4\ 2H_2O$). This method determines the physical and chemical properties of the printed device based on the binding strength. Consequently, powder and binder combinations must be carefully studied. Figure 4 depicts a schematic of the PBP 3D printing method.

3D Printing Applications

More specifically, an increasing number of institutions are incorporating 3D printing techniques into their curriculum. Students are better prepared for the future since they can create prototypes without needing high-cost equipment, which is one of the educational benefits of 3D printing. Students gain knowledge about the uses of 3D printing by creating and fabricating tangible models. 3D printing closes the gap between ideas and pictures on paper or in a computer and their physical, three-dimensional realization.

3D printers are becoming widespread in schools and public libraries. Students are permitted to utilize 3D printers in class and for projects at universities. Companies such as MakerBot provide educators and students with certification courses in 3D printing applications. In addition, 3D printing tools are transforming STEM education by allowing students to create low-cost quick prototypes in the classroom and low-cost, high quality scientific equipment using open hardware designs. Students explore design, engineering, and architectural principles in order to gain knowledge of a variety of 3D printing applications. They are able to reproduce museum objects, such as skeletons and historical artifacts, to study in the classroom without the risk of harming fragile collections. They can obtain a fresh, three-dimensional perspective on topographic maps. In this context students in the field of graphic design are able to develop intricate models with ease. In science classes, students can construct and examine human organ cross-sections. and other biological specimens. Molecules and chemical compounds can be recreated in three dimensions by chemistry students (Tramonti *et al*., 2023; Achilli *et al*., 2022; Ananias and Gaspar, 2022).

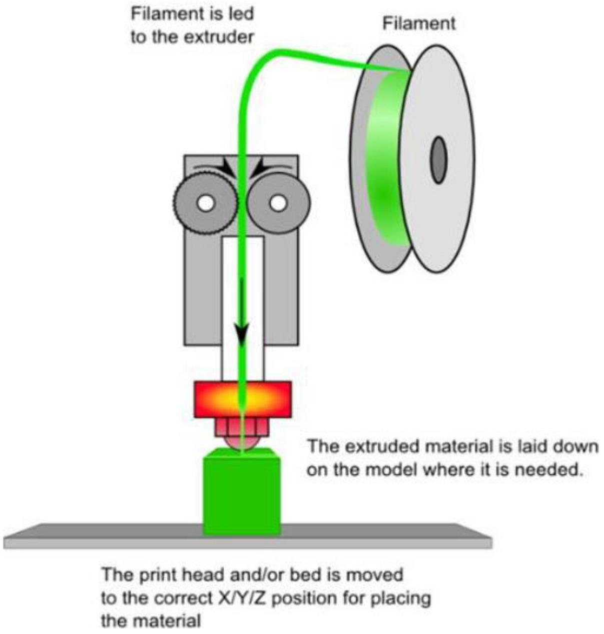

Fig. 3: FDM 3D printer schematic

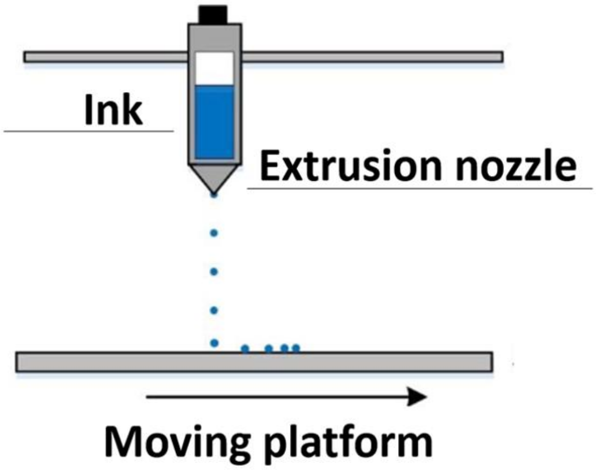

Fig. 4: PBP 3D printer schematic

Instead, 3D printing technologies have played a significant role in the sectors of rapid prototyping and customized production. Initially, 3D printing was intended as a faster approach for prototyping. A typical injection-molded prototype could cost hundreds of thousands of dollars and require several weeks to produce a single mold. This is an extremely impractical strategy if your goal is to enhance the design with each iteration. Traditional manufacturing requires weeks to produce a prototype, but with 3D printing technology, prototypes can be produced in hours for a fraction of the price. The automobile and aerospace industries are two major paradigms of sectors that benefit from developments in 3D printing technologies (Lim *et al*., 2016; Nichols, 2019; Chinthavali, 2016).

At increased production levels, conventional production is the most cost-effective approach. In situations when a product is not meant to be produced in large quantities, 3D printing is ideal since it enables the fabrication of a product in much smaller quantities or on an individual basis for a very low cost. Similarly, advances in Rapid Prototyping (RP) technology have led to the development of materials and processes, such as Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS), which are capable of the fabrication of end-use products, not just prototypes.

With the prevalence of cloud computing technology in the present day, there are currently companies that offer cloud-based additive manufacturing services, enabling consumers to create remote parts and objects without incurring the expense of purchasing a 3D printer. Consumers may now personalize objects using easy web-based design software and order their own customized products, made out of a 3D printer. The emergence of the digital twin's concept assists in this context (Kantaros *et al*., 2022b; Piromalis and Kantaros, 2022; Kantaros and Piromalis, 2022; Debroy *et al*., 2017; Mukherjee and DebRoy, 2019).

In the medical field, numerous 3D printing applications have emerged in recent years. These range from bioprinting, where biomaterials such as cells and growth factors are mixed to create tissue like structures that resemble their natural counterparts. 3D printed artificial prosthetics highlight the adaptability of 3D printing. Customized prostheses are complex and expensive to manufacture. Customized prosthetics can be produced and printed at a fraction of the cost using 3D printing. In the past, children in need of a prosthesis were required to wait before receiving one to ensure that they would not outgrow it. Today, a prosthetic may be 3D printed for them every few months. In some third-world nations, prosthetics were not considered affordable; nonetheless, 3D printed prosthetics now are becoming available (Tappa and Jammalamadaka, 2018; Chia and Wu, 2015).

Bioprinting permits the 3D printing of artificial organs, which limits the chances of organ failure problems in patients, which is vital for the patient, his or her family, and the healthcare system. As a cost effective and ethical method for identifying the adverse effects of medications and establishing safe dosages, 3D printed tissues have been developed for pharmaceutical research. Using the 3D printing method of Binder jetting, it is possible to make pills. Utilizable for treating conditions such as epilepsy, the approach enables the tablets to be very porous, allowing for large doses in a single pill that may be absorbed and digested quickly and efficiently (Daly *et al*., 2021; Mandrycky *et al*., 2016; Ozbolat *et al*., 2016).

In the sector of building construction, 3D printing offers a number of technologies that rely on 3D printing as the major technique for producing structures and construction components. In construction, 3D printing uses include the extrusion of well-known materials such as concrete and cement, powder bonding, and additive welding. 3D printing has several uses in the domestic, commercial, industrial, and public sectors of the building business. These technologies allow for more complexity and accuracy, faster building, cheaper labor, greater functional integration, and less waste (Sakin and Kiroglu, 2017; Tay *et al*., 2017).

In 2017, the first residential construction constructed in Yaroslavl, Russia, was completed. Totaling 298.5 square meters, 600 wall elements were printed in a store and installed on-site, followed by the completion of the roof structure and interior decoration (3213 sq ft). This is the first time anyplace in the world that the entire technical cycle, including design, construction permit, registration, and the connection of all engineering systems, has passed building standards (Hanna Watkin, 2017). The building was not designed for purely aesthetic reasons; a typical family now resides there. During the 1990s, 3D printing with concrete has been developed as a faster and more cost-effective method for creating buildings and other structures. Large scale 3D printers capable of producing concrete can be used on site to pour foundations and build walls. In addition, they can be utilized to print modular concrete components that are afterward assembled on-site.

In 2016, the first 3D printed pedestrian bridge was manufactured in Madrid's Alcobendas neighborhood (Rich, 2023). It was printed at 12 m (39 feet) in length and 1.75 meters (5 feet) in width using micro reinforced concrete (5.7 ft). The bridge was developed using parametric and computational design, which allowed for the optimal combination of lightweight and structural performance. As the first large scale public show of 3D printing technology in the realm of civil engineering, it was a landmark achievement for the global construction industry.

3D printing is used to generate architectural models, allowing for a faster turnaround of the scale model and increasing the overall speed and complexity of objects produced. It is being investigated as a means for constructing extraterrestrial habitats, such as those on the moon or Mars. Utilizing 3D printer technology for building construction, it has been selected to construct lunar habitat structures with artificial inflatable dwellings for sheltering human residents within the hardshell lunar structures. These dwellings would only require 10% of their structure to be transported from Earth, while the rest 90% would be comprised of lunar raw materials (Abbud-Madrid, 2021).

Surprisingly, the art and jewelry sectors have adopted 3D printing technology. With 3D printers, jewelers are able to explore concepts that would, otherwise, be impossible with conventional methods. Utilizing 3D printing materials such as thermoplastics and precious metals in raw material forms, it is possible to produce unique, one-of-a-kind jewelry pieces or customized items at a much lower cost. 3D printing has inspired artists worldwide. Particularly utilizing 3D printers using metal powders as raw materials, artists can now create intricate artworks (Yap and Yeong, 2014; Pasricha and Greeninger, 2018).

The enigmatic and renowned British street artist Banksy, whose works have been turned from 2D-3D via powder binding 3D printing, is a paradigm of the successful use of 3D printing technology in the art sector (Hanna Watkin, 2015). The Dutch artist Oliver van Herpt uses 3D printing to produce ceramic vases (Michelle, 2018). Gilles Azzaro, a computer artist, makes the intangible apparent by making 3D representations of voices from their sound waves (Lakshmi, 2023). Last year, the Prado Museum hosted a display of 3D-rendered artworks by renowned painters. The objective was to enable visually challenged individuals to touch previously inaccessible works (Tissen and Sharma, 2022).

4D Printing Applications

The idea of a pre-programmed smart item (manufactured from smart materials) appears to have numerous applications across industries. Major industries like automotive, healthcare, consumer goods, and aerospace are predicted to be major users of 4D printing technology. In the near future, however, the potential of 4D printing is expected to impact other important industries, including electronics, construction, industrial, etc., (Kuang *et al*., 2019; Zhang *et al*., 2019; Javaid and Haleem, 2019).

In the aerospace field, NASA utilized 4D Printing technology in order to develop a futuristic textile that is constructed of metal, yet it can fold and change shape, protecting the wearer (or the covered vessel) from collisions that may tear holes in people or ships. The surface of the woven metal is composed of squares that are connected on the back, but the entire system may be manufactured at once due to intelligent production (rather than stitched together) (Ntouanoglou *et al*., 2018). By sending 4D printers into space, astronauts would be able to recycle and reconstruct the material for various applications on demand. This multifunctional cloth, created by the jet propulsion laboratory, offers thermal protection characteristics and can keep machinery and people warm. Despite its flexibility, the mail has a high tensile strength and, depending on which side faces outward, can reflect or absorb light for heat regulation.

In addition, using 4D printing, airbus and the MIT self-assembly printing lab have developed a programmable carbon fiber intake component for the aviation industry. The component's construction material is programmable carbon fiber. This automatically adjusts to regulate the airflow, which in turn allows the aircraft engine to cool. The benefit of this innovation is that it can replace heavy mechanical control systems while also cutting fuel expenses (Jennifer, 2020).

In the sector of regenerative medicine, however, the use of 4D printing has been described for unique applications. 4D printing has the potential to transform regenerative medicine by enabling the fabrication of living tissues and organs with the ability to alter their shape or qualities over time. Some applications of 4D printing in the aforementioned sector might include the following:

- Tissue engineering: 4D printing could be used to create living tissue structures, such as blood vessels, skin, or muscle, that could be used to replace damaged or diseased tissue in the body (Tamay *et al*., 2019)
- Scaffold free organ printing: 4D printing could be used to create functional organs, such as hearts, livers, or kidneys, using a patient's own cells, eliminating the need for scaffold materials (Langford *et al*., 2020)
- Smart implants: 4D printed implants, such as artificial joints or heart valves, could be designed to change shape or properties over time, potentially extending the life of the implant and reducing the need for revision surgeries (Sahafnejad-Mohammadi *et al*., 2022)
- Self-healing materials: 4D printed materials for medical applications could be designed to self-repair small tears or damages, potentially extending the life of the implant or scaffold (Wang *et al*., 2022)
- Adaptive stents: 4D printing could be used to create stents that can adapt to changes in the body, such as expanding or contracting to fit the size of a blood vessel (Lin *et al*., 2020)
- Drug delivery systems: Potentially increasing the efficacy of therapies, 4D printing could be utilized to construct medication delivery systems capable of controlled drug release (Tran *et al*., 2022; Aversa *et al*., 2016c)

These are examples of the potential applications of 4D printing in regenerative medicine found in published literature and as the technology develops, it is likely that more and more creative uses will be found. However, it's worth noting that 4D printing technology is still in its infancy and it will be some time before it is utilized in clinical applications.

In the automotive industry, several specialists are intrigued by the self-inflating tire invented by BMW in partnership with MIT (Table 1). The silicone material that inflates in response to air pulses may represent the future of pneumatics. More specifically, in 2019, BMW announced that they had partnered with the Massachusetts Institute of Technology (MIT) to develop a self-inflating material. The material is made up of a flexible polymer that can be 3D printed and then inflated by an internal mechanism, such as a pump or a chemical reaction. This technology could be used to create car parts that can adapt to changes in temperature or pressure, such as air conditioning systems or tires. It could also be used to create inflatable structures for temporary housing or emergency shelters (Sophie Seidenath, 2018).

Table 1: Fundamental differences concerning 3D and 4D printing processes

Description	3D printing	4D printing
Dynamic shape change	No	Changes in shape, color, function, etc.
Materials used	Thermoplastics Metals and alloys Biomaterials and gels Nanomaterials	Smart materials like Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs)
3D printer type	SLA, FDM and SLS 3D printers'	SLA and multi material printers

Other fields, like fashion and apparel production, have also seen the use of 4D Printing technology. 4D printing can transform the fashion business by enabling the fabrication of clothes and accessories with shape or property changing capabilities. Examples of potential applications in this sector include the following:

- Smart clothing: 4D printed fabrics could be designed to respond to changes in temperature, humidity, or even the wearer's body movements, potentially creating "smart" clothing that can adjust to the environment or the wearer's needs (Leist and Zhou, 2016)
- Customizable clothing: 4D printing could allow for the creation of garments that can be customized to fit the wearer perfectly. For example, a 4D printed dress could expand or contract to fit the wearer's body shape (Leist and Zhou, 2016)
- Self-repairing clothing: 4D printed materials could be designed to self-repair small tears or damages, potentially extending the life of the garment (Choi *et al*., 2015)
- Adaptive clothing: 4D printed clothing could be designed to adapt to different weather conditions, such as becoming more insulated in cold weather or more breathable in hot weather (Leist *et al*., 2017)
- Inflatable clothing: 4D printed clothing could be designed to inflate and deflate, creating new ways of styling (Leist *et al*., 2017)
- Self-cleaning clothing: 4D printed clothing could be designed to self-clean, potentially reducing the need for frequent washing (Karagoz *et al*., 2021)

Conclusion

The technique of three-dimensional printing is very adaptable and efficient in terms of design, manufacture, and applications (Petrescu and Petrescu, 2019; Petrescu *et al*., 2017; Aversa *et al*., 2016a-b). In the future, 4D printing may be of immense importance due to its potential to transform industries related to manufacturing. Some of the key metrics that may be measured in 4D printing include the success rate of shape-shifting, the precision of the printed object, and the strength and durability of the final product. Additionally, factors such as the cost of materials and the time it takes to print an object may also be considered. However, further development of the technology is necessary before it can replace conventional manufacturing methods.

Current 4D printed structures are limited to simple deformations, like folding and self-assembling, which is insufficient for therapeutic bone tissue applications. Future research should concentrate on enhancing the complexity of shape change and the accuracy of resolution control. The mechanical properties of printed structures have drastically degraded as a result of frequent folding and unfolding. Nevertheless, the mechanical strength of printed structures is sometimes insufficient to withstand high pressures. Potential obstacles also include the manufacturing of deformable, replicable materials. It is projected that the practical application of 4D printing will increase greatly as the scientific sectors of material science, hardware technology, simulation, and cyber-physical systems advance. Future research in the aforementioned printing technologies is vital for advancing materials, printer systems, and product markets, among other essential areas.

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Antreas Kantaros: Written, edited.

Theodore Ganetsos and Dimitrios Piromalis: Conceptualization, edited.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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